

**Framework for Sustainability Assessments
providing a basis for evidence-based
and goal-oriented decision making support**

Based on the example of Electric Power Systems

Dissertation

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Preface and acknowledgements

There is little doubt that electricity has become an indispensable ingredient for modern societies to thrive and to secure our individual well-being. Today, the vast majority of our daily activities are powered by this invisible yet powerful resource: Heating systems ensure that we get through cold winters comfortably while other mammals have to resort to hibernation, refrigerators ensure that the shelf life of perishable food is prolonged until we feel like consuming it and modern ovens allow hot meals to be prepared without the chore of first collecting firewood. Moreover, we draw information on the latest news and communicate with our loved ones whenever and wherever we please with just a few clicks on our computers or smart phones. Furthermore, electricity ensures that key institutions can deliver critical services to the public, such as hospitals in making diagnoses and delivering treatments, or manufacturing industries that produce and deliver goods to their ever-growing consumer base. Clearly, we would find it very difficult to live our lives without electricity and the freedom it grants us.

In order to enable this energy supply, we build sophisticated power infrastructure and operate electrical devices that fundamentally alter natural energy and material flows on planet Earth; the combustion of fossil fuels, for example, is perceived to be a main driver of anthropogenic global warming and the cultivation of biofuels is causing unparalleled deforestation and soil erosion. Moreover, hydroelectric dams distort ecosystems and deprive river basins of vital sediment or freshwater, while nuclear power plants expose human populations to catastrophic risks and cause nuclear waste that requires storage in deep geological repositories for a very long time.

Against this backdrop, some scholars and political leaders are concerned that current power consumption patterns in industrialised countries may render future generations unable to meet their needs. This begs the question: How can we further improve the current level of well-being in industrialised countries without eroding the ecological capital of planet Earth? There are many potential answers to this question. One response often suggested is that such a way should meet the requirements of sustainable development (SD). The guiding principles of SD are, however, considered to be too ambiguous to operationalise and have given rise to a wide range of interpretations. The conception of SD can, however, be structured into three distinct dimensions:

- i) **Normative features of SD.** The guiding principles of SD express overarching objectives that seek to promote development for current generations and

safeguard a productive environment for future generations. What should be sustained, however, remains unclear.

- ii) **Instrumental aspects of governance.** Since pursuing business as usual is thought to impede opportunity spaces for future generations, an active mode of governance to operationalise SD is required. There is, however, little agreement on how such transitions should be conducted.
- iii) **Functional components of key systems.** To meet SD requirements, key systems will have to be transformed. Owing to fragmented responsibilities and system knowledge distributed across a wide range of actors, this calls for collective action to mutually grow understanding of the system.

Against this backdrop, it becomes apparent that additional research is required in order to operationalise the guiding principles of SD. With this thesis, I strive to contribute a more holistic and transparent framework for sustainability assessments that integrates the above dimensions. It strives to provide a comprehensive basis for evidence-based and goal-oriented decision making by determining relevant categories and enabling an evaluation of system data against predefined sustainability objectives. It assumes that more of the right data provides a better basis for informing decision making on the long-term development of key systems and, thus, may serve as a starting point for the design of policy instruments. My work aims to promote scientific discussion on appropriate methodologies for sustainability assessments, although putting such a framework into practice lies beyond the scope of my thesis.

Throughout the process of crafting the deliverables of this thesis, I faced numerous challenges related to the scope, the complexity of the research subject and the wide range of theoretical elements to be considered. I would like to take the opportunity to sincerely thank Prof. Dr Paul Burger of the Sustainability Research Group at the University of Basel for valuable discussions and reflections. Furthermore, I would also like to thank Dr Basil Bornemann and Dr Anita Brunner of the Sustainability Research Group at the University of Basel for sharing their expert knowledge with me. I would also like to add that the work of Prof. Dr Armin Grunwald and Jürgen Kopfmüller of the Institute for Technology Assessment and Systems Analysis at the Karlsruhe Institute of Technology on the Integrative Framework for Sustainable Development has proven invaluable to me as a basis for developing the Framework for Sustainability Assessments.

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List of Abbreviations

CBA	Cost-benefit analysis
CFC	Chlorofluorocarbons
CHF	Swiss franc
CO ₂	Carbon dioxide
CTI	Commission for Technology and Innovation in Switzerland
DDT	Dichlorodiphenyltrichloroethane
DETEC	Department of the Environment, Transport, Energy and Communications in Switzerland
DPSIR	Driving forces, pressure, state, impact and response
DPSWR	Driving forces, pressure, state, welfare and response
EC	European Commission
EIA	Environmental impact assessment
EK	Enquete Commission of Germany
ENTSO-E	European Network of Transmission System Operators for Electricity
EPCEU	European Parliament and the Council of the European Union
FCS	Federal Council of Switzerland
FOEN	Federal Office for the Environment in Switzerland
FOSD	Federal Office for Spatial Development of Switzerland
FSA	Formative scenario analysis
FSOS	Federal Statistical Office of Switzerland
GDP	Gross domestic product
GRI	Global Reporting Initiative
GW	Gigawatt
GWh	Gigawatt hour
IA	Impact assessment
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFSD	Integrative Framework for Sustainable Development
ILO	International Labour Office
IPCC	Intergovernmental Panel on Climate Change
kcal	kilocalorie
km	kilometre
kW	kilowatt
kWh	kilowatt hour

LCA	Life cycle assessment
MCDA	Multi-criteria decision analysis
MFA	Material flow analysis
mio.	Million
MW	Megawatt
MWh	Megawatt hour
NEI	Nuclear Energy Institute
NEPA	National Environmental Policy Act
NO _x	Nitrogen oxides
ppm	parts per million
PV	Photovoltaic
SD	Sustainable development
SDG	Sustainable development goals
SES	Socio-ecological system
SFDHA	Swiss Federal Department of Home Affairs
SFOE	Swiss Federal Office of Energy
SMA	Societal metabolism approach
SO _x	Sulphur oxides
SSI	Sustainable Society Index
Sv	Sievert
TJ	Terajoule
TW	Terawatt
TWh	Terawatt hour
UNCED	United Nations Conference on Environment and Development
UNCSD	United Nations Conference on Sustainable Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
V	Volt
W	Watt
WCED	World Commission on Environment and Development
WHO	World Health Organisation
WWF	World Wide Fund for Nature
YLL	Years of lives lost

1 Exposition of problem and structure of thesis

Since the dawn of civilisation, humankind has been striving to improve human well-being. A review of selected events in the history of human and societal development reveals that improvements in well-being were often made possible through research and the discovery of new tools and techniques. However, while the implementation of new technologies has created new opportunities for human populations (Mesthene 1970), it is also increasingly perceived as a driving force for higher levels of resource consumption and environmental degradation (WCED 1987).

In the early stages of our history, during the prehistoric era, basic tools such as the bow and arrow or flints led to incremental improvements in the well-being of hunters and gatherers by increasing the odds of success when hunting prey or boosting the chances of survival against natural predators. The development of such new technologies depended then on the availability of natural resources, like wood or stones, and resulted in negligible waste in the form of organic debris (Humphrey 2006).

During medieval times more complex innovations emerged and new resources, such as metal deposits, were discovered that allowed the production of iron-based weaponry for warfare, advanced tools for farming, sturdy shelters for housing and religious monuments for spiritual purposes (Wigelsworth 2006). The use of more advanced tools led to higher productivity in harvesting crops and animal husbandry and brought the first forms of material wealth (Banham & Faith 2014). As a result, the natural life expectancy of peasants rose as human settlements found themselves in a better position to fend off wild animals or barbaric tribes. In parallel, the natural streams of rivers were altered to better provide freshwater to growing human populations (James & Lecce 2013). Moreover, during that era, Europe saw significant declines in forest cover, which was driven by the need for resources to build homes, obtain fuel for heating and turn woodlands into cultivated land (Perlin 1989; Williams 2006). The ecological footprint of human populations on planet Earth started to expand.

The age of industrialisation led to the discovery of additional resources and new technologies which would eventually fundamentally alter the lives of every civilian; several inventions, such as electricity, lighting, industrial automation or automobiles led to significant increases in productivity (Hitomi 1994; Morton Jr. 2002). The invention of the light bulb as well as machinery-supported manufacturing, for example, led to producing a higher number of goods within shorter periods of time (Juslén, Wouters & Tenner

2007). While these technologies further improved the material wealth of societies, they also brought new forms of pollution as well as social issues (Ashton 1998; Hobsbawm 1996). The combustion of fossil fuels and the use of acids, for example, led to a massive decline in air and water quality (Earnhart 2016; Rosenfeld & Feng 2011). At that time, however, scientific understanding of the source of pollution and its harmful effects on human beings was limited and early forms of such pollution were initially discounted as irrelevant (Thorsheim 2006). The rapid expansion of industrial production also had an impact on social structures: the labour force was attracted to new vibrant growth centres in sprawling cities and due to the unequal distribution of the benefits of development, income disparities rose (Hirschman & Mogford 2009). In response to this, workers formed labour unions to increase their negotiating power and to bargain collectively for better wages (Howell 2007). Despite rising levels of pollution and growing social inequality, human populations also continued to grow during that period (Alfonseca, Munoz Perez & Gonzalo 2016).

The information age has promoted the broad deployment of information and communication infrastructure. Moreover, it has brought a wide range of new electrical devices, such as computers and smart phones (Headrick 2015; Mowery & Simcoe 2002). Satellites and the global deployment of the internet have turned a planet with fragmented political autonomies into a more globalised and mutually interdependent community, where trade is increasingly conducted through the internet and social media allow contacts to be developed across vast distances (Souitaris & Cohen 2003; Uimonen 2015). These technologies have fuelled a new wave of global international trade, allowing for greater specialisation of corporate enterprises and the introduction of new services (Castells 2011). Furthermore, the commercialisation of plastics has fostered mass manufacturing of consumer products (Blair Crawford & Quinn 2017). During this period, human well-being has continued to improve, as suppliers increasingly respond to individual preferences (Humbert 2007). While the gains in human well-being achieved through modern infrastructure are undisputed, the erection of the latter and growth in international trade have further accelerated resource depletion and caused more pollution (Cesano & Gustafsson 2000; Van Veen-Groot & Nijkamp 1999). Moreover, the electrification of modern societies, the growing number of electrical devices in operation and increased levels of mobility have led to hitherto unprecedented surges in energy consumption (Niu, Jia, Wang, He, Hu & Liu 2013; Wang, Mu, Kang, Song & Ning 2010). At the same time, the application of modern information and communication technologies has given rise to new societal issues related to private security and property rights (Kizza 2013). However, the establishment of a global information network

monitoring resource stocks and pollution has also led to an increased interest in and understanding of the ecology of our planet (Smith & Smith 2000). Against this backdrop, some actors fear that current and future levels of consumption and pollution might soon exceed critical thresholds and therefore promote environmental conservation (Blanco & Razzaque 2011).

Based on this brief overview of selected events in human history with a focus on science, technology, society and ecology, I shall summarise some key assumptions and critical interdependencies: Firstly, the human race has been striving for improvements in human well-being since the dawn of civilisation. Secondly, the discovery and deployment of new technologies has played a crucial part in achieving those improvements in human well-being. Thirdly, the implementation of new technologies has driven resource consumption and caused pollution. Fourthly, the interrelationship between societal development and environmental degradation has increased substantially in importance during the information age owing to increased understanding of the planet's ecology and the footprint of our actions. Fifthly, some actors are concerned that current levels of resource exploitation and pollution may impede future development.

To further explore the critical interdependencies between human well-being, technological development and environmental degradation, I shall briefly outline two intensively researched cases: The *international cooperation to protect the ozone layer* and the *programme on malaria prevention* in tropical regions. These two cases demonstrate how societies and the environment are intricately interwoven:

- i) **International cooperation to protect the ozone layer.** During the nineteen eighties, geophysicists and meteorologists identified a steady decline in ozone in the atmosphere including a large annual springtime decrease, reducing the protective shield against harmful ultraviolet irradiation (Farman 1985). This was identified as potentially causing skin cancer and eye damage in human beings (Gallagher, Lee, Bajdik & Borugian 2010). While the depletion of the ozone layer was first observed in Antarctica, its cause was traced back to aerosol sprays containing chlorofluorocarbons (CFC) used in industrialised countries. As a result of the broad recognition of this issue among scientists and political leaders, the latter were determined to agree on international cooperation; in 1986 those nations with major CFC producers signed the Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP 1986). This treaty reflects a binding agreement to phase out

the production of substances driving the depletion of the ozone layer. Today, other organic compounds successfully substitute CFC without causing similar effects on the environment. In the meantime, global ozone levels are thought to have stabilised and the ozone layer is expected to recover (IPCC 2005).

- ii) **Programme on malaria prevention.** Vast parts of tropical and subtropical regions are exposed to malaria, a potentially fatal disease that leads to the deaths of hundreds of thousands of people every year (WHO 2014a). During World War II an organochloride called dichlorodiphenyltrichloroethane (DDT) was developed to protect both the military and civilians from malaria and typhus. Owing to its effectiveness, DDT was also widely applied as an insecticide in agriculture after World War II (Kinkela 2013). Only a decade later, the magnitude of the side effects on human well-being, involving a high prevalence of cancer and neurotoxic effects (Bear 2006; Dalvie 2013), and the environment, such as a massive reduction in bird fertility (Nakamaru, Iwasa & Nakanishi 2003), became apparent and an intense public discourse evolved. In 1972 the United States of America (USA) issued a ban on the agricultural use of DDT. In 1995, a global action plan, called the Stockholm Convention on Persistent Organic Pollutants (UNEP 1995), outlawing amongst other things the use of DDT, was signed. In the wake of the ban on DDT, researchers looked for other approaches to prevent malaria from spreading. Today, one recommended approach to protect local communities from malaria involves the provision of insecticide-treated mosquito nets (WHO 2014a). However, recent surveys show that the recipients of these nets are using them for fishing thus nullifying the expected effects of malaria protection (McLean, Byanaku, Kubikonse, Tshowe, Katensi & Lehman 2014).

Both cases accentuate the introductory claim that the application of new technologies may cause environmental and societal problems. They also highlight that the resolution of such complex issues requires collective contributions by various actors towards a common goal. Meanwhile, scientific evidence suggests that the implementation of some technologies relating to essential infrastructure in industrialised countries, such as nuclear or coal-based power plants, may severely erode the ecological capital of planet Earth, potentially affecting the well-being of human populations in the future (Danzer & Danzer 2016; IPCC 2005; Steinhäuser, Brandl & Johnson 2014). In contrast

to the cases on the ozone layer and malaria prevention, however, scientific evidence of these cases does not hint at issues restricted to specific regions, but rather at complex crises spanning the entire globe; according to scientific studies, some key natural resources and energy carriers are becoming increasingly scarce (Henderson 2014). Furthermore, the fragility of some critical ecosystems vital to human well-being, such as forests and oceans, is perceived to be increasing (Zetland 2011). Some scientists argue that this form of environmental degradation is likely to lead to diminished yields of ecosystem services in the future (Grunewald & Bastian 2015). Against this backdrop, it is often argued that current consumption patterns in industrialised countries may be the driving force behind these environmental issues as they are perceived to exceed the ability of our planet to reproduce natural resources and absorb pollution (Rees 1992). Accordingly, pursuing current development paths is expected to potentially undermine opportunity spaces for future generations, and both political leaders and researchers on sustainable development (SD) deem it necessary to redesign infrastructure that drives severe forms of environmental degradation and provides critical outputs to societies (WCED 1987). Such a transformation aims to lower resource consumption levels and reduce pollutant emissions while still improving human well-being.

The energy system is one of the systems that enable essential services, but is also seen as a major driver of environmental degradation (Danzer & Danzer 2016; IPCC 2005; Steinhauser, Brandl & Johnson 2014). Today, energy systems are exposed to dynamic developments and new technological options exist, such as renewable energy and smart grid technologies (Jülch 2016; Olindo, Jäger, Smets, Van Swaaij & Zeman 2016; Strbac 2008), which promise lower levels of resource consumption and less pollution, as well as economic benefits (Beeton & Meyer 2015; Hadorn 2015). In addition, a more general trend towards the electrification of transport and heating systems can be observed such that attention in the overall energy system is increasingly shifting towards electric power (Jones, Harms & Heinen 2016; Lieven 2015). Against the backdrop of the increasingly prominent role played by electricity systems in modern societies, and the more general features this system exhibits,¹ it is not surprising that we are facing an intensive debate among scientists, politicians, environmental agencies and business representatives on what electric power systems should look like in the future.

¹ Electricity systems are socio-technological systems that contribute to human well-being but which also cause environmental degradation that may potentially undermine opportunity spaces of future generations.

1.1 Current state of electric power systems

Electricity systems are responsible for generating and distributing electric power to electrical devices in private households, businesses and public institutions to enable energy services (Grigsby 2012; Gonen 2014). These services are used to improve living conditions and enable the provision of goods and services (Ahmad, Mathai & Parayil 2014). Today, electric power systems in industrialised countries often rely on portfolios of power plants and sophisticated power grids to provide electricity at all times and at the lowest possible cost to consumers. A reliable electricity supply has enabled industrialised countries to guarantee their citizens high standards of living by ensuring the delivery of vital energy services, such as lighting, cooking or heating, with the cost of electricity amounting to just a fraction of a household's budget (IEA 2013).

However, in order for electric power systems to fuel societal development, natural resources are spent, energy carriers harnessed and in some cases severe forms of pollution are caused in the process of transforming energy carriers into electricity (Raj Ghandehariun, Kumar & Linwei 2016; Sassoon, Hermann, Hsiao, Milkovic, Simon & Benson 2009; Şengül, Bayrak, Aydınalp Köksal & Ünver 2016). More specifically, scientific evidence suggests that some power infrastructures in industrialised countries are the main contributors of long-term environmental degradation, causing among other things nuclear waste, climate change, water scarcity, deforestation, distortion of natural ecosystems and depletion of finite resource stocks (IEA 2012; IEA 2013; IPCC 2007; UNFCCC 2004).

Nuclear power can be used to illustrate this dilemma: On the one hand, current generations benefit from low electricity costs as the pricing of electric power in many countries does not fully consider the costs of decommissioning nuclear power plants or the disposal of nuclear waste, as these costs are often not yet fully known (SFOE 2014a), hence, they cannot be considered in pricing models for electricity tariffs. On the other hand, since the costs of decommissioning nuclear power plants and the disposal of nuclear waste are often not covered in electricity bills for current generations, they will have to be borne by future generations (Segelod 2006).

Fossil fuel-based electricity generation may serve as another example. Current power market mechanisms in Europe incentivise operators to determine the operating orders of power plants according to variable costs (Clò, Cataldi & Zoppoli 2015). In the case of coal power, variable costs are determined mainly by the price of coal and the costs of

operating the power plant (McNerney, Farmer & Trancik 2011). Burning fossil fuels, however, is considered to be a major driver of the global warming that is thought to increase extreme weather events, such as windstorms, floods and droughts, and cause rising sea levels (IPCC 2007). Such external costs are not, however, inherently part of the variable cost calculations of coal-based power plants. In Europe, they are meant to be covered by the carbon emission trading scheme. This scheme has not, however, yet been implemented on a global basis and significant exclusions exist (Butzengeiger 2005). Like nuclear power, owing to the delayed effect of global warming, future generations will have to bear these external costs while current generations enjoy low electricity tariffs today.

The current situation is expected to even accelerate: Economists have found evidence that in the past economic growth was often accompanied by increases in electricity consumption whenever energy sources were abundant (Stern 2011). Since the global economy is growing steadily, a continued increase in electricity consumption is projected throughout the next decades. Accordingly, if a productive natural environment is to be safeguarded for the future, then, instead of merely reducing the pollution caused by power plants, some scientists deem measures to decouple electricity consumption from economic growth and thus curb electricity consumption to be inevitable (IEA 2014). Such reductions in electric power consumption can, for example, be achieved through higher levels of energy efficiency in electrical devices or changes in lifestyles (Bin & Dowlatabadi 2005)². The latter may be supported by the increased transparency of the individual electricity consumption of consumers (Wood & Newborough 2003). Furthermore, research and development has led to the discovery of new clean power generation and smart grid technologies, which could contribute towards a new design for electric power systems that has fewer resource requirements and reduces pollutant emissions by tapping into the potential of renewable energy fluxes (Stamford & Azapagic 2014). For the time being, however, the potential contribution of new technologies remains unclear due to a lack of experience regarding the way these innovations may be fully integrated into existing systems.

Against this backdrop, a heated debate is unfolding among scientists, politicians and organised institutional actors on what the design of electric power systems in industrial-

² Schmidt and Weigt recently provided a comprehensive overview of the efficiency and sufficiency literature (Schmidt & Weigt 2015).

ised countries should look like in the future.³ While some actors argue in favour of a substantial transformation of existing electric power systems through policy steering instruments (Eikeland & Inderberg 2016), others fear that the risks of implementing new technologies could outweigh the expected benefits, such as a rising number of black-outs caused by stochastic power generation of renewable energy technologies (Laleman & Albrecht 2016). The decisions to be taken, however, will be highly relevant as today's choices on the future design of critical infrastructure systems, will inevitably have resounding effects on opportunity spaces for future generations (Di Leo, Pietrapertosa, Loperte, Salvia & Cosmi 2015).

The case for urgency is further accentuated by the fact that key decisions on the future design of some electric power systems in industrialised countries need to be taken soon, as critical parts of the power infrastructure are about to reach the end of their technical lifespan (ENTSO-E 2012). Accordingly, important long-term decisions need to be made within the next few years while the strengths and weaknesses of new technologies are still being explored and controversially debated. Furthermore, due to the long investment cycles of power infrastructure components, which may last up to 60 years (IEA 2010), upcoming decisions will inevitably create path dependences and technological lock-ins. However, owing to the different views on what requirements electric power systems should meet in the future and the vast number of uncertainties associated with the expected contributions of new technologies, no common agreement has yet been reached. The possible development paths currently being discussed by scientists and politicians in many industrialised countries, including Switzerland, can be roughly categorised into three distinctive scenarios (SFOE 2013):

- i) **Fossil fuels.** The first scenario focuses on maintaining low electricity costs for current generations by replacing outdated power generation capacities with fossil fuel-based power stations. The supporters of this scenario perceive fossil fuels to be a reliable and cost-efficient energy source.
- ii) **Nuclear power.** The second scenario seeks to prevent greenhouse gas emissions from breaching critical thresholds and stabilise global tempera-

³ Within this thesis, I shall focus primarily on industrialised countries for two reasons: First, the power infrastructure in modern societies is thought to be the main driver of environmental degradation. Second, while some emerging economies are in a position to build clean infrastructure components at competitive costs from scratch, industrialised countries face the challenge of transforming already existing complex socio-technical systems. This is exactly the aspect of system transition that I seek to explore in more detail.

ture levels through the promotion of nuclear power. Advocates of this option favour either the construction of additional nuclear power capacities or a replacement of older ones through next-generation nuclear power plants.

- iii) **Renewable energy technologies and energy efficiency.** The third scenario is based on a new green energy policy where renewable energy and smart grid technologies are deployed and high energy efficiency levels lower the consumption of natural resources and decrease pollutant emissions.

If industrialised countries are striving for societal development that does not erode the ecological capital and thereby preserves opportunity spaces for future generations, then a development path has to be chosen that resolves the current environmental problems and continues to drive human development. Assuming that current consumption patterns are part of the problem, then changes in human lifestyles may also need to be encouraged (Hirschnitz-Garbers, Tan, Gradmann & Srebotnjak 2016). In such a case, some scientists and political leaders argue that societal development may have to be actively monitored and directed according to objectives that secure human development and preserve environmental productivity. They argue that governing the development of such a system may require predefining normative requirements that mirror the principles of SD and deploying instruments that facilitate such a transformation (UNCED 1992; WCED 1987).

Such an endeavour is expected to first require the establishment of an agreed model with overarching objectives that guide the actions of actors in the system (Newig, Voss & Monstadt 2008). One approach foresees then translating the abstract requirements of the guiding principles into more tangible rules or conditions (Kopfmüller et al. 2001). In parallel, an understanding and agreement on the essential components of the system need to be obtained to determine which stages of energy, matter and information flows are of relevance for societal development. These stages are then evaluated in sustainability assessments: thus, system data is evaluated against the predefined normative targets to pin down unsatisfactory developments (Grunwald & Rösch 2011). Ideally, current data is enhanced with information on the expected contributions of new technological options to simulate potential future states of the system. Such scenario assessments will allow key interdependencies to be identified and help to infer possible future problems (Stamford & Azapagic 2014). The results of such a process could then serve as a starting point for developing policy measures that seek to direct system development towards sustainability objectives.

In such an *evidence-based* and *goal-oriented* approach, sustainability assessments are expected to assume a pivotal role: they extract and evaluate system data against pre-defined sustainability requirements and thereby provide a comprehensive basis for informing decision makers on long-term developments in key systems.

1.2 Current state of sustainability assessments

In order to serve their purpose, sustainability assessments consist of a set of basic features that relate to the system under review on the one hand and normative objectives mirroring the requirements of SD on the other:

- i) **System functionality.** Sustainability assessments are applied to specific systems and extract data related to the performance of essential features to provide a basis for *evidence-based* decision making. To compound a comprehensive set of data, the evaluation scheme has to include features of both ex post and ex ante analysis to determine areas of immediate concern as well as to pay attention to potential future developments and problems.
- ii) **Normative requirements.** Sustainability assessments contribute to the operationalisation of SD and aim to direct development according to pre-defined sustainability requirements. Accordingly, in order to provide a basis for *goal-oriented* decision making, system data has to be evaluated against predefined targets that mirror the guiding principles of SD.

Sustainability assessments often draw on different methodologies (Dombi, Kuti & Balogh 2014; Evans, Strezov & Evans 2009; Grunwald & Rösch 2011; Heinrich, Basson, Cohen, Howells & Perie 2007). A review of the existing literature reveals that authors mainly apply methods that stem from economics, engineering and environmental sciences, such as life cycle assessments and cost-benefit analysis (Greco 2004; Hauschild & Huijbregts 2015). While these methods have indeed been proven to be appropriate for extracting and comparing data on energy and matter flows, they do not provide sufficient guidance on determining essential system components. Furthermore, they often only partly embrace the social aspects of complex human-environment systems and lack features that allow simulating the potential future states of a key system. Moreover, they are devoid of normative features. Hence, life cycle assessments and cost-benefit analysis can fully contribute towards neither a holistic system analysis, encompassing societal steering aspects, nor the deduction of goals based on normative

requirements. Accordingly, drawing exclusively on such methods results in sustainability assessments being only partly composed of the required basic features and thus impedes decision making.

There is growing consensus among scholars and political leaders that today's long-term environmental issues can also be attributed to human activity (IPCC 2005). The sustainability challenge is therefore increasingly being perceived as a societal problem. The social sciences offer a wide range of instruments for the description and analysis of the realm of social actors and governance (Luhmann 1984; Van Zeijl-Rozema, Cövers, Kemp & Martens 2008). Typical approaches in the social sciences, however, such as social or political theory (Dryzek, Honig & Phillips 2008; Kivisto 2008) tend to discard the technical and ecological aspects of systems. Reverting exclusively to traditional approaches of social sciences is, thus, likely to neglect ecological issues that hamper human development.

Combining methodologies from the environmental and the social sciences reflects a relatively new, but promising, field of research. This type of interdisciplinary study covers system analysis more holistically and seeks to systematically identify essential system properties: system analysis of human-environment interaction and socio-ecological regimes are examples of such approaches (Haberl & Fischer-Kowalski 2007; Moran 2010). While they allow for a more holistic analysis of the system in question, they do not yet add the missing ingredient to empower sustainability assessments with the ability to consider potential future developments. Assuming that a significant part of today's electric power infrastructure will also serve a vital purpose in the future, then it is likely that new technologies and policies have to be integrated with existing system components. Such analyses are often based on proven system modelling methods where interdependencies among essential system components are defined (Pidd 2004). The output of system modelling can then be used to simulate and describe scenarios or possible future states of the system (Ross 2012). While such scenario assessments are sometimes carried out by electric utilities to test the robustness of infrastructure components (Tleis 2008), these methods can also be applied on more systemic levels.

In order for sustainability assessments to be able to evaluate empirical system data against goals that reflect the objectives of SD, the corresponding targets need to be defined beforehand. Such an endeavour resembles a methodologically entirely distinct effort: The abstract normative cornerstones of SD are broken down into a set of rules that

resembles a less ambiguous interpretation of the normative requirements (Kopfmüller et al. 2001). These rules can then serve as a basis for determining general goals for criteria in sustainability assessments. The derived set of rules then ensures that the system development can be directed according to the normative requirements of SD.

Accordingly, today's contributions may have to be enriched with complementary methodologies to cover the missing features of sustainability assessments. This discrepancy may be traced back to some degree to the fact that sustainability assessments historically emerged from environmental impact assessments (EIA). The latter were originally introduced in the USA as mandatory procedures against the backdrop of increasing environmental problems stemming from infrastructure projects or the release of toxic chemicals (Marriott 1997). EIA are designed to assess the environmental burdens caused by products or infrastructure. The government then only grants distribution rights or concessions if environmental degradation does not breach certain thresholds. Against this backdrop, it is fully understandable that EIA are devoid of some of the methodological features sustainability assessments should bear. Accordingly, I expect a review of existing sustainability assessments to potentially reveal some of the following shortcomings:

- (i) There is insufficient coverage of essential system components, such as social aspects, as a result of definitions that are too narrow in scope.
- (ii) Owing to a lack of system modelling, data analysis can be expected to be based on ex post analysis, potentially neglecting ex ante analysis.
- (iii) High variability in the selected criteria and indicators owing to the absence of systematic system depictions and modelling.
- (iv) Lack of normative rules, which obstructs the process of determining meaningful sustainability targets.
- (v) Because data is not related to SD, goals are likely to be absent, impeding the evaluation of system data against sustainability objectives.

Since such potential shortcomings can most likely be attributed to a lack of a systematic procedure that seamlessly integrates the functional aspects of the system and the normative requirements of SD, with this thesis I shall strive to contribute a *framework*

for sustainability assessments that provides a basis for *evidence-based* and *goal-oriented* decision making. Moreover, owing to the importance of electric power systems in modern societies and the key upcoming decisions to be made on power infrastructure, I shall provide exemplary results for missing basic features based on the example of electricity systems.

1.3 Research question

Assuming that sustainability assessments are designed to provide a basis for *evidence-based* and *goal-oriented* decision making for the long-term development of key systems, then the expected shortcomings in today's sustainability assessments are likely to increase the risk of erroneous decision making, as today's applied methodologies can be expected to only partly cover the relevant features of sustainability assessments. Against this backdrop, chosen policy measures are more likely to hold the risk of not delivering on intended changes. At this point, I claim that a more comprehensive and systematic approach can be expected to reduce the risk of omitting relevant aspects. Developing such a *framework for sustainability assessments* will require applying and combining a set of different and relatively new methodologies. Since I expect the review of the existing literature to reveal several distinct shortcomings, I shall strive to contribute an overall framework composed of different theoretical elements. Accordingly, I shall create a framework that integrates methodologically distinct contributions that as a whole seek to enhance the basis for *evidence-based* and *goal-oriented* decision making. Thus, with this thesis I aim to answer the following research question:

How should sustainability assessments be designed methodologically to provide a basis for evidence-based and goal-oriented decision making on the long-term development of key systems?

Owing to the important role played by electric power systems in modern societies and the pressure associated with the looming replacement of key parts of the electric power infrastructure in industrialised countries, I shall make contributions to the hitherto missing aspects of the *proposed framework* based on the example of electric power systems. My scientific contributions will therefore focus, on the one hand, on providing a *framework for sustainability assessments* in general. On the other hand, I shall demonstrate the strengths and weaknesses of the *proposed framework* by producing exemplary contributions of missing basic features based on the example of power systems. I

shall, however, restrict my research scope to an aggregated level and thus not strive to derive indicators and target values, that are likely to vary across regions or societal value schemes.

1.4 Approach

A review of current proposals for sustainability assessments reveals that a wide range of structural features and methodologies is applied. I see at least two sources for this heterogeneity. Firstly, this variation may be partly traced back to the fact that sustainability assessments originally emerge from EIA. These authors that base their work on EIA often complement their environmental analysis with additional social criteria so as to incorporate development-related requirements from SD. Secondly, owing to the high ambiguity of SD, it is also not surprising that there is a high variation on the structural features and methodologies that sustainability assessments should encompass. Accordingly, I cannot rely on existing methodologies.

Against this backdrop, it becomes obvious that I first have to specify and argue for a set of structural features that I deem relevant in order for sustainability assessments to provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision-making support. In contrast, methodologies can be expected to differ across systems to account for the different themes and processes taking place. Focusing on the structural features of sustainability assessments, I shall draw on those features of EIA that are essential in order to assess the environmental impacts of infrastructure projects. I shall then enhance this set of proven structural features by adding elements that refer to those additional themes that were introduced by the conception of SD. Based on this approach I shall then draw up a set of structural features that encompasses relevant categories of methodologies, irrespective of the system properties subject to a sustainability assessment. These structural features may then serve as categorical settings for reviewing today's contributions on sustainability assessments for electricity systems.

I shall then proceed by evaluating a selection of prominent and recent scientific contributions on sustainability assessments against these structural features in order to identify shortcomings in sustainability assessments of electric power systems. Based on this review, I can determine today's knowledge gaps and thus propose methodological contributions that are directed at the specific challenges electric power systems face today to overcome these knowledge deficiencies. Owing to the vast scope of sustainability assessments and the wide range of developments taking place in electric power

systems, one might expect different methodologies to be proposed for each challenge so as to best address theme-specific issues. However, while my work will be directly related to electric power systems, the focus of my thesis will be on developing a scheme that encompasses the relevant structural features and that can also be applied to other key infrastructure systems, such as water supply systems.

Based on the analysis of knowledge gaps and methodologies, I shall provide a key deliverable of this thesis: to present a generic *framework for sustainability assessments* that can be applied to key infrastructure systems, such as electric power or water supply systems. The *proposed framework* will consist of a set of structural features with corresponding methodologies. The methodologies proposed within this thesis, however, will only be applicable to electricity systems as they are specifically geared towards the properties of this system: energy flow analysis, for example, is an indispensable method for analysing energy conversion and efficiency ratios in electric power systems, while methodologies that focus on the hydro cycle are required when assessing water supply systems. The point here is that only the structural features of the *proposed framework* are designed to be universally applicable, such as ex ante analysis or an enrichment of the guiding principles of SD to forge a set of goals for sustainability assessments, while the methodological investments are specific to the system under review. However, in order to explore more easily the strengths and weaknesses of integrating these structural features into the *proposed framework*, I shall also provide examples of the hitherto missing features in the sustainability assessments of electric power systems. This will allow me to more easily explore opportunities and limitations stemming from the proposed methodologies specifically related to the sustainability assessments of electric power system, as well as draw conclusions on the viability of the structural features of the *proposed framework* in general.

The electricity system-specific contributions may also be regarded as additional key deliverables of this thesis and will largely depend on identified shortcomings in today's sustainability assessments of electric power systems and the proposed methodologies. I will therefore review the scientific state-of-the-art on effective methods and approaches and argue for appropriate methodologies to remedy identified issues. In some cases, I shall invest methodologies that are today successfully applied in other contexts, such as creating a holistic system representation. In other cases, my contributions have not been tried before, such as drawing up a set of criteria related to the governance of electric power systems or translating the guiding principles of SD into general goals as criteria for electricity systems. Furthermore, since my contributions are not re-

lated to specific case studies, they cannot account for regional specifics or be related directly to cultures or value schemes. This is not necessary, however, as they primarily serve the purpose of further supporting the discussion on the strengths and limits of the *proposed framework*. A hallmark of this thesis will lie with linking functional aspects of the system aspects with goals of transformation governance. In order to achieve this, I shall decide on an up-to-date interpretation of SD enrich it to construct a set of conditions that can be translated into general goals for power systems.

Once both the general structural features of the *framework for sustainability assessments* and the electric power system-specific contributions have been presented, I shall review the results against current scientific contributions. This analysis seeks to identify whether the *proposed framework* is indeed in a position to confirm existing information and elicit entirely new sets of information and goals that have hitherto been absent. Accordingly, the review serves to draw conclusions on the strengths and weaknesses of the *framework for sustainability assessments* in general and thereby determine whether its application could also create value for other key infrastructure systems. This step will also involve an assessment of both which of the identified shortcomings could easily be remedied by expanding the methodological base and which cannot be resolved without fundamentally reengineering the structural and methodological design of the *proposed framework*. Lastly, I shall look for synergy opportunities that can be harnessed by identifying additional research efforts in regard to the *framework for sustainability assessments* and providing an overview of additional research opportunities.

1.5 Structure of thesis

This thesis is structured into four major parts to deliver the scientific contributions: Firstly, I shall start with an introduction that provides background information on electricity systems and the guiding principles of SD. Secondly, I shall proceed with a review of a selection of current scientific contributions on sustainability assessments of power systems to identify shortcomings in current approaches. Based on identified knowledge gaps, I shall then argue for appropriate methodologies to be applied in the *framework for sustainability assessments*. Thirdly, I shall present my scientific contributions. Fourthly, I shall conclude this thesis with a comparative analysis of my contributions against the research sample, as well as a methodological discussion of the strengths and limits of the *proposed framework*, including an overview of further research opportunities:

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- i) **Introduction.** Chapters 2 and 3 are dedicated to describing the key features of power systems and the hallmarks of SD. In chapter 2, I shall invest existing literature on electricity systems, the challenges they are currently facing, as well as new technological opportunities and scenarios which are today controversially debated. I shall then lay out the current state of the discussion on SD and transformation governance in chapter 3. This chapter concludes with a contribution from my side consisting of outlining the basic features of sustainability assessments based on a review of key events in the evolution of EIA, SD and sustainability assessments.
- ii) **Methodology.** In chapter 4, I shall present and evaluate a sample of current contributions on sustainability assessments of electricity systems against the basic features of sustainability assessments introduced in chapter 3. I shall then identify knowledge gaps based on shortcomings in today's sustainability assessments in chapter 5. These knowledge gaps will serve as a basis for formulating the research question, which this thesis aims to answer in chapter 6. I shall then present the cornerstones of the *framework for sustainability assessments* in chapter 7 and explore appropriate methodologies to be applied to systematically fill the knowledge gaps and provide exemplary contributions for electric power systems.
- iii) **Scientific contribution.** In chapter 8, I shall provide a holistic system representation of electric power systems that covers the functional constitutive elements, including enabling and constraining factors. Chapter 9 serves to systematically deduce criteria based on the system representation. For these contributions, I shall draw on approaches related to coupled human-environment systems, energy and matter flow analysis, as well as socio-ecological regimes. A current scientific interpretation of the guiding principles of SD will serve as a basis for formulating steering rules and general goals for criteria in chapter 10. I shall proceed with deducing a set of instrumental rules and general goals based on reflexive transformation governance for criteria in chapter 11. For these two endeavours I shall draw on the approach of conceptual deduction and revert to the structural features of the Integrative Framework for Sustainable Development (IFSD) approach.

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- iv) **Discussion.** I shall compare the exemplary results of the *framework for sustainability assessments* for electric power systems with the contributions reviewed in chapter 4 to explore the strengths and weaknesses of the *proposed framework* in chapter 12. In chapter 13, I shall carry out a methodological discussion on my contributions in view of the originally formulated research question and the identified knowledge gaps in chapters 5 and 6. I shall conclude my thesis by sharing thoughts related to the operationalisation of the *proposed framework*, including aspects on participation and suggestions for further research opportunities.

Accordingly, *Figure 1* depicts the structure of this thesis, displaying the four major parts and corresponding chapters on the left-hand side and the contents and interdependencies of the chapters on the right-hand side. This figure highlights that sustainability assessments consist of a functional dimension related to the system under review and a normative dimension directed at sustainability objectives and transformation governance. Furthermore, it depicts the strong interdependencies among the functional features of the system and the normative aspects of the SD that are brought together in sustainability assessments.

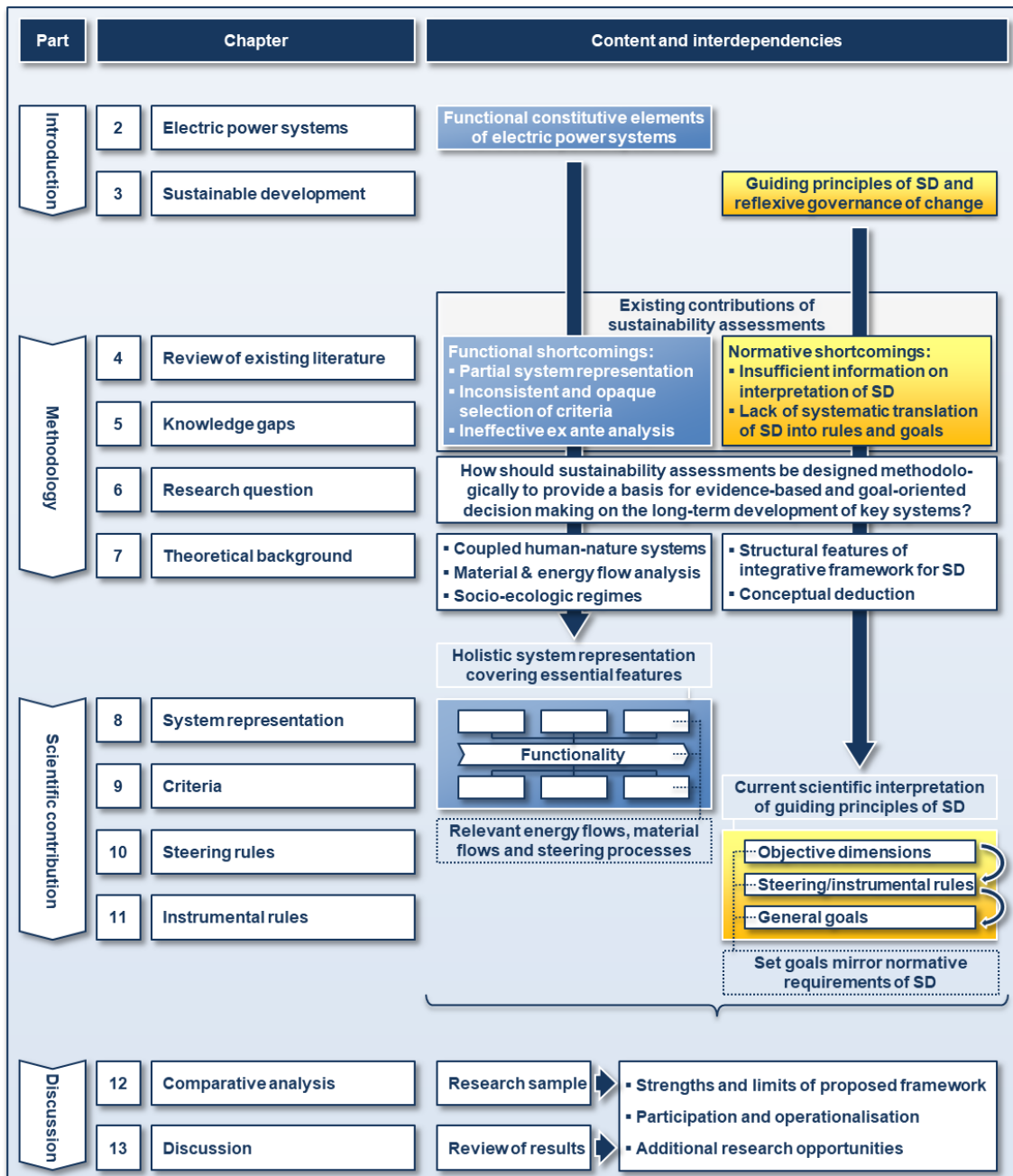


Figure 1: Structure of the thesis

(Own elaboration)

1.6 Expected contribution to the discussion

Based on the specified research question and the applied approach, I strive to add a set of distinctive scientific contributions to the discussion on sustainability assessments in general and electric power systems in particular:

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- i) **Systematic framework for sustainability assessments.** I shall develop a systematic and generic *framework for sustainability assessments* composed of the basic features of sustainability assessments. It will draw on distinct theoretical elements to provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision making. This framework will encompass relevant system features and extract data for relevant criteria based on both ex post and ex ante analysis. It will be designed in such a way that system data can be evaluated against predefined objectives, mirroring the normative requirements of SD.

 - ii) **Holistic system representation for electric power systems.** In this thesis, I shall strive to provide an exemplary system representation that comprehensively and holistically frames the scope for future sustainability assessments of electric power systems. This system representation will cover the functional constitutive elements of the system: Electricity systems are responsible for generating and distributing electricity to private households, corporate enterprises and government institutions to power a wide range of energy services, such as heating or cooling. Assuming a common agreement on the core functionality of electricity systems can be reached, then a system scope that covers the system functionality, including societal and environmental enabling and constraining factors, can be universally defined, so long as essential system properties remain stable over a longer period of time.

 - iii) **Criteria for electric power systems.** A system representation that comprises the relevant system components could also serve as a sound basis for systematically screening the system for relevant flows and obtaining a comprehensive set of criteria. Hence, I shall systematically deduce a set of criteria for sustainability assessments of electric power systems. Deriving criteria from a system representation will render sustainability assessments less susceptible to criticism that it may be biased because undesired criteria were omitted on purpose. Proposing a set of universally applicable indicators lies beyond the scope of this contribution.

 - iv) **General goals for criteria for electric power systems.** Without predefined targets, an evaluation of system data against sustainability requirements is not possible. Accordingly, sustainability assessments that lack a clearly de-

defined target system cannot fully provide a basis for *goal-oriented* decision making. One way to remedy this deficiency could lie with formulating an exemplary set of steering and instrumental rules based on a current scientific interpretation of SD. These rules may then be used to conceptually derive an exemplary set of general goals for criteria. This contribution also enables me to link sustainability assessments to transformation governance and to relate the steering capacity with the system in question.

To summarise, I shall strive to draw up a more comprehensive and transparent *framework for sustainability assessments*. Ultimately, the *proposed framework* also aims to be applicable to other complex coupled human-environment systems, such as agricultural or water supply systems. Furthermore, it will be designed so as to account for reflexive governance in modern democracies. The *proposed framework* is meant to provide additional insights for strategic discussions on the development of long-term key systems that provide essential public services. Accordingly, it is not meant to be applied as a management planning tool, but rather strives to expand knowledge on the system itself and contribute to a better understanding on goals.

Moreover, I shall aim to contribute to a clearer understanding of sustainability assessments in general and their application to electric power systems in particular to address two distinctive dimensions: Firstly, the functional part is related to the system in question and encompasses relevant system properties to extract relevant system data. Secondly, the normative part is directed at the normative features of SD and provides a set of goals and addresses instrumental aspects to transform the system so that it meets sustainability requirements. This differentiation is important as the functional components of sustainability assessments for electric power systems are bound by biophysical limitations and societal aspects, while normative elements may differ depending on the interpretation of the guiding principles of SD.

I shall proceed by investigating the existing literature on the current state of electric power systems in industrialised countries. This overview will outline system functionality and touch on current challenges, opportunities and perceived development paths.

2 Electric power systems

In this chapter I shall invest existing literature on electric power systems and their current challenges and technological opportunities to provide a broad overview of the system in question as background information. Accordingly, the chapter does not contain an original contribution to the understanding of electricity systems, but rather gives an overview of their components, as well as related issues and potential developments, against the backdrop of existing literature. Hence, while it frames and describes the object of the study, a systematic analysis thereof will be carried out in chapters 8 and 9 when providing a holistic system representation and conducting detailed analyses.

As a starting point, I shall first argue for the central role that electric power systems assume in modern societies by ensuring human well-being and enabling high levels of productivity in the manufacturing and service industries. I shall then proceed to outline the functional value creation stages of electricity systems, including the interdependencies of governance, electric power infrastructure and the environment. Since sustainability assessments are intended not only to consider existing functions but also potential future technologies, I shall also touch on identified potential opportunities arising from new renewable energy and smart grid technologies and the new requirements they impose on governance. Furthermore, to ensure that more detailed aspects of the system in question are also covered, I shall touch on some of the cornerstones of current discussions on possible scenarios for electric power systems based on the example of Switzerland.

2.1 Relevance of electricity in modern societies

The components of the electric power systems are responsible for generating and distributing electricity to private households, businesses and public institutions to power electrical devices (Clough, Saad & Gould 2013). These appliances provide a wide range of energy services critical to the daily lives to their users: lighting, heating and cooling, cooking and cleaning, information, communication and entertainment, the fueling of electric forms of transportation and the automation of processes in mass manufacturing industries (Bedir, Hasselaar & Itard 2013; Kavousian, Rajagopal & Fischer 2013; Kipping & Trømborg 2015; McLoughlin, Duffy & Conlon 2012). Against this backdrop, one can say that electric power systems have two functions: Firstly, they increase well-being or improve the living conditions of human populations and, secondly, they enable the efficient delivery of goods and services. Thus, electricity is of high relevance

to its users as it is a precondition for benefitting from energy services and some of the output of electrical devices is required to meet essential needs (Hughes 1993).

The relevance of electricity for private households can be further illustrated with a few practical examples: electric power ensures physical health, for example by maintaining an appropriate room temperature, and enabling the cooking and storing of food and beverages (Smith 2014). Furthermore, electricity opens up new opportunities for obtaining information and cultivating social contacts by enabling the use of modern information and communication technologies, such as the internet and smart phones, (Haythornthwaite & Wellman 2002). The electricity consumption patterns of private households are still somewhat unknown, as today just an annual count of electricity consumed is often measured. Only recently have electric power suppliers started deploying modern smart meters to measure electric power consumption more frequently (Warren 2014). This allows the drivers of electricity consumption to be identified more accurately thus enabling policy makers to design steering instruments more specifically (Firth, Lomas, Wright & Wall 2008).

At the same time, electricity has become an essential prerequisite for businesses and public institutions to produce and deliver goods and services: in manufacturing industries, where process automation enables cost-efficient mass manufacturing, a reliable supply of electricity has become an indispensable requirement for operating assembly lines that produce large quantities of standardised goods sought after by a large customer base (Hitomi 1994; Juslén, Wouters & Tenner 2007). In parallel, a secure electricity supply is also a prerequisite for information and communication services for service providing economies or public administrations (Armey & Hosman 2016; Sadorsky 2012).

Owing to the strong dependency of modern economies to electric power systems, the cost of electricity today plays a vital role for price sensitive consumers, as the energy services required to meet essential needs are, obviously, of high priority. This is also at least partly true for private households: a high electricity bill can have a significant impact on the constrained household budget of a low-income family, potentially crowding out goods and services that are perceived of lesser immediate value (Neuhoff 2008), such as education. For corporate businesses, the cost of electricity can have a deciding impact on the competitiveness of energy-intensive companies in international markets (Cox, Peichl, Pestel & Sieglöcher 2014). Accordingly, a stable and cost-efficient supply of electricity has become a necessary precondition to achieve development in

modern societies. Owing to the vital output that electric power systems provide to societies, policy makers and power suppliers are under pressure to provide a stable electricity supply at low cost.

2.2 Functionality

In order for electric power systems to provide their consumers with electricity, electric power infrastructure is erected and operated. Today's power infrastructure in industrialised countries is designed to integrate power generation technologies that were introduced more than half a century ago, such as coal-based, nuclear or hydroelectric power plants (Duffy 2013; Morton Jr. 2002). The sites for these power stations were then often determined by the natural occurrence of energy carriers or valleys and locations were sought far from human settlements, owing to the risks and the pollution these technologies expose residents to (Danzer & Danzer 2016). To achieve cost-efficient power generation, large power plants were built by vertically integrated power suppliers so as to achieve the benefit of economies of scale (Fetz & Filippini 2010). Originally, these power suppliers operated power plants and grids to deliver electricity to consumers in regulatory monopolies (Künneke 1999).

To secure a stable supply of electricity, operators adjust power generation to consumption loads, build power grid capacities that are able to cope with expected consumption loads and implement ring-based power grid topologies (Solé, Rosas-Casals, Corominas-Murtra & Valverde 2008). Moreover, the power infrastructure is often interconnected across political borders (Lagendijk 2008). Maintaining power grid stability often involves the active use of storage systems, such as hydro pumped storage power stations, or back-up generators (Oberschmidt, Klobasa & Genoese 2013). Power system operators continuously monitor the frequency and voltage of power grids and adjust power generation to consumption loads to prevent blackouts (Miller & Malinowski 1994). Accordingly, the functionality borne by the technical components of power infrastructure can be categorised into four distinct stages of value creation:

- i) **Extraction of energy carriers.** The first transformation stage deals with extracting the energy carriers; this involves prospecting, exploration, development and exploitation to obtain uranium, coal, natural gas or crude oil (Hartman & Mutmanski 2002). For hydroelectric power plants, dams are built to channel and collect large quantities of water, while for biomass-based power plants organic energy carriers are planted, cultivated and har-

vested (McGowan, Brown, Bulpitt & Walsh Jr. 2009). The energy carriers are then transported to power stations to generate electricity. However, this first stage does not exist for energy flux-based power generation technologies, such as solar photovoltaic (PV) systems or wind farms. Since energy fluxes cannot be stored, suitable sites, where the respective preconditions are met, such as high levels of solar irradiation or wind velocity, are first explored and then the corresponding power plants are erected on-site (Janke 2010).

- ii) **Conversion of energy fluxes or carriers into electric power.** The second stage of value creation transforms energy fluxes or carriers into electricity. Today, a wide range of power generation technologies exists, such as fossil fuel-based, nuclear, geothermal and hydroelectric power plants, wind farms and photovoltaic cells. Power plants can be classified into different types of power stations: thermal power stations transform thermal energy into mechanical power, often through the combustion of a fuel. Fossil fuel-based, nuclear, geothermal, some biomass and waste heat power generators or solar thermal power plants rely on this type of technology (Sarkar 2015). Hydroelectric power plants (Clemen 1999) and wind farms (Tong 2010) transform the kinetic energy in moving water masses or wind into electricity. Photovoltaic cells convert sunlight into electricity (Lorenzo 1994). There are other, less frequently applied, power generation technologies, such as tidal power harnessing energy from oceans (Lyatkher 2014).
- iii) **Distribution of electric power to electrical devices.** The third stage of value creation delivers electricity from producers to consumers through power grids (Chambers 1999). Transmission grids convey electricity from large power plants towards consumption centres across vast distances. The distribution grid, which is mainly fed by the transmission grid and mid-sized power plants, then distributes electricity to consumers. The sophistication of power grids is mainly determined by the capacity of electricity that needs to be transferred and the volatility of generation and consumption loads. Since both loads need to match at all times, power system operators adjust generation and consumption loads to ensure a stable supply of electricity and prevent blackouts (Vaahedi 2014). In alpine countries, such as Switzerland, Austria and Norway, hydro pumped storage power plants often provide valuable power generation flexibility. In electricity systems where generation or

consumption loads can be actively controlled, the power grid can more easily be planned. Should both generation and consumption loads be highly volatile, then power grids often have to consider higher security margins to cope with unexpected peaks in power generation or consumption load profiles (Vadari 2012). Moreover, in such cases, a larger capacity of back-up power generation is required by the power system operator to match generation with consumption loads as both are highly unpredictable (Lund, Lindgren, Mikkola & Salpakari 2015).

- iv) **Consumption of electric power to deliver energy services.** In the fourth stage of value creation, electricity is spent to power electrical devices and thereby enable the consumption of energy services. This transformation stage takes place in various types of appliances. As already mentioned, private households tend to consume a number of the aforementioned energy services to meet essential needs, whereas manufacturers, service industries and public institutions inevitably require energy services to provide goods and services in modern societies. To obtain the right to draw electricity from the grid, consumers are either provided with electricity as part of a non-discriminatory public service or are given the option to choose freely between different electricity products offered by competing power suppliers.

Against this backdrop, one can argue that the value creation stages of electricity systems, including the embedded functionality, are instrumental in delivering indispensable input to two main consumer groups: Electric power systems deliver energy services to private households to improve well-being and to manufacturing and service industries to deliver goods and services.

The diagram in *Figure 2* depicts the technical design of power infrastructure in industrialised countries. The four value creation or transformation stages, including metering, are shown from left to right.

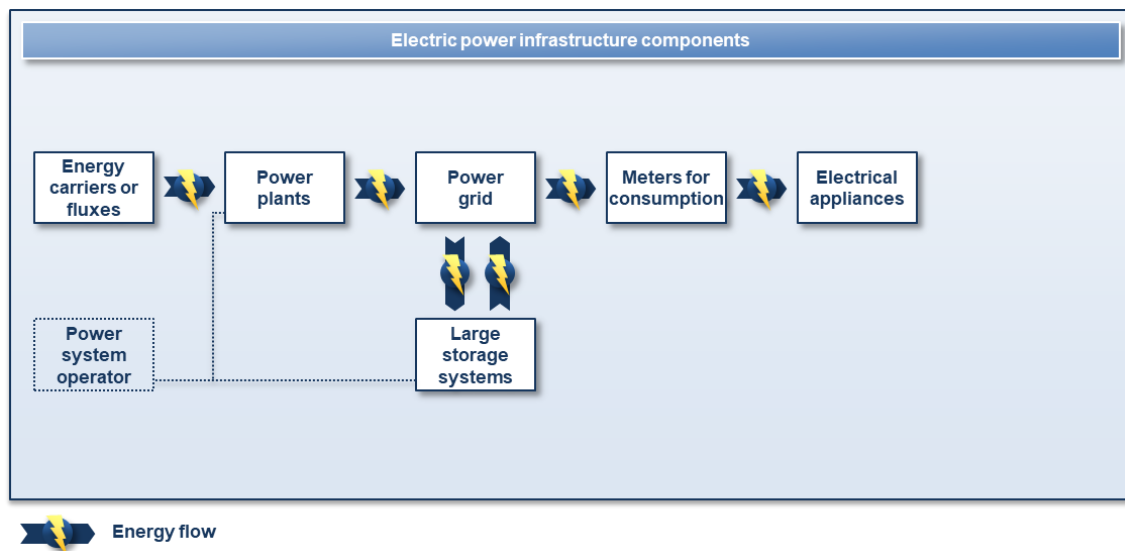


Figure 2: Traditional technical design of a power infrastructure

(Own elaboration)

When talking about systems in general, drawing appropriate system boundaries tends to be a challenge owing to the complexity of the system. So far I have presented the major functional components of the system by drawing rather traditional boundaries. For both the practical and theoretical reasons presented later, however, I do not want to restrict the system boundaries of electric power systems to the elements displayed in Figure 2. As additional key elements, I intend to include the governance level, which steers the deployment and operation of technical infrastructure components, and the environmental dimension, which provides the necessary energy flows and natural resources, as well as absorbing the pollution caused by the technical components of electric power systems. If these two additional layers as elements of the system were to be omitted, the system would be inadequately represented and it would be difficult to understand the drivers of the current debate on the potential future requirements of electric power systems.

2.3 Governance and the environment

Power infrastructure is defined through negotiation and deliberation among various actors. Regarding the aforementioned steering components of electric power systems, at this stage I will only point to the close relationship between the power infrastructure and electrical devices and how they are determined through policy instruments and decisions in market environments. One of the key features of governance is to determine the market design for key infrastructure systems. In most industrialised countries, pow-

er markets originate from monopolistic structures (Morton Jr. 2002). Many operators of power infrastructure components are today still owned by the government and utilise power generation and distribution technologies based on long-term planning processes approved by political leaders (Breeze 2014). Furthermore, as a result of the monopolistic regulations in some countries, some power markets in industrialised countries still offer only limited opportunities for consumers and non-governmental actors to influence the deployment of power generation and distribution technologies through product choice or participatory processes (Kagiannas, Askounis & Psarras 2004). Private investors are reluctant to invest in power infrastructure as they tend to perceive such deals as unattractive owing to high risk exposure:

- i) **Public ownership.** Some power generation technologies rely on the use of publicly owned land, such as rivers for hydroelectric power generation. The respective land area is generally owned by the government and concessions need to be obtained to ensure that the public interests are not violated, such as the provision of freshwater. In order to protect such interests, governments are sometimes either reluctant to consider private bidders or impose additional requirements that are too costly to meet (EC 2005).
- ii) **Risk exposure.** Some power generation technologies hold the risk of catastrophic accidents or nuclear proliferation including unresolved issues related to the disposal of nuclear waste (IAEA 2005). Nuclear power stations are often only partly insured despite being run to the highest security standards (Francis 1977). Since financial investors seek investment portfolios with predictable and optimal risk-return ratios, they tend to turn down investment opportunities in such assets (Mariotte 2011).
- iii) **Return on investment.** The financial payback cycles of some large-scale power generation and grid technologies can last more than 60 years (Rogner 2012). This renders some projects unattractive for private investors seeking short-term profits. Accordingly, financing such projects often requires, at least partly, the support of government funding (Linares & Conchado 2013).

In recent years, however, regulators have been increasingly promoting power market liberalisation, especially in Europe, to create competition among suppliers and thereby secure an electricity supply at the lowest possible cost (EPCEU 2009). However, such

an endeavour also runs the risk of negating the expected benefits due to supplier concentration and the promotion of unsustainable technologies (Green 2006; Ringel 2003).

Electricity consumption has been gradually increasing throughout the past decades in industrialised countries owing to ongoing electrification processes (IEA 2013). Traditionally, the consumption of electric power is not regulated by power utilities in industrialised countries because of the hugely important role electricity plays in the daily schedule of consumers, as outlined in section 2.1. For manufacturing industries, however, the concept of demand-side management is increasingly applied, where consumers give power suppliers the right to shut down and repower appliances, which enables power suppliers to plan consumption loads better (Paulus & Borggreffe 2011). At the same time, policy makers are increasingly implementing policies that promote energy efficiency in order to lower the energy consumption of appliances, cars and buildings. This is often achieved through the deployment of energy efficiency standards (Tsvetanov & Segerson 2013).

Concerns relating to the impact of power infrastructure on the environment have been expressed for quite some time, but more recently controversial debates among policy makers, scientists and business leaders have been unfolding on the long-term effects of the current power infrastructure in industrialised countries on the environment and human health (Danzer & Danzer 2016; IPCC 2005; Steinhauser, Brandl, & Johnson 2014). While electric power systems in industrialised countries meet the originally formulated requirements to provide reliable electricity at relatively low cost, it is increasingly questioned whether these requirements are still valid and whether electric power systems will still be able to do so in the future. During the past decades the combined work of scholars has led to solid scientific evidence on a number of ecological issues stemming from the construction and operation of power infrastructure components in industrialised countries:

- i) **Reach of energy carriers.** Fossil and nuclear energy carriers are formed over millions of years and, as such, their reserves are limited. While there are conflicting views on the extent of fossil and nuclear energy carriers, there is scientific evidence that their exploitation can significantly erode the natural environment (Princen, Manno & Martin 2015).
- ii) **Climate change.** Scientific evidence suggests that the combustion of fossil fuels to generate electricity is a major driver of global warming (IPCC 2005).

This certainly also applies to biomass-based power stations where the energy carriers harvested cause deforestation (Incropera 2015).

- iii) **Nuclear accidents and waste.** The number of nuclear power plants in operation is increasing (Schneider & Froggatt 2014), although serious accidents, such as the ones that occurred in Chernobyl and Fukushima (Mahaffey 2015), result in the public feeling less confident about this technology. Furthermore, the disposal of nuclear waste, which requires deep geological repositories over a very long period of time, remains unresolved (Narkuniene, Poskas, Kilda & Bartkus 2015).
- iv) **Distortion of ecosystems.** The construction and operation of hydroelectric power plants can significantly distort ecosystems, potentially resulting in the failure of ecosystem (Anderson, Freeman & Pringle 2006; Jager & Smith 2008). Moreover, some power generation technologies can lead to acidification and eutrophication of aquatic ecosystems (Roth et al. 2009).
- v) **Resource consumption.** Power plants and grids consume considerable quantities of resources and in some cases require vast areas of land (Roth et al. 2009). Furthermore, thermal power stations put pressure on water resources (Kablouti 2015) while electrical devices are also known to require large amounts of resources (Sugiyama, Honma & Mishima 2016).
- vi) **Electromagnetic fields.** The impact of power grids on human health continues to be controversial, as long-term studies are deemed necessary to analyse the effects of electromagnetic fields (WHO 2014b).

The discussion on the appropriateness of today's power generation and distribution technologies is further fuelled by the advanced age of key components of the power infrastructure in industrialised countries (Ellingwood 1998; Kitsutaka & Tsukagoshi 2014). Given the solid scientific evidence that the electric power infrastructure in industrialised countries contributes to severe forms of environmental degradation, some researchers and enterprises are increasingly looking for technological alternatives (Jülch 2016; Olindo, Jäger, Smets, Van Swaaij & Zeman 2016). Accordingly, a broad range of new technologies is today readily available.

2.4 New technological opportunities and their potential consequences for the system

In addition to what I have sketched so far on the current state of electric power systems in industrialised countries, new options for further developing or transforming these systems is another essential factor when talking about electricity systems today. Recent research and development efforts on new renewable energy and smart grid technologies are increasingly creating viable long-term alternatives to the existing technologies that cause today's problems (Augenstein 2015; Momoh 2012; Olindo, Jäger, Smets, Van Swaaij & Zeman 2016; Strbac 2008).

Throughout the past decade, the competitiveness of clean power generation technologies, such as wind farms or solar PV systems, has increased substantially (Manwell 2010; Solanki 2011). Furthermore, solar PV systems can be installed directly on the roof of consumers' dwellings which is often referred to as distributed power generation (Staffell, Brett, Brandon & Hawkes 2015). In such cases, power generation and consumption occur at the same location, enabling consumers to also become producers. This increasingly popular concept is often captured by the creation of the term '*prosumer*' (Kesting & Bliet 2013). Prosuming offers new distinctive opportunities for both electricity consumers and power suppliers (Kästel & Gilroy-Scott 2015). However, a broad deployment of distributed power generation technologies would call into question the current power grid designs that primarily manage energy flows from power generation centres to consumers (Jenkins, Long & Wu 2015).

Accordingly, the concept of 'prosuming' can have far-reaching consequences for established power infrastructure in industrialised countries; in such cases, power grids may have to be increasingly able to transfer the excess power generated by one '*prosumer*' to another '*prosumer*' with a shortage of supply (Ramachandran, Costello, Kingston, Grijalva & Egerstedt 2012). To master this process, new smart grid technologies with enhanced information and communication capabilities are likely to be required to enable the increased control and management of energy flows (Bush 2014; Liu, Zeng & Liu 2011). Against this backdrop, new technologies would be required to start, operate and shut down electrical appliances (Strbac 2008). Moreover, local storage systems, which are also in the process of becoming more competitive, might be required to provide a flexible power supply (Jülch 2016; Sorensen 2015); in systems with many '*prosumers*', such battery systems could help to store excess electricity generated during periods of peak power generation to later bridge periods with a shortage of supply in a community

(Oberschmidt, Klobasa & Genoese 2013). Smart home technologies could expand to provide entirely new types of energy services, for example in the area of home security, eldercare and childcare (De Silva, Morikawa & Petra 2012). These services could further improve human well-being and increase the energy efficiency levels of manufacturing and service industries (Louis, Calo, Leiviskä & Pongrácz 2015).

New technologies and concepts such as 'prosuming' can potentially be expected to have major impacts not only on technical components, but also on other aspects of the power system (Olkkonen, Korjonen-Kuusipuro & Grönberg 2016). Against this backdrop, some scholars go a step further and argue that these developments call for changes in governance to promote energy transitions (Fouquet 2016; Kern & Rogge 2016). In Europe, the European Union perceives market liberalisation as a necessary means to promote industrial efficiency (EPCEU 2009). There is a general perception that competitive market designs enable consumers to influence the deployment of power generation technologies more easily through customer choice (Neenan, Kinnell, Bingham & Hickman 2016). Moreover, in non-monopolistic markets civil society actors are likely to enjoy access to a wider range of participatory instruments (Bae et al. 2014). Some researchers, however, argue that breaking up monopolies will not be enough to deal with the current efficiency and sustainability issues, as achieving energy transition is likely to require the deployment of a dedicated set of policy instruments (Pollitt 2012). Three requirements are frequently mentioned in scientific papers that are expected to promote market efficiency and the deployment of new clean technologies:

- i) **Market liberalisation.** In some markets, power suppliers still operate in monopolies where consumers of electricity pay tariffs according to their power generation mix (Künneke 1999). For these monopolies there is little incentive to develop new products, as customers have limited options and other market actors are barred from offering their solutions. To create incentives for power suppliers to respond to growing demand for distributed power generation solutions or tap into the potential of smart grid technologies, some researchers and policy makers propose market liberalisation (Müller, Steinert & Teufel 2008). Market liberalisation is thought to put more pressure on corporate costs as well as innovation, as power suppliers then face competition from new market actors that have been granted market access (Markard & Truffer 2006).

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- ii) **Harmonisation of construction and energy policy.** Distributed power generation technologies can be integrated into buildings, which are subsequently enhanced by the ability to generate electricity and manage energy flows through smart grid technologies (Yang & Athienitis 2016). Accordingly, some scientists argue that new policies to promote distributed power generation and energy efficiency have to consider requirements of on-site power generation, such as connectivity and net metering regimes (Krasko & Doris 2013). To further facilitate the penetration of distributed power generation and energy efficiency technologies, regulations and standards may need to be harmonised, as current versions are perceived to contain elements barring the implementation of new technologies (Williams et al. 2016). The deployment of solar PV, for example, depends on regulations related to construction planning, monument conservation and grid connectivity (Gaiddon, Kaan & Munro 2009).

 - iii) **Promotion of smart grid technologies.** In electricity systems where the majority of power generation is based on energy fluxes, power generation can no longer be actively controlled by system operators. In such cases, power consumption has to be adjusted to erratic power generation; instead system operators issue commands to waken dormant devices, operate appliances or shut off electrical devices to conserve power according to the availability of electricity (Strbac 2008). To be able to still secure a stable supply of electricity, some researchers perceive policies enabling smart grid technologies, such as demand-side management (Warren 2014) and smart metering (Sharma & Saini 2015) to be key prerequisites. However, this trend also raises questions about security and privacy (Xiao 2013).

Since substantial parts of the existing power infrastructure in industrialised countries, including hydroelectric power plants and the technical components of power grids, already contribute towards meeting sustainability requirements, a future technical design for electric power systems will likely contain features of both the existing power infrastructure and distributed power generation. Hence, the research focus has shifted to integrating more renewable power generation technologies (Lopez & Espiritu 2011). Against this backdrop, it seems obvious that we should strive for the transformation of existing electric power systems to bring together the best parts of the established power infrastructure and new technologies rather than building new ones from scratch. *Figure 3* depicts a technical design for power infrastructure that relies on both existing

power infrastructure components and elements pertaining to new technologies, such as increased management of energy flows. Essentially, it displays the previous diagram of a traditional technical design for power infrastructure but enhances it with new features of distributed power generation and smart grid technologies. Accordingly, it emphasises the need for a data system operator that controls devices according to the electricity generated.

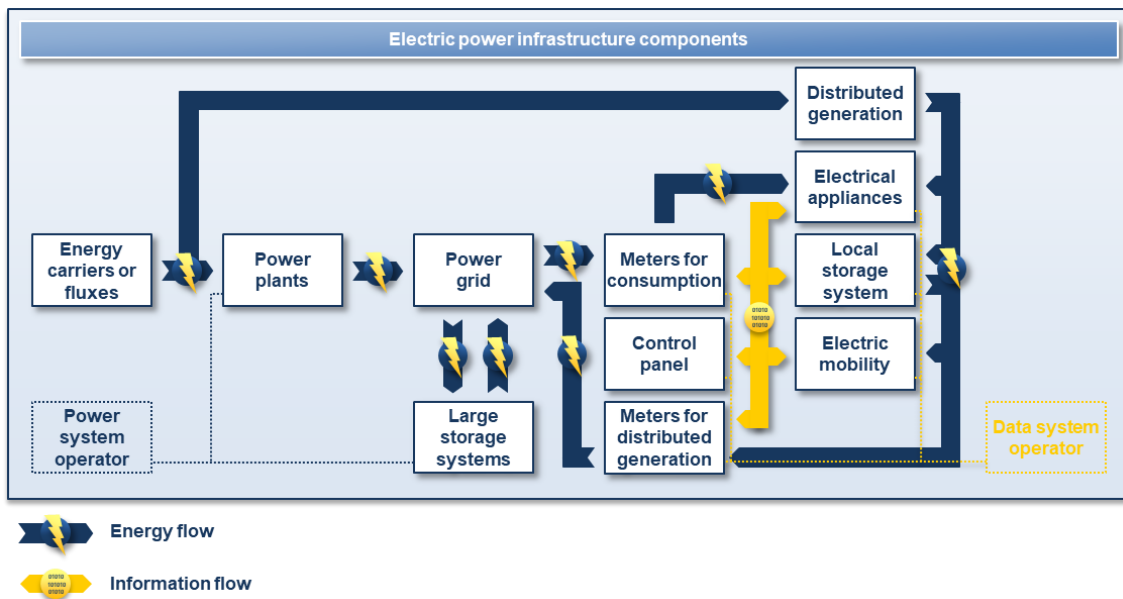


Figure 3: Potential design of power infrastructure integrating new technologies
(Own elaboration)

While some of the current features of power infrastructure will also be of value for a sustainable future, it is important to acknowledge that a broad deployment of distributed power generation and smart grid technologies would question the viability of simultaneously pursuing a renewal of nuclear power or introducing fossil fuel-based power generation capacities. Accordingly, general development scenarios are at least partly mutually exclusive and the decision on which development path should be based will have a resounding impact as it may cause technological lock-ins due to the long life spans of some components of the power infrastructure (Lee & Gloaguen 2015). Such decisions must surely depend on the norms and values of a society. However, they also depend on the storytelling about these pathways, or in other words, on what they are thought to look like. This leads me to the last element of this background chapter on electric power systems: I shall point to the current state of debate on conceivable scenarios for electric power systems by using the case of Switzerland as an example.

2.5 Scenarios for Switzerland

The current technical design of the power infrastructure in Switzerland is strongly influenced by hydroelectric power, accounting for up to 55%, and nuclear power, contributing roughly 40% to the electricity generation mix. The remaining 5% is provided by fossil fuel-based power generation, wind farms, solar PV systems, biomass power stations and some district heating systems in bigger cities (SFOE 2014b). Efforts to tap into the potential of geothermal energy have so far been unsuccessful in Basel, Zurich as well as St. Gallen, and media response has been quite negative (Stauffacher, Muggli, Scolobig & Moser 2015). Prior to presenting the scenarios that are currently being discussed, I shall briefly recapture the key milestones related to the development of the Swiss electric power infrastructure.

The natural occurrence of rivers and lakes in the alpine regions of Switzerland results in the high potential for hydroelectric power generation, and state-owned power suppliers have built large hydroelectric power plants in Southern and Central Switzerland during the past century, while additional projects have also been developed (Deane, Gallachóir & McKeogh 2010; Hagin 2012). In addition, nuclear power plants have been built in the lowlands and sophisticated power grids deployed to deliver electricity to rural and urban consumers. Since the power generation profiles of hydro pumped storage power plants can be actively altered by system operators and this technology accounts for a significant part of the power generation mix in Switzerland, power generation can be easily adjusted to consumption (Rehman, Al-Hadhrami & Alam 2015). Moreover, hydro pumped storage capacities have assumed a key role in energy trading to generate additional arbitrage revenues (Zafirakis, Chalvatzis, Baiocchi & Daskalakis 2016). Having such large flexible power generation capacities obviously, reduces the need for demand-side management. This is almost exclusively conducted with industrial consumers, where declining price tariffs and flexible revenue-sharing models are offered by power suppliers to ensure customer retention.

Against the backdrop of this power generation mix, a controversial debate is also unfolding in Switzerland on how the electricity system should be developed for the future. This discussion revolves around a scenario analysis carried out by prognos, which was mandated by the Swiss Federal Office of Energy to provide scenarios as input for policy processes (prognos 2011). While the large share of hydroelectric power remains undisputed, the discourse focuses on nuclear power and alternative options based on new renewable energy technologies together with possible intermediary solutions. Nu-

clear power takes the centre stage insofar as its 40% share currently resembles a critical part of the Swiss electricity generation mix (SFOE 2014b). Since Switzerland is home to some of the oldest nuclear power plants in the world, a discussion on appropriate life spans and replacement alternatives has been triggered (NEI 2015). There are two critical elements to this debate: Firstly, while some actors deem nuclear power as sufficiently safe to prolong operation to as long as 60 years or even beyond, the national nuclear security agency only grants permission for continued operation if periodic security assessments are passed (FCS 2009). In contrast, other actors request immediate shut-downs of the oldest nuclear power plants and seek to establish predefined decommissioning dates for the others not exceeding international guidelines. Secondly, the Swiss parliament already decided not to replace existing nuclear power plants with new ones. However, this option remains part of the debate and was also included as one option in the scenarios produced by prognos (prognos 2011). Moreover, advocates for a strategy based on renewable energy technologies argue that today there is a unique window of opportunity to find alternatives to nuclear power. Should Switzerland opt to construct new nuclear power plants, they argue, then this decision will inevitably lead to path dependences due to their long life span.

Accordingly, so far, scientists, politicians, industry representatives and environmental associations have not been able to reach a consensus on what requirements the future power system in Switzerland should meet and what the technical implementation should look like. The three scenarios produced by prognos are currently being explored in the public discussions in preparation for an upcoming public vote (prognos 2011):

- i) **Business as usual.** The first scenario foresees the mere replacement of existing nuclear power plants with new ones. Advocates of this scenario argue that this strategy secures a stable electricity supply and low power generation costs (Rehner & McCauly 2016; Rothwell 2004). Those opposing this scenario, emphasise that a large portion of the generating costs of nuclear power plants are carried forward to future generations, as the costs of decommissioning, disposal of waste and exposure of the population to catastrophic risks are not appropriately considered in electricity tariffs (Segelod 2006; SFOE 2014a; Williams 2007). These claims are confirmed by recent research suggesting that the generating costs of new nuclear power plants in Europe may indeed be much higher than originally assumed (Harris, Hep-tonstall, Gross & Handley 2013).

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- ii) **Introduction of natural gas.** The second scenario assumes a partial replacement of nuclear power with natural gas power plants. Since the generating profile of this technology can respond better to changes in consumption than nuclear power plants, such a replacement would allow for a larger share of renewable power generation technologies (Stathopoulos & Paschereit 2015). Furthermore, supporters of this scenario highlight that introducing gas turbines can secure relatively low total electricity costs for current generations (West 2012). However, the total costs for future generations are expected to increase as climate change increases (IPCC 2005).

 - iii) **New energy policy.** In the third scenario, nuclear power is substituted by a wide range of renewable power generation, smart grid and energy efficiency technologies. This scenario is, however, thought to require more than just a mere substitution of power plants: it is expected to require a fundamental transformation of the current power infrastructure design to integrate more features of distributed power generation through a disruptive energy transition (Kern & Rogge 2016; Meadowcroft 2009). Since the share of erratic power generation is expected to rise in this case, the deployment of technologies allowing for control over parts of power consumption profiles, for example through demand-side management, is expected to be a necessary precondition (Strbac 2008). Initial costs for current generations are considered to be higher than today, as both new renewable energy and smart grid technologies require investments (West 2012). However, future generations ought to benefit from this scenario as these investments reduce long-term pollution substantially and decrease external costs (SFOE 2013).

While these three scenarios were produced for Switzerland, similar scenarios are being explored in other industrialised countries, where scientists, policy makers and market actors face similar situations. *Figure 4* depicts the three scenarios under discussion for the future development of the electricity system in Switzerland. The table also contains short summaries of the power generation technologies they rely upon, the expected impacts on consumption behaviours, the potential benefits for current and future generations and the anticipated impacts on the environment (prognos 2011).

	Business as usual	Introduction of natural gas	New energy policy
Power generation mix	Nuclear and hydroelectric power	Natural gas and hydroelectric power	Hydroelectric, wind and solar PV power
Effects on consumption	No changes in behaviour with few applications of demand-side management	No changes in behaviour with few applications of demand-side management	Changes in behaviour and demand-side management as critical success factors
Benefits and ecological burdens	<ul style="list-style-type: none"> ▪ Low electricity costs for current generations ▪ Higher electricity costs for future generations ▪ Nuclear waste and risk of catastrophic accidents 	<ul style="list-style-type: none"> ▪ Low electricity costs for current generations ▪ Higher electricity costs for future generations ▪ Contribution to climate change 	<ul style="list-style-type: none"> ▪ Higher electricity costs for current generations ▪ Low electricity costs for future generations ▪ Low long-term pollution

Figure 4: Scenarios for a transformation of the power system in Switzerland
(Adapted from prognos 2011)

While the debate on the future design of the electric power system in Switzerland focuses on the above scenarios, it remains unclear which requirements electric power systems will have to meet in the future. A consensus on what the system should sustain, however, is a necessary precondition for a *goal-oriented* development of the system. Furthermore, how a system transition, if any at all, can be carried out is for now also far from obvious. Following the path presented by the scenario related to new energy policy would seem to be a potentially challenging task: some key components of power infrastructure are to be replaced, such as nuclear power plants, by new ones, such as more solar PV systems, and entirely new functionalities, such as a bi-directional energy flow management in smart grids, are to be introduced.

This begs the question: Why should a society decide to take such a demanding route? There are many possible answers to that question. One response often brought into the discussion is that such a route shows what we need to do to meet the requirements of SDS. The guiding principles of SD do indeed aim to provide an answer to this question (WCED 1987). To clarify the overall background to my argument further, I shall proceed by elaborating the key cornerstones of the SD and the methodological contributions it may offer to resolve the current issues faced by electric power systems in industrialised countries.

3 Sustainable development

At the end of the previous chapter, I referred to SD as a societal model that is thought to frame decisions regarding future key systems, such as electric power systems. However, it is a well-known fact that there is no one generally accepted interpretation of SD (Hopwood, Mellor & O'Brien 2005; Kates, Parris & Leiserowitz 2005). Moreover, there is a broad and controversial debate on the governance of transformation and on how SD should be assessed, although the fact that both aspects are intrinsic components of SD is undisputed. Accordingly, my thesis must take these elements into account without, however, striving to make a contribution to one of these three discussions on the conceptions of SD, governance of SD and the overall methodological debate on sustainability assessments. Hence, this chapter mainly serves to lay out of those essential elements of SD, governance and sustainability assessments that I need to consider in my undertaking. My approach comprises attempting to distil the elements from the debate on these three sustainability related fields that have the potential to be accepted across different theoretical perspectives.

The focus regarding SD is to reveal the normative requirements of the guiding principles. I shall start by highlighting early conceptions of human development issues stemming from environmental degradation and will then proceed by pointing out the evolution of the normative requirements of the SD. The second section on governance will concentrate on instrumental rules for the governance of SD. In this regard, I take governance instead of government only as the overall undisputed starting point and elaborate on those elements that are decisive in actively directing the development of key systems against SD requirements. Finally, I shall complete this chapter by formulating the structural features of sustainability assessments. Starting with a review of the evolution of impact assessments in general, I will present the basic features of sustainability assessments, thus providing a basis for *evidence-based* and *goal-oriented* decision making according to system data and sustainability objectives.

3.1 Normative requirements

Some scholars estimate the birth of the normative features of the SD conception to go back as far as the age of the Greek philosophers. During that time, the first discussions emerged encompassing themes of ecology and the environment and quality of life. While the debate on this complex subject is thought to have manifested mostly during periods of severe crisis, it is also seen as the dawn of a growing understanding on the

critical interrelationship between human development and the environment and a recognition that a productive environment contributes to human well-being (Grober 2010).

The first written evidence of the normative requirements of SD is to be found in the book *Sylvicultura Oeconomic* on forestry management written by Hans Carl von Carlowitz in 1713 (Mathe 2011). During that period, the ever-expanding agriculture and mining industries led to unprecedented deforestation in Europe (Foster & O’Keefe 2000) and Von Carlowitz perceived wood as an indispensable resource for current and future generations. He concluded that long-term conservation plans are required to secure reliable livelihoods for future generations⁴ and timber should therefore only be harvested to the degree that trees can grow back. Throughout the early twentieth century, this concept was elaborated based on the same core idea, namely, to harvest renewable resources within the boundaries of regeneration rates (Bettinger, Boston, Siry & Grebner 2008).

In 1972, the Club of Rome published the book *The Limits to Growth* which gained much attention from the media, researchers and politicians. Against the backdrop of economic stagnation in industrialised countries and strong population growth in developing countries, environmental deterioration was, according to the book, perceived to be the biggest long-term threat to modern societies. The authors developed a model to investigate the causes, interrelationships and implications of five major trends up to 100 years into the future. These trends comprised (i) the acceleration of industrialisation, (ii) rapid population growth, (iii) widespread malnutrition, (iv) the depletion of non-renewable resources and (v) environmental degradation. This global model was based on system dynamics and implied the exponential growth of all five factors. Ultimately, the model revealed generally catastrophic decline scenarios. The authors drew the conclusion that if present trends were to continue, the limits of growth would be reached sometime within the next 100 years. They argued that a rather sudden and uncontrollable decline in both the human population and industrial productivity would be the most probable result. They emphasised that immediate action could reverse the prevailing trends and lead to ecological and economic equilibrium (Meadows, Randers & Meadows 1972).

⁴ To be specific, I shall add that the definition of future generations in Von Carlowitz’s writing primarily consisted of the wealth of his chieftain.

The Limits of Growth was the starting point of a long-lasting controversial debate on the interdependencies of economic growth, resource depletion and pollution. However, many scientists and politicians criticised the underlying methods as they urged among others that technological progress was underestimated and declines in economic growth are more likely to result in increased poverty. Today, researchers perceive *The Limits to Growth* as having paved the way towards a differentiated discussion on the complex interrelationships between human development and environmental conservation (Bardi 2015) rather than as a reference point on that relationship.

A decade later, the United Nations established the United Nations World Commission on Environment and Development (WCED) in response to a broader recognition that poverty can only be overcome through development and that the latter has become inseparable from environmental issues. The Commission was mandated to examine critical environmental and development issues and make proposals on how to resolve them. The results of this analysis were published in a paper called the *Brundtland Report* or *Our Common Future* in 1987. The study concluded that the previously compartmentalised world with local issues had evolved into a global community facing one single crisis: an increasing resource gap between developing and industrial nations, while much of the planet's ecological capital had already been irreversibly consumed. The authors stressed that current development patterns in industrialised countries may have succeeded in meeting the needs of their current generations, however, they might also jeopardise the ability of future generations to meet their needs. Accordingly, based on the assumption that long-term development can only be achieved with a productive ecological resource base, the WCED provided the most frequently quoted definition of sustainable development: "*A development ensuring to meet the needs of the present without compromising the ability of future generations to meet their needs*" (WCED 1987). Moreover, the Commission concluded that to achieve SD three conditions have to be considered:

- i) Technology, social organisation and the ability of the biosphere to absorb emissions of human activity impose limits.
- ii) Lifestyles and consumption patterns that lie within the planet's ecological means need to be adopted.
- iii) SD cannot be defined as a fixed state of harmony, but rather resembles a reflexive process ensuring that the exploitation of resources, financial in-

vestments, technological progress and institutional change are consistent with future needs.

To counter prevailing development patterns in industrialised countries, the Commission proposed that international cooperation should be strengthened and integrated policies on the environment and human development at national levels should be promoted. These policies are intended to keep human populations within the range of ecological resources, increase food security, protect species and ecosystems, decouple economic growth from energy consumption, decrease the resource-intensity of manufacturing and service industries as well as adopt explicit settlement strategies in response to uncontrolled urbanisation. Ultimately, the report pointed out that human populations grew vastly throughout the past century, causing unintended impacts on the atmosphere, soil and water, thus requiring far-reaching changes within the next decades (WCED 1987).

In 1992, the United Nations Conference on Environment and Development (UNCED) was held to promote nations' implementation efforts with regard to SD. Representatives from more than 170 countries participated. At this conference, nations voluntarily committed themselves to a non-binding action plan called [Agenda 21](#). This action plan aims to take a balanced and integrated approach to environmental and developmental issues. The programme areas of [Agenda 21](#) are structured into four sections:

- i) A social and economic dimension addressing development issues, such as poverty, consumption patterns, population growth, human health, sustainable human settlement and sustainable settlement in decision making.
- ii) Fostering of conservation and management of resources for development involving the protection of the climate, land resources, forests, fragile ecosystems, biodiversity, oceans and freshwater resources and the control of toxic chemicals, and hazardous and radioactive waste.
- iii) Strengthening the role of major groups, including women, children, indigenous people, non-governmental organisations, local authorities, workers and trade unions, business and industry as well as the scientific and technological community.
- iv) Definition of means of implementation, such as financial resources and mechanisms, technology transfer, science, education, national mechanisms

and international cooperation, international institutional arrangements, international legal instruments as well as mechanisms and information for decision-making.

This conference had a global impact: Nations committed to [Agenda 21](#) voluntarily agreed among others to develop and implement national sustainability strategies by 2002 (UNCED 1992). One of these efforts represents the [Enquete Commission's](#) report *Schutz des Menschen und der Umwelt* for Germany in 1998. The [Enquete Commission](#) based its contribution on the three pillars approach, structuring sustainability into environmental, social and economic dimensions with overarching objectives. For the environmental dimension, the objective focuses on the conservation of those ecosystem services that are vital for human well-being. The objective of the economic dimension is to reduce scarcity and increase welfare, whereas the objective of the social dimension is to preserve social coherence and productivity. This three-pillar structure, which has meanwhile become a hallmark of SD, was complemented with a set of management rules for each dimension. If the objectives and management rules are followed, then society can be considered sustainable. Furthermore, quantitative indicators were developed to measure progress and allow for an assessment (EK 1998).

Switzerland adopted a similar approach to meet its obligations under [Agenda 21](#). Firstly, the overarching objectives of [Agenda 21](#) were transcribed into national legislation by amending the national constitution (FOSD 2012). In line with the Swiss form of government, some of the strategic objectives were also adopted by cantons and communities. Following the guidelines of [Agenda 21](#), a sustainability strategy (FCS 2012) and goals (FOSD 2012) were formulated. Subsequently, aggregated criteria and specific indicators were defined to extract and compare current system data against the predefined goals (FOSD 2012). The resulting gaps then serve as a basis for developing policy steering instruments (FOSD 2013). This endeavour was accompanied by sustainability reporting to provide transparency on the predefined goals, the current situation and the policy instruments deployed for interested parties (FSOS 2012).

During a United Nations Conference on Sustainable Development held in 2012, the member states of [Agenda 21](#) reaffirmed their commitment to work towards meeting the predefined objectives. Furthermore, a review of the progress achieved so far was conducted, implementation gaps were identified and new emerging challenges addressed. The conference produced the report *The Future We Want* (UNCSD 2012).

More recently, the UN adopted a post-2015 development agenda titled *Transforming our World: The 2030 Agenda for Sustainable Development* containing a set of sustainable development goals (SDG) to continue global efforts to promote human development (UN 2015).⁵

Obviously, the characteristics of SD drawn from political documents are quite general. While they give an indication of the general direction, they are in need of interpretation. An operationalisation of the general guiding principles of SD requires interpretation in order to derive tangible criteria and goals, to the effect that different governmental and non-governmental interpretations of SD result.⁶ This is not surprising because societies as well as different groups within a society tend to agree on different norms, values and principles according to social preferences, local cultures or religious beliefs. Furthermore, objectives may also be linked to regional circumstances, such as the achieved level of social and economic development, knowledge on critical environment-development issues or the availability of precious resources or specific types of energy fluxes or carriers.

The different interpretations of the normative features of SD lead to a broad variety of objectives to be pursued (Hopwood, Mellor & O'Brian 2005; Kates, Parris & Leiserowitz 2005; Van Zeijl-Rozema, Cövers, Kemp & Martens 2008). These different perspectives on SD involve, for example, contributions with a strong focus on ecological boundaries (Hueting & Reijnders 2004), normative questions on what goals a system has to sustain (McCool & Stankey 2004), analyses of the relevance of local specifics (Brand & Karvonen 2007) and concepts of strong versus weak sustainability (Williams & Millington 2004). The manifold interpretations reveal that different underlying normative choices are made to assign, for example, a higher priority to the preservation of ecological capital over human development or vice versa.

Furthermore, the number of interpretations can also be partly explained by the evolution of SD: While early work focused mainly on resource scarcity and population

⁵ This thesis was in its final stages prior to the official release of the SDG in autumn 2016. Accordingly, a systematic consideration of the SDG was no longer possible. However, while I acknowledge their relevance in political contexts, I would like to emphasise that the goal of this thesis lies with drawing up a scientific framework for sustainability assessments. In contrast, the SDG would seem to be a political consensus and were, thus, not produced through scientific analysis. Against this backdrop, I consider more dated sustainability literature (WCED 1987) enriched with recent scientific interpretations to be a more adequate basis for my endeavour in developing a sound scheme for scientific analysis.

⁶ The breadth of results originating from the operationalisation of Agenda 21 has also been subject to scientific analyses (Haward & Van der Zwaag 1995).

growth, seeking to prevent an overexploitation of exhaustible resource stocks, the focus of the debate later shifted to the fragility of ecosystems and how the productivity of ecosystems affects the human well-being of current and future generations. The discussion ultimately expanded its scope from a purely environmental focus to also consider aspects of fragility related to economic and social productivity. Today, the debate on SD even encompasses subjects outside the scope of traditional human-environment systems, such as the long-term viability of social security systems in industrialised countries.

Figure 5 summarises the discussion on the normative features of the SD from the seventies up to today. This figure shows from top to bottom how the focus of the key literature has moved from resource scarcity and population growth in the seventies to fragility of ecosystems and human well-being today, although more recent literature has broadened the scope of analysis to topics on economic productivity and social fragility. Moreover, the scope of the analysis has also expanded from a regional focus of forestry and fisheries to more global issues like climate change.

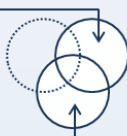

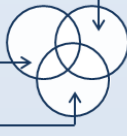
Period	Focus	Discussion	Examples
1970 to 1980	<p>Resource scarcity</p> <p>Population growth</p> 	<p>Issue Exhaustion of resource stocks beyond regeneration rates.</p> <p>Effect Decline in economic growth and human population owing to the inability of the planet to cope with pollution.</p>	<ul style="list-style-type: none"> Forestry Fisheries
1980 to 2000	<p>Fragility of ecosystems</p> <p>Human well-being</p> 	<p>Issue Increasing fragility of ecosystems resulting in diminished ecosystem services.</p> <p>Effect Decline in social productivity and impairment of opportunity spaces for future generations.</p>	<ul style="list-style-type: none"> Climate change Freshwater provision
2000 to today	<p>Fragility of ecosystems</p> <p>Economic productivity</p> <p>Social fragility</p> 	<p>Issue Increasing fragility of ecosystems and decline in social and economic productivity.</p> <p>Effect Reduction in societal transformation potential towards new objectives and requirements.</p>	<ul style="list-style-type: none"> Climate change Social security

Figure 5: Evolution of the debate on sustainable development

(Own elaboration)

As already mentioned at the beginning of this chapter, this section serves primarily to provide an overview of selected key milestones of the evolution of the conception of SD

in order to provide a frame for the normative basis for my work in the rest of this thesis. However, this overview also sheds light on the fact that while the *Brundtland Report* (WCED 1987) still holds the most frequently cited interpretation, the discussion on *what is to sustain* has given rise to a wide range of proposals for interpreting the normative features of SD (Sneddon, Howarth & Norgaard 2006). While *Our Common Future* assumed, without a doubt, the central role in paving the way to a more comprehensive understanding on the interrelationships between human development and environmental deterioration and provided overarching objectives and instruments for the attainment thereof, there is good reason to believe that it may in the meantime have become outdated. Despite the fact that many authors of sustainability assessments base their contribution on this famous interpretation (Gallego Carrera & Mack 2010; Grunwald & Rösch 2011; Maxim 2014), I argue that it may be more appropriate to base my contribution on a scientific interpretation that also incorporates more recent findings of the scientific debate on SD. Against this backdrop, I shall argue for a more recent interpretation of SD in chapter 7. This will enable me to base my contributions on sustainability assessments on a current scientific perception of the normative features of SD.

However, the conception of SD not only provides guidance on *what should be sustained*, but also acknowledges the importance of system transformation and policy instruments for carrying out such transformation. Since system transitions are part of governance, I shall therefore dedicate the next section to discussing the strengths and weaknesses of traditional governance and exploring key aspects of reflexive governance that might be better equipped to deal with current sustainability challenges.

3.2 Instrumental aspects

The guiding principles of SD imply the need for goal-oriented steering of societal development. The core idea behind SD is based on a deep discontent with current development patterns and the recognition that collective action is required to gear societal development towards more sustainable trajectories (Meadowcroft 2011). On the one hand, this assumes that societal development can be influenced to move in a desirable direction (Meadowcroft 1999). On the other hand, the implementation of SD seems to require a fundamental transformation of key systems delivering crucial services to their actors in a way that they no longer cause long-term environmental degradation. Moreover, governance of SD also seems to ask for changing the steering settings: The *Brundtland Report* argues for a more integrative policy approach in comparison to more traditional sectoral policies.

However this is further conceptualised, it remains undisputed that some form of active governance is required. For this thesis, I shall define governance as a process of institutionalised interactions between government institutions and other actor groups to achieve collective goals (Lange, Driessen, Sauer, Bornemann & Burger 2013). Such an understanding is both broad enough to capture the manifold steering phenomena and sufficiently specific to encompass the different components of steering, namely policy, politics and polity, on many different steering levels. Hence, the different modes of governance are captured. In the following discussion I do not want to raise the question: What governance is best suited to deal with today's complex sustainability challenges? Rather, I strive to provide a brief overview of some of the key aspects of SD governance which scholars could agree upon,⁷ starting with background information on traditional governance.

In the past, government institutions were concerned with constructing key infrastructures, establishing administrative capacity to exercise political power and building a welfare state to distribute the benefits of economic growth among the population. These undertakings were perceived to be subject to low uncertainty and complexity:

- i) **Clear goals.** Government institutions were able to define goals for development endeavours without involving other actors. This made the process of developing goal-oriented approaches relatively easy⁸ compared to today's sustainability challenges, such as climate change.
- ii) **Centralisation of system knowledge.** Administrations carried the relevant knowledge on system components to be developed without having to rely on cooperation with other actors.
- iii) **Centralisation of decision-making power.** Ownership of infrastructure was fully centralised on state-owned actors, enabling control over development undertakings without the need to consider shared responsibilities.

Based on these perceived characteristics of development endeavours, the instruments of forecasting, analysis and bureaucracy proved to be effective in driving societal development (Hiller & Healey 2008). Although these development projects were deliv-

⁷ At this stage, I would like to point to the huge body of literature on modes of governance and how it is linked to SD (Steurer 2010; Treib, Bähr & Falkner 2007).

⁸ However, this should not be confused with the claim that achieving such goals has been a relatively easy undertaking.

ered, the corresponding infrastructure has started to have unintended effects, such as long-term environmental degradation or technological hazards, which in turn questions the efficacy of the instruments applied. This not only demands a shift in focus from deploying infrastructure to better aligning it, but also requires increased efforts in integrating policies (Kemp, Parto & Gibson 2005). At the same time, the pursuit of increased specialisation led to a gradual decentralisation of ownership so that today a number of actors assume shared responsibility for the development and operation of key infrastructure. Accordingly, the focus of government institutions in industrialised countries shifted from establishing new infrastructure towards integrating systems and preventing erosion of the ecological capital (Beck 1994). These endeavours are also directed at achieving SD. However, they are subject to much higher levels of uncertainty and complexity:

- i) **Unclear goals.** Normative objectives of SD demand a reflexive process to respond to unintended consequences, rather than a fixed vision of the future. This leads to a high level of ambivalence on goals and calls for open-ended approaches to dealing with plurality (Stirling 2009).
- ii) **Decentralisation of system knowledge.** Complex sustainability issues arch across different social actors, technologies and ecological capacities leading to a fragmentation of key system knowledge among various actors (Pahl-Wostl 2007).
- iii) **Decentralisation of decision power.** The ownership of relevant system components, which are to be transformed to remedy sustainability issues, often rests on multiple actors. This requires coordination among different actors, who may follow different agendas to collectively resolve such complex issues (Czada & Schimank 2000).

There is broad agreement among scholars and policy makers that traditional instruments to steer societal development relying on command and control, such as legislation or standards, or market-based approaches, including information campaigns or financial incentives, may no longer be able fully deal with current sustainability challenges (Newig & Voss 2010). Hence, new modes of governance, which are better geared to respond to high uncertainty and complexity, may be required (Lange, Driessen, Sauer, Bornemann & Burger 2013). Some scientists argue that steering societal development is increasingly becoming a shared responsibility among government and market actors

as well as civil society (Rhodes 1997). They argue that in order to implement SD, governance may have to strive for a co-evolutionary understanding, increased participation and social learning (Newig, Voss & Monstadt 2008). This may require the deployment of a different set of policy steering instruments, such as procedural policies and a mutual definition of sustainability visions or experiments. They emphasise that to enable the collective organisation of societal steering, governance may have to create new opportunity spaces (Voss, Bauknecht & Kemp 2006). Due to a strong focus on feedback and learning, these modes of governance are often referred to as reflexive governance. Two of the most frequently applied and researched approaches to reflexive governance are transition management and adaptation management:

- i) **Transition management.** This approach originates from system theory and evolutionary economics and is geared to resolving issues in socio-technical systems, such as energy systems or agriculture (Rotmans, Kemp & Van Asselt 2001). Transitions are understood as fundamental changes in major systems involving shifts in dominant technologies and societal practices over a long period of time. A core requirement for this governance is a comprehensive understanding of the key system dynamics and collective organisation that influence societal development. The governance of transition management is structured into four stages: Firstly, a broad range of actors bearing key knowledge of the system in question create a transition vision in so-called transition arenas. Secondly, based on this vision, a transition agenda is drawn up mirroring translations of the vision to objectives for individual organisations, including forms of cooperation among actors. Thirdly, actors develop and test transition experiments while successful innovations are further pursued. Fourthly, a monitoring or reflexive process ensures that learnings on transitions are shared (Meadowcroft 2011).

- ii) **Adaptive management.** Researchers on resource management, modern ecology and resilience theory developed adaptive management for socio-ecological systems. This is based on the recognition that ecosystems are subject to different evolutionary processes which operate on different time scales. Furthermore, several equilibrium states exist. Accordingly, it is being argued that the management of ecosystems has to be flexible and adaptive, as the environment evolves in various cycles of destruction and regeneration as opposed to the linear growth patterns human societies strive for. The central objective of adaptive management lies in maintaining the resilience

of socio-ecological systems by increasing their capacity to cope with complex dynamics. Since the consequences of interactions with ecosystems are too complex to predict and it is not possible to foresee the right measures, experiments are carried out to test new innovations and to collectively gain insights on the resulting effects on the environment. Policies are then cautiously adjusted based on the results obtained. Moreover, advocates of this approach argue that the current trajectory that seeks maximum sustainable yields may have to be discarded, as accomplishing this task is likely to lead to the increased vulnerability of ecosystems. Special attention should be paid to maintaining diversity which is thought to enhance the resilience of ecosystems and socio-ecological systems (Gunderson & Holling 2001).

Both approaches foresee the collective contributions of different actors towards common objectives: In transition management, actors come together to mutually define visions which serve as a basis for developing innovation projects. In adaptive management actors collectively conduct new experiments. Furthermore, both approaches exhibit features of assessments, where the current state is evaluated against predefined objectives: in transition management, a comparison is carried out of the performance of the projects conducted against predefined targets. Similarly, in adaptation management the success of innovations is evaluated to decide whether policies are to be adapted.

Whether these two approaches are really appropriate is a question that has been subject to controversial debates and scientific analyses (Folke, Hahn, Olsson & Norberg 2005; Foxon, Reed & Stringer 2009; Loorbach 2010; Meadowcroft 2009; Voss, Smith & Grin 2009; Voss & Bornemann 2011), but answering this question clearly lies beyond the scope of this thesis. At this stage, their discussions serve as examples of the general characteristics of SD governance as stated above. Nonetheless, at a more general level, there is a broad consensus among many scholars that the successful implementation of SD is likely to require closer collaboration between administrations and non-governmental actors, as well as between government agencies (Steurer 2010). Against this backdrop, I take it to be a good assumption for my work that the traditional ways of governing may no longer be fully capable of dealing with complex sustainability issues: SD governance is confronted with unclear goals, decentralisation of system knowledge and of decision power and has to take these features into account. Accordingly, SD governance will most likely have to be based on reflexive governance and, for my work here, I shall assume that reflexive governance is a necessary precondition for SD.

Figure 6 compares the cornerstones of traditional governance with transition and adaptive management based on the arguments presented in this section. The objectives and instruments of traditional governance are shown on the left-hand side of this figure, while the same information is displayed for reflexive governance on the right-hand side. Furthermore, a brief summary of the key cornerstones of transition management and adaptive management is provided.

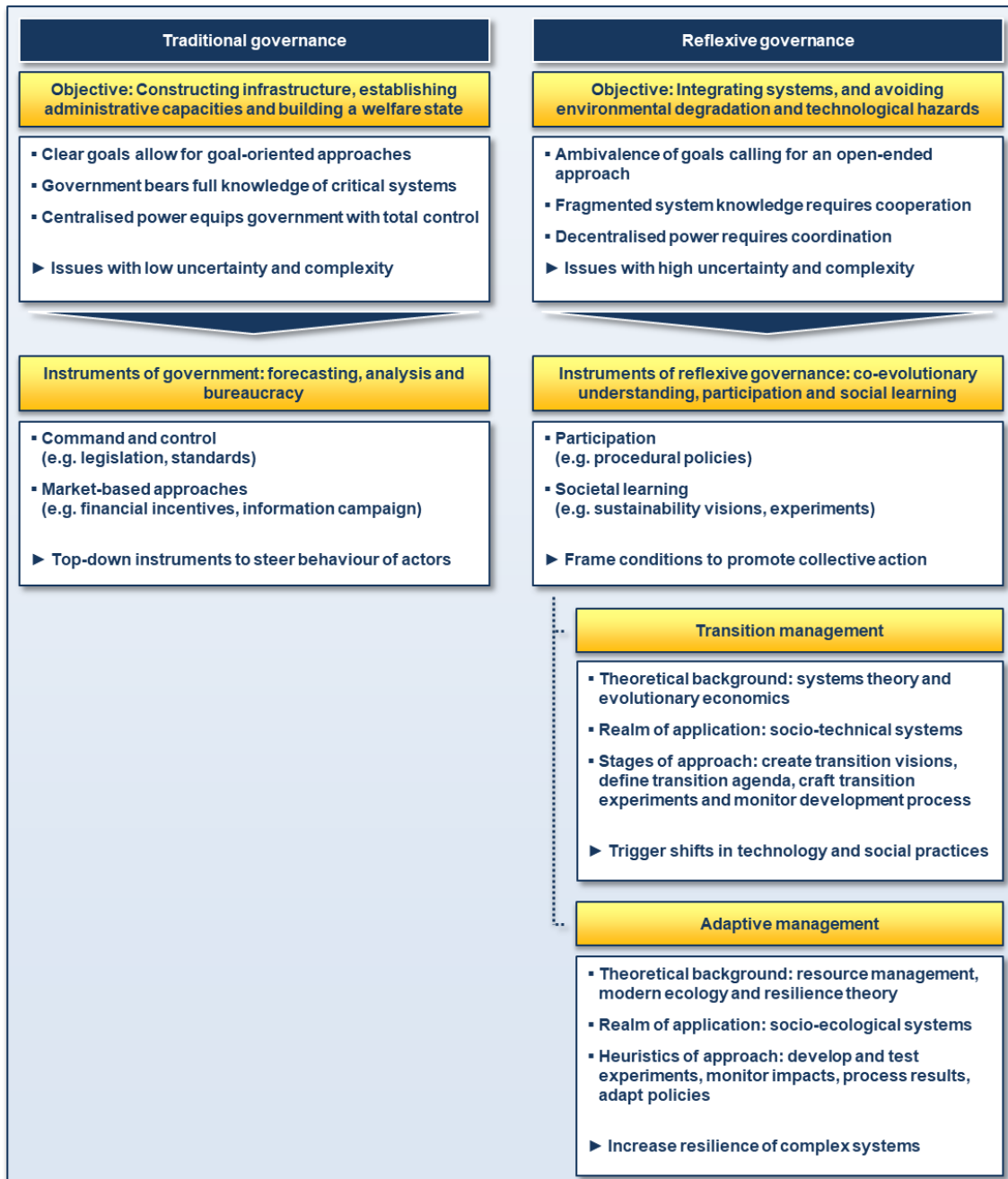


Figure 6: Traditional and reflexive governance

(Own elaboration)

When talking about SD, so my arguments goes, we cannot only take into account the potential target, namely, *what should be sustained*; we also need to consider the conditions and requirements for societal transformation. Accordingly, SD and SD governance are intrinsically linked. Understanding the state of SD, as well as steering societal transformation towards more sustainable development, calls for some form of evaluation or assessment. This leads us the third part of this chapter.

3.3 Sustainability assessments

Scholars and politicians generally agree that assessment schemes are part of a set of steering instruments that seek to inform decision making on the long-term development of key systems (Pope, Annandale & Morrison-Saunders 2004). Adopting well-founded assessment tools and approaches is thought to reduce the risks of potentially erroneous decision making. These procedures are often referred to as impact assessments (IA) and sustainability assessments are a type of such IA. Many researchers assign pivotal roles to sustainability assessments as they are designed to provide a basis for *evidence-based* and *goal-oriented* decision making (Bond, Morrison-Saunders & Howitt 2012): By evaluating data from a system under review against predefined sustainability requirements, sustainability assessments lay the foundation for supporting or rejecting critical development projects or policy instruments. Owing to the resounding impact the results of sustainability assessments can have, the quality of the underlying data plays a crucial role.

Today, a wide range of sustainability assessments is applied by various actors and some researchers argue that sustainability-related decisions are often made without sufficiently comprehensive analyses (Gibons 2012; Morrison-Saunders & Pope 2013). Against this backdrop, I shall first summarise key events in the evolution of IA that led to what we today call sustainability assessments. Owing to the high number of sustainability assessments approaches proposed today, I shall then point to established cornerstones of IA and argue for a set of additional basic features that sustainability assessments should exhibit in order to provide a sound basis for *evidence-based* and *goal-oriented* decision making for the long-term development of key systems and to reduce the risk of omitting crucial aspects. Accordingly, this section aims to lay out the basic structural components of sustainability assessments, which will serve as a basis for a review of current proposals for sustainability assessments in chapter 4.

Sustainability assessments are still relatively new instruments as the origin of such usually, but not necessarily, multi-criteria evaluations can only be traced back as far as the nineteen seventies: Against the backdrop of increasing environmental issues, some government agencies started declaring environmental impact assessments (EIA) as mandatory procedures (Ecclestone 2008).⁹ These evaluation schemes were primarily designed to assess the ecological impacts of infrastructure projects or new goods, such as chemicals (Marriott 1997). Some scientists argue that even these earliest versions of IA exhibit normative and instrumental features (Bartlett & Kurian 1988; Boggs 1995; Caldwell 1982): On the one hand, EIA are subject to the objectives of environmental conservation and human development while, on the other hand, they institutionalise fact-based decision making. Accordingly, the general perception is that EIA resemble procedurally rational decision-making approaches, where the provision of *more relevant* data is thought to lead to *better* decisions (Cashmore & Kørnølv 2012). In parallel, however, some scholars argue that EIA may have also contributed towards establishing a general perception that decision makers have to trade off environmental conservation against social or economic development (Wathern 1988).

More than a decade later, the global recognition of the report *Our Common Future* had a profound impact on the normative features of IA: Hitherto used to provide a description of impacts of key infrastructure projects or new products on the environment, they were now seen as instruments to drive the operationalisation of SD with a strong focus to achieve intergenerational justice (Cashmore & Kørnølv 2012). In parallel, the debate on the operationalisation of SD also brought about shifts in the perception on appropriate modes of SD governance: There is a broad consensus among scientists on SD that implementing SD may have to encourage some form of participation, for example by involving experts or groups of people, to broaden the knowledge base or develop solutions (Bond, Viegas, Coelho & Selig 2010). Accordingly, IA are today deployed in some cases to promote mutual learning in general (Hertin, Turnpenny, Jordan, Nilsson, Russel & Nykvist 2009; Jha-Thakur, Gazzola, Peel, Fischer & Kidd 2009) or, in other cases, on the analysis of interdependencies within complex coupled human-nature systems in particular (Bond & Morrison-Saunders 2011). Thus, the role of IA changed from merely informing decisions, such as in EIA, to assessing contributions to sustainability objectives. Ultimately, this development gave rise to what we call today sustainability assessments.

⁹ Some scientists consider the adoption of the National Environmental Policy Act in the USA to have paved the way for more systematic IA-based approaches to inform decision making (Ecclestone 2008).

Meanwhile, sustainability assessments are frequently applied to critical development endeavours or sectoral policy strategies in some countries and the results are often discussed publicly (Ali 2012). They are often holistic in nature and cover social, economic and environmental aspects (Santoyo-Castelazo & Azapagic 2014). Accordingly, framing the relevant system scope is a major challenge for every sustainability assessment. However, while traditional EIA do not strive to assess contributions to SD and focus on providing descriptive information on resource consumption and pollutant emissions, sustainability assessments are designed to evaluate data against predefined sustainability requirements which express goals for development. Hence, to inform decision makers comprehensively, I argue that sustainability assessments have to meet two distinct requirements: Firstly, they have to cover the relevant features of the system in question.¹⁰ Secondly, they have to make transparent the normative assumptions on the operationalisation of the normative guiding principles of SD.¹¹ Against this backdrop, I argue that the basic features of sustainability assessments must consider both the functional aspects of the system and the normative requirements of SD.

However, while EIA have become proven routines that have served their purpose successfully over the decades and their basic features and underlying methods are today standardised, sustainability assessments have suffered the same fate as the conception of SD: the ambiguity of the model not only gives rise to a multitude of different interpretations of SD, but the design of sustainability assessments is also subject to pluralism (Davison 2001). While the debate on *what should be sustained* continues at a general level, universally applicable objectives for sustainability assessments cannot be unequivocally determined: Since the perception on what is considered sustainable is also bound to the values, norms and principles of individuals or groups within a society, it may not be possible to obtain a single best solution for all actors if their views differ (Pope & Morrison-Saunders 2012). There are cases where even two government agencies of the same state come to different conclusions for the same projects (Pope, Morrison-Saunders & Annandale 2005). In order to bypass this dilemma, some authors of sustainability assessments refrain from evaluating system data against predefined sustainability objectives, preferring to compare development options in order to recommend the least unsustainable one (Scanlon & Davis 2011). Similarly, the ambiguity in answering the general question of *how this should be sustained* transcends the realm of sustainability assessments as effective forms for participation is still being ex-

¹⁰ I will argue later that these features are the functional aspects of the system.

¹¹ Several scientific papers highlight the hybrid character of SD in general (Christen & Schmidt 2011).

plored (Doelle & Sinclair 2006; Monnikhof & Edelenbos 2001): Some authors use participatory approaches to bring a group of people together to discuss the many facets of the problem at hand (Gastil & Black 2008), while others revert to expert interviews to determine priorities for criteria or indicators and thereby delegate decisions on *what should be sustained* to their interviewees (Ribeiro, Ferreira & Araújo 2013). These examples illustrate the pluralism faced today when talking about the constitutive elements of sustainability assessments. Furthermore, it is a well-known fact that assessment processes have to be context specific to work, by considering values, cultures and political aspects (Bina 2008). Accordingly, sustainability assessments might be subject to ambiguity by design.

Against this backdrop, it becomes obvious that I cannot rely solely on investing existing theory to present the basic structural features of sustainability assessments. I rather have to formulate and argue for a set of basic components that constitute sustainability assessments. To do so, I shall adopt a two-stage approach to determine the necessary components of sustainability assessments: Firstly, I shall take those elements of EIA that are undisputed and have proven to be effective in providing a basis for *evidence-based* decision making. Since both EIA and sustainability assessments aim to do exactly that, there is good reason to believe that the methodological components of EIA will also be of use in sustainability assessments. Secondly, I shall then argue for those features that I deem necessary to consider the new requirements brought into the discussion by the SD model. The review of selected milestones in the evolution of IA revealed that the orientation to normative objectives is a fundamentally new requirement. Accordingly, I argue that sustainability assessments have to be able to evaluate system data against predefined normative objectives. This is a new feature, hitherto absent in EIA. Against this backdrop, I argue that, in contrast to EIA, sustainability assessments also have to provide a basis for *goal-oriented* decision making. Hence, I shall also argue for a set of basic features to provide a basis for *goal-oriented* decision making. Together, these elements can be expected to make up the necessary features of sustainability assessments. Hence, I shall proceed by first elaborating those elements of EIA that can be expected to also equip sustainability assessments with the ability to provide a basis for *evidence-based* decision making.

National laws are the primary source of the requirements imposed on the contents of EIA; these policies vary across jurisdictions, but the following features can consistently be found: (i) A description of the environment prior to the implementation of the project, (ii) an outline of the planned endeavour including alternatives, (iii) an analysis of the

expected impacts on the environment and human health, and (iv) an overview of measures to reduce the impacts (Frischknecht & Schmied 2009). Furthermore, in order to operationalise EIA and meet these requirements, authors consistently draw on the following basic features and methodologies:

- i) **Criteria.** EIA often provide data of specific indicators on an aggregated level to summarise the performance of key areas of the system in question. Criteria group data of indicators belonging to the same theme across several system components or value creation stages. '*Greenhouse gas emissions*' is an exemplary criterion measuring all types of gaseous emissions that, among others, drive global warming. '*Energy efficiency*' is another exemplary criterion used to measure energy conversion losses across technical components or transformation stages in energy systems. Accordingly, criteria serve the purpose to facilitate an overview of relevant subjects of the assessment to enable, for example, decision makers to spot areas of concern easily (Myllyviitta, Holma, Antikainen, Lätthinen & Leskinen 2012; Papadopoulou & Antoniou 2014; Pollesch & Dahle 2015).

- ii) **Indicators.** EIA often contain indicators providing detailed quantitative data on specific aspects of a system involving various system components (Bruinen de Bruin et al. 2015; Nguyen, Bonetti, Rogers & Woodroffe 2016). To extract this data, life cycle assessments are often used (Corsten, Ramírez, Shen, Koornneef & Faaij 2013; Li, Zhu & Zhang 2010). '*Carbon dioxide emissions*' in ppm or '*Solar irradiation*' in W/m^2 are typical examples of indicators potentially used in EIA. Indicators serve the purpose of pinning down the exact source of unsatisfactory developments and enable the development of policy measures that address specific system issues. While some perceptions exist that target values are an integral part of indicators, this does not hold true for EIA, where predefined goals are often absent. For the sake of transparency, I shall therefore treat target values, which also appear in sustainability assessments, as a distinct structural element.

- iii) **Ex post analysis.** The criteria and indicators included in EIA, as well as their methods such as life cycle assessments, aim to extract and report information to environmental government agencies. In some jurisdictions, authors of EIA are obliged by law to produce alternative options to the proposed solution (Frischknecht & Schmied 2009). Meeting this requirement

raises questions on appropriate time scales to inform decision makers. A review of published EIA shows that the majority of authors opted to present the impacts of options based on data pertaining to the present or the near future (Rocchetti & Beolchini 2014; Suleman, Dincer & Agelin-Chaab 2015). While this is sufficient to meet the requirements in some countries, it may not be forward looking enough in sustainability contexts to allow opinions to be formed on whether opportunity spaces are also preserved for future generations. This, however, is a subject that I shall touch on later in this section.

Based on this overview of the key features of EIA, I am in a position to summarise three core components that can also be expected to be necessary in sustainability assessments: *criteria*, *indicators* and *ex post analyses*.

This now raises the following question: What additional requirements have to be covered by sustainability assessments to not only inform decision makers according to the legal requirements stemming from the National Environmental Policy Act (NEPA), but also to evaluate the contributions made by certain endeavours against sustainability objectives? In order to answer this question, I shall revert to three new key requirements that are highlighted by *Our Common Future* and, thus, are additional requirements of NEPA regulations: Firstly, SD imposes the objective that the ecological capital has to be maintained for future generations. In contrast to NEPA, I argue that this objective mirrors a condition against which the current state of a system may be evaluated to draw conclusions on the attainment of SD. Accordingly, while under NEPA laws it is sufficient to conduct an environmental impact assessment process, the normative objectives of SD call for an evaluation against predefined sustainability targets. Since I have already acknowledged the manifold interpretations of SD, I argue that sustainability assessments need to contain structural features related to a description of the chosen normative foundation and goals for criteria and indicators. Secondly, the overarching objective of SD to preserve opportunity spaces for future generations implies that development endeavours need to be reviewed on long time schedules. Against this backdrop, it seems reasonable to also introduce a basic component that addresses *ex ante* analysis. Thirdly, there is broad agreement among researchers on SD that attaining SD is likely to require system transitions where a close collaboration among state-owned institutions and other types of societal actors is required (Bond & Morrison-Saunders 2011; Hertin et al. 2009; Jha-Thakur, Gazzola, Peel Fischer & Kidd 2009). This demands a holistic system analysis encompassing social actors and their societal steering processes. Accordingly, I argue that sustainability assessments need to con-

sider these three additional requirements. I shall proceed by further elaborating this set of additional features, which is expected to equip sustainability assessments with the ability to provide a basis for *goal-oriented* decision making:

- iv) **Normative foundation.** The ambiguity of the conception of SD has given rise to various interpretations of the guiding principles. Most perceptions are based on an integrated approach related to environmental, social and economic development to achieve intra- and intergenerational justice. However, it is a well-known fact that different interpretations exist (Lélé 1991). The approach of weak vs. strong sustainability shows that interpretations of SD can vary significantly or even be contradictory (Neumayer 2013). As argued earlier, sustainability assessments have to be based on an interpretation of SD in order to be able to evaluate system data against sustainability objectives. However, I also argued that assessment schemes have to be adapted to specific contexts (Bond & Morrison-Saunders 2012). Accordingly, while one has to choose an interpretation of SD, there is little point in striving for a standardisation of the normative basis for sustainability assessments. Against this backdrop, I argue that authors should provide transparency on which interpretation they chose for the sake of comparability and to enable discussions on how interpretations of SD affect the results of sustainability assessments.

- v) **Steering and instrumental rules.** It is a frequent complaint that the ambiguity of the guiding principles of SD obstructs the operationalisation of the conception, as it is too abstract to directly determine tangible goals. Against this backdrop, one way of translating abstract sustainability objectives into more specific targets lies with applying a multi-step procedure. The latter has proven successful in facilitating the process of breaking down ambiguous sustainability principles into an enriched set of rules (Kopfmüller et al. 2001): '*To harvest renewable resources within regeneration rates*' is an exemplary steering rule for a key infrastructure system. Providing information on the process of formulating general goals based on the guiding principles of SD will allow for a better understanding on how objectives are translated into more tangible metrics. Such a procedure could promote discussions on the appropriateness of methodologies and allow for differentiated comparisons of results with other assessments that draw on different normative foundations or approaches. Accordingly, I argue that steering and instru-

mental rules are another essential structural component of sustainability assessments.

vi) **General goals and target values.** It is widely acknowledged among scholars of SD that while EIA serve the purpose to inform decisions on environmental governance, sustainability assessments are intended to evaluate contributions to SD (Cashmore, Gwillam, Morgan, Cobb & Bond 2004; Sadler 1996). This does, however, require translating the rather abstract normative objectives of SD into more tangible goals. A review of sustainability assessments that contain targets revealed that most contributions previously focused on instrumental aspects (Wood 2002) with only occasional examples that exhibit substantive sustainability goals (Jones et al. 2005; Theophilou, Bond & Cashmore 2010). Assuming that the same structural elements of EIA are being reused in sustainability assessments, such as criteria or indicators, then some researchers argue that the normative objectives of SD could be broken down and mapped to these criteria and indicators (Moldan, Janoušková & Hák 2012). In line with this argument, general goals may be derived from an interpretation of SD for each criterion using the multi-step procedure elaborated above. Such an approach would allow for system data to be assessed against SD goals to identify areas of unsatisfactory performance. While such an approach has only been tried on a more aggregated level, initial results look promising (Grunwald & Rösch 2011). Accordingly, I also argue that general goals and target values are a basic feature of sustainability assessments.

vii) **Ex ante analysis.** Traditionally, sustainability assessments are applied to human-environment systems which are known to evolve over time (Bell & Morse 2008). This aspect is of relevance, as SD addresses issues of equity among current and future generations¹² (Dresner 2008). Sustainability assessments therefore assume a long-term perspective as the pursuit of SD inevitably requires that today's projects refrain from leaving toxic legacies to future generations.¹³ EIA, in contrast, are designed to assess relatively

¹² At this stage, I would like to add that so far no consensus has been reached among researchers on exactly what form of equity should be established among generations (Stoffle, Stoffle & Sjölander-Lindqvist 2012).

¹³ The case of nuclear power can also be used to illustrate this interdependency. Nuclear power offers low electricity costs to current generations at the expense of passing on unre-

short-term impacts of endeavours without considering the societal or technological developments that may happen in the distant future (Adam 2004). Accordingly, EIA are only partly able to deal with lengthy time frames. Some scholars argue that one way to consider aspects of intergenerational justice is to complement the basic features of EIA with sophisticated system models that allow probable scenarios to be produced (Gutzler et al. 2015). Based on scenario assessments, potential long-term effects may be identified early. Accordingly, I propose to include *ex ante* analyses in the list of constitutive elements for sustainability assessments.

- viii) **System representation.** As outlined in section 3.2, my work is based on the assumption that today's sustainability challenges are characterised by a fragmentation of key system knowledge across various types of societal actors. Not surprisingly, key literature on SD consistently suggests involving actors in processes related to sustainability assessments (Boer 1995; Hartley & Wood 2005). There is, however, little agreement among scholars on the most appropriate form of participation (O'Faircheallaigh 2010). Nonetheless, authors tend to agree that some form of participation is required in order to build a common understanding on the problem at hand and develop potential solutions as well as to involve actors in decision making. Such collaborations are known to have the potential to foster mutual learning, as different views and approaches are explored to gain insights on functional, instrumental or normative aspects (Glasbergen 1996; Sinclair & Diduck 2001). Coming back to my introductory remark that system knowledge can be expected to be scattered across various actors, then some form of participation can contribute to a clearer understanding of the system subject to the analysis. Such an endeavour is likely to include defining relevant system properties, or components, which are likely to be part of a sustainability assessment. Without going into a detailed discussion on the most adequate form of participation here, I shall assume that creating a holistic system representation is a prerequisite for any sustainability assessment to determine relevant system features and that such an endeavour might require the involvement of various actors.

solved issues with the disposal of nuclear waste to future generations (Drottz-Sjöberg 2010; Stoeglehner, Levy & Neugebauer 2005).

Within this section, I first elaborated how sustainability assessments evolved from EIA and then argued why EIA need to be enriched with additional basic features in order to be able to assess contributions to SD. I then explored the additional features which are thought to enable sustainability assessments to provide a basis for *evidence-based* and *goal-oriented* decision making on the long-term development of key systems. Accordingly, I argue that in order to operationalise sustainability assessments successfully, they may have to exhibit those functional and normative structural elements which I presented in this section.

Against this backdrop, *Figure 7* schematically compares the structural elements of EIA on the left-hand side with those of sustainability assessments on the right-hand side. This figure shows that EIA require fewer structural features to meet the requirements stipulated under NEPA. The diagram also highlights the increased complexity that sustainability assessments exhibit in comparison with EIA.

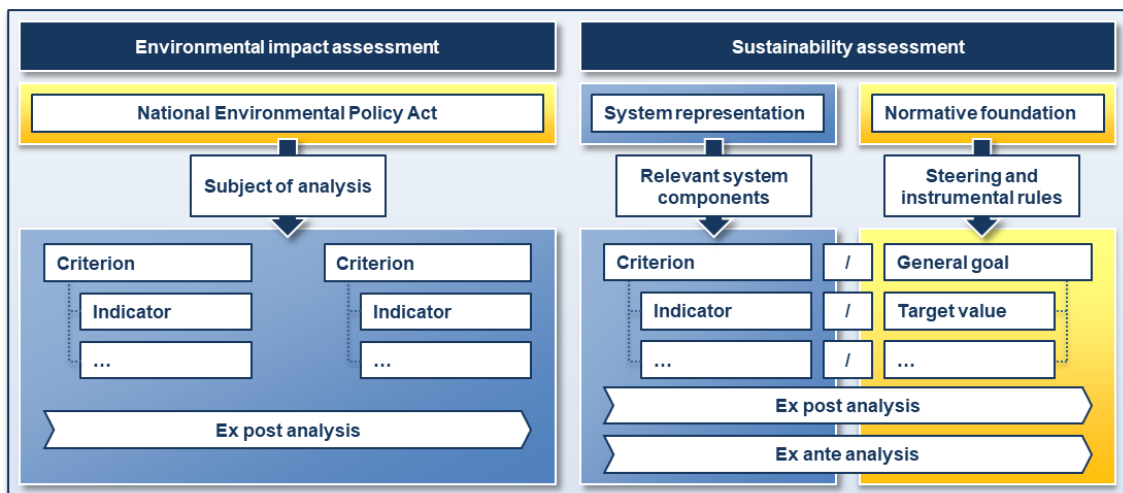


Figure 7: Comparison of basic features of EIA with sustainability assessments
(Own elaboration)

The structural elements of sustainability assessments elaborated in this section will serve as a basis for reviewing and discussing proposals on sustainability assessments in the next chapter. I will therefore focus mainly on contributions proposed by the scientific community and to a lesser extent on how their methodological proposals diffuse to practical applications of other actors, such as government institutions, associations or market actors.

The review of today's sustainability assessments will serve as a basis for identifying shortcomings in today's sustainability assessments. Since I stressed the high relevance of electric power systems in modern societies, I shall review only contributions related to this system. Accordingly, I shall proceed with a presentation and discussion of a sample of current contributions comprising sustainability assessments of electricity systems.

4 Review of existing literature

This chapter serves the purpose for reviewing and discussing a selected sample of scientific contributions on sustainability assessments in the field of energy according to the basic features of sustainability assessments defined in section 3.3. The output of this endeavour will consist of a summary of identified shortcomings in today's contributions in relation to the basic features for sustainability assessments that were previously provided.

An overview of the actors producing sustainability assessments today will serve as a starting point for my analysis in this chapter. I shall then proceed to selecting a sample of sustainability assessments for evaluation, consisting of recent contributions and those proposals that significantly shaped the scientific debate on sustainability assessments, and present a brief summary on selected key content. I shall then evaluate the sample of sustainability assessments against the basic features presented in the previous section. Based on this analysis, I shall be in a position to identify shortcomings in existing contributions. Furthermore, I shall review a smaller sample of practical contributions by other actors to assess to what degree issues pertaining to scientific contributions are carried forward to sustainability policies, standards and reports.

4.1 Actors and interests

Today, sustainability assessments and related documents, such as sustainability reports, are published by a wide range of actors who may be classified into four distinct groups: researchers, policy makers and administrations, market actors, and civil society actors. These actors assume different responsibilities in society and their interests vary, so that their contributions serve different purposes:

- i) **Researchers.** Scientists develop and propose new approaches and methods for sustainability assessments. Furthermore, they conduct specific case studies to discuss the strengths and limits of proposed methodologies. In some cases, they draw on sustainability assessments to demonstrate the proficiency of specific technologies (Shortall, Davidsdottir & Axelsson 2015). Scholars exhibit a strong methodological focus and seek to continuously refine applied approaches and methods. Today, sustainability assessments are still relatively new instruments and research on this subject is therefore still at an early stage (Cinelli, Coles & Kirwan 2014). The quality of scientific

contributions is very important as scientific proposals can be expected to serve as a basis for practical applications of other actors.

I expect contributions from scientists to consist of a wide range of proposals on approaches and methods to be applied while. I also expect researchers to conduct case studies in the field to explore the strengths and weaknesses of specific approaches or methods.

- ii) **Policy makers and administrations.** Voluntary commitments by member states made in the context of [Agenda 21](#) have put pressure on governments to implement policies promoting SD. Against this backdrop, some policy makers seek to adopt the guiding principles of SD in national constitutions and conduct sustainability assessments to monitor the developments in key systems and identify areas for intervention. In some cases, sustainability assessments are based on sectoral policy strategies, such as regional planning (Ali 2012). The alignment of SD requirements with policies is perceived as a continuous process where indicators are adjusted according to developments (Gallego-Álvarez, Galindo-Villardón & Rodríguez-Rosa 2015). Administrations often cooperate with scholars and tend to apply those methodologies that are proposed by researchers.

Transcribing sustainability requirements into national policies is a key challenge for administrations. I expect contributions to display a strong focus on operationalising SD. Their contributions are of high relevance, as market actors are meant to relate their sustainability reporting to policy objectives.

- iii) **Market actors.** Operators of power infrastructure may draw on scientific sustainability assessments as an input to develop new business models (Heikkurinnen & Bonnedahl 2013). Furthermore, new regulatory incentives originating from sustainability assessments may allow agile suppliers to capitalise on new business opportunities. Moreover, manufacturers and suppliers sometimes publish sustainability reports to obtain licences to operate infrastructure facilities, such as mines or power plants, or to demonstrate benefits of specific projects to the public. The realisation of key infrastructure projects often requires EIA or some form of multi-criteria assessment to acquire corresponding concessions. The motivation of infrastructure operators to produce sustainability reports therefore may also lie with gaining so-

cial acceptance (Prno & Slocombe 2012). The sustainability reports of power infrastructure operators are vital for monitoring purposes, as they have access to data on the performance of system components otherwise unavailable to governments.

I expect these contributions to provide less of a holistic system evaluation and to potentially be biased towards supporting own strategies or projects. Ultimately, the goal of these sustainability reports can be expected to lie primarily with presenting the beneficial aspects of corporate enterprises or their endeavours to gain permissions from administrations and the public. However, while the number of published sustainability reports is on the rise, their impact on actor interaction remains questionable (Barkemeyer, Preuss & Lee 2015).

- iv) **Civil society.** Organised institutional actors seek to influence policy processes in favour of their members. Based on members' preferences, they develop common positions on policies and participate in public processes on behalf of their members and thereby invest their interpretation of SD. Sustainability assessments are sometimes seen as effective instruments for environmental organisations to combat specific projects whenever they feel that ecological aspects are underrepresented (WWF 2013). Sectoral associations support members by developing standards for sustainability reports (Rahdari & Rostamy 2015), while internationally accepted reporting standards are also increasingly applied (Roca & Searcy 2012).

I expect contributions from environmental organisations to be geared to emphasising the adverse effects of specific projects on the environment or the strengths of clean technologies. In contrast, I expect proposals by sectoral associations to resemble standards for sustainability reporting. Their contribution is important as manufacturers and suppliers may base their sustainability reporting on standards promoted by sectoral agencies.

Based on this overview, it becomes obvious that scientific contributions are highly relevant as other actors are likely to base their work on proposed methodologies. This emphasises the vital importance of applying effective approaches and methods in sustainability assessments. However, market actors can also be expected to consider contributions by sectoral agencies: They may opt to base their work on standards, such as

the Global Reporting Initiative (GRI 2015; Marimon, Del Mar Alonso-Almeida, Del Pilar Rodríguez & Cortez Alejandro 2012), or consider indices, like the Sustainable Society Index (Van de Kerk & Manuel 2008). *Figure 8* shows the four main actors mentioned previously including their interests. Furthermore, the figure illustrates how scientific proposals and standards are disseminated from researchers and associations on the left to policy makers and administrations, as well as manufacturers and operators, on the right.

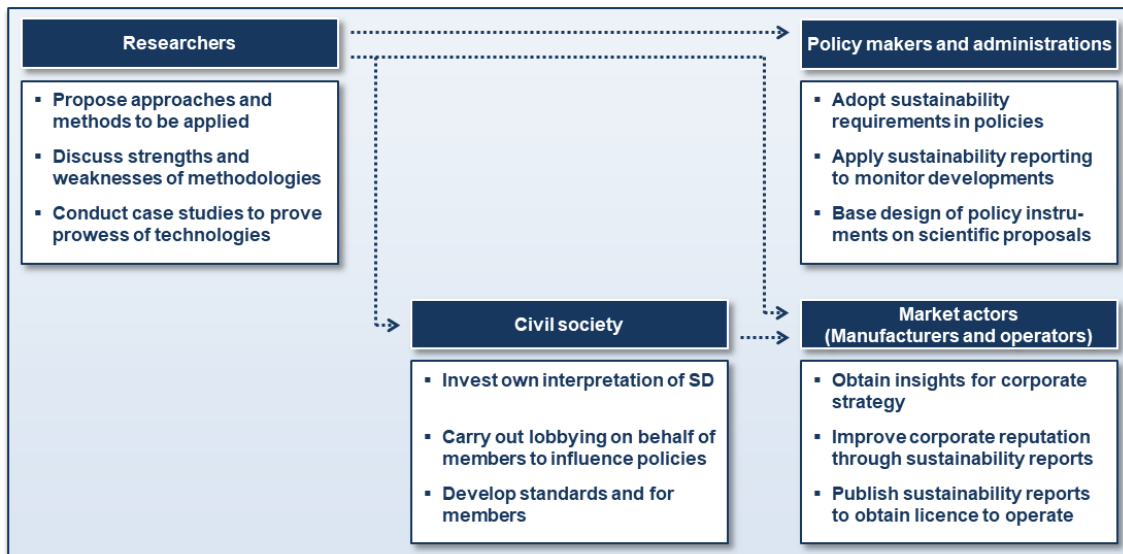


Figure 8: Actors and interests related to sustainability assessments

(Own elaboration)

I shall proceed by selecting contributions to be reviewed in more detail according to the structure of actors publishing sustainability assessments and related documents.

4.2 Selection of research sample

To obtain a representative picture on the current state of scientific proposals for sustainability assessments, policy instruments to operationalise SD, standards and reports, I shall split the sample into two categories: research contributions and practical applications. I shall first review scientific proposals in more detail as their contributions often serve as a starting point for efforts of other actors.

For scientific contributions, I shall consider those proposals that had a strong impact on the discussion on appropriate methodologies for sustainability assessments, starting from the year 2000. Moreover, I shall consider some of the more recent and most fre-

quently cited contributions which have also had a strong influence on the current debate on sustainability assessments. I expect these contributions to exert a strong influence on future practical applications.

Table 1 lists the selected scientific contributions in alphabetical order. It provides the names of the authors, the year of the publication, the title of the paper, a short description of the aim and scope, as well as a brief summary of the applied methodologies:

Authors	Year	Title	Aim and scope	Methodology
Afgan, Carvalho & Hovanov	2000	Energy system assessment with sustainability indicators	Development of indicators for energy systems based on the concept of sustainability	Conceptual deduction of indicators with a case study
Dombi, Kuti & Balogh	2014	Sustainability assessment of renewable power and heat generation technologies	Evaluation of most beneficial renewable energy technologies	Multi-criteria assessment with expert choice
Evans, Strezov & Evans	2009	Assessment of sustainability indicators for renewable energy technologies	Assessment of renewable energy technologies against sustainability indicators	Life cycle assessment
Gallego Carrera & Mack	2010	Sustainability assessment of energy technologies with social indicators	Development of a set of social indicators for energy technologies	Synthesis of literature and expert survey
Grunwald & Rösch	2011	Sustainability assessment of energy technologies: towards an integrative framework	Development of an integrative sustainability framework with normative aspects	Conceptual deduction of principles with case study
Heinrich, Basson, Cohen, Howells & Perie	2007	Ranking and selection of power expansion alternatives for multiple objectives	Development of a methodology to rank power expansion alternatives	Multi-criteria and scenario analysis with case study
Hirschberg et al.	2005	Neue erneuerbare Energien und neue Nukleuranlagen: Potenziale und Kosten	Evaluation of costs and potentials of renewable energy tech. and nuclear power	Synthesis of expert opinion and literature
Jeswani, Gujba & Azapagic	2011	Assessing options for electricity generation from biomass on a life cycle basis	Evaluation of co-firing coal and biomass based on environmental impacts and costs	Life cycle assessment
Karger & Hennings	2009	Sustainability evaluation of decentralized electricity generation	Evaluation of decentralised power generation based on sustainability criteria	Scenario analysis with expert choice & value tree analysis
Kowalski, Stagl, Madlener & Omann	2009	Sustainable energy futures	Development of multi-criteria assessment with scenario analysis for democracies	Participatory multi-criteria analysis with scenario analysis
Matteson	2014	Methods for multi-criteria sustainability and reliability assessments of power systems	Development of method for normalisation and ranking of criteria and indicators	Dynamic multi-criteria optimisation framework
Maxim	2014	Sustainability assessment of electricity generation technologies using weighted MCDA	Ranking of power generation technologies based on sustainability criteria	Multi-criteria analysis with interviews with academics
Onat & Bayar	2010	The sustainability indicators of power production systems	Evaluation of power generation technologies against predefined indicators	Multi-criteria assessment
Ribeiro, Ferreira & Araújo	2013	Evaluating future scenarios for the power generation sector using a MCDA tool	Evaluation of different power generation scenarios	Multi-criteria decision analysis with an expert panel

Roth et al.	2009	Sustainability of electricity supply technology portfolio	Development of an approach to evaluate electricity supply options	Multi-criteria decision analysis with a survey
Rovere, Borghetti Soares, Basto Oliveira & Lauria	2010	Sustainable expansion of electricity sector	Development of method to analyse expansion of electricity generation	Multi-criteria assessment
Santoyo-Castelazo & Azapagic	2014	Sustainability assessment of energy systems	Development of decision-support framework for power systems	Multi-criteria and scenario analysis with case study
Schenler, Hirschberg, Burgherr, Makowski & Granat	2009	NEEDS: New Energy Externalities Developments for Sustainability	Evaluation of electricity generation technologies	Multi-criteria analysis with stakeholder consultation
Sharma & Balachandra	2015	Benchmarking sustainability of Indian electricity systems: An indicator approach	Development of an indicator-based hierarchical multi-dimensional framework	Application of indicator framework with a case study
Stamford & Azapagic	2011	Sustainability indicators for the assessment of nuclear power (paper and SPRIng report)	Evaluation of sustainability of nuclear power based on decision-support framework	Life cycle assessment and scenario analysis

Table 1: Overview of current scientific proposals

(Own elaboration)

Owing to the vast number of available policy steering instruments, sustainability reports and standards, I shall only consider a few examples of practical contributions. For policy makers and administrations, I shall focus on one country which has put substantial effort into meeting the requirements of *Agenda 21* and has implemented international recommendations. Since I used Switzerland in section 2.5 as an exemplary case, I shall do the same in this section as well for the sake of comparability. As for civil society actors, I shall consider a few contributions of international associations that have exerted a strong influence on the debate on sustainability requirements for electricity systems. To create a holistic picture on how scientific proposals are disseminated to other actors, I shall also consider contributions of market actors. Here, however, I shall only focus on the operators of electric power infrastructure that require political permission to operate power plants and grids. Again, for the sake of comparability I shall select sustainability reports from Swiss power suppliers to review the way in which some of their sustainability reports relate to scientific contributions and sustainability requirements in policies.

Table 2 provides an overview of the practical contributions under review based on the same structure as provided for *Table 1*:

Authors	Year	Title	Aim and scope	Methodology
Axpo	2015	Nachhaltigkeitsbericht 2013/2014	Presentation of how Axpo assumes its responsibility on SD	Multi-criteria analysis

BKW	2015	Nachhaltigkeitsbericht 2014	Presentation of efforts to reduce environmental impacts.	Multi-criteria analysis
ewz	2015	Geschäfts- und Nachhaltigkeitsbericht 2014	Presentation of efforts to attain SD.	Multi-criteria analysis
Federal Council of Switzerland	2012	Sustainable Development Strategy 2012-2015	Adoption of sustainability requirements in national legislation	Policies
Federal Statistical Office Switzerland	2006	Switzerland's ecological footprint - A contribution to the sustainability debate	Validation of existing sustainability indicators for the ecological dimension	Life cycle assessment
infras	2010	Stromeffizienz und erneuerbare Energien	Comparison of the technical and economic impacts of electricity scenarios	Scenario analysis with expert interviews
International Atomic Energy Agency	2001	Indicators for sustainable energy development	Proposal for energy indicators to be used by government institutions	Multi-criteria analysis
International Energy Agency	2014	Energy efficiency indicators: Essentials for policy making	Support for policy makers in defining energy efficiency indicators and policy strategies	Multi-criteria analysis
iwb	2015	Geschäfts- und Nachhaltigkeitsbericht 2014	Presentation how iwb meets social and ecological expectations	Multi-criteria analysis
Swiss Federal Department of Home Affairs	2013	MONET Nachhaltige Entwicklung messen.	Monitoring of SD in Switzerland	Multi-criteria analysis and conceptual deduction
Swiss Federal Office of Energy	2001	Nachhaltigkeit: Kriterien und Indikatoren für den Energiebereich	Definition of indicators for energy sectors	Multi-criteria analysis
World Health Organisation	2012	Health indicators of sustainable energy	Proposal for health indicators for the energy sector	Multi-criteria analysis

Table 2: Overview of current practical contributions

(Own elaboration)

The entire research sample consists of 20 scientific proposals and 12 practical applications and serves the purpose of creating a holistic picture of the current state of the art regarding sustainability assessments of electric power systems. I shall proceed by providing a short summary of the key aspects of each scientific proposal.

4.3 Presentation of scientific proposals

In this section, I shall briefly present the key contents of the scientific proposals for sustainability assessments of the research sample. This overview will later serve as a starting point to explore to what extent the existing literature covers the structural features of sustainability assessments as elaborated in section 3.3:

-
- i) *Afgan, Carvalho and Hovanov (2000)* wrote one of the first contributions on sustainability indicators for energy systems. The authors deduce a set of criteria and indicators based on an interpretation of the *Brundtland Report* and group them into four categories: resource, environment, society and economy. The system scope considers energy production and consumption. The assessment is carried out for four electric power generation technologies and three consumer groups, while formulas are used to rank criteria (Afgan, Carvalho & Hovanov 2000).

 - ii) *Dombi, Kuti and Balogh (2014)* propose a multi-criteria assessment with choice experiment surveys to identify the most favourable renewable energy technology. They argue that all technologies lead to some form of environmental degradation, so choice experiments are required to prioritise indicators. The authors define seven sustainability attributes for which a set of choices is provided. Empirical data for 17 technologies is then mapped to the attributes. Based on their analysis, the authors conclude that solar concentrated power, hydroelectricity and geothermal power are the most sustainable power generation technologies (Dombi, Kuti & Balogh 2014).

 - iii) *Evans, Strezov and Evans (2009)* emphasise in their paper the relevance of conducting life cycle assessments across the entire life cycle. The authors then proceed by assessing renewable energy technologies according to indicators. Data for indicators is obtained by consulting the literature, while each indicator is weighted equally for ranking. Their study concludes that wind power is preferable to other renewable energy technologies (Evans, Strezov & Evans 2009).

 - iv) *Gallego Carrera and Mack (2010)* perceive the evaluation of SD to be historically too driven by ecological aspects. They argue that until quite recently, social and economic factors have been underrepresented. Against this backdrop, the authors present a set of social indicators accounting for the challenges of long-term decision making. They select indicators based on the literature, while for measurement purposes they conduct expert interviews. The paper concludes that nuclear power is perceived as the least sustainable option, while solar electric power received the best evaluation (Gallego Carrera & Mack 2010).

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- v) *Grunwald and Rösch* (2011) present an integrative framework which is based on three overarching sustainability objectives. Based on these goals, normative principles and instrumental rules are formulated. This framework considers technology as a contribution to societal development. For each of the principles a set of indicators is defined. The results of the evaluation are compared with a reference system and indications are given as to whether a process can be expected to have a positive or negative impact (Grunwald & Rösch 2011).

 - vi) *Heinrich, Basson, Cohen, Howells and Perie* (2007) propose a new approach to ranking power expansion alternatives based on multi-criteria decision analysis complemented with scenario analysis. Performance and confidence criteria are used to determine a portfolio of preferred alternatives. The authors then simulate and evaluate 24 scenarios according to indicators. Sensitivity diagrams are reviewed to assess the robustness of rankings. The study concludes that decisions need to be made within a set of equally preferable alternatives (Heinrich, Basson, Cohen, Howells & Perie 2007).

 - vii) *Hirschberg et al.* (2005) conduct a holistic assessment on the costs and potentials of new renewable energy technologies and nuclear power for Switzerland as an input for the development of policy scenarios. The analysis focuses on technical, ecological and economic aspects of power generation technologies. They neither explore aspects of power distribution or consumption, nor do they provide target values or general goals (Hirschberg et al. 2005).

 - viii) *Jeswani, Gujba and Azapagic* (2011) conduct a life cycle assessment of a thermal power plant based on the co-firing of coal and biomass. The life cycle assessment covers the entire life cycle from cradle to grave with the exception of aspects related to power grids. The authors define 13 scenarios and a set of indicators for evaluation. The results suggest that increased shares of biomass reduce the environmental impacts of the power plant, but also increase power generation costs (Jeswani, Gujba & Azapagic 2011).

 - ix) *Karger and Hennings* (2009) run scenario analyses of the advantages and disadvantages of distributed power generation plants against the backdrop

of the increased deployment of domestic solar PV systems in Germany. First, actors are invited to create conceivable visions. These scenarios and a set of criteria, deduced through value-tree analysis, are then presented to experts who evaluate whether criteria are met by the scenarios based on an analytic hierarchy process. The analysis concludes that distributed power generation offers both benefits and risks, but the overall rating depends on what indicators are deemed of high importance (Karger & Hennings 2009).

- x) *Kowalski, Stagl, Madlener and Omann* (2009) apply a multi-criteria analysis approach with participatory scenario analysis. Authors define more than a dozen criteria and five renewable energy scenarios for Austria. They also develop a model with forecasting-type scenarios based on an exploratory stage with stakeholder engagement. Stakeholders then weigh criteria to rank scenarios. The authors conclude that multi-criteria analysis can serve as a starting point for decision making in political arenas (Kowalski, Stagl, Madlener & Omann 2009).

- xi) *Matteson* (2014) perceives deficiencies in current sustainability assessments relying on multi-criteria decision analysis in terms of ranking power generation technologies. The author proposes a new method that combines experience curves, technology progress models, life cycle assessments and thermodynamics within a dynamic multi-criteria optimisation framework. He selects indicators on economic, technical, environmental and social performance and calculates best and worst values based on current data of existing electric power systems (Matteson 2014).

- xii) *Maxim* (2014) contributes an assessment and ranking of power generation technologies based on a set of indicators. The author draws on methods from the realm of life cycle assessments to derive values for each indicator. Multi-criteria decision analysis is then applied to support decision making based on expert interviews. This contribution recommends the implementation of large hydroelectric power plants and stresses the importance of basing policies on empirical evaluations (Maxim 2014).

- xiii) *Onat and Bayar* (2010) propose the selection of indicators based on the principles of accessibility, availability and acceptability. Indicators are grouped under perceptual, political, legal and economic factors. Power gen-

eration technologies are assessed against the set of indicators and then weighted. According to their results, wind and nuclear power are considered most sustainable. However, when also considering long-term developments, their work recommends solar PV as the preferred technology (Onat & Bayar 2010).

- xiv) *Ribeiro, Ferreira and Araújo* (2013) stress in their study the benefits of multi-criteria analysis to evaluate power generation technologies holistically. Furthermore, the authors emphasise the importance of personal judgement in this process and propose a new multi-criteria assessment tool including scenarios. They draw on an expert panel to evaluate impacts and weigh criteria. Respondents are most favourably disposed to coal-based power generation and renewable scenarios (Ribeiro, Ferreira & Araújo 2013).
- xv) *Roth et al.* (2009) evaluate sustainable electricity supply options for a state-owned power supplier against the backdrop of expiring electricity import treaties and aging nuclear power plants in Switzerland. They apply a multi-criteria decision analysis approach based on current data and projections for technologies up to 2030. For their evaluation, the authors consider economic, environmental and health-related criteria. Their approach foresees a manual weighting of indicators. The applied preference profiles end up recommending hydroelectric and geothermal power (Roth et al. 2009).
- xvi) *Rovere, Borghetti Soares, Basto Oliveira and Lauria* (2010) propose a multi-criteria assessment with scenario analysis to evaluate electricity generation technologies. The authors apply criteria and indicators from the technological, social, environmental and economic dimensions to expansion alternatives. According to this approach, electricity generation based on sugar cane yields the most favourable results due to the high number of local jobs created and the relatively low greenhouse gas emissions (Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010).
- xvii) *Santoyo-Castelazo and Azapagic* (2014) propose a new decision support framework comprising scenario analysis, life cycle assessment and costing, social sustainability assessments and multi-criteria decision analysis. To identify the effect of weightings applied to criteria, sensitivity analyses are carried out. Specific results are obtained through a case study conducted in

Mexico. Upon simulation of eleven scenarios and under consideration of 17 criteria, the current approach based on fossil fuels is perceived as unsustainable due to the high costs and the environmental burden. The most favourable scenario relies on renewable energy technologies and nuclear power. The authors propose changes in policies to fulfil obligations relating to international treaties (Santoyo-Castelazo & Azapagic 2014).

- xviii) *Schenler, Hirschberg, Burgherr, Makowski and Granat* (2009) provide an energy technology roadmap with broader decision support beyond cost evaluation. The research team proposes an approach based on total cost calculations and multi-criteria decision analysis. They recommend criteria and indicators structured according to the three pillars approach for the value chain stages of extraction of energy carriers, power generation and distribution (Schenler, Hirschberg, Burgherr, Makowski & Granat 2009).
- xix) *Sharma and Balachandra* (2015) propose an indicator-based multi-dimensional framework to promote a transition to a more sustainable electricity system against the backdrop of a rapidly growing economy in India. Their contribution constitutes a hierarchical framework with dimensions, themes, sub-themes, composite indicators and measurable indicators. In addition to the traditional sustainability dimensions of society, economy and the environment, the authors consider a fourth institutional dimension. They apply upper and lower thresholds based on existing system data for evaluation (Sharma & Balachandra 2015).
- xx) The United Kingdom Research Councils established the multidisciplinary *SPRIng project* on the sustainability assessment of nuclear power to produce a comprehensive sustainability analysis for the United Kingdom. This assessment encompasses all stages of value creation and contains a multi-criteria analysis with technical, environmental, economic and social indicators. Furthermore, it is complemented by long-term scenarios reaching as far as the year 2070. The authors conclude that according to stakeholder preferences, nuclear power is the worst option. They note that considering sustainability aspects is of high importance and preferences depend on values (Stamford & Azapagic 2011; Azapagic et al. 2011).

Based on these short summaries of each scientific contribution, I shall proceed by evaluating whether the basic features of sustainability assessments introduced in section 3.3 are covered in the above scientific contributions. I shall provide the results in a table that is structured according to the following procedure:

- i) The first two columns on the left of the above-mentioned table contain the name of the author and the year in which the paper was published.
- ii) Columns three to eight provide information on whether the authors consider aspects of electric power systems related to the social, technical and environmental dimensions. Since the scope of the system plays a crucial part in framing the data to be analysed for decision making, I shall not only consider the previously mentioned three dimensions, but also break down the technical dimension further into the four stages of value creation which were elaborated in section 2.2. At this stage, however, I have no intention of assessing the degree to which these system properties have been evaluated in detail.
- iii) Columns nine and ten indicate whether the scientific contributions entail criteria or indicators. Like the analysis on system scope, this analysis is carried out without exploring detailed definitions.
- iv) I shall mark which proposals entail features of ex post or ex ante analyses in columns eleven and twelve. Once more, I only intend here to denote whether sustainability assessments apply such methodologies or not. However, for those cases where authors conduct some form of long-term scenario analysis without producing a set of possible future states of the system, I shall put a tick in brackets to indicate that requirements on ex ante analysis are partly met.
- v) I shall indicate whether authors elaborate what interpretation of SD they refer to in the column labelled normative foundation. For those contributions where researchers attempt to relate sustainability assessments to definitions of the *Brundtland Report*, I shall add a tick in brackets as the corresponding requirements are at least partly met.

- vi) I shall indicate which authors produce a set of rules used to break down the guiding principles of SD into more tangible targets. In those cases where authors relate their work to aspects pertaining to the operationalisation of the SD model, I shall place a tick in brackets.
- vii) I shall add a tick for those proposals that provide general goals for criteria or target values for indicators in the corresponding columns. In cases where authors mention that sustainability assessments are used as instruments for achieving policy goals, I shall put down a tick in brackets.

Table 3 lists the scientific contributions of sustainability assessments for power systems reviewed in this section. It provides an overview of which basic features of sustainability assessments, presented in section 3.3, are covered in the research sample.

Authors	Year	Social dimension	Extraction of resources	Power generation	Power distribution	Power consumption	Ecological dimension	Criteria	Indicators	Ex post analysis	Ex ante analysis	Normative foundation	Steering and inst. rules	General goals	Target values
Afgan, Carvalho & Hovanov	2000	✓	✓	✓	-	✓	✓	-	✓	✓	(✓)	-	-	-	-
Dombi, Kuti & Balogh	2014	✓	-	✓	-	-	✓	✓	-	-	-	-	(✓)	-	-
Evans, Strezov & Evans	2009	✓	✓	✓	✓	-	✓	-	✓	✓	-	-	-	-	-
Gallego Carrera & Mack	2010	✓	-	-	-	-	-	✓	✓	✓	-	(✓)	-	-	-
Grunwald & Rösch	2011	✓	✓	✓	-	-	✓	✓	✓	✓	-	✓	✓	(✓)	-
Heinrich, Basson, Cohen, Howells & Perie	2007	✓	-	✓	-	-	✓	-	✓	✓	(✓)	-	-	-	-
Hirschberg et al.	2005	✓	-	✓	-	✓	✓	-	✓	-	(✓)	-	(✓)	(✓)	-
Jeswani, Gujba & Azapagic	2011	✓	✓	✓	-	-	✓	-	✓	✓	(✓)	-	-	-	-
Karger & Hennings	2009	✓	✓	✓	✓	-	✓	✓	-	✓	(✓)	-	-	-	-
Kowalski, Stagl, Madlener & Omann	2009	✓	-	✓	-	-	✓	✓	-	✓	(✓)	-	-	-	-
Matteson	2014	✓	-	✓	✓	-	✓	✓	✓	✓	(✓)	-	-	-	-

Maxim	2014	✓	-	✓	-	-	✓	✓	✓	✓	-	(✓)	-	-	-
Onat & Bayar	2010	-	✓	✓	-	-	✓	-	✓	✓	-	-	-	-	-
Ribeiro, Ferreira & Araújo	2013	✓	-	✓	-	-	✓	✓		-	(✓)	-	-	-	-
Roth et al.	2009	✓	✓	✓	-	-	✓	✓	✓	✓	(✓)	-	-	-	-
Rovere, Borghetti Soares, Basto Oliveira &	2010	✓	✓	✓	-	-	✓	✓	✓	✓	(✓)	-	-	-	-
Santoyo-Castelazo & Azapagic	2014	✓	✓	✓	✓	-	✓	✓	-	✓	(✓)	-	(✓)	-	-
Schenler, Hirschberg, Burgherr, Makowski &	2009	✓	✓	✓	-	-	✓	✓	✓	✓	-	-	-	-	-
Sharma & Balachandra	2015b	✓	✓	✓	✓	-	✓	✓	✓	✓	-	-	-	-	(✓)
Stamford & Azapagic Azapagic et al.	2011 2011	✓	✓	✓	-	-	✓	✓	✓	✓	(✓)	-	-	-	-

Table 3: Analysis of scientific contributions

(Own elaboration)

The analysis of the scientific research sample has created a homogenous picture. This suggests that the research sample sufficiently covers the breadth of the current scientific contributions on sustainability assessments of electric power systems.

However, the overview also shows that only criteria and indicators, and the system aspects of the social, technical and ecological dimensions of electric power systems, are consistently covered; just a few contributions venture into the realm of providing a sophisticated system model to produce potential scenarios for ex ante analysis. Furthermore, normative aspects related to the guiding principles of SD seem to be strongly underrepresented in general. Moreover, while all contributions covered the technical dimension of electricity systems, most papers under review seem to be somewhat biased towards power generation technologies. These results ask for a detailed analysis of the scientific research sample.

4.4 Discussion of the scientific proposals

The review of the research sample reveals that there is a significant gap between the basic features of current scientific proposals and the previously defined structural features of sustainability assessments. Furthermore, there is also a remarkable variety of methodologies applied in the scientific research sample. These fundamental differences hint at more systemic issues or a lack of consensus on the key features that

constitute sustainability assessments. However, so as not to draw hasty conclusions, I shall proceed with discussing the most prominent disparities:

- i) **System representation.** According to the list of basic features, sustainability assessments of electric power systems should consider the essential components of the system to reduce the risk of erroneous decision making resulting from the omission of relevant data. Regarding technical system components, this translates into the requirement to cover the four previously introduced stages of value creation. While the majority of sustainability assessments under review consider most stages, some contributions share an exclusive focus on power generation technologies (Dombi, Kuti & Balogh 2014; Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Kowalski, Stagl, Madlener & Omann 2009; Maxim 2014; Ribeiro, Ferreira & Araújo 2013). However, among the contributions reviewed, only one (Karger & Hennings 2009) explores the benefits and risks of distributed power generation. Furthermore, aspects of power grids are seldom considered (Evans, Strezov & Evans 2009; Karger & Hennings 2009; Matteson 2014; Santoyo-Castelazo & Azapagic 2014; Sharma & Balachandra 2015). Moreover, only two studies consider elements of electricity consumption (Afgan, Carvalho & Hovanov 2000; Hirschberg et al. 2005).

Based on this analysis, I take it that there are *conflicting views on appropriate system boundaries* for sustainability assessments of electric power systems. For those contributions that explicitly focus on power generation technologies (Dombi, Kuti & Balogh 2014; Jeswani, Gujba & Azapagic 2011; Karger & Hennings 2009; Maxim 2014; Onat & Bayar 2010; Ribeiro, Ferreira & Araújo 2013), crucial parts of electric power systems are omitted by design. These contributions are likely to omit key information for decision makers, thus jeopardising *evidence-based* decision making.

- ii) **Criteria and indicators.** The review of scientific contributions confirms that today's sustainability assessments often apply both criteria and indicators. However, in some cases only criteria (Dombi, Kuti & Balogh 2014; Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Ribeiro, Ferreira & Araújo 2013; Santoyo-Castelazo & Azapagic 2014) or indicators (Afgan, Carvalho & Hovanov 2000; Evans, Strezov & Evans 2009; Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Jeswani, Gujba

& Azapagic 2011; Onat & Bayar 2010) are employed. While these differences may be partly explained by the different aims and scopes of research papers, there is exceptionally high variability in the criteria and indicators that are proposed. This hints at little agreement among authors on which criteria or indicators provide relevant data for decision making. This is surprising, as all contributions are dedicated to the same system or specific parts thereof. Against this backdrop, one could expect strong similarities among proposed criteria and indicators. In contrast, the following list entails exemplary indicators that were only proposed once, which further demonstrates the disagreement among authors on the relevant aspects of the system: investment of capital (Afgan, Carvalho & Hovanov 2000), trust in risk management (Gallego Carrera & Mack 2010), preservation of biodiversity (Grunwald & Rösch 2011), technical efficiency factor (Hirschberg et al. 2005), percentage of imported inputs (Rovere, Borghetti Soares, Basto Oliveira and Lauria 2010), ability to respond to demand (Maxim 2014), energy source availability (Onat & Bayar 2010), equity (Roth et al. 2009), proliferation (Schenler, Hirschberg, Burgherr, Makowski & Granat 2009), entrepreneurship (Sharma & Balachandra 2015) and indicators on technological lock-ins (Stamford & Azapagic 2011). This begs the question: Why did other authors not also suggest these indicators if all the authors developed criteria and indicators for the very same system?

Based on this analysis, I conclude that today *a high variability in the selection of criteria and indicators* in sustainability assessments of electric power systems can be observed. As argued above, criteria and indicators play a key role in identifying areas of intervention. Omitting certain criteria or indicators may mean that some issues remain unidentified. This further impedes *evidence-based* decision making.

- iii) **Ex post and ex ante analysis.** The sample can be split into three types of scientific contribution: The first category encompasses proposals that refrain from providing any form of scenario assessment at all (Dombi, Kuti & Balogh 2014; Evans, Strezov & Evans 2009; Gallego Carrera & Mack 2010; Grunwald & Rösch 2011; Maxim 2014; Onat & Bayar 2010). The second group entails contributions that introduce scenarios to compare power generation technologies (Heinrich, Basson, Cohen, Howells & Perie 2007; Jeswani, Gujba & Azapagic 2011; Kowalski, Stagl, Madlener & Omann

2009; Ribeiro, Ferreira & Araújo 2013; Roth et al. 2009 and Rovere, Borghetti Soares, Basto Oliveira and Lauria 2010). The third category provides broader scenario analyses with prospective elements (Afgan, Carvalho & Hovanov 2000; Hirschberg et al. 2005; Karger & Hennings 2009; Santoyo-Castelazo & Azapagic 2014; Stamford & Azapagic 2011; Azapagic et al. 2011). Even contributions in the third category, however, only partly correspond to the dedicated basic feature; the proposal of *Hirschberg et al.* (2005) for example, places the potentials of power generation technologies in relation to projected consumption. However, to simulate potential future states of the system, a sophisticated model of the system is required. Such a model not only lists the relevant system components, but also looks at the interdependencies among components. None of the proposals under review provide a system model that allows for an exploration of the way changes in frame conditions affect other components.

At this point, I argue that the *ex ante analyses* provided *only partly simulate parts of the system*. This may not, however, be fully explained by the too narrow scope definition applied in many contributions. Rather, I argue that developing scenario assessments requires additional methodological contributions related to system modelling and scenario formation. In the absence of such methodologies, authors may find it difficult to conduct *ex ante* analysis in line with the structural components introduced in section 3.3. To compensate for this shortcoming in existing sustainability assessments, authors would first have to develop a sophisticated system model encompassing the relevant system features and then produce possible scenarios.

- iv) **Normative basis.** Authors base their proposals on three different types of sources: Members of the first group base their contribution on a broader introduction to sustainability challenges involving themes such as development needs, resource scarcity and pollution (Evans, Strezov & Evans 2009; Heinrich, Basson, Cohen, Howells & Perie 2007; Karger & Hennings 2009; Rovere, Borghetti Soares, Basto Oliveira and Lauria 2010; Sharma & Balachandra 2015). The second group of contributions relates their work specifically to enforced policies in Europe (Dombi, Kuti & Balogh 2014; Hirschberg et al. 2005; Jeswani, Gujba & Azapagic 2011; Kowalski, Stagl, Madlener & Omann 2009; Onat & Bayar 2010; Ribeiro, Ferreira & Araújo 2013; Roth et al. 2009; Santoyo-Castelazo & Azapagic 2014; Schenler, Hirschberg,

Burgherr, Makowski & Granat 2009; Stamford & Azapagic 2011) or newly introduced environmental standards (Matteson 2014). A few proposals explicitly refer to SD or the *Brundtland Report* (Afgan, Carvalho & Hovanov 2000; Gallego Carrera & Mack 2010; Grunwald & Rösch 2011; Maxim 2014), while only *Grunwald and Rösch* (2011) fully base their work on the guiding principles of SD.

Against this backdrop, I conclude that only the contribution of *Grunwald and Rösch* (2011) fully provides the aforementioned basic feature of the normative basis for sustainability assessments of electric power systems. They not only provide information on their interpretation of SD, but also refer to it when formulating rules (Grunwald & Rösch 2011). The *absence of a normative basis* in other contributions obstructs the process of deriving general goals, mirroring the requirements of SD, to criteria and introduces new challenges in weighting, prioritising or ranking criteria and indicators. However, without choosing an interpretation of SD, there is no normative basis for providing guidance on which objectives the system has to meet. The research sample also shows that in the absence of such a basis, authors tend to rely on participation and thus leave key decisions to experts or the public.

- v) **Steering and instrumental rules.** Nineteen out of 20 scientific contributions provide proposals for sustainability assessments without producing a set of rules that seeks to translate the normative requirements of SD into more tangible targets as a basis for defining general goals later. The following four contributions are notable exceptions as they specifically relate their results to aspects of the operationalisation of SD: *Dombi, Kuti and Balogh* (2014) stress that their framework can support energy policies in strategic planning and the development of policy steering instruments promoting the deployment of renewable energy technologies. They also propose to utilise their framework for monitoring and technology-specific forecasting purposes (Dombi, Kuti & Balogh 2014). In addition, *Hirschberg et al.* (2005) relate their analysis to policy goals. *Santoyo-Castelazo and Azapagic* (2014) provide a wide range of recommendations for changes in policy based on their sustainability assessment. This advice involves more stringent emission standards, a dedicated analysis of the potential of renewable energy technologies, the introduction of policies reducing electricity consumption and the deployment of financial incentives to promote low-carbon power genera-

tion technologies (Santoyo-Castelazo & Azapagic 2014). *Grunwald and Rösch* (2011) provide a set of substantial and instrumental principles based on the guiding principles of SD. However, they refrain from providing detailed reasoning on how they translate their interpretation of SD into more specific principles (Grunwald & Rösch 2011).

Since almost all contributions refrained from drawing on steering or instrumental rules to systematically translate a normative basis into more specific goals, I conclude that there is a general *lack of steering and instrumental rules* used to determine targets. Accordingly, only the contribution of *Grunwald and Rösch* (2011) provides a set of rules that fully corresponds with the previously specified structural feature on rules for sustainability assessments, as they explicitly provide a set of rules.

- vi) **General goals and target values.** Most scientific contributions seek to recommend generation technologies or development paths to be pursued. In order to derive such proposals, a wide range of methodologies is applied. One research study opts to weigh criteria and indicators equally (Evans, Strezov & Evans 2009), while another deems manual ranking to be a necessary step in the process (Santoyo-Castelazo & Azapagic 2014). Some scholars revert to methods that contain formulas for weighting purposes (Afgan, Carvalho & Hovanov 2000; Matteson 2014; Rovere, Borghetti Soares, Basto Oliveira and Lauria 2010). The most common approach, however, foresees drawing on experts and stakeholder panels or considering previously stated social preferences (Dombi, Kuti & Balogh 2014; Gallego Carrera & Mack 2010; Heinrich, Basson, Cohen, Howells & Perie 2007; Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Maxim 2014; Ribeiro, Ferreira & Araújo 2013; Roth et al. 2009; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Stamford & Azapagic 2011) to rank criteria or indicators and thereby derive a single best solution. *Hirschberg et al.* (2005) relate the potential of power generation technologies to policy goals, while *Sharma and Balachandra* (2015) benchmark the Indian power system against other countries. *Grunwald and Rösch* (2011) evaluate their results against a reference scenario.

To summarise, most scientific *contributions are devoid of general goals*. This is surprising, as sustainability assessments are designed to evaluate

system data against sustainability objectives by design. The contributions of *Hirschberg et al. (2005)*, *Sharma and Balachandra (2015)* and *Grunwald and Rösch (2011)* partly cover the previously defined structural component. The omission of general goals renders sustainability assessments unable to provide a basis for *goal-oriented* decision making as extracted data cannot be evaluated against predefined sustainability goals. In the absence of gap analysis between system performance and sustainability objectives, policy makers will find it more difficult to develop effective policy steering instruments to induce specific changes.

The review of the scientific sample of sustainability assessments of power systems reveals a number of systemic shortcomings in the current contributions. *Table 4* shows the domains and basic feature of sustainability assessments on the left-hand side, while the shortcomings in current sustainability assessments proposed by scientific research groups identified in this section are listed on the right-hand side of the table.

Domain	Basic feature	Shortcomings
Functional	System representation	Conflicting views on appropriate system boundaries
Functional	Criteria and indicators	High variability in the selection of criteria and indicators
Functional	Ex post and ex ante analysis	Ex ante analyses only partly simulate parts of the system
Normative	Normative foundation	Absence of a normative basis
Normative	Steering and instrumental rules	Lack of steering and instrumental rules
Normative	General goals and target values	Contributions are devoid of general goals

Table 4: Shortcomings in scientific contributions

(Own elaboration)

This prompts the question of whether the deficiencies prevalent in today's scientific proposals are also present in the practical contributions of other actors. Accordingly, I shall proceed by briefly presenting and analysing contributions of non-scientific actors.

4.5 Presentation and discussion of practical contributions

While these practical contributions do not reflect sustainability assessments per se, they either strongly relate to them, such as strategies, or are applied variations for a part of the system thereof, like sustainability reports. Practical contributions are also

important, as they are required to achieve a system transition.¹⁴ I shall proceed by providing a short overview of each contribution:

- i) *Axpo* is a state-owned operator of power plants and electricity trader based in Switzerland. It delivers wholesaler electricity to other power suppliers. Its sustainability report contains strategic sustainability objectives together with goals and presents historic data. A list of indicators is provided and for some of these indicators quantitative data is provided, results are explained and trends are discussed (Axpo 2015).
- ii) *BKW* is another state-owned power supplier in Switzerland. In its annual sustainability report *BKW* presents selected indicators together with target values and measures are defined for reaching goals. The report contains a description of the life cycle of coal without quantitative data. For some of the indicators historic data with trends are provided (BKW 2015).
- iii) *ewz* is a power supplier owned by the city of Zurich that produces a combined financial and sustainability report annually. The report stresses the importance of cradle-to-grave life cycle assessments and emphasises the need to direct business development according to policy objectives. Its report provides indicators on health, safety and the environment (ewz 2015).
- iv) In 1997, the *Swiss Federal Council* approved the national strategy for SD in accordance with obligations resulting from the Earth Summit in 1992. This strategy is regularly updated and contains objectives on SD (FCS 2012). To operationalise the strategy, a workgroup provides a set of criteria with corresponding indicators and trend evaluations. Indicators are meant to measure system developments that contribute to evaluating the attainment of policy objectives. However, specific goals are not pursued (SFOE 2001).
- v) In a joint effort, in 2001 the *International Atomic Energy Agency* and *International Energy Agency* produced indicators for sustainable energy development as a proposal for nations committed to monitoring developments relat-

¹⁴ Power suppliers often publish sustainability reports that contain vital information on the economic and ecological performance of power infrastructure components, such as economic returns or emissions of greenhouse gases (ewz 2015; iwz 2015). Only power suppliers have access to this information, which is important to assess whether the overall system is on a sustainable pathway.

ed to the use, costs and effects of energy (IAEA 2001). The contribution consists of a set of indicators which was updated in 2005 to include criteria. Furthermore, the scope was expanded to the value creation stages of energy carrier extraction, power generation and distribution (IAEA 2005).

- vi) Against the backdrop of ever-growing energy consumption, the *International Energy Agency* developed a set of indicators for energy efficiency. The authors assign indicators to categories and provide information on the purpose and relevance of each indicator. Historic data from selected countries is presented for benchmarking purposes. These indicators focus exclusively on the consumption stage of the value chain, but neglect social and environmental aspects (IEA 2014).
- vii) The Swiss government mandated *infras* and *Locher et al.* to create a report on the ecological footprint in Switzerland. This approach compares existing consumption levels with planet Earth's ability to produce resources and break down pollution. However, it ignores the current levels of well-being achieved by the countries under review. Accordingly, developing countries are outperforming industrialised countries in this report. The report concludes that existing consumption patterns in Switzerland exceed the abilities of the environment and have to be altered to preserve the ecological capital of planet Earth (FSOS 2006).
- viii) The scenario analyses of the Swiss power system provided by *infras* evaluate the economic potential of a green policy scenario against pursuing business as usual. This report does not reflect traditional sustainability assessment, lacking indicators and target values, but contains scenario-based advice for policy development rooted in a system model. The analysis concludes that pursuing energy efficiency and new renewable technologies creates more local jobs than reinvesting in nuclear power (*infras* 2010).
- ix) *iwb*, a state-owned power supplier in Switzerland, also produces a combined financial and sustainability report that provides information on corporate strategy, business performance and sustainability indicators. The sustainability chapters share historic data on indicators measuring the impact of *iwb*'s business on health, human safety and the environment (*iwb* 2015).

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- x) To operationalise the sustainability strategy, the *Swiss Federal Council* implemented the MONET approach. This has undergone several iterations of refinement and the current version consists of 45 principles with approximately 75 indicators across all sectors (SFDHA 2013).
 - xi) In 2012, the *World Health Organisation* produced a shortlist of indicators for energy systems related to health. The WHO emphasises the importance of relating indicators to existing policies. It refrains, though, from providing target values for indicators or defining criteria (WHO 2012).

This overview of practical applications provides evidence that the current shortcomings in scientific proposals are not only present in the practical contributions of other actors, but are even accentuated: Studies by government institutions analyse only parts of the electric power systems to present specific aspects (FSOS 2006; infras 2010) rather than conducting holistic assessments that consider relevant system components. Furthermore, proposed standards for criteria and indicators for energy systems (IAEA 2001; IEA 2014; WHO 2012) provide extensive lists of criteria and indicators to freely choose from, potentially resulting in the omission of key aspects of the system. Moreover, these lists are entirely devoid of sustainability goals and scenario assessments. Lastly, sustainability reports produced by market actors only partly relate to policy objectives and thereby impede monitoring efforts. Power suppliers freely choose those indicators which they see fit and provide historical data or information on goal accomplishment selectively (Axpo 2015; BWK 2015; ewz 2015; iwv 2015).

The fact that shortcomings in scientific proposals transcend to the domain of practical applications further emphasises the importance of robust methodologies applied in sustainability assessments. It seems obvious that my next step has to lie with identifying knowledge gaps based on the shortcomings identified in scientific proposals.

5 Knowledge gaps

The review of existing literature revealed a number of specific shortcomings in the current sustainability assessments of electric power systems. In this chapter, I shall explore the identified weaknesses from a methodological perspective in more detail and determine areas for scientific contributions from my side. I shall pursue this endeavour according to the previously defined structure for the basic features of sustainability assessments.

I see substantial gaps in at least five specific fields, namely (i) system representation, (ii) criteria and indicators, (iii) ex post and ex ante analysis, (iv) normative basis, and (v), steering and instrumental rules, general goals and target values. Whereas the first three relate to the subject domain, the last three provide information on the normative direction for sustainability assessments. My underlying assumption here is that if these shortcomings are remedied, sustainability assessments can provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision making. I shall characterise the above gaps and specify my related contributions in individual sections.

5.1 System representation

The starting point of my endeavour on this subject is the claim that the variety of premises invested in assessments transcends the domain of well-known options for interpreting SD.¹⁵ At this point, I claim that the heterogeneity of criteria and indicators in assessment schemes also results from different approaches to the very object of assessment – the electric power system itself. Many scientific contributions reviewed in chapter 4 focus on specific technical components of electric power infrastructure, such as power generation technologies. Only a few assessment systems include other relevant variables like power grids or electrical devices providing energy services. Furthermore, existing assessments rarely touch on governance, which plays a pivotal role in operationalising sustainability requirements.

Against this backdrop, I can accentuate the claim made before: I not only claim that we face different system representations, but also that in existing sustainability assessments of electric power systems, the system itself is only partially represented. Such

¹⁵ These interpretations may involve, among others, the concept of weak or strong sustainability, interpretations favouring resilience or justice-based sustainability or the three pillars approach (Hartwick 1978; Holling 1973).

assessments are non-holistic in the sense of missing substantial elements. In my view, a too narrow system scope in sustainability assessments jeopardises decision making because potentially crucial data is not considered. The omission of key components of electric power systems may misinform decision makers, such as for example the selection of power generation technologies, and may have a significant impact on the design of power grids: Neglecting the resources required to build and operate power grids, for example, penalises distributed power generation. In this case, however, the overall system can be expected to require fewer metals. This case illustrates that the performance of individual system components must be assessed as part of an overall system analysis. Assuming we can agree that the function of electric power systems lies with achieving human well-being and enabling the provision of goods and services, we should then also be able to agree that the core functionality of the system is borne by technical power infrastructure and electrical devices, including critical interdependencies among social actors and the environment. Against this backdrop, I argue that sustainability assessments of electricity systems should also be subject to system boundaries encompassing societal and ecological capacities, as the latter frame the extent of the technical components.

Consequently, with my thesis I strive to contribute, among other things, a more holistic system representation serving as a basis for sustainability assessments of electric power systems. I strive to provide a system scope that considers the relevant transformation stages of power infrastructure and electrical devices, including relevant enabling and constraining factors of the environment and societal transformation processes. Moreover, I shall point towards interfaces with other key systems. In order for this system representation to adequately cover key components and interfaces, I shall draw on approaches that are able to analyse interdependencies and interactions between the social realm of actors and the ecological capacities of complex human-environment systems. Such an approach will have to exert a strong focus on decision making to govern these relationships.

Today, such approaches are frequently applied to research related to biodiversity (Hill et al. 2015; Maxim, Spangenberg & O'Connor 2009), agriculture (Hun Lee, Kakinuma, Okuro & Iwasa 2015; Zhou, Mueller, Burkhard, Cao & Hou 2013) or aquatic ecosystems (Langmead et al. 2009; Pinto et al. 2013; Roy, Martin, Irwin, Conroy & Culver 2011) where the impacts of human development on the environment immediately become apparent. The driver-pressure-state-impact-response (DPSIR) approach (Atkins, Burdon, Elliott & Gregory 2011; Omann, Stocker & Jäger 2009), which assesses exact-

ly these relationships, variations thereof (Cooper 2013) and socio-ecological system analysis (cf. Altaweel 2008; De Aranzabal, Schmitz, Aguilera & Pineda 2008; Elsayah, Guillaume, Filatova, Rook & Jakeman 2015; Kelly et al. 2015; Purdue & Berger 2015), are examples of such approaches. However, so far only a few efforts have been made to systematically develop a holistic representation of electric power systems based on one of these methodologies.

Accordingly, my contribution will consist of selecting and arguing for an appropriate approach and applying it to power systems. The deliverable of this contribution consists of a holistic system representation of electricity systems encompassing the relevant system components. Accordingly, it may also serve as a basis for a contribution related to the systematic deduction of criteria or scenario assessments at a later stage.

5.2 Criteria and indicators

The second significant shortcoming in existing sustainability assessments of electric power systems relates to the high variability of criteria and indicators prevalent in the scientific contributions reviewed in chapter 4. The seemingly erratic selection of criteria and indicators may be partly explained by different definitions of system boundaries: Excluding a part of the system from the assessment automatically renders the criteria and indicators associated with related components obsolete. While the argument related to the insufficient assessment scope certainly holds true for the breadth of criteria and indicators applied, it does not yet explain why some sustainability assessments dedicated to specific system components, such as power generation technologies, apply some indicators, such as nuclear waste or fatalities, while others focussing on the same type of system component refrain from doing so. This situation unnecessarily exposes these sustainability assessments to criticism of arbitrary selection of indicators.

At this point, I claim that the high variability of the chosen indicators can also be explained by methodological shortcomings; namely, a lack of systematic deduction of criteria and indicators from a sufficiently comprehensive system definition. Many authors of the sustainability assessments reviewed in chapter 4 opted to either consult existing literature to select indicators or relied on participatory processes. While both procedures may at first glance add to the credibility of the set of indicators, such approaches do not ensure that the relevant system properties are considered. Against this backdrop, I argue that the risk of neglecting vital aspects of the system under evaluation can be mitigated on the one hand by referring to a holistic system representation that en-

compasses the relevant system features; if a depiction of electric power systems considers the essential system properties, then this system representation is likely to also encompass the relevant energy, matter and information flows. If this argument proves to be true, then a set of criteria and indicators can be deduced from such a holistic system representation that covers the relevant system flows including societal steering processes. On the other hand, the above-mentioned risk can be mitigated by conducting systematic deductions of criteria based on energy and material flow analysis as well as socio-ecological governance. A set of criteria that is systematically deduced based on the relevant stages of system flows and societal steering processes can be expected to further reduce the risk of missing vital aspects of the system.

While energy and matter flow analyses are frequently carried out for the analysis of specific technical components of electric power systems (Garcia, Marques & Freire 2014; Stamford & Azapagic 2014) or individual parts thereof (Asdrubali, Baldinelli, D'Alessandro & Scrucca 2015; Lopes Silva, Delai, Delgado Montes & Ometto 2014; Oliveira et al. 2015; Restrepo, Bazzo & Miyake 2015; Santoyo-Castelazo, Gujba & Azapagic 2011; Sherwani, Usmani & Varun 2010; Turconi, Boldrin & Astrup 2013), such an endeavour has not yet been carried out across all stages of value creation. Some scholars point out that such approaches also bear risks if they are solely applied on downstream processes, ignoring upstream productivity (Bidstrup 2015). Furthermore, approaches and methods analysing energy and matter flows often do not consider interactions within the social realm of actors. Accordingly, I am looking for a complementary theoretical element that is able to conceptualise interactions among actors. Hence, I shall additionally draw on approaches related to environmental governance (Cent, Grodzińska-Jurczak & Pietrzyk-Kaszyńska 2014; Hackett 2015; Mattor et al. 2014; Taylor & De Loë 2012), which so far have been rarely applied in the context of holistic analyses of electric power systems.

The proposed methodologies to fill the knowledge gaps on system representation, as well as criteria and indicators, are strongly interlinked. Accordingly, I shall first draw on the holistic system representation discussed in section 5.1 and then contribute a systematic analysis of energy, matter and information flows of electricity systems. This analysis will serve as a comprehensive basis for deducing a set of exemplary *criteria* which cover the essential aspects of electric power systems. Producing a list of exemplary *indicators*, however, lies beyond the scope of my contribution. There is good reason to believe that indicators depend, among other things, on regional specifics or values.

5.3 Ex post and ex ante analysis

Some of the sustainability assessments of electricity systems reviewed in chapter 4 exhibit another shortcoming related to the time horizon applied: They are devoid of the features of ex ante analysis. While some contributions entail some form of comparative technology assessment or normative scenario analysis, these variants of ex ante analysis cannot fully serve my intended purpose; that is, to produce possible future states of the system under review. Such scenarios assessments are, however, of value to policy makers as they hint at potential future problems. Moreover, they may serve as a basis for designing and deploying policy steering instruments in the early stages of developments to prevent major issues from affecting critical tipping points.

Accordingly, scenario assessments may shed light on potential development paths for long-term decision making: ex ante analysis may give insights on how systems could potentially unfold if specific trends prevail and thus serve as an early warning system. At this point, I claim that the absence of scenario assessments may potentially be traced back, on the one hand, to the fact that the sustainability assessments under review fail to address critical parts of power systems or focus exclusively on one system component, such as power generation technologies. On the other hand, the review of scientific proposals also revealed that virtually none of the authors opted to develop a sophisticated system model with quantified correlations among system components, even though such a model is a necessary prerequisite for computing possible scenarios. Against this backdrop, I argue that the absence of system models or scenario assessments can, among other things, also at least be partially explained by a lack of considering the key interdependencies among system components.

A holistic representation of electric power systems could not only serve as a robust basis for appropriately framing the scope or systematically deducing criteria, as argued in sections 5.1 and 5.2, but may also serve as an ideal basis for a system model; a system representation strives to capture the relevant system properties. Accordingly, one can meet the first prerequisite by drawing on the system representation. In order to develop a system model, interdependencies among relevant system components have to be further defined. Moreover, since some of the relevant steps in deducing criteria systematically, namely, to determine relevant stages of energy and matter flows as well as societal steering processes, are also necessary preconditions for developing a system model; the deliverables of the aforementioned two contributions can be expected to also be of use when developing a system model. Once correlations have been defined

and, thus, the system model is developed, potential scenarios can be simulated and described.

System modelling and scenario assessments are today common practice for energy systems to gain insights for policy development. Accordingly, it is safe to say that such an endeavour has become a standard routine in a number of industrialised countries and emerging economies. Energy scenarios are frequently developed to assess potential development paths (Komiyama & Fujii 2015; Luukkanen et al. 2015; Pregger, Nitsch & Naegler 2013; Roinioti, Koroneos & Wangensteen 2012; Spataru, Drummond, Zafeiratou & Barrett 2015; Zhu, Li, Huang, Fan & Nie 2015). My contribution therefore does not lie primarily with defining an exemplary robust system model or developing exemplary scenarios, but rather with proposing to use the same system depiction and analysis used to deduce criteria as a basis for the system model and scenario assessments. One can expect increased consistency among the deliverables which may create benefits for monitoring processes: if the same representation and analysis of the system are used to determine criteria for sustainability assessments and to produce possible scenarios of ex ante analysis, then results can be more easily brought together as they draw on the same functional basis. This seems obvious here, as in this particular case the process of monitoring system developments through sustainability criteria and the process of deriving potential future states of the system are rooted in the same system model.

However, since scenario analyses for electricity systems are today frequently provided, my contribution will focus on this shortcoming to elaborate suitable methodological features to produce scenario assessments of a holistic system representation. Accordingly, the provision of an exemplary system model or exemplary scenarios for electricity systems that could be applied in sustainability assessment contexts offers no new scientific insights and therefore lies beyond the scope of this thesis.

5.4 Normative basis

Most contributions of the scientific research sample of sustainability assessments of electric power systems contain a fourth methodological flaw: the vast majority of scientific contributions are based on comparative analyses of technologies or participatory approaches rather than an evaluation of system data against predefined sustainability objectives. Accordingly, most authors refrain from formulating sustainability goals, while only a few contributions refer to policy objectives that may entail sustainability require-

ments or the guiding principles of SD, with the exception of the contribution of *Grunwald and Rösch* (2011).

At this point, I claim that this weakness may partly result from the approaches and methods applied: most contributions under review rely exclusively on methodologies related to the functional dimension of sustainability assessments, such as life cycle assessments to quantify resource requirements or emissions of technical components. Since these instruments focus on the analysis of the system in question and are unfit to provide guidance on answering the question: *What should be sustained?*, I argue that in the absence of methodologies directed at the normative notions of SD, those authors may find it difficult to relate system data to long-term sustainability goals so long as they draw exclusively on methodologies related to analyses of energy and matter flows. Only the contribution of *Grunwald and Rösch* (2011) defines general sustainability objectives with reference to the guiding principles of SD. In their paper, *Grunwald and Rösch* (2011) apply an integrative framework for SD that considers normative notions of SD and allows for the formulation of substantial sustainability principles. Their approach essentially enables them to systematically enrich the ambiguous model into more tangible requirements (Kopfmüller et al. 2001).

Against this backdrop, I argue that most authors of sustainability assessments under review may find it difficult to define sustainability requirements due to the absence of a normative foundation that may serve as a basis for systematically deriving more specific sustainability goals. However, such an interpretation of SD represents a necessary precondition for such an endeavour, which allows gaps on missing goals and targets to be consistently filled, as the contribution of *Grunwald and Rösch* (2011) so vividly demonstrates.¹⁶ However, as outlined in section 3.1 a wide range of proposals for interpretations of SD exists today. A key challenge for the authors of sustainability assessments therefore lies with choosing an interpretation of SD that mirrors the current state of the scientific discussion.

Accordingly, my contribution on this topic will lie with selecting an interpretation of the conception of SD that reflects the current state of the scientific debate. However, as mentioned above, there are various proposals that may serve as a starting point. These may either be a theory of justice or, more likely, a scientific interpretation of SD. Without going into a detailed discussion at this point, I claim that the selection of the

¹⁶ The integrative framework for sustainable development has hitherto also been applied to research on sustainable land use and urban development (Kopfmüller 2006).

normative basis is likely to have a strong impact on the long-term goals to be met. However, by explicitly providing information on the chosen interpretation of SD, readers may better understand the underlying norms, principles and value schemes that enriched the interpretation. This will more easily facilitate a discussion on the appropriateness of the chosen interpretation. Consequently, I shall explore different interpretations of SD that could serve as a basis for sustainability targets and shall argue for my selection.

5.5 Steering and instrumental rules, general goals and target values

The sustainability assessments under review in chapter 4 exhibit further methodological shortcomings by refraining from providing any form of goals, linking sustainability objectives to criteria or indicators. This is surprising, as the relevance of goals in sustainability assessments is unchallenged (Moldan, Janoušková & Hák 2012). Today, different approaches are applied to determine sustainability requirements in those rare scientific proposals where a form of goal orientation is provided: In some cases, goals are derived from policy objectives (Howard, Saba, Gerrard & Modi 2014; Velázquez Gomar 2014). Other authors respond to conflicting results in their multi-criteria assessments by leaving the necessary interpretation of the results to policy makers or experts of the system in question or revert to interviews with selected stakeholders to determine priorities (Dombi, Kuti & Balogh 2014; Maxim 2014; Ribeiro, Ferreira & Araújo 2013). However, these authors run the risk that such participatory processes may ultimately result in the setting of goals that potentially oppose the normative cornerstones of SD as it is by no means guaranteed that experts or representatives of the public relate their preferences to the guiding principles of SD. Furthermore, in the absence of unambiguous sustainability requirements, a core requirement of sustainability assessments is no longer met: to evaluate extracted field data against predefined sustainability objectives and thereby provide a basis for drawing *evidence-based* and *goal-oriented* conclusions on the long-term development of key systems.

To set goals that mirror the normative requirements of SD, one has to revert to a normative basis as outlined in section 5.4. Current scientific interpretations of the SD model may ideally serve as a basis for systematically formulating more tangible sustainability goals. In section 4.4, I argued that the approach applied in the scientific contribution of *Grunwald and Rösch* (2011) was the only one to meet the previously de-

fined basic feature on steering and instrumental rules of sustainability assessments. Their approach provides a clear structure for systematically producing goals based on a normative basis for sustainability assessments. This further emphasises what I have already touched on in section 5.4: If we strive for objectives that reflect the guiding principles of SD, then the selection of a normative basis is a necessary precondition. Against this backdrop, I argue that the lack of a normative basis in most of the scientific contributions under review is an insurmountable barrier to defining meaningful goals, which reflect the normative requirements of SD, as criteria for sustainability assessments of electric power systems.

However, in order to produce more tangible goals for sustainability assessments, both a normative basis and a holistic system representation are required. I have already committed to developing a holistic depiction of electricity systems and arguing for an up-to-date scientific interpretation of SD in sections 5.1 and 5.4. So these inputs should be readily available by the time I start looking into systematically producing exemplary goals for sustainability assessments of electricity systems.

The current scientific debate on the conception of SD and SD governance also emphasised that goals are not only required for the biophysical part of the system, but also for governance aspects; as highlighted in section 3.1, the United Nations actively promotes approaches that seek to establish the cornerstones of SD in national constitutions (UNCED 1992). These sustainability principles often impose obligations on governments to define sustainability objectives and monitor developments. Assuming that modern societies seek to establish instruments that provide a sound basis for *evidence-based* and *goal-oriented* decision making on the long-term development of key systems, then sustainability assessments which evaluate criteria and indicators against predefined sustainability requirements are likely to take centre stage in this process (Holden 2013; Pires & Fidélis 2015). In such regimes, the analysis of rational data is used to inform decision making. Thus, the integration of indicator schemes, which extract system data, and policy processes, which draw conclusions for the deployment of policy steering instruments based on system data, become vitally important (Holman 2009). The current debate on the involvement of sustainability assessments in governance revolves, among other things, around participatory approaches to trigger policy changes (Bell & Morse 2014). While some of the evaluated scientific contributions incorporate participatory approaches to derive or weigh criteria and indicators as already mentioned, few of them shed light on how these measurements drive policy change.

Against this backdrop, I argue that the instrumental aspects of power system sustainability assessments are underrepresented in the current scientific contributions.

The discussion on the conception of SD and SD governance and could potentially open up entirely new research streams involving governance processes, policy instruments and institutions. Owing to the vast complexity of challenges associated with governance and SD, I shall focus the scope of this contribution on one essential aspect of governance: transformation governance, or governance of change, which is sought to drive system transitions. The latter is exactly the aspect of governance that SD often refers to.

Similar to deriving goals related to the biophysical aspects of the system, a holistic system representation it is likely to serve only as a starting point for an analysis of governance aspects: I expect that the system depiction will not be sufficiently worked out and shall therefore require a more detailed elaboration of reflexive transformation governance. Accordingly, I shall first have to specify reflexive governance, or features thereof, in more detail in relation to inducing system transitions. While an integration of sustainability assessments in governance is a necessary precondition for meeting sustainability objectives, it also requires distinctive contributions. I shall focus here on addressing the instrumental requirements that must be met in order to operationalise SD.

This raises questions on what methodologies are best able to facilitate the formulation of more tangible goals for the functional and instrumental part in sustainability assessments. Since developing such an approach is a vastly complex task on its own and *Grunwald and Rösch* (2011) demonstrated that robust methodologies already exist, I shall invest the existing literature and focus with my contribution on the formulation of exemplary general goals for criteria. Accordingly, I will draw on an existing framework for this endeavour. The resulting general goals will complement the previously derived set of criteria for the sustainability assessments of electric power systems. The process of producing general goals for criteria will also indirectly yield some form of prioritisation of criteria, as criteria irrelevant to the normative requirements of SD are likely to not receive any goals.

To summarise, my exemplary contributions related to sustainability requirements for power systems in sustainability assessments will consist of a systematic formulation of general goals for criteria based on (i) a current interpretation of SD, (ii) a holistic representation of electricity systems, and (iii) a reflexive governance of change.

5.6 Conclusions

Exploring the previously identified knowledge gaps revealed that current scientific contributions relating to sustainability assessments of power systems mostly apply methodologies geared to a detailed analysis of energy and matter flows in specific systems components. However, to provide a more comprehensive basis for *evidence-based* decision making, additional methodologies are required to encompass the relevant system features, more systematically derive criteria and consider potential future system developments, thus reducing the risk of omitting key system aspects. Accordingly, I shall strive to contribute towards more holistic analyses of electricity systems.

Furthermore, in order to answer questions on what long-term requirements electric power systems have to meet, the sample under review suggests reverting to participatory approaches relating to policy objectives or drawing on comparative assessments. However, in order to provide a sound basis for *goal-oriented* decision making referring to the normative features of SD, I argue that approaches are required which allow system data to be evaluated against sustainability objectives. This requires a systematic formulation of more tangible goals from the normative and instrumental notions of SD. Accordingly, I shall strive to contribute towards equipping sustainability assessments with goals that mirror the requirements of a current scientific interpretation of SD.

To summarise, all my contributions together aim at providing a more holistic and transparent approach to sustainability assessments in general. These individual scientific contributions are part of a holistic *framework for sustainability assessments*. This framework is based on the previously presented features of sustainability assessments, as elaborated in section 3.3, and seeks to integrate functional aspects of a system under review with the normative and instrumental requirements of SD. The framework will be based on a set of distinctive theoretical elements and methodologies. In order to stimulate further scientific discussions on how sustainability assessments should be constructed in order to provide comprehensive bases for *evidence-based* and *goal-oriented* decision making, I shall make a dedicated effort to present information and provide corresponding arguments in favour of my proposals.

In order to demonstrate the strengths of the proposed framework and explore the limits, I shall produce a set of exemplary results based on electric power systems for those basic features that are today largely absent in sustainability assessments of electricity systems. Once more, I would like to emphasise that these exemplary deliverables pri-

marily seek to promote further discussion on the operationalisation of sustainability assessments and are far from being universally applicable.

Based on the analysis of knowledge gaps in this chapter, I am now in a position to formulate an appropriate research question for this thesis that will guide the delivery of my contributions as touched on in this chapter.

6 Research question

This chapter is dedicated to formulating a research question based on the knowledge gaps identified in the previous chapter and in accordance with the basic features of sustainability assessments introduced in section 3.3. Furthermore, I shall presume to express expectations on how these contributions will contribute to a more comprehensive basis for *evidence-based* and *goal-oriented* decision making support for the long-term development of key systems. A short summary of the purpose of sustainability assessments and the identified knowledge gaps in current sustainability assessments of electricity systems serves as a starting point for my task in this chapter.

There is broad consensus among scholars and policy makers that if we are truly striving for SD, then we require active governance. Assuming that modern societies strive for the *evidence-based* and *goal-oriented* development of key infrastructure that meets the normative requirements of SD, there are good reasons to believe that the application of steering instruments is part of such an endeavour. One task required consists of evaluating relevant data on key systems against predefined sustainability objectives. Sustainability assessments are designed to do exactly that. However, in order for sustainability assessments to contribute their part, they have to be composed of a set of structural elements beyond EIA, as elaborated in section 3.3.

The review of the research sample in chapter 4 has shown that the current scientific contributions on sustainability assessments of electricity systems are only partly composed of these structural elements. Some vital components, such as holistic system depictions or normative and instrumental aspects of SD, are mostly absent. The absence of some of these features is expected to only partly enable sustainability assessments to provide a sound basis for *evidence-based* and *goal-oriented* decision-making support.

With this thesis, I strive to provide a *framework for sustainability assessments* and the methodological contributions that have hitherto been absent in sustainability assessments. The proposed framework will be based on building blocks formulated in section 3.3 and seeks to provide a comprehensive basis that may inform decision making more transparently and holistically. Accordingly, the research question of my thesis seeks to address the general question of what basic features are required for sustainability assessments to provide a sound basis for *evidence-based* and *goal-oriented* decision-making support.

Ultimately, the identified shortcomings are expected to constrain the *evidence-based* and *goal-oriented* development of key systems in many ways: a too narrow scope definition and an arbitrary selection of indicators, for example, increase the risk of erroneous decision making owing to the omission of relevant data. A substitution of general goals through benchmarking, trend extrapolation, comparative analyses or participatory approaches is likely to jeopardise decision making, as reliable references reflecting normative sustainability requirements cannot be guaranteed. The sum of these shortcomings eventually results in reducing sustainability assessments to purely descriptive exercises and thereby renders their results only partially fit for societal steering purposes. Accordingly, I shall dedicate my thesis to answering the following research question, which aims to aggregate the identified individual issues into an overall question:

How should sustainability assessments be designed methodologically to provide a basis for evidence-based and goal-oriented decision making on the long-term development of key systems?

To answer this research question, I shall provide the necessary contributions related to the structural elements of sustainability assessments described initially. Furthermore, I shall produce exemplary contributions for hitherto missing basic features in the sustainability assessments of electric power systems.

Since the missing methodological features can be separated into the two methodically distinct categories of (i) functional contributions related to the system in question, and (ii) normative and instrumental aspects referring to the principles of SD, I shall structure my contributions so as to fill the identified knowledge gaps in sustainability assessments of power systems according to these two categories.

Figure 9 provides an overview of the identified knowledge gaps and intended contributions. This diagram shows the structural components of sustainability assessments on the left-hand side. For this figure, however, I opted to split general goals and target values into two distinct structural elements. For methodological reasons, which I shall explain in chapter 7, I shall only pursue a contribution to producing a set of exemplary criteria for sustainability assessments of power systems. The second column shows the aggregated results of the review of the current state conducted in chapter 4 on which components are frequently covered in the research sample. The third column provides a first preliminary assumption on how the knowledge gap can potentially be filled or

whether proven methodologies are already frequently applied. The fourth column then summarises the planned contributions of my thesis.

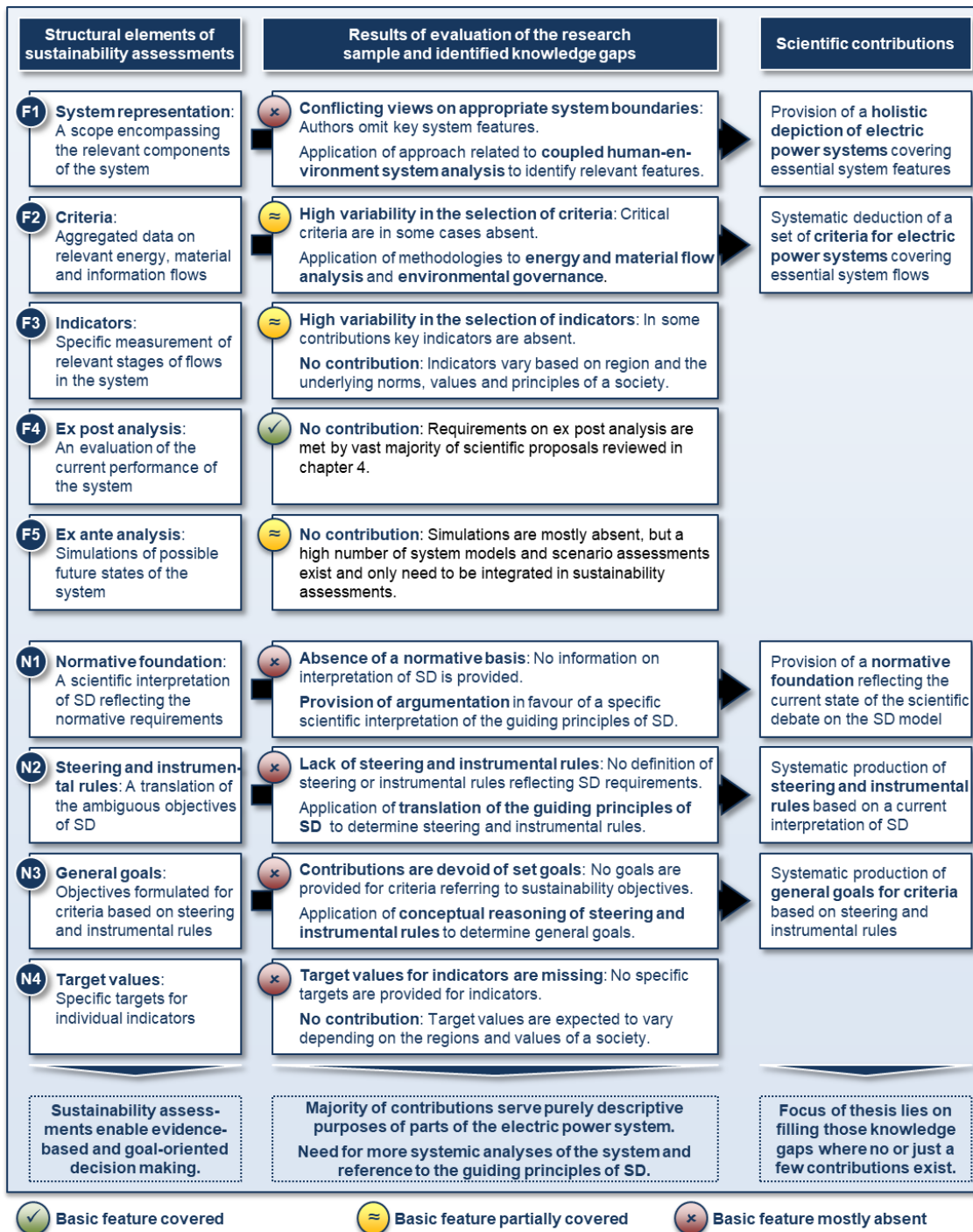


Figure 9: Knowledge gaps and scientific contributions

(Own elaboration)

The diagram shows that the basic feature of ex post analysis is sufficiently covered by the research sample and does not require further scientific contributions. Although

there is high variability in the indicators prevalent in sustainability assessments, as I have already pointed out, the indicators are likely to depend on the individual system subject to analysis: The natural occurrence of energy carriers or fluxes varies across regions, for example, or societies adopt different norms, principles and values. Since I strive to develop an aggregated framework, I shall not follow up on this basic feature of sustainability assessments. I shall also refrain from providing a contribution on ex ante analysis, albeit for a different reason: While sophisticated ex ante analysis is also underrepresented in the research sample, solid contributions on scenario assessments and system models already exist. As such, it is more of a question of how to integrate them within sustainability assessments. Against this backdrop, I shall proceed with exploring the functional, normative and instrumental contributions of this thesis, some of which are examples provided for electric power systems. The proposed framework for sustainability assessments, which aims to provide a comprehensive basis for *evidence-based* and *goal-oriented* decision making, will be presented in more detail in chapter 7.

6.1 Functional contributions

In order to answer the above research question, I shall provide distinct methodological contributions to fill the individual knowledge gaps related to the functional dimension of power systems:

- i) **System representation.** A holistic depiction of electric power systems is developed that encompasses all stages of value creation, including interdependencies among ecological capacities and the social realm of actors. I shall briefly touch on interfaces to other key systems in modern societies.
- ii) **Criteria.** A systematic deduction of criteria for sustainability assessments is carried out based on the holistic system representation of electricity systems and an in-depth analysis of energy and matter flows, as well as societal steering processes. I shall, however, not deduce indicators since, as already mentioned above, they are likely to vary across regions and societies.
- iii) **Ex ante analysis.** I shall refrain from developing a system model with quantified interdependencies among key system components to simulate potential scenarios, as this is frequently covered in research papers or political analyses. However, in chapter 7 I shall argue briefly for those methods that I deem effective.

To summarise, I shall contribute towards overcoming three of the identified functional shortcomings in the current sustainability assessment of power systems. These contributions aim to promote a more comprehensive basis for *evidence-based* decision-making support; the provision of a holistic system representation and the systematic deduction of criteria are expected to serve as a sound basis for sustainability assessments of electricity systems so as to extract and present essential system data.

Applying a more systematic procedure is expected to reduce the risks of misinforming decision makers through the omission of essential system properties. Furthermore, should the same depiction of electricity systems, encompassing the relevant functional system components, be applied by other authors of sustainability assessments, then this would lead to the increased comparability of results resulting from an identical basis for system data. Moreover, relying on the same system representation for ex ante and ex post analysis is likely to increase the consistency of the results of monitoring the processes on system developments and scenario assessments. Therefore, there is good reason to believe that the functional contributions may increase the reliability and trustworthiness of extracted system data and thereby provide a more comprehensive basis for *evidence-based* decision-making support for the long-term development of power systems.

6.2 Normative and instrumental contributions

In addition, I shall also provide scientific contributions related to knowledge gaps on the normative and instrumental features of the guiding principles of SD:

- iv) **Normative foundation.** I shall first select a current interpretation of SD and argue why I chose this specific normative basis.
- v) **Reflexive transformation governance.** According to latest research on SD and SD governance, reflexive transformation governance is a necessary precondition for conducting system transitions and meeting sustainability requirements. Accordingly, I shall specify a reflexive governance of change that will later serve as a basis for determining criteria and general goals.
- vi) **Steering rules and instrumental rules.** The chosen interpretation will serve as a basis for developing enriched conditions of the interpretation of SD. This set of steering and instrumental rules will address the specifics of

power systems and reflexive transformation governance to tie in with the holistic system representation and requirements of SD. In order to translate the SD model into a set of rules, I shall draw on a multi-step procedure, which, obviously, is subject to personal interpretation and cannot be universally applicable. Rather, it produces exemplary sets of steering and instrumental rules that will later facilitate a further translation of sustainability objectives into general goals.

- vii) **General goals.** Based on the previously formulated steering and instrumental rules, I shall further enrich the set rules into general goals for criteria. This will allow decision makers to evaluate system data against predefined sustainability requirements.

The above-mentioned contributions will be made in order to fill the normative and instrumental knowledge gaps. I expect these contributions to empower sustainability assessments of electric power systems to provide a more comprehensive basis for *goal-oriented* decision making: that is, providing a current scientific interpretation of SD will lay the groundwork for a consideration of normative sustainability principles in sustainability assessments and enable the definition of general goals for criteria. Furthermore, the definition of goals that reflect sustainability requirements allows for an evaluation of the system performance against sustainability goals. Such an evaluation will make it easier for conclusions to be drawn on whether a system is on a sustainable pathway as opposed to other approaches related to benchmarking, participation, trend or comparative technology analysis.

Now that I have framed the tasks of my thesis, I shall proceed with a review and discussion of the strengths and limits of the current approaches and methods applied in sustainability assessments of electric power systems. Based on such a discussion, I shall then present and argue for those methodologies that I expect to be effective in filling the identified knowledge gaps.

7 Theoretical background

In order to answer the research question presented in chapter 6, I shall provide two distinct types of scientific contributions. On the one hand, I shall develop a framework for sustainability assessments consisting of theoretical elements and the structural features presented in section 3.3; on the other hand, I shall develop contributions for electric power systems. In order to provide these deliverables, I shall first explore and reflect on appropriate methodologies. Hence, this chapter serves two purposes:

- i) **Framework for sustainability assessments.** In the first section, I shall set out the cornerstones of the proposed framework for sustainability assessments. This framework will be applicable to different types of complex coupled human-environment systems and I shall argue for theoretical elements that can be expected to enable the provision of new scientific contributions.

- ii) **Approaches and methods for sustainability assessments of electricity systems.** In subsequent sections, I shall discuss in more detail a selection of methodologies specifically geared to electric power systems and argue for those approaches or methods that I deem fit to respond to the identified shortcomings in today's sustainability assessments of electricity systems. My goal here lies in highlighting effective methodologies for those basic features of sustainability assessments that were not fully covered by the contributions under review in chapter 4. Since the knowledge gaps cover a wide range of research subjects, spanning from the analysis of energy and material flows including societal steering processes to formulation of normative and instrumental rules based on a scientific interpretation of SD, I shall discuss distinct methodologies for each theme.

Accordingly, I shall proceed with presenting the cornerstones of the proposed framework for sustainability assessments, which is intended for the analysis of complex coupled human-environment systems.

7.1 Cornerstones of the proposed framework

A summary of the purpose and structure of the proposed framework will serve as my starting point for this endeavour. Sustainability assessments are conducted on complex socio-ecological systems and are designed to provide a basis for *evidence-based* and

goal-oriented decision making for the long-term development of key systems. In order to serve that purpose, I argued in section 3.3 that sustainability assessments have to encompass the essential features of the system under review. This part is often referred to as the functional dimension of a sustainability assessment, where relevant stages of biophysical flows, as well as societal steering processes, are evaluated. Furthermore, I also argued that this functional dimension has to be complemented with a normative dimension that refers to the objectives of SD. Based on an analysis of the system performance against sustainability requirements, decision makers can be expected to be better able to safeguard opportunity spaces for future generations when deciding on development options, as opposed to drawing on evaluation schemes that are devoid of sustainability goals. Based on this two-dimensional structure, I shall first revisit the structural components of sustainability assessments introduced previously to provide an overview of the proposed framework:

- i) **System representation.** In order to identify relevant system components, I propose to apply approaches related to coupled human-nature system analysis to identify the functional constitutive elements of the system in question, including enabling and constraining factors. This analysis not only has to encompass technical aspects of the system, but also has to consider the actors' social realm, where the goals of the system, and thus also the technical design, are determined.
- ii) **Criteria.** Based on such a holistic system representation, I propose to revert to methods taken from the realm of system flow analysis to determine those biophysical flows that are particularly relevant to secure the intended output of the system. At the same time, an analysis based on socio-ecological regimes or environmental governance can be expected to support the process of identifying relevant societal actors and their steering processes. These analyses are expected to provide a sufficient basis for systematically deducing criteria for the relevant stages of energy and material flows, including societal steering processes.
- iii) **Indicators.** While potential indicators could in theory also be systematically deduced from above-mentioned analyses, it remains contested whether such a procedure would be appropriate. Some indicators might only be identified if the system were home to specific system components; for example, in a region deprived of fossil fuels, a stringent analysis would obvi-

ously miss the identification of such energy carriers and is likely not to produce a corresponding indicator. Since I intend to provide a framework applicable to complex human-environment systems in general, I argue that the analysis of indicators lies outside the scope of my endeavour here. Accordingly, an analysis of appropriate methodologies to determine indicators has to be postponed to further research.

- iv) **Ex post analysis.** Assuming that we are striving for a comprehensive basis for *evidence-based* decision support and that the analysis of historical system data can also contribute to decision making for the development of key systems, especially to pin down areas of immediate concern, then methodologies are required that will extract and analyse system data for each criterion. Life cycle assessments have proven to be adequate methods for endeavours directed at the analysis of biophysical flows to locate sources of unsatisfactory developments. Moreover, an analysis of societal steering processes through approaches related to socio-ecological regimes or environmental governance is expected to allow data related to societal actors to be obtained.
- v) **Ex ante analysis.** In order to identify potential future problems, exploring historical system data has to be complemented with scenario assessments. For this basic feature, I propose to develop a system model where correlations among interdependencies of essential system components are defined. Approaches related to system modelling are often used to serve that purpose. Subsequently, exploratory scenario analysis can be used to simulate possible future states of the system. The results are likely to yield clues to potential development paths the system may take.
- vi) **Normative basis.** In order to evaluate the system performance against predefined objectives that mirror the normative requirements of SD, I propose to revert to a current scientific interpretation of the guiding principles of SD. As elaborated in section 3.1, the focus of the debate on human development and environmental degradation has shifted from resource scarcity to the fragility of socio-ecological systems. Accordingly, I propose to select an interpretation that accounts for that development.

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- vii) **Steering and instrumental rules.** It is a frequent complaint that the conception of SD is too abstract to operationalise. Accordingly, in order to translate the ambiguous model into more tangible goals, I propose to draw on a multi-step procedure. By applying such a procedure, the normative basis can be further enriched with interpretations and thereby broken down into a more tangible set of steering rules and instrumental rules.

 - viii) **General goals.** Based on the previously defined steering and instrumental rules on the one hand and the detailed analysis of biophysical flows as well as societal steering processes on the other, I propose to systematically derive general goals for criteria by applying the above-mentioned multi-step procedure.

 - ix) **Target values.** In section 3.3, I argued that specific targets are required for indicators and that these goals have to correspond on an aggregated level to the general goals of criteria. However, since I also argued above that indicators are likely to be region-specific, and concrete targets for indicators can be expected to also depend on the principles, norms and values of a society, I contend that in democracies, the production of target values for indicators should probably consider some form of societal negotiation and deliberation.

Against this backdrop, *Figure 10* provides an overview of the proposed structural features and theoretical elements of the functional and normative dimensions of the framework for sustainability assessments of complex socio-ecological systems. These structural features are supposed to be universally applicable to complex socio-ecological systems. However, in order to be able to explore the strengths and weaknesses of the proposed framework better, in this thesis I shall make contributions that are specific to electric power systems. These contributions require the methodological investments that are outlined in the subsequent sections of this chapter.

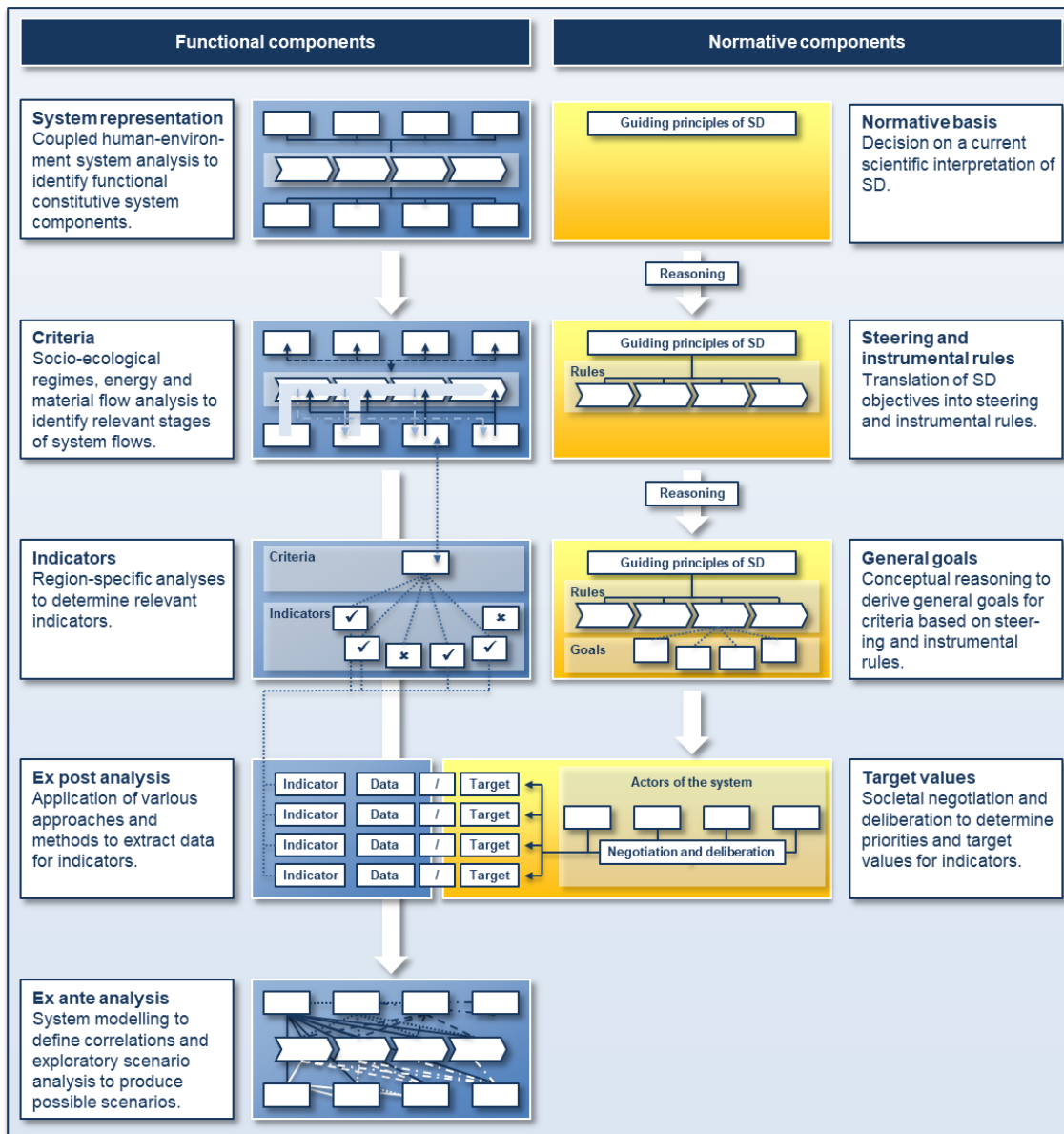


Figure 10: Overview of the functional and normative parts of the framework

(Own elaboration)

Since this framework acknowledges the high priority societal steering processes assume in electric power systems, I shall pay special attention to governance. In section 3.2, I argued that recent research on the governance of SD has resulted in the broad recognition that the operationalisation of SD is likely to require a mode of governance that recognises the specifics of sustainability challenges. Accordingly, the governance of SD has to take into consideration the fragmented responsibilities of system components, a wide distribution of system knowledge and unclear goals in order to better respond to adverse developments in complex coupled socio-environmental systems.

Against this backdrop, I argued that the operationalisation of SD may require reflexive governance to address the challenges involved. Furthermore, since I am mainly interested in system transformation, I shall focus on the governance of change that may facilitate system transitions. Hence, for this thesis I shall not only assume that reflexive governance of change has been established, but I shall also lay its cornerstones.

Based on this overview of the proposed framework, I shall proceed by discussing theoretical options specifically for electricity systems and arguing for appropriate approaches to conduct sustainability assessments of electric power systems. At this stage, I would like to point out once more that, while the structure introduced above can be applied universally to complex socio-ecological systems, the proposed theoretical investments are specifically geared to electric power systems. Accordingly, I shall first explore and discuss appropriate methodologies related to creating a holistic system representation of electric power systems.

7.2 Theory for system representation

It is common methodological knowledge that representations of systems are dependent on the system boundaries drawn or the research interests involved. Moreover, complex systems can never be fully represented as a result of the manifold factors and interactions they involve. However, one can try to identify the relevant constitutive elements of a system in terms of its functional contribution together with these elements' relevant interactions with the system's environment. Uranium is not a functional prerequisite for electric power systems, but power generation is. The presence of a free market among producers and consumers is not a functional prerequisite but electric power distribution is. Accordingly, the goal of this topic is twofold: Firstly, I shall strive to identify the functional constitutive elements of electric power systems together with their relations to the system's environment as an instrument for defining the scope of sustainability assessments. I will thereby argue for a holistic analysis that pays attention to essential interdependencies among societal actors, technical components and ecological capacities. Secondly, I not only want to pave the way for a commonly shared understanding of these functional components of electric power systems, but I also aim to lay the foundation for later tasks in the sustainability assessments of electric power systems, involving, for example, a systematic deduction of criteria. Accordingly, the key question to be answered on the system scope is: *What methodology may serve to produce a holistic system representation that encompasses the functional constitutive components of sustainability assessments, including enabling and constraining factors?*

This question is directed at identifying those functional elements that I regard as necessary members of the set of factors to be considered in sustainability assessments.

To identify the functional constitutive components for a holistic representation of electric power systems, I need certain theoretical background investments regarding holistic representations of systems. A holistic representation of an electric power system has to encompass both human and natural elements including their interactions. Coupled human-nature or socio-environmental systems (SES) aim to do just that. Electricity systems are exemplary coupled human-nature systems because they contain physical energy and material flow components, as well as strong societal components, such as defining and operationalising goals directed at human well-being. The combination of these two types of elements in technological artefacts is a further hallmark of coupled human-nature systems. I am therefore looking for a well-founded conceptual scheme for analysing coupled human-nature systems. Against this background, this section argues for why I propose the theoretical scheme offered by the socio-ecological approach of societal metabolism (Fischer-Kowalski & Weisz 2005; Fischer-Kowalski & Erb 2006). Using these theoretical investments, chapter 8 then presents an exemplary holistic depiction of electric power systems and demonstrates the relevance of this kind of representation by analysing different cases to deduce the effects of the scope definition on the outcome of the sustainability assessment.

In sustainability assessments, there are two widely used approaches for identifying relevant elements of electric power systems; namely, DPSIR assessing driving forces, pressure, state, impact and response (Atkins, Burdon, Elliott & Gregory 2001; Cooper 2013; Omann, Stocker & Jäger 2009), and some combination of energy and material flow analysis, often life cycle assessments (LCA), together with cost-benefit analysis (CBA) (Asdrubali, Baldinelli, D'Alessandro & Scrucca 2015; Garcia, Marques & Freire 2014; Lopes Silva, Delai, Delgado Montes & Ometto 2014; Oliveira et al. 2015; Restrepo, Bazzo & Miyake 2015; Santoyo-Castelazo, Gujba & Azapagic 2011; Sherwani, Usmani & Varun 2010; Stamford & Azapagic 2014; Turconi, Boldin & Astrup 2013). The former was developed to capture exactly what I am interested in. In DPSIR, the classic flow components are expressed by pressure, such as resource extraction, state such as for example resource stock, and impact, such as emissions from resource use. Furthermore, social factors representing driving forces, such as consumption patterns, and reactions, such as policy decisions or societal steering criteria, are explicitly taken into account. DPSIR is meant to display a dynamic, reflexive system, where actors have the opportunity to react with steering instruments to developments in other domains. As

electric power systems obviously include human driving forces, such as business and consumer interests, and are steered by policy instruments for example, DPSIR seems to be a promising candidate for a systemic analysis of electricity systems. However, there are well-known shortcomings to this approach. Stocks, representing the state category for example, could refer to natural, social or financial capital. Moreover, social capital could also function as a drive or even belong to the domain of reaction. Accordingly, it is far from evident whether the five general categories representing the DPSIR approach are really able to function as an unambiguous conceptual scheme for systemic analysis. As these five categories could be applied to social and natural components in the same way, it is by no means clear how they could conceptually steer the analysis of the interaction between social and natural components of electricity systems. DPSIR points to abstract dynamic criteria that the representation of a system has to consider, rather than providing a theoretically sound methodological instrument for analysing coupled human-nature systems. While it certainly serves well for many practical and pragmatic assessment approaches, it cannot offer the theoretical foundation I am looking for.

Whereas DPSIR fails to offer a transparent and well-defined approach, LCA together with CBA fulfil that requirement. LCA have become standardised instruments with which researchers attempt to cover all biophysical aspects of a product's life cycle. However, LCA cannot capture social components; it focuses on the causal, material flows and not on the reasons for, or the social drivers of, for example, electricity demand. This is why LCA are often accompanied by CBA. Benefits display the social goal of welfare, expressing well-being in the sense of preference satisfaction in economic terms. Total costs, including externalities, entail the social and financial capital invested to achieve the goals. CBA can be carried out on different levels, from the micro level, such as businesses, to the macro level which involves societal decisions. CBA provides important information on efficiency, that is, on the best possible relation between investments and achieved outcomes. Theoretically, given full information and assuming that welfare provides a satisfactory metric of well-being, CBA could cover all the relevant social factors. Hence, on the one hand CBA is complementary to LCA by capturing the missing social elements of the LCA and, on the other hand, by being able to calculate the social costs of the elements identified by LCA. As a result, at first glance the combination of CBA and LCA seems to offer a reasonable solution to what I am looking for: it displays the systematic link between social and natural aspects and provides the rationale for decisions.

However, this approach has two conditions: Firstly, that all relevant factors have to be known and, secondly, that all relevant information is available. If this is not the case and I misrepresent the system in question, then I will also miscalculate the combined CBA and LCA. Moreover, there is some risk that the system's boundaries would be drawn according to the available data and not according to what is a relevant factor. Without neglecting the usefulness of a combined CBA and LCA, I would like to avoid these risks. Accordingly, the general shortcoming of combined LCA and CBA consists in representing the complex societal system as a black box.¹⁷ Therefore, I want to first take a step back to ensure that the system analysis is based on a satisfactory theoretical foundation.¹⁸ The critical review of DPSIR and combined CBA and LCA reveals that I first need to understand the system's relevant components and their respective structural relations. As developing such an understanding must be guided by theory, I am looking for a theoretical approach that is able to conceptualise the dynamic coupling within human-environment interactions.

To do so, I propose drawing on the societal metabolism approach (SMA) developed by, among others, Peter Sieferle (Sieferle 1997) and Marina Fischer-Kowalski (Fischer-Kowalski & Weisz 2005; Fischer-Kowalski & Erb 2006)¹⁹. Contrary to natural metabolism, societal metabolism is intended and socially organised. Its key feature is human labour. According to SMA, human beings not only act but, by their action, they also invest labour to shape their natural environment and thereby create hybrids between the natural and the social. A human being is itself a hybrid insofar as it is partly natural in terms of its metabolism and partly social, for example in that it symbolically interacts through communication. More importantly, humans create artefacts, such as domesticated animals or technology, by investing labour. These artefacts can be reduced neither to material and energy flows nor to symbolic social meaning. Moreover, although the societal metabolism is built upon individual actions, it is not reducible to them. Hy-

¹⁷ Schellnhuber's (1999) famous world-system, for example, consists of a multitude of energy and material-flow factors. However, only three general human impact factors are acknowledged. These factors are not specified, but explicitly taken as black boxes (Schellnhuber 1999).

¹⁸ There are further problems associated with CBA in sustainability assessments that I shall not explore further here, such as how to deal with uncertainties and future generations.

¹⁹ One might be wondering why I do not base my work on the contributions of Ostrom (2009). A detailed debate on their strengths and weaknesses in relation to SMA would go beyond the scope of this thesis. Consequently, I shall merely point to the fact that Ostrom directs her analysis to a resource unit within a specific space, while electricity systems are quite different in that respect.

brids such as technology, or a complex structure such as an electric power system, are collectively organised, requiring both division and coordination of labour.²⁰

Figure 11 displays the mutual relationships. Although human labour shapes and influences natural energy and material flows to create artefacts, these artefacts are products of societal activities and shape societal activities in return. Societal organisation may include markets, research activities, control mechanisms or ownership structures. Moreover, as there is no social organisation without rules, norms and values, the organisation of energy and material flows includes values, norms and rules by definition. Accordingly, if I base a systematic analysis of electric power systems on such a theoretical frame, a sustainability assessment cannot focus only on technology assessment. Technologies, artefacts and their consequences for energy and material flows, as well as their impact on the general environmental state, are only a part of the picture. Against this backdrop, I argue that a system representation also needs an appropriate treatment of the societal organisation.

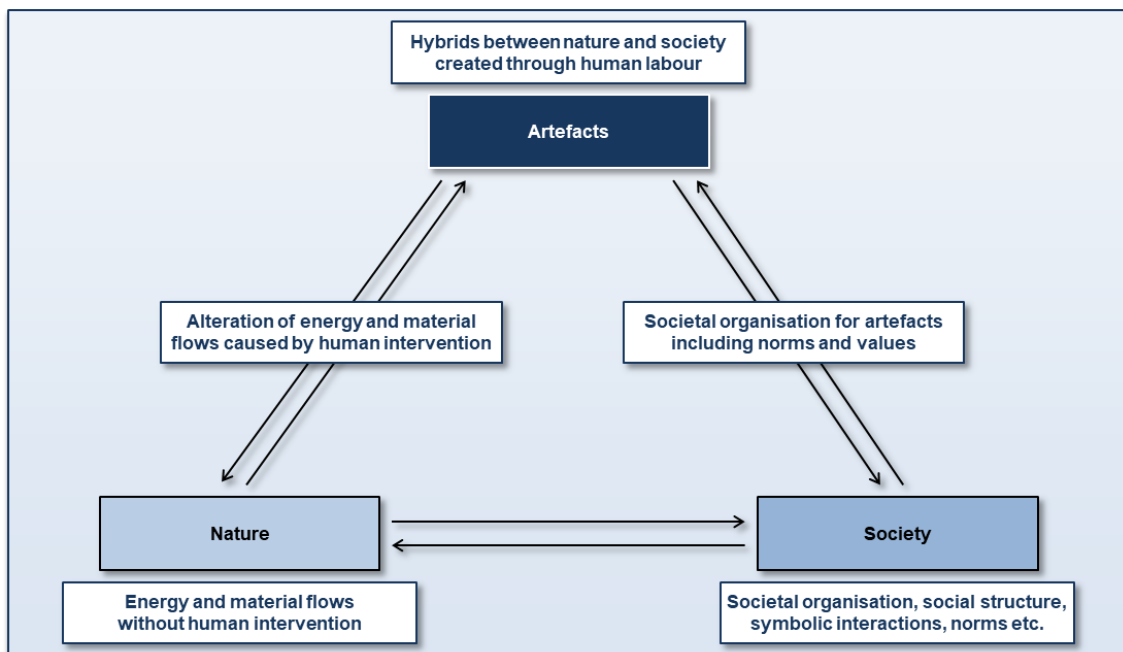


Figure 11: Schematic depiction of societal metabolism approach

(Own elaboration)

Accordingly, I propose to apply the SMA approach related to coupled human-nature systems in order to create an exemplary holistic representation of electric power sys-

²⁰ One may define societal metabolism as the system of collectively organized activities that creates both goods to serve human purposes and is impacted by the resulting emissions and waste.

tems that encompasses the relevant components. This depiction of electricity systems will later serve as a basis for systematically deducing criteria for sustainability assessments of electricity systems. I shall elaborate the system representation based on SMA in chapter 8.

7.3 Theory for criteria

One of the features of sustainability assessments is to extract and evaluate data regarding predefined criteria. Accordingly, authors face the question on how to select the relevant criteria for assessing a system. The answer to this question depends without doubt also on the system boundaries. Against this backdrop, it becomes obvious that the definition of the system scope, or in other words what constitutes the functionality of the system, has a deciding effect on the range of potential criteria to be assessed.

Today, there is broad agreement among researchers that electric power systems bear the functionality of extracting energy carriers, generating and distributing electric power and powering electrical appliances to provide energy services. This functionality essentially ensures that electric power systems can serve their purpose: improving the well-being of people and enabling the mass production of goods and services for businesses. While a vast number of new technologies is currently in development, the system functionality is assumed to remain constant for future as well. Today, power grids transmit electricity from power plants to consumer centres; in the future, however, an increased penetration of distributed renewable energy and smart grid technologies is expected. This may require power grids to transmit excess electricity from numerous '*prosumers*' to consumers without onsite power generation. While the role of power grids might change in such a case from a one-way power supply to a disposal of excess electricity from '*prosumers*' to consumers, the core functionality of power grids, namely, to transmit and distribute electric power, remains the same. Assuming that an agreement on the functional constitutive elements of electric power systems can be reached, as argued in the previous section, then potential criteria applied to system components to measure energy and material flows, including societal steering processes, should also be the same. If this assumption holds true, then I should be able to draw up a set of criteria for sustainability assessments of electric power systems.

The functionality of electric power systems is, however, also affected by enabling and constraining factors lying outside the technical infrastructure components: the natural occurrence of energy fluxes, such as wind or solar radiation, determines the power

generation potentials of wind farms and solar PV systems. Furthermore, new smart grid technologies, such as demand-side management, can be applied to modify consumption patterns to power generation profiles. Accordingly, these enabling and constraining factors, which can be found in the social and environmental dimensions of electric power systems, may also exert a strong influence on the system functionality. Against this backdrop, I argue that, in sustainability assessments, aspects of the social and environmental dimensions also need to be evaluated:

- a) Social actors and societal structures define the technical design and actively steer the development of the technical components of electricity systems;
- b) Ecological capacities define the extent of the technical components through resource stocks, the availability of energy sources and emission sinks.

Consequently, I argue that factors that enable and constrain functionality can also be expected to be the same for each electric power system, since both the availability of the core functionality and its preconditions are what constitute electric power systems. Obviously, however, while factors such as precipitation or participation in policy processes exist, they may vary across regions and jurisdictions. Nonetheless, even if the values of these factors differ, the system components still remain relevant. For example, fewer sunshine hours per day may indeed reduce the potential or production of solar PV generation, but the number of sunshine hours does not affect the general function. Accordingly, if my claim proves to be right, then one should be able to draw up a common set of criteria for the system functionality including enabling and constraining factors. Since such criteria are based on the functionality of the electric power system or relevant social or environmental frame conditions, I should be able to deduce such criteria from a holistic system representation that encompasses the relevant system components.

However, at this point I also acknowledge that a holistic system representation is likely to be too abstract to serve as a basis for deriving criteria systematically, and that the relevant energy and material flows, including societal steering processes, first need to be identified and worked out in more detail. Accordingly, a detailed analysis of energy and material flows across the four stages of value creation borne by the technical components of the system and the societal steering processes governing these biophysical flows are a prerequisite for such an endeavour. Taking such a holistic view on electric power systems as a starting point is likely to result in a shift of focus from today's tech-

nology evaluations to more systemic assessments. In holistic analyses, measuring the carbon dioxide emissions of a coal-based power plant, for example, is not a primary objective as only a fraction of total emissions is reviewed. However, assessing this type of emission resulting from one hour of lighting, for example, can be expected to yield a more complete picture, as data of the entire life cycle is considered. A key advantage of such a systemic approach lies in considering a more complete set of information in decision making. While the contribution of cooking to climate change, as another example, obviously depends on the selection of electric power generation technologies, applying a more holistic approach will also account for other measures, such as endeavours to promote energy efficiency.

Accordingly, the aim of my contribution on criteria for electric power systems is twofold: Firstly, I shall provide an overview of the relevant energy and material flows of electric power systems, as well as societal transformation processes based on the previously developed holistic system representation. Secondly, I shall then deduce criteria for relevant system components, capturing the respective biophysical flows and social processes. Accordingly, I intend to answer the following question related to criteria in this section: *What methodologies prove to be effective for determining the criteria that are of relevance to evaluate energy and material flows, including societal transformation processes, in electric power systems?*

To analyse relevant flows based on a holistic system representation, I shall first invest methodologies related to energy and material flow analysis to cope with the biophysical aspects of the system. I shall then proceed by elaborating why the aforementioned methods need to be enriched with an element pertaining to the system's societal steering components (Baerlocher & Burger 2010). The output of this contribution will consist of a set of criteria to be utilised in sustainability assessments of electric power systems. I shall present this deliverable in chapter 9. In chapter 12, I shall then compare and discuss the proposed exemplary set of criteria in relation to contributions of the research sample in a broader context. Accordingly, I shall continue by exploring appropriate methods for the analysis of energy and material flows.

In section 7.2, I touched on such methods to reflect on the appropriateness of energy and material flow analysis in framing the scope for sustainability assessments. While I acknowledged the relevance of such analysis in the context of sustainability assessments, I then deemed LCA and CBA to be inappropriate for determining system boundaries. In this section, however, I will argue why these methods are indeed invalu-

able for sustainability assessments when evaluating energy and material flows in more detail to extract system data.

Material flow analysis (MFA) is a systematic assessment of flows and stocks of material and is applied within predefined boundaries of systems and time. MFA connects the sources, the pathways and the intermediate and final sinks of a material. The results of an MFA can be controlled simply by comparing the balance of all material inputs, stocks and outputs. This distinct characteristic of MFA renders the method attractive for decision support. MFA can be considered a method that establishes the inventory of a LCA which strives to assess as many substances and compounds as possible to create as complete a picture as possible (Brunner & Rechberger 2003). Against this backdrop, I conclude that MFA and LCA are complementary and are in a position to measure energy and material flows across ecological and technical system components and thereby meet the methodological requirements. Furthermore, since LCA measure substances and compounds of materials, they already entail measures which may be re-used for sustainability assessments.

However, LCA face two well-known challenges: firstly, unavailability or uncertainty of data can limit the use of LCA and, secondly, the results of the LCA depend on the system boundaries drawn. LCA are often used in sustainability assessments of electric power systems and in most cases the scope is framed to assess power generation technologies (Dombi, Kuti & Balogh 2014; Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Kowalski, Stag, Madlener & Omann 2009; Maxim 2014; Ribeiro, Ferreira & Araújo 2013). Since LCA are traditionally applied with a downstream scope, the results of these assessments often only consider resource and energy consumption during the value creation stages of resource extraction and power generation, ignoring the later stages of power distribution and consumption. In order to provide a holistic analysis encompassing all transformation stages, a LCA has to be applied to the final stage of power consumption by electrical devices. This last stage offers a wide range of energy services to users, involving, among other things, lighting, heating and cooling. Measuring the total resource use and energy consumption, for example, by one hour of cooling food in a refrigerator will yield the required results, as opposed to measuring the resource and energy consumption of a hydroelectric power plant which generates the required electricity. Deducing criteria based on a systematic analysis of energy and material flows will also eliminate some of the issues faced by other approaches: Some scholars select indicators based on expert interviews and/or literature reviews (Gallego Carrera & Mack 2010; Maxim 2014; Ribeiro, Ferreira & Araújo 2013).

However, both approaches are prone to omissions, as experts or authors may be unfamiliar with certain aspects of the system.

While an application of LCA to energy services will yield the required criteria for the biophysical part of the system, I still need a complement displaying the reflexive aspect of societal reactions, namely, the steering component of the system in question. The previously introduced SMA itself does not give criteria for analysing the societal organisation, especially the steering-related factors. The SMA is generally intended for empirically relating types of societies to types of energy and matter use (Krausmann, Fischer-Kowalski, Schandl & Eisenmenger 2009). Accordingly, the SMA needs a conceptual complement that is not only able to guide the representation of the societal organisation, but is also able to represent the relevant societal components for transforming the metabolism in question. To serve that purpose, scholars participating in a long-standing discussion on regimes have more recently worked out approaches for socio-ecological regimes (Holtz, Brungach & Pahl-Wostl 2008; Pahl-Wostl, Holtz, Kastens & Knieper 2010; Paavola, Gouldson & Kluvánková-Oravská 2009).

The socio-ecological part of the system analysis refers to the first domain I am interested in, namely, energy and material flows established for serving human purposes. The term '*regime*' refers to the organisational or steering aspect. One may thus be tempted to identify '*regime*' with the set of laws and regulations framing a specific field. According to such an understanding, the main actors to be taken into account would be governmental actors. However, this would not only be too narrow a characterisation but would also ignore today's scientific state of the art. The huge literature on governance, for example, points to many cases of multistakeholder involvement, especially for transforming energy and material flows (Kooiman 2003; Pierre & Peters 2000; Stoker 1998). Ostrom's (2009) analysis of favourable conditions for avoiding the well-known tragedy-of-the-commons effect refers to the following as categories for successful (self-) organisation: collective choice rules, norms and social capital involved, leadership and entrepreneurship, and knowledge among users. If '*regime*' represents those elements that are involved in collective actions then two things are clear: firstly, that there is more included just rules and regulations, and secondly, that there are certainly actors other than politicians and government officials included. If, for example, technology development together with the requisite actors has to be considered within the '*regime*' of electric power systems, then the '*regime*' should allow for including them in the picture.

If socio-ecological regimes are understood as frames for collectively organising energy and material flows for human purposes, namely, frames for collectively coordinated actions, then we cannot include only those elements needed for guiding the flows or developing artefacts. We also have to include those elements relevant for establishing the plans in the first place (Baerlocher 2012). The social sciences normally refer to negotiation and deliberation as societal processes that not only devise these plans but also adapt them according to knowledge and experience. Plans are of course goal directed, and these goals represent what societies – composed of actors – agree upon. Accordingly, there is good reason to expect that, if electric power systems are treated as an organised social-metabolic system, then their detailed analysis takes into account many general and particular facets of societal organisation, functions and artefacts, and their effects on and relations to the environment. As a result, I propose to draw on approaches of socio-ecological regimes to capture the relevant social aspects of a system.

Accordingly, I propose applying energy and material flow analysis, complemented by an approach related to environmental governance, to yield a detailed description of electricity systems. This analysis will then serve as a basis for systematically deducing a set of common criteria expressing the generic functional components of electric power systems. The results will be presented in chapter 9 and further discussed in chapter 12.

7.4 Theory for ex ante analysis

Once a process to extract system data has been established and a set of criteria defined, then the prerequisites for ex post analysis are met. However, in section 3.3, I argued that scenario assessments also serve an essential purpose in providing a basis for *evidence-based* decision making. At the same time, the review of current contributions in chapter 4 revealed significant shortcomings in sustainability assessments of electricity systems in terms of ex ante analyses. These forward looking assessments seek to build knowledge on possible future states of the system and hint at potential future development paths or issues. In order to simulate such scenarios, a sophisticated model of the system under review is required. However, because system models are a simplification of reality, complex systems cannot be fully replicated in models. This results in well-known methodological delimitations and authors are forced to reduce complexity and focus on relevant system components.

In order to determine the essential system features for ex ante analysis, I propose to draw once more on a holistic system representation enriched with details on energy and material flows as well as societal steering processes. Thus, I argue that the deliverables on system representation and criteria may also serve as a sound starting point for developing a comprehensive system model that focuses on relevant system aspects. However, in order to come up with a system model, those contributions need to be further enriched with correlations among system components; energy policies favouring renewable energies, for example, can be expected to increase the deployment of solar or hydro power generation. Alternatively, the continued operation of coal-based power generation technologies without carbon capture technologies can be expected to keep greenhouse gas emissions at high levels.

Once the system model is developed, potential future states of the system can be simulated. The focus here falls on producing possible scenarios that lie beyond mainstream development paths. Accordingly, areas for policy intervention can be identified on the basis of hypothetical future states of the system. Furthermore, early warning indicators can be applied to observe and respond to adverse developments in the early stages. Moreover, the results of scenario assessments enable fruitful discussions to take place on the relevance of system components and critical interdependencies. However, since a vast number of system models and scenario assessments meeting the above requirements already exist and the aforementioned shortcomings in today's sustainability assessment can be traced back to the application of methods that are designed to serve other purposes, I shall reduce my objective here to a theoretical contribution. Accordingly, I shall argue for an approach that is effective for covering the structural feature of ex ante analysis for sustainability assessments as outlined in section 3.3. I shall aim to answer the following question: *What approach is able to simulate possible future states of complex human-nature systems and supports evidence-based decision making in sustainability assessments based on a detailed system analysis?*

To answer this question, I shall invest the theoretical elements related to system modelling and scenario assessment. As argued above, the proposed methodologies will have to be able to cope with the simulation of hypothetical situations that may potentially develop over time. These scenarios will serve as a basis for deliberating on whether specific potential developments ought to be prevented, diverted or encouraged by decision makers (Goodwin & Wright 2005). In this section, I shall therefore discuss why I propose to draw on approaches related to system modelling and exploratory scenario analysis to model system interactions and compute scenarios (Kosow & Gassner

2008). Possible deliverables, such as developing a sophisticated system model or producing a set of exemplary scenarios are, however, beyond the scope of this thesis. Accordingly, I shall proceed with a discussion on frequently applied approaches and argue for exploratory scenario analysis in more detail.

Scenario analysis is a widely appraised and established tool to support long-term planning and decision making (Bunn & Salo 1993). For scientific purposes, scenario analysis is often applied as a systematic technique to construct assumptions on interdependencies among system components and driving forces of change. Today, there are three types of scenario analyses that are frequently applied in the context of sustainability issues (Berkhout, Hertin & Jordan 2002):

- i) **Normative scenarios.** In this regard, a set of predefined scenarios is created based on policy goals or expert opinion (Karger & Hennings 2009). Such scenarios often resemble those potential future states of the system that policy makers deem desirable or feasible to achieve through the deployment of policy instruments.
- ii) **Comparative scenarios.** In order to compare the contribution of a set of preselected technologies to a system, comparative scenarios are developed and assessed to determine which technologies should be implemented on an isolated basis (Jeswani, Gujba & Azapagic 2011; Rovere, Borghetti Soares, Basto Oliveria & Lauria 2010).
- iii) **Explorative scenarios.** In contrast to the other two approaches, explorative scenario analysis²¹ does not yield predictions of the future, but rather provides a range of development paths or possibility spaces (Kowalski, Stagl, Madlener & Omann 2009; Ribeiro, Ferreira & Araújo 2013).

Normative scenarios are often applied to demonstrate the impact of specific technologies or policy instruments on the welfare of a society or the environment. They are also frequently applied in policy processes by government institutions to trigger societal discourse and form opinions on which policy scenario should be pursued. The same can be said about comparative scenarios, which assess the effects of technologies. Accordingly, both approaches aim to discuss ways and means of reaching a predefined

²¹ Explorative scenarios analysis can encompass both features of quantitative and qualitative scenario analysis.

goal or state. Against this backdrop, I argue that these two approaches may not be fully able to meet the previously specified requirements for ex ante analysis, that is, to produce potential future states of a system and thereby expand the current system understanding. Despite being widely applied, I argue that normative and comparative scenarios hold significant shortcomings if they are to be applied in the context of sustainability assessments. To operationalise the guiding principles of SD, various actors are thought to have to take actions based on the current knowledge of the system and the potential future states. However, in order to increase the understanding of possible future states, some form of explorative scenario analysis is required, where system states are not predefined.

In order to run explorative scenarios, a system model is required. This model can then serve as a basis for scenario research. To do so, it has to encompass the relevant system components, which include social actors, technical components and the environment. Accordingly, if used for the analysis of electric power systems, such a model has to entail human driving forces and interests as well. Hence, deriving potential scenarios based on a holistic system model will not only reveal future states of the system, but will also contribute to a better understanding of potential options for objectives. Based on such an approach, where scenarios result from simulations of a system model, it is possible to gain insights on potential outcomes of strategies (Burger & Zierhofer 2005). Consequently, exploratory scenario analysis provides exactly what I am looking for: a comprehensive scheme to produce potential future states and thereby enable insights to be gained on which development paths may unfold and what options for intervention exist. Furthermore, since explorative scenario assessments can cope with qualitative aspects, they may also be applied to complex human-environment systems, such as electric power systems. As a result, I propose to invest an exploratory scenario analysis approach to derive scenarios for sustainability assessments.

At this point, I would like to touch on recent research findings related to qualitative research. The inclusion of participatory elements in the scenario analysis process may yield additional benefits for transforming key systems to more sustainable states for three reasons: Firstly, engaging with actors may enable a transfer of scientific knowledge on normative objectives from scholars to other actors. Those actors would then be more likely to consider such normative aspects in their future actions. Secondly, owing to feedback received from respondents and practical experience, researchers may in turn broaden their knowledge base on the system. Thirdly, involving other actors may reduce expert bias, as scientists will be less inclined to introduce their values

into their analysis (Scholz 2001). However, introducing participatory elements into explorative scenario analysis lies beyond the scope of this thesis.

Applying exploratory scenario analysis raises two questions: What system scope is appropriate and which approach is better equipped to derive the exploratory scenarios? I shall first provide an answer related to scope. Systems can be modelled at various levels, ranging from aggregated overviews with a focus on interdimensional relationships among components to models for individual system components or various interconnected technical components of power infrastructure (Deane, Gracceva, Chiodi, Gargiulo & Gallachóir 2015). The latter models are frequently applied to simulate the technical loads of power grids (Garces 2016) or a district (Allegrini et al. 2015) with the aim of determining optimal capacities for power infrastructure components or estimating the maximum deployment potential for renewable energy technologies (Bakirtzis, Simoglou, Biskas, Labridis & Bakirtzis 2015). Accordingly, they serve the needs of system operators to maintain reliable power infrastructures. However, the aim of my endeavour here does not lie with identifying the technical limitations of established technical system components, but rather with creating a more general overview of the system, encompassing relevant system features as a basis for scenario assessments. Thus, I propose to frame the system scope in such a way as to capture the dynamic interdependencies of relevant components at a more aggregate level.

This brings us to the second question related to choosing an effective approach to compute exploratory scenarios. Today, a broad diversity of approaches on scenario analysis exists. Originating from early contributions in the nineteen seventies, early endeavours sought to develop consistent scenarios as a basis for strategic decisions. Today's approaches differ primarily in respect of the process used to develop scenarios and assess consistencies and plausibilities (Steinmüller 1997). Accordingly, based on the homogeneity of the available approaches under review, scenario analysis can be roughly structured into the following common stages: Firstly, the scope and system boundaries are defined. Secondly, relevant impact factors, describing the state and dynamics of a system component, are defined. Thirdly, interdependencies among impact factors are evaluated. Fourthly, scenarios are generated based on a simplified system model. Fifthly, scenarios are developed and described (Kosow & Gassner 2008).

Against this backdrop, I propose to base ex ante analysis for sustainability assessments of electric power systems on exploratory scenario analysis and for the implementation I recommend applying the proven stages of scenario development. At this

stage, I would like to point out once again that the key strengths of exploratory scenario analysis lie in producing potential future states of a system. The results are, in sustainability assessment contexts, used to increase understanding of the system.

7.5 Theory for normative basis

The guiding principles of SD strive for human development that does not erode the environment and thereby maintains opportunity spaces for future generations. This conception clearly bears the features of a normative objective. In order to operationalise SD, sustainability assessments are designed to evaluate to what degree that objective is attained. However, the rather abstract objectives formulated in the *Brundtland Report* have led to a controversial debate on what exactly should be sustained. Accordingly, several interpretations of SD have evolved. Despite a lack of consensus on what exactly should be sustained, there is common ground among scholars of social sciences that the guiding principles of SD address a general distributional question on resources and the fragility of ecosystems. To answer distributional questions, researchers traditionally draw on theories of justice. These theories can have a deciding impact on the operationalisation of SD; drawing on a purely economic approach in policy making based on national income can be expected to promote measures to increase the gross domestic product (GDP). Should the GDP grow, then according to that interpretation society can be considered to be on the right track to fulfil the objectives. Alternatively, referring to a broader interpretation that seeks to safeguard a wide range of human rights is likely to lead to a number of additional requirements having to be met to accomplish the sustainability challenge. Such rights may involve, among others, granting access to political processes or preventing discrimination against minorities.

Accordingly, conducting sustainability assessments inevitably requires a choice for a specific scientific interpretation of the guiding principles or theory of justice in order to determine what objectives are to be met by the system in question. While authors of sustainability assessments may be reluctant to exercise such a decision, due to its resounding effects, a selection of a normative basis is a necessary precondition for setting goals for sustainability assessments. In this section, however, I do not intend to contribute to the broader discussion on what should be sustained. Nonetheless, I shall present different interpretations of SD and argue for an interpretation that reflects the current state of the scientific debate. I expect this interpretation to pave the way for the more systematic formulation of general goals for criteria in chapters 10 and 11. I shall

proceed by summarising the current procedures applied in sustainability assessments of electric power systems and exploring their shortcomings.

Today, authors of sustainability assessments often draw on benchmarking approaches, expert interviews or trend analyses to either select or prioritise criteria and indicators. These approaches are, however, based on ranking schemes that are in no way related to the normative features of SD. It is by no means clear, for example, whether the winner between a technology benchmarking process or a positive trend in energy efficiency meets the requirements for societal development and conservation of the ecological capital of planet Earth as formulated in the *Brundtland Report*. Moreover, an increasing trend in the consumption of renewable resources may not necessarily lead to an over-exploitation of the resource stock, as long as consumption remains within the boundaries of regeneration rates. However, defining goals for criteria in sustainability assessments which mirror the normative requirements of SD will allow exactly that: to answer the question of whether certain development patterns lead to meeting or failing the overarching objective. Accordingly, within this section I strive to select a normative foundation that mirrors the objectives of SD. This interpretation will later serve as a basis for systematically formulating goals for the criteria in sustainability assessments. Hence, I aim to answer the following question in this section: *Which normative bases exist that appropriately reflects the current understanding of the sustainability challenges faced and what approaches serve the process of systematically formulating general goals for sustainability assessments?*

Answering this question will first require deciding on a current scientific interpretation of SD. I shall start this endeavour by exploring the key sustainability literature that is often highlighted in scientific discussions on SD. I shall add to this review by exploring the strengths and weaknesses of these conceptions. I shall then present key theories of justice, which may be required to augment the reviewed conceptions with additional normative features. Against this backdrop, I will then be able to argue for an interpretation of SD that is based on the guiding principles and reflects the current state of the scientific debate. Using these theoretical investments, I shall present a normative foundation that I deem appropriate as a basis for later formulating goals for criteria in sustainability assessments at the end of this section. I shall start by presenting and discussing broadly accepted exemplary features of interpretations of SD that have strongly influenced the discussion on the operationalisation of SD:

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- i) **Ecological sustainability.** The concept of resilience in ecological systems emerged from environmental sciences and promotes the restriction of pollutant emissions to the level that ecosystems can absorb (Holling 1973). While this concept was developed prior to the guiding principles of SD, aspects of resilience are often highlighted in scientific discussions on how to operationalise SD.
 - ii) **Weak versus strong sustainability.** This concept evaluates conflicts of resource distribution among generations. Weak sustainability allows depleting natural capital to increase human capital. The concept of substituting resources for intergenerational justice was developed prior to the *Brundtland Report* (Hartwick 1978).
 - iii) **Guiding principles of SD.** The most frequently cited definition of SD is a “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (WCED 1987).

Concepts of ecological sustainability, such as resilience, originate from sciences that analyse disturbances in ecosystems. These disruptions may either be manmade or caused by natural catastrophes. The aim of concepts related to ecological sustainability lies in maintaining and improving the resilience of ecosystems (Holling 1973). However, the resulting effects of ecosystem failures on human development were originally not fully explored. Thus, interpretations based on such concepts tend to focus on the environmental part of SD and often exclude vital societal aspects of SD. Meanwhile, resilience is increasingly also seen as a system property of socio-ecological systems: the function of such human-nature systems has to be maintained. Nonetheless, concepts concerning resilience often refrain from considering human well-being as the overarching objective. Accordingly, I argue, without going into a detailed discussion here, that this interpretation is likely to only partly mirror the requirements of the guiding principles of SD.

The concept of weak versus strong sustainability encompasses both the societal and the environmental dimensions of SD. Furthermore, this concept is based on rules, where, for example, weak sustainability allows the consumption of natural capital so long as human capital is created. In contrast, strong sustainability seeks to pass natural capital on to future generations (Hartwick 1978). At first glance, this conception seems to better meet my requirements, as both social and environmental aspects are considered. However, there are also well-known shortcomings to this conception: applying an

approach based on weak sustainability would lead to most industrialised countries being considered sustainable so long as their economy keeps growing. Accordingly, in extreme cases, weak sustainability could be seen as a conception that essentially promotes the exploitation of all natural resources so long as human development is achieved, ignoring the potential future implications resulting from an eroded environment. This, however, strongly opposes the original aim of SD: to safeguard the ecological capital for future generations. At the same time, the concept of strong sustainability does not allow non-renewable resources to be exhausted even if these resources are spent to develop technologies that promote tapping into the potential of renewable resources. As such, the conception of strong sustainability is often perceived as impeding development in general. I take these arguments as sufficient to conclude that this concept only partly meets my requirements.

The *Brundland Report* offers a much appraised definition of SD that is often used as a basis for further scientific contributions (WCED 1987). It acknowledges the strong interdependencies between productive ecosystems and human development. Furthermore, it addresses the distributional question on intra- and intergenerational justice. Moreover, it raises awareness on the relevance of active and reflexive governance for resolving sustainability issues. Accordingly, I consider the guiding principles of SD to encompass the normative features I am looking for. However, the *Brundtland Report* faces two major criticisms:

- i) **Unclear definition of needs.** According to the *Brundtland Report* future generations have to be able to meet their *needs*. However, what exactly these *needs* comprise is not further specified. This is especially problematic when referring to future generations, as we cannot know today what the *needs* of future generations will be.
- ii) **Unclear relationship among generations.** The distributional question on intra- and intergenerational justice is addressed but not explored further. Accordingly, the relationship between current generations and future generations is not clear.

These two ambiguous aspects of the guiding principles of SD are perceived to be major drivers for the plurality of interpretations that impedes a consistent operationalisation of SD, as critical cornerstones of the overarching objectives remain unclear: while the importance of securing the well-being of future generations is broadly acknowl-

edged, it is far from obvious whether these *needs* only entail essential needs, such as the provision of food and freshwater, or encompass broader criteria that make up a good life, such as access to political rights or protection against discrimination. Accordingly, I argue that, for my endeavour, the definition given by the *Brundtland Report* is also too ambiguous to serve as a basis for setting goals for sustainability assessments. While the *Brundtland Report* raises distributional questions, it does not answer how resources and the benefits of development should be shared among the current and future generations. Hence, I argue that sustainability assessments cannot just generally refer to the general *Brundtland* line of reasoning, but have to be further informed by a theory that can provide answers to the two questions above.

Theories of justice, which reflect a set of norms and values as guidelines for action, are able to provide rules that may consider, among other things, future generations in the process of distributing precious resources. Accordingly, to answer the question on how to distribute resources, one may have to draw on the rules of theories of justice to enrich the definition of the *Brundtland Report* with further normative features. The latter should then be sufficiently detailed to serve as a basis for defining more tangible goals for sustainability assessments. Ultimately, I argue that this endeavour can be expected to provide a more elaborate normative foundation. Today, four metrics of justice are broadly acknowledged by social scientists and are referred to in the context of SD:

- i) **Welfare.** Definition of well-being as the efficient allocation of production factors that allows the gross domestic product to be measured (Kuznets 1934).
- ii) **Primary goods.** Definition of a set of natural and social goods that human beings are thought to require to achieve well-being (Rawls 1971).
- iii) **Basic needs.** Definition of a few essential goods that comprise minimum resource requirements to maintain physical human health (ILO 1976).
- iv) **Capabilities approach.** This theory focuses on what individuals are able to do and the freedom they have in making choices (Sen 1985).

Without going into the detailed aspects of these theories of justice, my modest attempt here lies with demonstrating how the selection of a theory of justice to enrich the guiding principles affects the operationalisation of SD. An interpretation of SD that refers to the basic needs approach, for example, may reduce development objectives to the

pursuit of eliminating poverty (ILO 1976). However, even the interpretation on what constitutes basic needs varies from very restricted perspectives that consider only food, clothing and shelter to relatively more encompassing views which additionally include sanitation, education, healthcare and social participation. Nonetheless, introducing rules of the basic needs approach into an interpretation of SD can be expected to result in a society without poverty being considered sustainable. Alternatively, the capabilities approach offers a wider definition of minimum necessary conditions to be met and focuses on the provision of opportunity spaces (Sen 1985). Here, compared to the basic needs approach, additional requirements need to be met, such as offering protection against discrimination or enabling participation in political processes. The point here is obvious: the underlying theory of justice to be used for the enrichment of the guiding principles has a substantial impact on goals for sustainability assessments.

Providing a contribution to the operationalisation of well-being or arguing for the most appropriate theory of justice to be used clearly lies beyond the scope of this thesis. My aim in this section lies with merely drawing attention to the fact that the selection of the underlying theory of justice can potentially have a huge effect on the goals that are subsequently applied in sustainability assessments. Accordingly, in order to accomplish the task of this section, I will have to invest an existing interpretation of SD.

Based on recent research, I propose to enrich the definition of the guiding principles of SD as formulated in the *Brundtland Report* with rules that encompass a broader range of conditions to be met: *Sustainable development aims to achieve well-being by considering ecological frame conditions, such as productivity and the resilience of ecosystems, that are vital for future human well-being, and the potential for societal transformation* (Burger et al. 2018). I shall refer back to this normative basis in chapters 10 and 11 when formulating a set of rules and general goals for criteria in sustainability assessments of electric power systems.

In this section, I provided the normative prerequisite to formulate general goals for criteria. I shall now proceed to answer the second part of the initially formulated question by exploring appropriate approaches that facilitate the process of deriving general goals for criteria in the sustainability assessments of electric power systems based on the normative foundation presented above.

7.6 Theory for reflexive transformation governance

According to the guiding principles of SD, a development is sought that not only achieves well-being for current generations, but also preserves opportunity spaces for future generations. The *Brundtland Report* further concludes that current consumption patterns in industrialised countries are thought to erode the ecological capital (WCED 1987). Against this backdrop, scientists argue that future development in industrialised countries has to be readjusted, as business as usual is perceived to potentially obstruct future generations from achieving similar levels of well-being (Adger & Jordan 2009; Griffin 2010; Meadowcroft, Langhelle & Ruud 2014). Keeping in mind that today's key infrastructure is characterised by fragmented responsibilities and disagreements on goals, and critical system knowledge is scattered across various actors, in order for such societies to direct development, a collective organisation of work towards a common goal is required.

The subject of governance and SD is a complex one encompassing various themes, such as institutions and policy instruments. A comprehensive analysis of the latter clearly lies beyond the scope of this thesis. However, one may try to describe those aspects of governance that are relevant to enable a transition from today's systems to more sustainable states. Such a focus on governance will then serve as a basis for systematically assessing the social realm of the actors in a system under review. An evaluation of such requirements will then shed light on whether preconditions have been met to transform the system in question according to the normative features of SD. Hence, the key question to be answered on the broader subject of operationalising SD is: *What requirements for societal transformation processes are to be evaluated to determine whether a transition to a more sustainable electricity system can be made?*

This question is directed at identifying those requirements on the instrumental level that are functionally relevant when one seeks to operationalise SD by transforming a society. To answer this question, I will make two contributions: Firstly, I shall provide an overview of those features of reflexive transformation governance that are considered relevant to conduct system transitions. Secondly in section 7.7, I shall argue for an approach that allows a set of instrumental requirements to be formulated for evaluating reflexive governance of change.

In order to derive requirements for the reflexive governance of change, I shall invest two distinctive theoretical elements related to governance and the formulation of goals.

On the one hand, governance has to include those steps that are relevant for steering a system. These procedural components could be provided by a framework for the reflexive governance of change. On the other hand, instrumental rules on this transformation governance have to be formulated. Accordingly, in this section, I shall first provide an overview of the essential features of the reflexive governance of change and then argue in section 7.7 for an appropriate methodology to formulate the instrumental rules that governance has to meet. Using these theoretical investments, I will present and argue for a set of criteria in chapter 9 and instrumental rules in chapter 11. I shall compare these contributions to existing contributions in order to explore the strengths and limits of my proposed approach with regard to criteria and instrumental rules for sustainability assessments in chapter 12.

Today, there is a wide range of scientific proposals on what mode of governance is required for SD (Jordan 2008; Van Zeijl-Rozema, Cövers, Kemp & Martens 2008). However, a consensus on the most suitable mode of governance has not yet been reached. For this thesis, I shall base my contribution on the reflexive governance of change, consisting of five structural elements, to direct development in a dynamic environment.²² These five structural components are consistently mentioned in the scientific literature and reflect the current state of the scientific debate on the implementation of SD and essential features of reflexive transformation governance:

- i) **Guiding principles of SD.** A set of guiding principles is developed which expresses the overarching goals and mirrors the norms and values accepted by society. For my thesis, I shall refer to the previously provided definition of SD: *Sustainable development aims to achieve well-being by considering ecological frame conditions, such as the productivity and resilience of ecosystems vital for future human well-being, and the societal transformation potential* (Burger et al. 2018). The principles aim to guide the actors, subject to this system, in their actions (Newig, Voss & Monstadt 2008).
- ii) **Objective dimensions, steering rules and instrumental rules.** The guiding principles are translated into objective dimensions for key systems that serve critical human purposes. More tangible steering and instrumental rules are then formulated, which refer to objective dimensions and which are

²² I already provided an argumentation in section 3.2 why many scholars deem today reflexive governance as a precondition to operationalise the SD.

specific for the system in question.²³ Typical examples for such rules are '*to harvest renewable resources within the limits of their regeneration rates*' or '*to ensure participation in societal decision-making processes*'. In essence, these rules are conditions that have to be met by the system. By enriching abstract objectives into more elaborate pieces, actors can more easily facilitate the efficient organisation of their work. Furthermore, since such rules are based on the setting of common goals, actors can collectively contribute to commonly shared goals. Once the rules are met, the system meets the guiding principles (Kopfmüller et al. 2001).

- iii) **General goals for criteria.** Steering and instrumental rules pave the way to the setting of goals for criteria in sustainability assessments. This allows data on relevant system features to be evaluated against predefined goals corresponding to the guiding principles. Typical examples of general goals for criteria are: '*to prevent an increase in global temperature of more than two degrees Celsius*' or '*to eliminate the risk of catastrophic manmade accidents*'. This evaluation aims to identify gaps between the system performance and the normative objectives of SD. In democracies, potential conflicts among goals are likely to involve negotiation and deliberation (Grunwald & Rösch 2011).

- iv) **Organisational set-up and policy steering instruments.** The results of the evaluation of system data against goals are the starting point for a refinement of the organisational set-up and the deployment of new or the adaptation of existing policy steering instruments. The structural set-up ensures societal decision making, such as public voting or the formation of organised institutional actors, negotiation and deliberation, regulations and sanctions. Policy instruments are deployed to induce behavioural changes in the system, for example by granting subsidies, imposing taxes, banning specific compounds or granting rights to citizens. The ultimate goal of policy instruments is to provide incentives that, directly or indirectly, alter the activities of individuals or groups towards common objectives (Meadowcroft 2007; Newig, Voss & Monstadt 2008).

²³ I shall argue in section 7.7 in favour of applying a multi-step procedure with deductive reasoning.

-
- v) **Reflexive process.** A reflexive process is established to ensure continuous learning among actors, as well as actor-environment interdependencies, such as understanding the effects of human activities on the environment and the repercussions these have for human populations. This involves, among other things, research and development and societal learning processes, and aims to mitigate the risk of creating path dependence or technological lock-ins (Grin 2006; Stirling 2004; Voss, Bauknecht & Kemp 2006).

The cornerstones of the reflexive governance of change are broadly supported by key literature on SD, such as the *Brundtland Report* (WCED 1987). Furthermore, *Agenda 21* proposed a wide range of implementation instruments that corresponds to the proposed governance, such as monitoring system development through criteria and general goals, organisational set-up or policy steering instruments (UNCED 1992). Some implementation efforts on the part of member states are also in line with the proposed governance: In Germany, for example, a set of rules was developed to operationalise SD (EK 1998).

Figure 12 summarises the cornerstones of the proposed reflexive transformation governance, which is meant to actively facilitate a transformation of the system in question. On the left-hand side of the figure the five structural features of are shown. The middle part of the illustration summarises the key elements of each structural feature, while the right-hand side shows the applicable scope. Accordingly, this figure shows that the scope of the operationalisation of the guiding principles of SD has to encompass society as a whole. However, it also depicts that objective dimensions, steering rules, instrumental rules and general goals for criteria are likely to be system specific, if used as a basis for operationalising sustainability assessments.

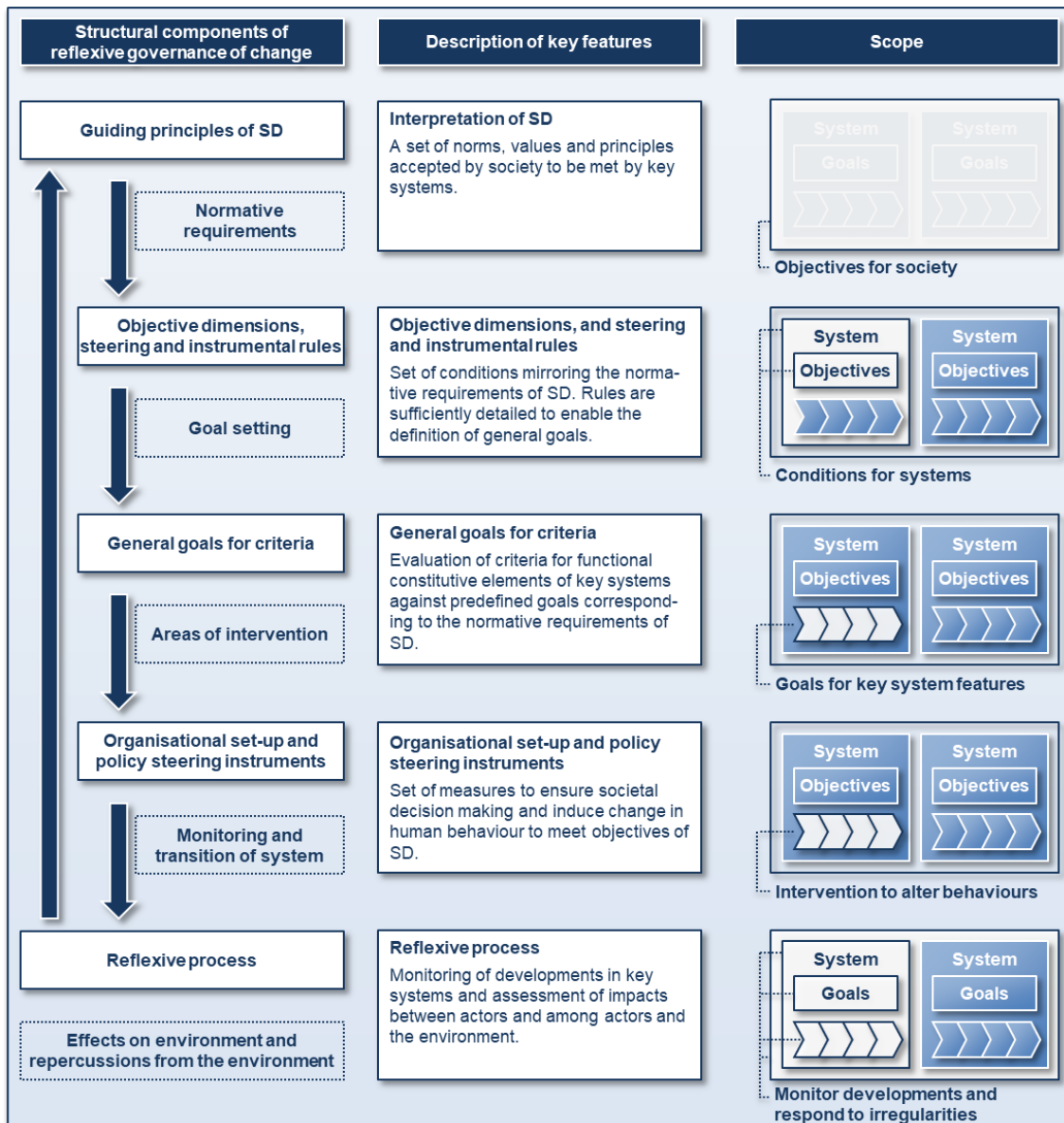


Figure 12: Structural features of reflexive transformation governance

(Own elaboration)

According to these functional components of reflexive governance of change, sustainability assessments assume a central role in extracting and evaluating data against predefined sustainability goals. These refer to the objectives of SD in order to set goals for the operationalisation and provide decision support for intervention. Hence, in order for sustainability assessments to play their part, they have to be seamlessly integrated with other structural features of reflexive governance of change. This leaves only one task still to do in this chapter: to identify an approach that supports the process of deducing general goals for criteria in sustainability assessments of electricity systems.

7.7 Theory for steering rules, instrumental rules and general goals

As argued in chapter 3, predefined sustainability goals for criteria are a necessary precondition for carrying out sustainability assessments. In order for such targets to provide a basis for *goal-oriented* decision making towards sustainability objectives, these goals have to mirror the normative features of SD. Only in this way will sustainability assessments be in a position to evaluate whether the system under review is on track to accomplishing the overarching sustainability objectives. It is a frequent complaint, though, that the guiding principles of SD is too abstract to operationalise. Accordingly, I proposed in section 7.5 to augmenting the SD definition of the *Brundtland Report*.

However, while augmenting the guiding principles of SD with further normative requirements resolved some of the issues, it still seems to be of little value in trying to derive tangible targets for criteria directly from an interpretation of SD. This is because the gap between the objectives of SD and the specific criteria pertaining to a system under review still seems to be too big. One can, however, try to break down the process of translating the normative requirements of SD into separate steps. Such an endeavour could, for example, entail first formulating the core objective dimensions reflecting the key cornerstones of SD in relation to the system under review. Subsequently, one could then try to define more detailed steering and instrumental rules for each objective dimension. While each rule addresses both a key normative notion of SD and a critical system aspect, in such an endeavour all rules together will then cover the objectives of SD and the entire system in question. Attention has to be paid that the rules define conditions that need to be met. '*Consumption of renewable resources does not exceed regeneration rates of the resource stocks*' or '*Emissions caused by electric power infrastructure lie within the boundaries of emission sink capacities*' are exemplary rules reflecting specific notions of an interpretation of SD while still relating to the electric power system. Such rules may then serve as a basis for systematically determining general goals for criteria. Applying such a multi-step procedure enables the authors of sustainability assessments to assess whether a key system meets the objective by evaluating system data against the general goals of criteria.

Such an endeavour ensures that the system under review can be evaluated against the overarching normative objectives of SD and creates transparency that may facilitate a scientific discussion on the interpretation of the normative features of SD. Furthermore, it may stimulate a discussion on appropriate methodologies to be used to formulate

more specific goals. Against this backdrop, I will strive to formulate a set of objective dimensions and steering and instrumental rules that constitute the key cornerstones of the previously introduced interpretation of SD. Moreover, I shall then strive to formulate general goals for criteria for the sustainability assessments of electric power systems. Accordingly, I seek to answer to following question in this section: *Which approach serves the process of formulating steering rules, instrumental rules and general goals for criteria based on an interpretation of SD and reflexive transformation governance?*

In order to formulate objective dimensions, steering rules, instrumental rules and general goals for criteria, I shall draw on a multi-step procedure. In order for this approach to serve my purpose, a special condition has to be met: the procedure has to consider both the normative objectives of SD and the functional aspects of electricity systems.

Conceptual deductions are today frequently applied to translate abstract requirements into more tangible targets. The integrative framework for sustainable development (IFSD) is an exemplary approach that involves relying on conceptual deductions with reasoning and was specifically developed to provide guidance on the process of translating the normative requirements of SD into a set of more specific rules. It consists of a number of structural features that may prove useful for my endeavour (Kopfmüller et al. 2001). Accordingly, I shall proceed by presenting this approach in more detail and shall thereby strongly follow the arguments of the authors of the IFSD. I will then proceed by arguing why I choose to reuse the structural elements of the IFSD approach for my endeavour. I shall present and discuss exemplary formulated objective dimensions, steering rules, instrumental rules and general goals for criteria for sustainability assessments of power systems in chapters 10 and 11. A discussion on the strengths and limits of the applied methodology will take place in chapter 12 where I shall reflect on my contribution in relation to the research sample reviewed in chapter 4.

The IFSD is a conceptual scheme that can be used to facilitate the process of translating objectives or rules or based on the guiding principles SD for complex human-nature systems (Kopfmüller et al. 2001). It has previously been applied in the context of sustainability assessments of electric power systems (Grunwald & Rösch 2011). According to the authors of the IFSD approach, in order for guiding principles to serve as a basis for operationalising the transformation of a complex coupled human-environment system, three preconditions have to be met. Firstly, the subject of the assessment has to be defined. In my particular case, the subject is the electric power system. Secondly, a clear definition of SD has to be provided. For this precondition, I shall refer to the en-

riched interpretation of SD presented in section 7.5. Thirdly, it must be possible to operationalise the guiding principles in question. Without going into a detailed discussion on whether the operationalisation of SD is feasible or not, I shall follow the authors of the IFSD approach, who assume that the operationalisation of SD is possible.

The authors of the IFSD approach point out that their methodology presents a well-founded scheme to support the process of operationalising SD (Kopfmüller et al. 2006). The IFSD approach is not structured according to the three pillars approach, but it is based on what is defined by the authors as the three normative constitutive elements of SD:

- i) **Intra- and intergenerational justice.** The level of well-being achieved by current generations should also be preserved for future generations.
- ii) **Global orientation.** Collective action among various actors is required beyond political borders towards a common goal to overcome today's complex sustainability challenges.
- iii) **Anthropocentric approach.** Current generations bear a moral responsibility to preserve the ecological capital for future generations.

Following the IFSD approach, the next step in the process to operationalise SD consists of translating the constitutive elements into generic normative objectives. According to the authors of the IFSD approach, three objectives exist:

- i) **Securing the existence of the human race.** The first objective aims to prevent the extinction of the human race. It is considered a prerequisite for any justice aspirations by the authors of this approach.
- ii) **Upholding society's productive potential.** The second objective seeks to prevent an erosion of the societal production and transformation potential to ensure that future generations will still be able to live humane lives.
- iii) **Keeping options for development and action open.** The third objective strives to maintain opportunity spaces so that future generations are not deprived of the options that today's generations are able to exercise.

Following this approach, the above objectives are translated in the next step into a set of rules reflecting the minimum necessary conditions to be met (Kopfmüller et al. 2001). Here, the IFSD approach distinguishes between substantial sustainability principles and instrumental sustainability principles. The substantial sustainability principles are directed to the question: *What should be sustained?* I shall continue by first elaborating on the translation of objectives into substantial sustainability principles. The process of reasonably deducing these rules is partly based on the framework of the planetary trust theory by Brown-Weiss (9189). *Table 5* displays the three objectives and fifteen substantial rules of sustainability as contained in the IFSD approach:

Securing the existence of the human race	Upholding society's production potential	Preserving options for development and actions
Protection of human health	Sustainable use of renewable resources	Equal access to education, information and an occupation
Securing the satisfaction of basic needs	Sustainable use of non-renewable resources	Participation in societal decision-making processes
Autonomous self-support	Sustainable use of the environment as a sink	Conservation of the cultural heritage and of cultural diversity
Just distribution of natural resources	Avoidance of unacceptable risks	Conservation of nature's cultural functions
Compensation for extreme differences in income and wealth	Sustainable development of real, human and knowledge capital	Conservation of social resources

Table 5: Normative objectives and substantial rules of sustainability

(Own elaboration based on Kopfmüller et al. 2001)

At the same time, the IFSD approach also contains a set of instrumental principles. However, these rules are directed at the question: *How should this be sustained?* This part addresses aspects of governance and system transition. The IFSD approach comes with ten instrumental principles, which describe how the substantial sustainability principles can be implemented. The instrumental principles are listed in *Table 6*:

Instrumental rules of sustainable development
Internalisation of external social and environmental costs.
Adequate discounting.
Restrictions on debt.
Fair international economic relations.
Encouragement of international cooperation.
Society's ability to respond.
Society's reflexivity.

Self-management.
Self-organisation.
Balance of power.

Table 6: Instrumental principles of sustainability

(Own elaboration based on Kopfmüller et al. 2001)

The IFSD approach does not, however, resolve conflicts. Each rule can only be satisfied in accordance with limits set by other rules. This conceptual scheme foresees that for each rule a core scope, where no weighting factors are applied, and peripheral scope, where weightings are used to partly resolve conflicts, are defined. The IFSD approach reveals conflicts in a structured way rather than seeking to resolve them. Hence, applying to the IFSD approach will not automatically result in single best solutions. Instead it supports decision making by resolving conflicts through negotiation and deliberation (Grunwald & Rösch 2011).

At this point, I shall go back to the task originally specified for this section: to choose and argue for an approach that facilitates the process of translating the objectives of SD into general goals for criteria for the sustainability assessments of electric power systems by applying a conceptual scheme. Since I am primarily looking for structural features that facilitate the translation of the guiding principles into goals, I intend to only reuse the structural features of the IFSD approach.

The strengths of the structural features of the IFSD lie in its multi-layer approach and the systematic procedural steps. As such, I deem its structural features to form a sound conceptual scheme that enables the formulation of more tangible goals for criteria in sustainability assessments. However, the reuse of the constitutive elements, objectives, substantial rules and instrumental rules seems inappropriate for my endeavour. The IFSD approach was originally developed in 2001 and the three normative constitutive elements no longer reflect the current state of the scientific debate on SD; one of the rules strives to meet basic needs. As elaborated in section 7.5, fulfilling basic needs may no longer be appropriate and a more encompassing definition of well-being is promoted by the scientific research community. A careful review of published information did not yield insights on how objectives, substantial rules and instrumental rules are derived from the guiding principles of SD. Therefore, for the time being it is unclear, for example, exactly how the five rules related to the objective '*securing the existence of the human race*' are derived and how they contribute to the corresponding objective. Nonetheless, I argue that the structural features and procedure of this conceptual

scheme can be expected to prove valuable in my endeavour to systematically formulate steering rules, instrumental rules and general goals for criteria in sustainability assessments of electric power systems. Accordingly, to fully benefit from this scheme, I shall reuse its structural features and multi-step procedure, but I shall further augment the framework to better cater to the needs of my endeavour:

- i) **Normative foundation.** The integrative framework bases its objectives and rules on the interpretation of the *Brundtland Report*, which no longer reflects the current scientific debate. Accordingly, I shall rely to the definition provided in section 7.5. I shall call this structural element the normative foundation, which is in line with the term used in chapters 5 and 6.
- ii) **Objective dimensions, steering rules and instrumental rules.** While I intend to reuse the same structural features used by the IFSD approach, consisting of objectives and rules, I am hesitant to apply the same substantial and instrumental rules due to above reason. Furthermore, I shall produce and argue for a new set of rules geared specifically to electric power systems. This is necessary because I intend to go a step further and provide general goals for criteria in sustainability assessments for electric power systems. Consequently, since I plan to derive a more detailed set of goals, I expect to have to produce a set of rules that is directed at specific sustainability challenges faced today by that system. This is in contrast to the original goal of the developers of the IFSD approach: they strived to develop a system-unspecific scheme (Kopfmüller et al. 2011). I shall first design rather abstract objective dimensions that cover the essential normative parts of SD. Based on these objective dimensions I shall define more specific rules. I shall here distinguish between steering rules, related to the question *What should be sustained?* and instrumental rules, directed at the question *How should this be sustained?*
- iii) **General goals.** While the IFSD was developed to formulate objectives and rules based on the normative requirements of SD, I require an additional step to define goals for criteria in sustainability assessments of electricity systems, as already mentioned above. In order to provide a basis for *goal-oriented* decision making, sustainability assessments also have to exhibit more specific goals. Hence, I intend to go one step further with the present-

ed schematic framework by also formulating general goals for criteria in sustainability assessments.

In this section, I explored the theoretical background related to the translation of objective dimensions, steering rules, instrumental rules and general goals from the guiding principles of SD to provide goals for criteria in sustainability assessments. I expect this endeavour to enable me to answer both questions: *What should be sustained?* and: *How should this be sustained?*

I shall proceed with providing my first deliverable specific to sustainability assessments of electric power systems: a holistic depiction of electricity systems that encompasses the relevant system components including enabling and constraining factors.

8 System representation

In this chapter I shall provide a holistic system representation that encompasses the functional constitutive elements of electric power systems by applying the approach of coupled human-environment or socio-ecological system analysis (SES). I shall argue for a classification of the system into three distinct dimensions and point out certain components that serve the essential purpose of upholding the system functionality.

Furthermore, I shall present three conceptual cases to demonstrate the relevance of considering the functional constitutive elements of power systems, including their enabling and constraining factors in sustainability assessments. Accordingly, I shall proceed with the identification of the relevant system components of power systems.

8.1 Functional constitutive components

Considering both societal steering processes and biophysical flows is one of the hallmarks of socio-ecological system analysis. This approach structures representations of complex human-environment systems into three distinct dimensions to identify relevant system components: a social layer that is home to actors of the system, a technical layer that contains artefacts which are based on natural resources and are constructed by actors in the social layer to serve human purposes and, lastly, an environmental layer that encompasses resource stocks and emissions sinks. Accordingly, based on the categorical settings of the theoretical framework discussed, electric power systems can be represented by using the following three categorical elements (Sieferle 1997; Fischer-Kowalski & Erb 2006):

- i) **Social layer.** This dimension comprises social actors and their actions in regard to societal steering including negotiation and deliberation.
- ii) **Technical layer.** This dimension contains power infrastructure components and electrical devices that alter natural energy and material flows to improve living conditions and thereby cause pollution.
- iii) **Ecological layer.** This dimension encompasses energy and material flows that provide natural living conditions.

I shall apply these categories to describe the general features of electric power systems. Such a representation aims to reveal not only the relevant features within each layer, but also the relevant interactions between the layers.

While the functional core of electric power systems is located in the technical layer, the *ecological layer* supplies the biophysical basis for the realisation of power infrastructure and electrical devices. The ecological layer can be further structured into categories of enabling and constraining factors. Firstly, the environment provides basic living conditions, such as the provision of food and adequate temperature (Cain, Bowman & Hacker 2013). Secondly, energy flows serve as a basis for power infrastructure components and electrical devices to enhance living conditions (Sassoon et al. 2009). The availability of energy fluxes and carriers determines the potential of electric power systems to improve living conditions. Thirdly, material flows provide resources to construct and operate the technical components of electric power systems (Raj, Ghandehariun, Kumar & Linwei 2016; Şengül, Bayrak, Aydınalp Köksal & Ünver 2016).

The natural occurrence of energy fluxes and carriers determines opportunity spaces and limits for the technical design and extent of the system functionality: wind velocity and solar irradiation determine the potential of wind and solar power generation (Li et al. 2016; Polo 2015). Altering material flows by erecting and operating power infrastructure as well as manufacturing electrical devices, however, is known to cause a wide range of pollution to the atmosphere, water and soil (Atilgan & Azapagic 2015; Brizmo-hun, Ramjeawon & Azapagic 2015; Duncan et al. 2013; Fearnside 2016; Hirschberg et al. 2005; Raugeri & Leccisi 2016; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Sheldon, Hadian & Zik 2015). The limited resilience of ecosystems in withstanding pollution and continuing to deliver ecosystem services is thus an important factor to consider (Bölter & Müller 2016; Hooper, Beaumont & Hattam 2017; Matthews 2016). Excessive pollution can lead to the environment no longer being able to break down such emissions, resulting in degradation of the environment and consequently living conditions (Chen, Shao, Tian, Xie & Yin 2017). Against this backdrop, it becomes obvious that ecological factors can have a deciding effect on options for realising the technical components of electricity systems. Accordingly, I argue that sustainability assessments of electric power systems have to consider those elements that have a crucial role to play in energy and material flows:

- i) **The sun and moon.** The sun emits light and heat, thus generating solar energy fluxes that serve as a key source of life on planet Earth. Moreover,

the moon and the Earth's rotation cause the tides in large bodies of water. Both solar radiation and tidal waves can serve as sources for electricity generation (Olindo, Jäger, Smets, Van Swaaij & Zeman 2016; Alcorn & O'Sullivan 2013).

- ii) **The atmosphere.** The atmosphere of planet Earth regulates temperature, creates wind currents and causes precipitation. The resulting kinetic energy fluxes are another source of electricity generation (Singh, Chelliah & Agarwal 2014; Tong 2010).
- iii) **Ecosystems.** The energy carriers and renewable resources produced by ecosystems are required to build and operate power infrastructure. Furthermore, ecosystems exhibit some level of resilience with regard to pollution and absorb pollutant emissions (Bölter & Müller 2016 or Hooper, Beaumont & Hattam 2017).
- iv) **Earth's crust and core.** Our planet produces fossil, mineral and geothermal energy sources and provides metals and minerals, all of which are today essential ingredients for power infrastructure and electrical devices and are likely to play key roles in the future (Bauer et al. 2016; Purkus & Barth 2011).

The purpose of electric power systems is to transform energy and material flows into electricity which then powers electrical devices that provide energy services to enhance living conditions. The system functionality is embedded in the components²⁴ of the *technical layer* and supports four value creation, or transformation, stages: Firstly, energy carriers are extracted,²⁵ such as coal and uranium, or accrued, such as plants for biomass power and water for hydroelectric power (Burchart-Korol, Fugiel, Czaplicka-Kolarz & Turek 2016; Mukherjee & Sovacool 2014; Woods 2016). Second, energy fluxes and carriers are converted into electricity in power plants (Grigsby 2012). Third, electricity is distributed from power stations to users' electrical devices (Gonen 2014). Fourth, electricity is consumed in electric appliances to power energy services and thereby improve living conditions (Kavousian, Rajagopal & Fischer 2013; McLoughlin, Duffy & Conlon 2012). Since a provision of energy services requires today all four

²⁴ Both the technical power infrastructure and electrical devices resemble artefacts of electric power systems that are used to serve human purposes.

²⁵ In case of renewable energy fluxes, such as solar radiation or wind, power plants are built at suitable locations. Accordingly, in such cases this transformation stage is not needed.

transformation stages, I argue that sustainability assessments of electric power systems need to consider those artefacts in which the functionality is embedded. Against this backdrop, I argue that sustainability assessments have to encompass the four stages of value creation:

- i) **Mines, wells, fields and hydro dams.** Facilities are established to extract fossil, mineral or renewable energy carriers (Burchart-Korol, Fugiel, Czaplicka-Kolarz & Turek 2016; Mukherjee & Sovacool 2014; Woods 2016).
- ii) **Power plants.** Electric power stations are erected and operated to convert energy fluxes and carriers into electricity (Grigsby 2012).
- iii) **Power grids.** Electricity grids are built and operated to distribute electricity from power stations to consumers' electrical devices (Gonen 2014).
- iv) **Electrical devices.** Appliances are used to enable a wide range of energy services, including lighting, heating, cooling, cooking, cleaning, obtaining information, enabling communication, entertainment and recreation, fuelling means of transportation and automation of processes (Baker & Rylatt 2008; Bartiaux & Gram-Hanssen 2005; Bedir, Hasselaar & Itard 2013; Kavousian, Rajagopal & Fischer 2013; Kipping & Trømborg 2015; McLoughlin, Duffy & Conlon 2012; Parker 2003; Sanquist, Orr, Shui & Bittner 2012; Van Heddeghem et al. 2014; Xydas et al. 2016).

The technical components of electric power systems are determined by the decisions and actions of actors in the *social layer*.²⁶ Here, actors negotiate and deliberate on what living conditions are to be improved and which technologies should be deployed to do so. This involves an iterative interaction process of collective action where decisions are made to promote or discard specific technical options. Firstly, actors with vital knowledge of the system exchange knowledge on energy and material flows, technical options for ways in which the ecological capital can be altered to serve human purposes, potential repercussions from the environment on human populations, such as global warming, as well as to frame conditions to promote or abandon specific options (Van de Kerkhof & Wieczorek 2005). Secondly, goals are defined and existing frame conditions are adjusted to reach these objectives (Amer & Daim 2010; Nevens & Roorda

²⁶ As mentioned in section 7.6, I shall describe the social layer according to reflexive governance of change.

2014). Thirdly, in certain types of market environment, ranging from monopolistic structures to fully competitive markets, power stations and grids are constructed and operated to ensure the delivery of electricity to customers (Stoft 2002). Fourthly, these processes are in some way reflected, discussed and influenced publicly by organised institutional actors in civil society, such as environmental agencies, sectoral associations and grassroots movements (Dryzek & Pickering 2017; Kong, Salzmann, Steger & Ionescu-Somers 2002). Against this backdrop, I argue that sustainability assessments of electric power systems have to cover those actors and their actions that actively contribute to the realisation of the technical components of electricity systems, as their decisions and actions drive the implementation of the technical system functionality:

- i) **Researchers.** Scholars analyse energy and material flows, study development options, assess the effects of frame conditions on technologies and conduct research on repercussions from the environment (Bilotta, Milner & Boyd 2014).
- ii) **Policy makers and administrations.** Parliaments and government agencies define goals and set frame conditions by deploying policy instruments and providing organisational set-ups (Dean 2010; McKee 2009).
- iii) **Market actors.** Suppliers and manufacturers develop business models based on frame conditions. Manufacturers produce electrical devices and components of power infrastructure. Suppliers operate power infrastructure and supply consumers with electricity. Market actors determine the technical design of the power infrastructure and the use of electrical devices through demand and supply in some form of electricity market (Govindan, Seuring, Zhu & Farrido Azevedo 2016).
- iv) **Civil society.** This includes organised institutional actors, such as environmental agencies, sectoral unions or the media, that monitor system developments. They are exposed to the accidents and illnesses that stem from the power infrastructure or electrical devices. Based on the interests of their supporters, environmental agencies and sectoral unions seek to influence goals and sometimes launch their own initiatives (Eichbaum 1993).

The proposed structure of the holistic system representation is still sufficiently generic to be applied to different contexts, such as different geographical regions or jurisdic-

tions. While this depiction covers the relevant components of electricity systems, critical interfaces with other key systems can also play a pivotal role. Such interfaces are typically established in any of these layers. A review of the scientific literature reveals that a number of interdependencies among electric power systems and other key systems are deemed to be very important:

- i) **Regional planning.** This strategic planning process, carried out by government institutions, determines the land areas available for key infrastructure. Declaring areas of special interest, such as in the case of national parks, can reduce the potential, or impose additional requirements such as concessions, to tap into a country's national resources. Moreover, participatory processes may be required to obtain permission from local communities (Brandoni & Polonara 2012).
- ii) **Building construction regulations.** Such rules may impose additional requirements for distributed power generation technologies: standards may ease grid accessibility, grant priority for feed-in or impose conditions that safeguard architectural aesthetics. Thus, these laws may have a deciding effect on costs or enabling synergies, for example on net metering (Anaya & Pollitt 2015).
- iii) **Water supply systems.** Clean freshwater is made available for citizens by water treatment facilities. Electricity systems can, like agriculture, cause pollution in rivers and lakes. Moreover, thermal power generation technologies require large quantities of water for cooling purposes and raise water temperature. Accordingly, the interdependencies between these two key systems are often monitored and regulated (Ackerman & Fischer 2013).
- iv) **Transportation and heating systems.** Today, most industrialised countries rely to a large extent on fossil fuels. Should the electrification of transportation and heating systems be achieved, electric power consumption can be expected to surge. Accordingly, interdependencies among electricity, transportation and heating systems and corresponding trends are very important (Mathiesen, Duić, Stadler, Rizzo & Guzović 2012).

Incorporating the interdependencies among electricity and the above-mentioned systems and processes in a holistic system representation is a highly complex task. Since

such an endeavour is beyond the scope of my thesis, I merely touch on these interfaces here. *Figure 13* depicts the proposed three-layered representation of electric power systems, which encompasses the functional constitutive elements, including enabling and constraining factors. The social layer is shown on the top and contains the four identified main actors including their key actions. The technical layer, home to the four stages of value creation, is shown in the middle and includes relevant processes. At the bottom of the figure, the environment is shown together with the relevant stages of energy and material flows.

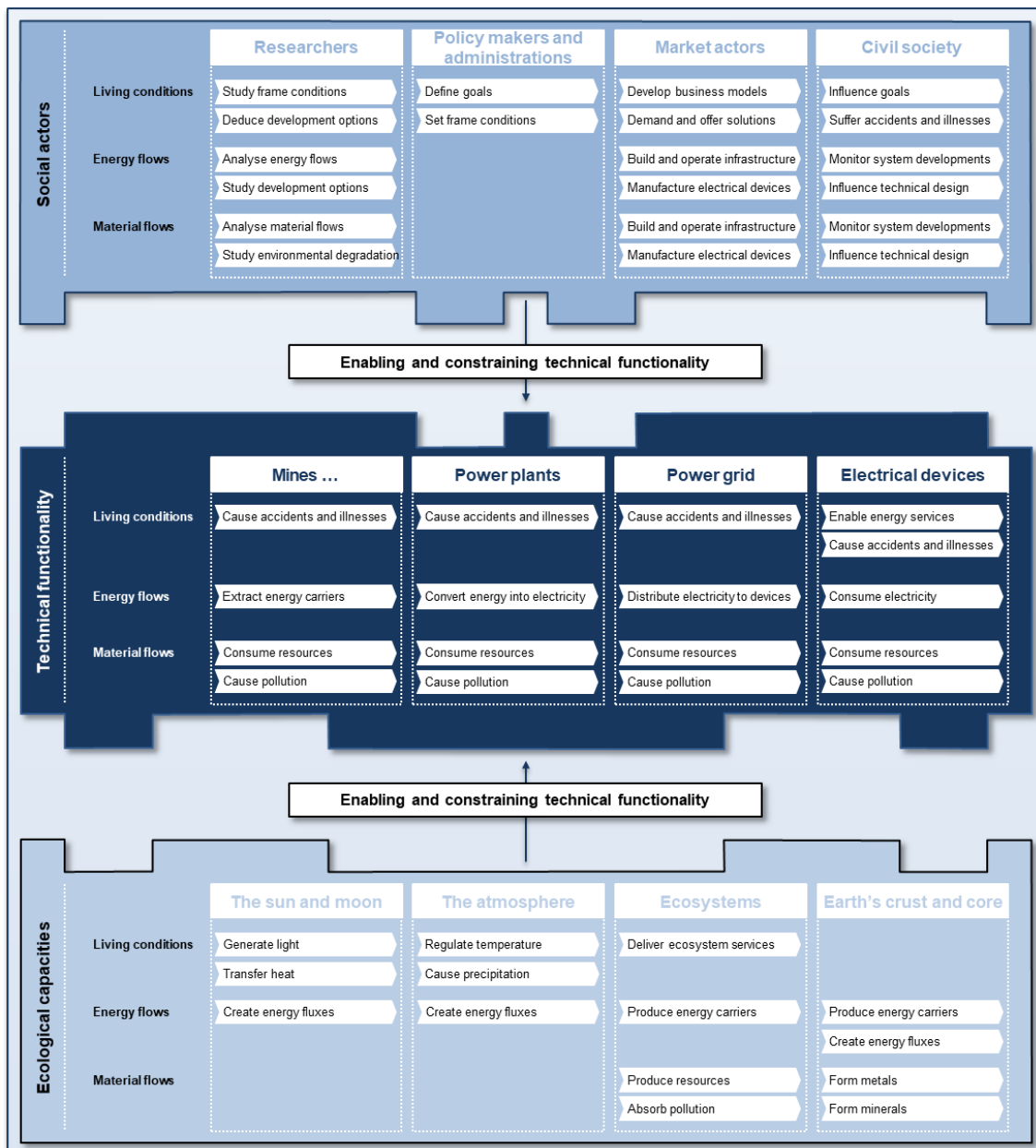


Figure 13: Holistic representation of electric power systems

(Own elaboration)

While the holistic representation of electric power systems comprises their constitutive functional elements together with their interfaces with the social and ecological environment, it does not yet adequately reflect the dynamic interactions within the layers or those that cut across the boundaries of the layers. A depiction of these aspects is a prerequisite for systematically deducing the criteria for sustainability assessments of electric power systems. A more detailed analysis of the three layers will be presented in chapter 9, when I shall examine the relevant aspects of the system in more detail.

Furthermore, in chapter 11, I will explore actor interactions and the requirements they impose on the ability to steer the transformations of such a complex system. However, my work on the subject of system representation is not yet complete here and I shall proceed by presenting three conceptual cases that further support the relevance of assuming a holistic perspective in sustainability assessments of electric power systems.

8.2 Case 1: Centralised and distributed power generation

Research and development during the past decade has led to the discovery of new distributed power generation technologies, such as solar PV systems (Olindo, Jäger, Smets, van Swaaji & Zeman 2016). However, understanding the unique benefits of distributed power generation requires new approaches for calculating electricity costs and resource consumption.

Today, a relatively small number of large conventional power plants with high capacities feed electric power into the electricity grids in most industrialised countries.²⁷ This set-up is efficient wherever large quantities of energy carriers naturally occur, such as vast deposits of coal or natural gas (Gurgul & Lach 2011). In such cases, large power plants benefit from low generation costs due to economies of scale (Hisnanick & Kymn 1999). In distributed power generation, however, small solar PV systems provide electric power on-site, which offers cost benefits for customers through net metering (Eid, Guillén, Frías Marín & Hakvoort 2014). Here, economies of scale are achieved through mass manufacturing and various synergies in installation (Nemet & Husmann 2012). Today, however, distributed power generation sometimes exhibits higher electricity costs compared to power drawn from grids. This can be attributed to, among other things, lower levels of technical efficiency and grid designs geared to cater to the needs of centralised power generation (Niemi & Lund 2010).

²⁷ Such a design of the technical power infrastructure is often referred to as centralised power generation.

However, distributed power generation bears two new value propositions: Firstly, close proximity to consumption can render some investments in power grids obsolete, especially in countries with small fragmented communities (Levin & Thomas 2012). In such cases, the costs of electricity and the attendant resource use may be lower compared to traditional power infrastructure designs in industrialised countries (Hammons 2008). Secondly, distributed power generation is installed on sites where the consumption occurs. In the case of solar PV systems, on-site installations of photovoltaic modules can lead to zero energy buildings and cost synergies, as materials for the construction of buildings such as roof tiles may not be needed, and some installation work only has to be carried out once (Shukla, Sudhakar & Baredar 2016).

For existing power suppliers that rely on proven power generation technologies, however, distributed power generation may be perceived as an unattractive investment opportunity or even as a risk for the existing business model:

- i) **Lower economic efficiency.** Today, power suppliers use a portfolio approach where the generation loads of their power plants are optimised according to wholesale market prices. Every investment in distributed generation may potentially reduce the returns of their existing portfolio, resulting in sunk costs for previous investments (Dillig, Jung & Karl 2016).
- ii) **Missing strategic fit.** Power suppliers' existing business model is based on operating an asset portfolio and they might find it difficult to reap the full benefits of diversifying into new markets, such as manufacturing or installing solar PV systems on private property (Brewer 1989).
- iii) **Conflicts with economics of power grids.** The deployment of distributed power generation alters the demands made on power grids and may require investment in other technical components, such as transformers (Del Rio & Unruh 2007). This may complicate the grid planning process.

Against this backdrop, monopolists may lack incentives to promote decentralised power generation technologies so long as new market entries are not possible. Accordingly, some scholars advocate changes in energy policy to promote the deployment of decentralised power generation technologies (Wolfe 2008).

Sustainability assessments that focus on an evaluation of power generation technologies without differentiating between centralised and distributed power generation are likely to ignore the two new distinct value propositions that distributed power generation technologies have to offer. Consequently, their technological analysis will yield incorrect data on electricity costs and resource use, thus penalising distributed power generation technologies and potentially erroneously informing decision makers.

Figure 14 compares the design of centralised power generation with distributed power generation. On the left-hand side a monopolistic market environment is shown where power suppliers are in full control of the decision on what technologies to deploy. In contrast, the right-hand side of the illustration shows a competitive market environment where power grids are fed with electricity from a variety of power plant owners. In this case, grid operators need to respond to the excess electricity produced by distributed generation.

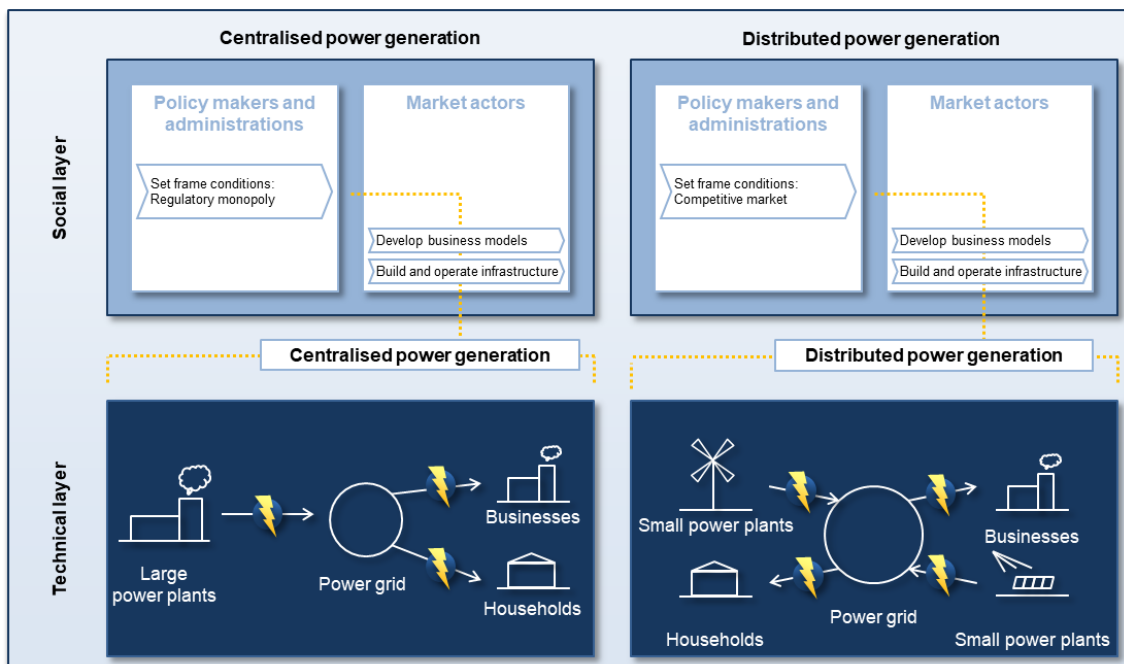


Figure 14: Centralised versus distributed power generation

(Own elaboration)

This conceptual case supports previous arguments in favour of a holistic representation as a basis for sustainability assessments of electric power systems. It emphasises that system components should not be assessed on an individual basis:

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- i) **Need for a differentiated approach for technologies.** Sustainability assessments that do not distinguish between applications of technologies as part of centralised or distributed power generation may only partly be able to identify the strengths and weaknesses of the applied technologies. The value proposition offered by a solar PV system, for example, is different depending on whether it is part of a centralised power generation design or deployed as a distributed generation technology.
 - ii) **Interdependency among technical components.** Distributed power generation, such as solar PV systems, may reduce costs and resource requirements of power grids. Hence, the overall performance of power grid components needs to be assessed in accordance with the power generation technologies in use.
 - iii) **Interdependency among the components of different layers.** Frame conditions imposed by policy makers may promote or hinder the implementation of distributed power generation technologies, as existing power suppliers may lack incentives to reinvent their business model. Accordingly, societal steering processes should determine the technologies to be deployed.

8.3 Case 2: Supply and demand management

A transition to electric power systems largely based on renewable energy, for example to meet climate change targets, is likely to require greater contributions of wind and solar PV power (Pleißmann & Blechinger 2017). The impact of such a transition, however, is expected to be greater than a mere replacement of power generation technologies due to the properties of erratic energy fluxes which result in significantly higher volatility in power generation loads (Bussar et al. 2016).

While energy carriers can be stored and spent whenever needed, the natural occurrence of energy fluxes is more stochastic and forecasting methods are only partly accurate (Prema & Rao 2015). Traditionally, electricity systems in industrialised countries relied on power plant technologies that are fuelled by energy carriers. In such cases, the concept of supply management was applied: power plants are operated according to electricity demand. Whenever demand rises, additional energy carriers are spent to increase power generation (Stoft 2002). Since power generation loads are predictable, the power grid can be built according to generation capacity, resulting in an efficient

use of power grids (Singh, Willi, Chokani & Abhari 2014). This mode of operation is convenient for consumers, as there are no restrictions on electricity consumption.

However, whenever a power generation mix is based mainly on renewable energy fluxes, new improved information and communications technologies enabling active power flow management and energy storage may be required (Jenkins, Long & Wu 2015).²⁸ Implementing demand-side management, however, is likely to bring about significant changes for consumers,²⁹ as electrical devices are operated in accordance with electricity generation (Strbac 2008). Accordingly, the system operator may have to resort to lowering electricity consumption whenever production falters as a result of, for example, changing weather patterns (Moura & De Almeida 2010). In such cases, owing to the erratic nature of energy fluxes, power grids may have to exhibit higher reserve margins to be able to cope with more substantial shifts in electricity generation (Torriti, Hassan & Leach 2010). This may require additional storage and back-up capacity or further investment in other power grid components (Oberschmidt, Klobasa & Genoese 2013). However, such investments may increase the costs or resource requirements of power grids (Jülch 2016). Accordingly, isolated assessments of wind farms, for example, can be expected to only partly attribute adverse effects of erratic wind-based power generation on resource requirements or the costs of power grids (Georgilakis 2008). Moreover, demand-side management imposes restrictions on the use of some electrical devices and therefore often faces barriers in implementation (Laicane, Blumberga, Blumberga & Rosa 2015). Nonetheless, the concept of demand-side management is today being selectively applied by large industrial consumers in exchange for financial incentives (Lindberg, Zahedian, Solgi & Lindkvist 2014).

Against this backdrop, some scholars expect a transition from supply management-based electricity systems to ones with substantial shares of demand-side management to require changes in policy (Luickx, Delarue & D'haeseleer 2010). While the merit order of power plants in supply management is traditionally determined by the system operator according to economic criteria (Stoft 2002), demand-side management is thought to need to be based on a broader range of criteria. Accordingly, policy makers may have to define procedures, data security standards and priority orders for shutting

²⁸ Owing to the physical properties of electricity, supply and demand have to match to maintain stable power grid frequencies and prevent blackouts. Storage systems, which are becoming more competitive, can help balance demand and supply (Jülch 2016).

²⁹ Demand-side management imposes fewer restrictions on consumers if an energy storage or electric vehicle is part of the system (Khoury, Mbayed, Salloum & Monmasson 2016; Mesarić & Krajcar 2015).

down electrical devices (Didden & D'haeseleer 2003). Such a framework may be required to prevent that essential energy services are denied to low income consumers with constrained budgets.

Against this backdrop, I argue that sustainability assessments that focus exclusively on the technical components of the electric power systems may overlook other effects on consumers' opportunities to obtain energy services. An imprudent implementation of technologies like demand-side management could potentially severely impede low-income households in their struggle to achieve well-being. While a largely renewable energy system certainly improves the ecological sustainability of power systems, if some actors are no longer able to meet rather basic needs it would be questionable whether such an electric power system supply is consistent with the principles of SD.

Figure 15 compares the technical options for altering energy flows in supply-side management with those available in demand-side management. On the left-hand side, the traditional approach is shown, where power suppliers adjust power generation according to consumption loads. On the right-hand side, a demand management-oriented design is shown, where system operators operate consumers' electrical devices. The upper part of the illustration suggests that evaluation criteria are likely to have to be more holistic whenever demand-side management is applied.

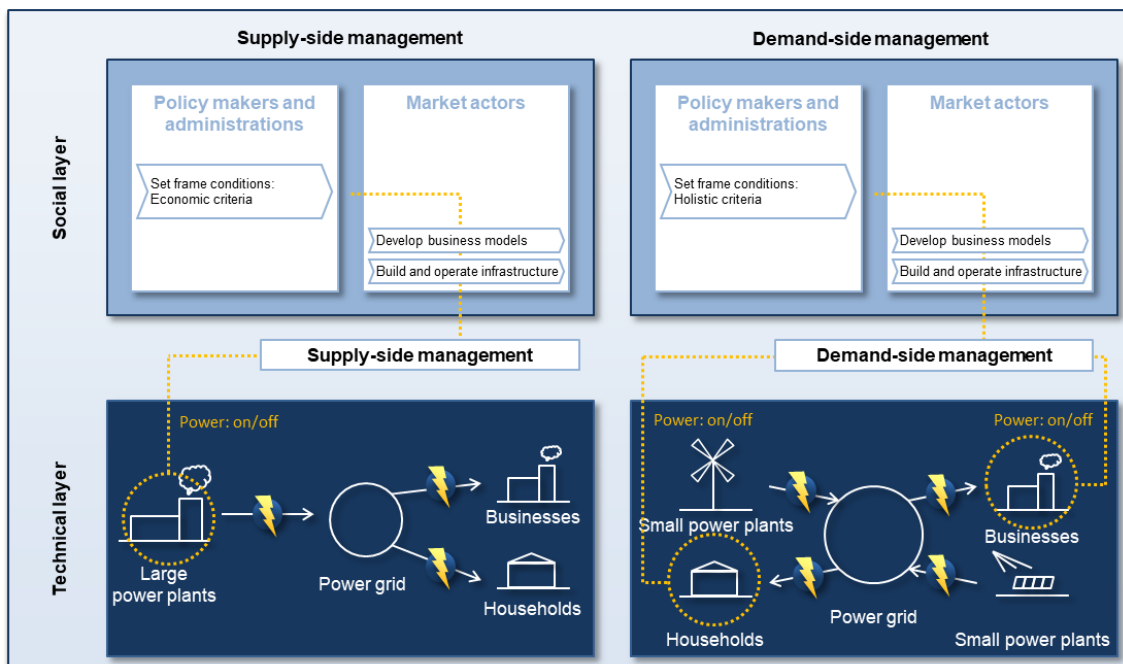


Figure 15: Supply versus demand-side management

(Own elaboration)

This second case further reinforces previous arguments in favour of considering all stages of value creation in sustainability assessments of electric power systems. Moreover, it highlights once more the relevance of covering aspects related to governance:

- i) **Interdependency among technical components.** An exploration of energy fluxes or carriers determines resource use and the costs of both power generation and power grid technologies.
- ii) **Interdependency among the components of different layers.** Today, the merit order of power plants is determined according to price signals obtained from wholesale electricity markets. However, this market design may no longer be fully appropriate when, for the process of matching supply and demand, when electrical devices are operated instead. Thoughtless implementations of demand-side management could potentially result in some consumers being unable to meet essential needs. Hence, sustainability assessments that exclude actors and their actions may not be in a position to evaluate whether the normative requirements of SD are fully met.

8.4 Case 3: Monopoly and competitive markets

During the past decade, research and development has led to the discovery of new renewable energy and smart grid technologies (Jülch 2016; Olindo, Jäger, Smets, Van Swaaij & Zeman 2016; Strbac 2008). Some of these technologies are a departure from the responsibilities assumed by existing suppliers in monopolies. Accordingly, some scholars argue that in order to fully benefit from the value proposition of new technologies, electricity markets may have to be liberalised to grant market access to the manufacturers and suppliers of new solutions (Jamassb & Pollitt 2011; Taniguchi 2013).

Historically, the operators of power infrastructure components were state-owned and their asset portfolio comprised a number of power plant assets with a fixed customer base. Against this backdrop, recent research studies suggest that regulatory barriers may exist for incumbents to explore new development paths (Vallés, Reneses, Cossent & Frías 2016). They argue that power suppliers may potentially neglect to utilise the opportunities offered by distributed power generation or energy efficiency (Pollitt 2012). Moreover, the deployment of new technologies is further hampered by the market dominance of incumbents and to a lesser degree by the financial constraints of power suppliers (Costa-Campi, Duch-Brown & García-Quevedo 2014). Furthermore, scientific ev-

idence suggests that consumers' limited knowledge of technologies and their benefits slows down the diffusion of new technologies (Sovacool 2009). Against this backdrop, some researchers conclude that changes in policies might be required to enable and accelerate market penetration of new distributed generation power, smart grid and energy efficiency technologies.

More specifically, in order to exploit the potential of such new technologies, some researchers perceive breaking existing power supply monopolies for new market actors to be necessary (Szabó & Jäger-Waldau 2008). While this view is controversial, it is the current approach of the European Union (Green 2006). However, in order for policy makers to retain influence over the development of electricity generation mixes and reduce societal risks in free market environments, market liberalisation is thought to have to be complemented by a set of policy instruments that steer the development of electric power infrastructures (Lund 2009; Ringel 2003). Furthermore, resource constrained environments are increasingly calling for measures to conserve electric power. Similarly, in order to influence power consumption patterns, a set of distinct policy instruments may be required to promote efficient or penalise wasteful electrical devices and consumption behaviours. Prominent examples of such measures are standards, information campaigns and the banning of wasteful technologies (Weil, Egan & Delta Cava 2006). Against this backdrop, some researchers argue that a successful deployment of new technologies in electric power systems requires more than just market liberalisation: the latter may have to be accompanied by a comprehensive set of additional policies to not only increase market efficiency, but also promote a transition to more sustainable electricity systems (Erdogdu 2013).

Accordingly, I argue that sustainability assessments that neglect the instrumental aspects of SD are likely to lack indicators assessing whether the actors in a system are working on measures to meet transition trajectories. Assuming that sustainability assessments are designed to direct development, then such a crucial omission is likely to impede the process of providing a basis for *goal-oriented* decision support.

Figure 16 compares typical steering mechanisms of policy makers in regulatory monopolies with those perceived to be required to steer developments in competitive markets. The left-hand side of the diagram depicts the direct influence government institutions may have in monopolies through the definition of corporate goals, as representatives are positioned in key decision bodies. The right-hand side of the figure shows that in competitive markets development is more likely to be steered by means of a dedi-

cated set of policy instruments that provide incentives for suppliers to alter their solutions portfolio. Furthermore, in competitive markets, suppliers might be under more pressure to adapt the solutions they offer as competitors may steal profitable customers.

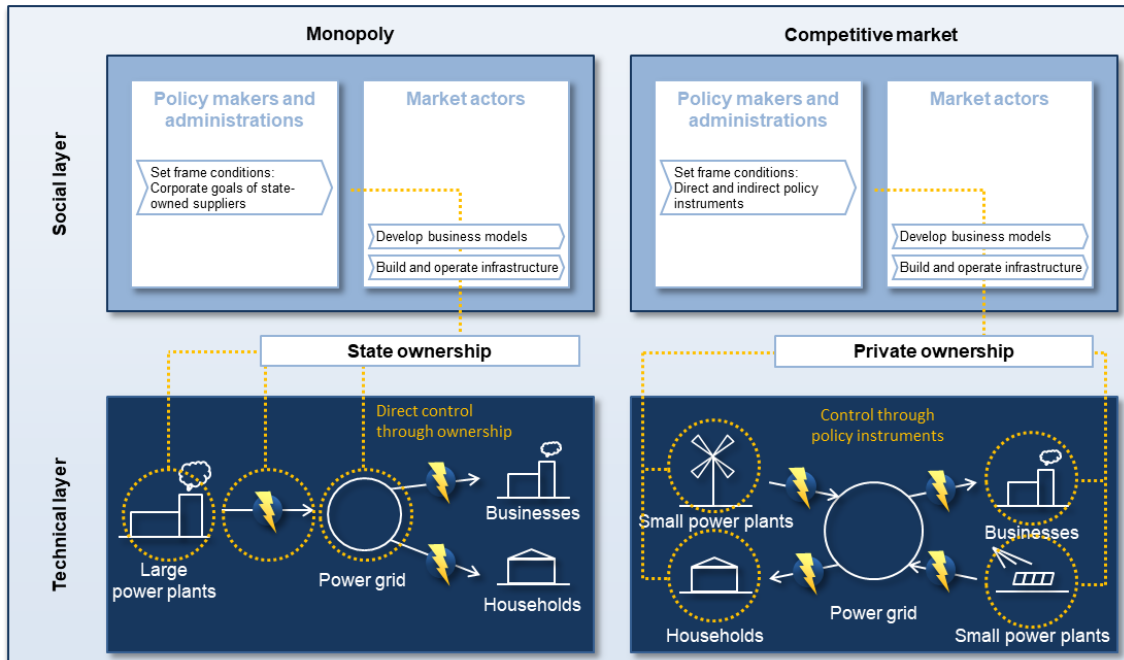


Figure 16: Monopoly versus competitive market

(Own elaboration)

The third case further emphasises the relevance of the instrumental notions of SD, namely, those features that are directed at operationalising system transitions to more sustainable states. This case thereby reinforces previous arguments by considering those features of governance in sustainability assessments as well. Furthermore, this case demonstrates the relevance of dynamic interactions between layers: policy instruments serve as enabling or constraining factors for new technologies. They can create opportunity spaces for new actors and put pressure on incumbents that do not actively contribute to the transformation of electric power systems according to predefined sustainability objectives.

8.5 Conclusions

In this chapter, I framed a holistic definition for sustainability assessments that encompasses the functional constitutive elements of electric power systems including relevant enabling and constraining factors. Based on the theoretical foundation of socio-

ecological system analysis, I propose an exemplary representation of electric power systems for sustainability assessments that incorporates actors in the social realm, the functionality of technical components, as well as the ecological capacity of the environment. Moreover, I analysed crucial interdependencies within the system.

The three conceptual case studies reinforce my arguments that isolated analyses of technical components, such as evaluations of comparative power generation technology, yield potentially misleading data owing to the omission of other critical aspects of the system and the dynamic interactions. However, I claim neither that the current focus in assessment schemes on power generation technologies has not substantially contributed to understanding the impacts of different choices nor that all identified components have to be considered in a system representation. I am fully aware of limitations in the number of components to be considered in system modelling as well as the constraints stemming from a lack of data. Nonetheless, if we are really striving for sustainability assessments that provide a more comprehensive basis for *evidence-based* decision making on the long-term development of electric power systems, then I argue for a more holistic system scope to reduce the risk of omitting relevant aspects of the system.

The analysis of the scope applied in today's sustainability assessments of electric power systems in chapter 4 revealed that electric power systems are today frequently reduced to being just a part of the system, such as power generation technologies. My contribution, however, aims to widen the scope of sustainability assessments of electric power systems by proposing an approach that encompasses also other relevant system components across all value creation or transformation stages, including enabling and constraining factors related to societal actors and ecological capacities.

However, while an aggregated system representation is a compulsory ingredient for sustainability assessments, it requires a more detailed analysis of the system as a basis to determine criteria that measure the performance of system components. Furthermore, additional normative features of the guiding principles of SD are required in order to evaluate extracted system data against goals reflecting the normative requirements of SD. This layout of as-yet missing basic features of sustainability assessments shows that I am still at an early stage of my thesis: I have not yet contributed to these tasks in this chapter as they represent conceptually distinct endeavours.

Accordingly, I shall proceed by providing the second power system-specific deliverable of this thesis: the systematic deduction of an exemplary set of criteria for electric power systems based on the holistic system representation produced in this chapter.

9 Criteria

The goal of this chapter is to systematically derive criteria for sustainability assessments of electric power systems based on the scope of the holistic system representation presented in chapter 8 and a detailed analysis of electricity systems. To accomplish this task, I shall draw on the theoretical background related to energy and material flow analysis for the biophysical aspects of the system. For the realm of social actors, I shall revert to theory on socio-ecological regimes. I shall thereby describe the essential stages of energy, material and information flows in electricity systems and systematically deduce criteria for sustainability assessments of electric power systems.

I shall start my contribution on the subject of criteria for sustainability assessments of electric power systems by elaborating on why I shall gear the contribution of this chapter to the output of the system: the guiding principles of SD strive to secure human development without eroding the ecological capital (WCDE 1987). Against this backdrop, I argue that considering the output of the system in sustainability assessments is a necessary precondition for evaluating improvements in human well-being and enabling the manufacture of goods and services. In contrast, if I were to base criteria for sustainability assessments on specific system components, such as power plants, I would no longer be able to draw conclusions on how changes in technologies affect the output of the system under review. The replacement of coal-based power plants with hydroelectric power generation is likely to reduce global warming, but can also be expected to increase distortions in aquatic ecosystems. However, to what extent this substitution of power generation technology affects the provision of lighting in households, for example, remains unclear as the output of the electric power system is not considered within the scope of such a comparative technology assessment. Hence, by defining criteria related to energy services, I argue that I am in a better position to capture changes in human well-being or the provision of goods and services.

Accordingly, I shall start the endeavour of this chapter by providing an overview of essential outputs provided by electric power systems today, often referred to as energy services, including the corresponding electrical devices which are required to enable the output. My undertaking here will inevitably involve providing dedicated criteria for each energy service due to the wide range of outputs provided today by modern power infrastructure and electrical devices and the essential part they play. In subsequent sections, I shall define criteria for energy and material flows as well as societal steering processes to enable assessments of the environmental burden caused by the technical

components and how societal development is steered. I expect this list of criteria to pave the way for sustainability assessments to evaluate the delivery of energy services against energy consumption, resource requirements and societal steering aspects.

9.1 Energy services

As previously explained, electric power systems have two core functions: they improve human well-being and support the process of providing goods and services. Accordingly, I argued previously that sustainability assessments have to analyse the relevant stages of energy and material flows of those system components that are responsible for ensuring this output. Furthermore, I argued that such undertakings also have to include factors enabling or constraining core system functionality, such as policy steering instruments or the natural occurrence of energy fluxes. Moreover, to capture relevant energy and resource requirements holistically, sustainability assessments have to consider upstream and downstream processes. Against this backdrop, it becomes obvious that I have to base my analyses on the output of these systems: If I first identify the key outputs, namely energy services, of electric power systems, then I can focus on downstream processes. Accordingly, I shall proceed by providing a summary of the energy services provided by electric power systems.

Based on the holistic system representation provided in chapter 8, electric power systems supply a wide range of energy services. These services are delivered by electrical devices operated by private households, public institutions and businesses. My first challenge here lies with identifying those energy services that improve human well-being or are key prerequisites for the provision of goods and services. One way to tackle this challenge is to review recent research on electricity consumption. The underlying assumption here is that by considering those electrical devices that account for the vast majority of electricity consumption, I can ensure that the most frequently consumed energy services are considered.³⁰ Accordingly, to do this, I shall draw on scientific studies related to electricity consumption: the pursuit of higher levels of energy efficiency has resulted in a vast number of insightful research studies on the subject of electricity consumption and related behaviours (Farinaccio & Zmeureanu 1999; Larsen & Nesbakken 2004). These studies strive to determine the drivers of electricity consumption and areas of intervention to induce more energy efficient behaviours (Ahmadi-Karvigh, Becerik-Gerber & Soibelman 2016; Jones, Fuertes & Lomas 2015). Since these stud-

³⁰ This approach assumes that those energy services that account for the majority of electricity consumption are also the most relevant.

ies discuss electricity end-uses and electrical devices in use, there is good reason to believe that such contributions are likely to provide a sound basis for a comprehensive overview of relevant energy services for private households. Once the relevant services are identified, I shall complement them with units of measurements to subsequently enable an evaluation of the service delivery in sustainability assessments. My goal here lies in measuring the output of the energy service rather than electricity consumption so as to relate it to potential benefits for consumers. I shall proceed by listing those energy services that are frequently consumed and are deemed relevant according to current research:

- i) **Lighting.** The technology for generating light serves the purpose of illuminating dark areas. For example, it can prolong activities into the night hours and allow people to access to the darker regions devoid of solar irradiation, such as mines. Furthermore, lighting technology plays a major role in modern information technology devices, such as computers and smart phones, to display information and enable communication. This energy service is provided by among other things, light bulbs and modern information technology devices and its output is often measured in lumen or lux (Bedir, Haselaar & Itard 2013).
- ii) **Heating.** To create suitable living conditions for human beings in colder environments, artificial heating is often required. In pre-modern times, campfires often served this purpose. Today, fossil fuel- or biomass-based heating systems are generally used. Some of the devices used to heat dwellings and offices, such as radiators and heat pumps, are powered by electricity (Kipping & Trømborg 2015). I include other devices used that generate heat, such as stoves and ovens, in this category since these appliances also serve the purpose of increasing temperature. To measure this energy service, I shall revert to a metric that captures increases in temperature.
- iii) **Cooling.** In warm climates, electrical cooling devices, such as air conditioning systems, ensure that temperatures in dwellings, workplaces and vehicles stay within conformable limits for human beings thus safeguarding human health (Kavousian, Rajagopal & Fischer 2013). For this thesis, I also include other devices used for cooling purposes in this category, such as refrigerators and deep freezes used to decelerate deterioration processes in

food and preserve the effectiveness of medicine. To measure this energy service, I revert to quantifying decreases in temperature.

- iv) **Cooking.** The preparation of some meals requires additional household devices, including electrical appliances such as blenders or grinders (McLoughlin, Duffy & Conlon 2012). Since this energy service focuses on the preparation of food, I shall apply a metric that captures the amount of nutritional energy value provided.
- v) **Cleaning.** Cleaning appliances are generally used to prevent infestations of vermin or illnesses caused by deteriorating organic matter. Today, homes are often equipped with various electric cleaning tools, such as washing machines, dishwashers or vacuum cleaners (Bartiaux & Gram-Hanssen 2005). Since this energy service aims to reduce pollution and safeguard human health, I propose to measure reductions in pollution.
- vi) **Information.** To obtain information on societal developments or personal matters, people often rely on modern information and communication devices, such as computers, televisions or smart phones. These devices provide information for decision making, entertainment or simply satisfy curiosity (Van Heddeghem et al. 2014). I propose to assess this energy service by quantifying the amount of data obtained.
- vii) **Communication.** The broad deployment of the internet, communication infrastructure and modern information technology devices enables interactive communication across vast distances. The resulting services, such as internet chats and social media profiles, have today become key tools for fostering contacts (Baker & Rylatt 2008). To measure the output of this service, I shall capture units of data exchanged.
- viii) **Entertainment.** Today, many people enjoy consuming various forms of entertainment broadcast via the internet, television channels, smart phones or radio frequencies (Sanquist, Orr, Shui & Bittner 2012). For this energy service I shall also measure data consumed.
- ix) **Recreation.** Leisure appliances, such as saunas and pumps for swimming pools, support the private recreation activities of the wealthier consumer

(Parker 2003). This energy service is often consumed by only a fraction of the human population and is not available to the public. For this energy service, I propose to measure hours spent as a unit of measurement.

- x) **Fuelling of mobility.** Today, various electric mobility technologies exist, such as trains and cars, and in some countries policies are in force to promote the deployment of such technologies (Lieven 2015). The purpose of this growing energy service is to enable the transport of people or goods to specific destinations³¹ (Xydas et al. 2016). Accordingly, I propose a unit of measurement related to distance covered.

This list of energy services covers those outputs related to the electricity systems function of improving human well-being according to recent research. It does not, however, yet contain services related to the second function of electric power systems. Accordingly, I shall proceed by looking into the second function of electricity systems, namely, to support enterprises and public institutions in providing goods and services.

Providing a comprehensive list of energy services related to this category proves to be yet another challenge: Past decades have brought about increasing levels of sectoral and functional specialisation in various industries (Duranton & Puga 2005). This development has fuelled the demand for distinctive electrical tools geared specifically to individual entrepreneurial needs. Accordingly, today commercial and institutional actors consume a wide range of very specific energy services. Providing an exhaustive list of these custom-made services clearly lies beyond the scope of this thesis as it would be a distinct research endeavour on its own. There is, however, another way to consider the second function of electric power systems: enterprises and public institutions consume energy and resources to manufacture goods and services. These outputs are later used by consumers in the above-mentioned energy services. Accordingly, I shall look for a methodology that measures energy and resource when consumers use their electrical devices.

In order to consider the energy and resources used to manufacture and provide goods and services during end-use stages, methods related to input-output or embodied energy analysis are often used (Brown & Herendeen 1996). For example, the resources required to manufacture a heat pump are then considered when assessing the re-

³¹ I shall also consider elevators and conveyor belts under this category as they serve the same purpose, namely, to transport people or goods.

source requirements of the energy service of heating. However, there are also known shortcomings to this method: some services, such as public lighting of monuments, are not likely to be captured by input-output or embodied energy analysis. To deal with such exceptions, I shall introduce a generic energy service covering those processes for manufacturing and providing goods and services that are not covered by input-output or embodied energy analysis.³² As for the unit of measurement, I shall apply a generic metric to capture the output provided by the corresponding process. Against this backdrop, *Table 7* lists the above-mentioned energy services including examples of electrical devices frequently used to deliver the corresponding output, including the generic energy service related to the provision of goods and services.

Energy service	Examples of electrical devices
Lighting	Lamps, light bulbs, computers, smart phones
Heating	Heating systems, stoves, ovens
Cooling	Air conditioning systems, refrigerators, deep freezes
Cooking	Blenders, grinders
Cleaning	Washing machines, dish washers, dryers, vacuum cleaners
Information	Computers, television, smart phones
Communication	Computers, television, smart phones
Entertainment	Internet, television, smart phones, radios
Recreation	Saunas, pumps for swimming pools
Fuelling of mobility	Trains, private cars, elevators, conveyor belts
Manufacturing of goods and services	Public lighting

Table 7: Overview of energy services and electrical devices

(Own elaboration)

Based on this overview of energy services, I am now in a position to deduce a first set of criteria for sustainability assessments of electric power systems. These criteria refer to the development aspect of SD by assessing the output of electric power systems. When assessed on an isolated basis, I expect those systems that succeed in supplying a wide range of often consumed energy services to their actors to score high. However, the attainment of these criteria does not yield information on whether a productive natural environment is preserved for future generations nor does it show how societal actors determine the delivery of those energy services.

³² Creating a list of those exceptions can be expected to result in a huge list of services, each of which contributes very little to the overall picture. Due to the limited impact of these services, I shall refrain from drawing up such a detailed list.

Accordingly, based on this overview of energy services, I shall formulate a criterion for each energy service, including exemplary units of measurement, so that each criterion measures the delivery of the corresponding energy service. Thus, *Table 8* displays the proposed criteria for energy services to evaluate the development aspects of the guiding principles of SD in sustainability assessments of electric power systems.

Id	Criteria for energy services	Exemplary unit of measurement
ES01	Provision of lighting	Lumen or Lux
ES02	Provision of heating	Degrees Celsius or Fahrenheit
ES03	Provision of cooling	Degrees Celsius or Fahrenheit
ES04	Provision of cooking	Calories
ES05	Provision of cleaning	Pollution
ES06	Provision of information	Unit of data
ES07	Provision of communication	Unit of data
ES08	Provision of entertainment	Unit of data
ES09	Provision of recreation	Hours
ES10	Provision of fuelling for mobility	Kilometres or miles
ES11	Provision of production of goods and services	Unit of output

Table 8: Criteria for energy services for electric power systems

(Own elaboration)

This overview also frames the scope for my next task related to analysing relevant energy flows and compiling a corresponding set of criteria. The list of criteria for energy services is the starting point for my next endeavour; that is, to systematically identify the relevant stages of energy flows, which are to be evaluated in sustainability assessments of electric power systems, and deduce a set of criteria.

9.2 Energy flows

As the first methodological step, I shall define system boundaries to analyse the energy flows in electric power systems: by drawing on the holistic system representation developed in the previous chapter, it becomes evident that my analysis has to cover energy flows from their origination, that is, the natural occurrence of energy fluxes and carriers, to the stage where electricity is used in electrical devices to provide energy services.

To carry out the analysis, I shall select a robust methodology that can live up to the task of describing complex energy flows in electric power systems. While a wide range of proven methods for the analysis of energy flows exists, I shall revert to Sankey diagrams for this task. This method is specifically designed for complex analysis of holistic energy systems and has, thus, been successfully applied previously in similar contexts. The method foresees describing and depicting the relevant stages of energy or electricity flows. Moreover, the quantities of energy or electricity that pass each stage are recorded (Soundararajan, Ho & Su 2014; Subramanyam, Paramshivan, Kumar & Mondal 2015). This method also accounts for the first law of thermodynamics: whenever energy is converted into another form, some of it is given off as heat. Hence, after each conversion stage, the quantity of available energy or electricity is reduced by the amount of conversion losses (Kittel & Kroemer 1980). Accordingly, one of the hallmarks of Sankey diagrams is to measure each conversion stage and therefore also quantify how much energy or electricity is passed on to the next stage.

However, prior tackling the task of depicting the relevant stages of energy flows in electric power systems, I shall first elaborate on the sources of energy fluxes and carriers in electric power systems. I shall then proceed to systematically describe the stages of energy or electricity flows until they are eventually consumed in electrical devices to provide energy services. According to current research, there are three main sources of energy on Earth:

- i) **The sun.** Life on Earth depends directly or indirectly on the sun as a key source of energy flux: solar irradiation provides light and heat to our planet and thus also has a strong influence on the weather and drives plant growth (Carlowicz & Hill 2006).
- ii) **Earth's crust and core.** The decay of natural radioactive elements in the interior of our planet creates heat. This heat sometimes naturally surfaces in the form of volcanoes or geysers (Turcotte & Schubert 2002).
- iii) **The sun and the moon.** The gravitational pull exerted by the sun, the moon and the rotation of the Earth create tidal waves. These waves exhibit kinetic energy (Talley 2011).

Since the sun is the most dominant source of energy fluxes on Earth, I shall proceed by first describing energy flows emanating from the sun before moving on to the other two

sources. I therefore revert to a sophisticated analysis conducted by Stanford University on exergy and carbon flows in natural and human systems to describe the stages (Sassoon et al. 2009).

While some of the incoming solar irradiation is redirected as a result of atmospheric reflection, the majority of solar energy is kept within the Earth's system. Some of it can even directly be used as solar energy to generate electricity in photovoltaic cells or heat in solar thermal power systems. Moreover, the sun heats the natural surfaces of land and water bodies at different speeds. The resulting difference in temperatures among natural surfaces gives rise to wind currents. These currents may also be exploited to generate electricity in wind farms. In parallel, clouds form and the precipitation that results creates and feeds into rivers and lakes. Moving water masses in rivers result in kinetic energy which enables hydroelectric power. Furthermore, solar irradiation also enters ecosystems and is partially absorbed by plants through photosynthetic processes. Some of these plants can then themselves be used as energy carriers in biomass-based power plants to generate electricity or produce biofuels. A portion of solar energy heats the planet's surface and some is lost as a result of surface reflection. This radiation-based, chemical and kinetic energy flow is the biggest source of energy fluxes for electric power systems on the planet (Sassoon et al. 2009).

There is also, however, a thermal energy flow that emanates from the Earth's crust and core. The interior structure of Earth can be separated into different layers: The lower layers encompass parts of our planet that are substantially hotter than the outer crust. Processes related to the natural decay of radioactive elements are key contributors to heat generation in lower layers. This heat can be directly exploited in geothermal power plants to generate electricity. Our planet's crust and core is also home to natural deposits of mineral and fossil fuels. While uranium naturally occurs in the Earth's crust and core, fossil fuels are formed through the decomposition processes that occur in dead organic matter under anoxic conditions. These processes form fossil fuels and take up to hundreds of millions of years. Today, mineral and fossil fuels are two types of energy carriers frequently used on planet Earth to generate electricity. However, to make these available to human populations, mining facilities are required (Sassoon et al. 2009).

There is also a gravitational energy flow on planet Earth. The sun, the moon and the rotation of our planet exert gravitational forces. These forces result in rising and falling sea levels in the form of tides in oceans. These moving water masses exhibit kinetic

energy that may be used in tidal power plants to generate electricity. This option is not, however, available to landlocked countries and today contributes only an insignificant portion to global electric power generation (Sassoon et al. 2009).

Once these natural energy flows are converted into electricity in power plants, the power grid distributes the electric power to consumers, where electricity is spent to run electrical appliances and enable the delivery of energy services. The process of transmitting and distributing electricity to consumers is subject to further conversion losses, which depend on the technical designs and power grid technologies deployed (World Bank 2016).

Figure 17 depicts energy flows in electric power systems, including the key stages they pass through, as explained in this section: The sources of the three energy fluxes are shown on the top of the diagram. Energy flows pass the above-mentioned stages towards the bottom, where power plants, power grids and electrical devices are shown. Hence, the upper part of the diagram shows the natural conversion processes of energy, while the lower part depicts how energy is first converted into electricity in power stations, then distributed by power grids and ultimately transformed into energy services by electrical devices. The various forms of losses, such as atmospheric reflection, atmospheric absorption, surface heating and reflection, conversion losses in power generation and distribution are also displayed in the upper section of the diagram as explained in this section. This depiction of energy flows thus illustrates how the available energy fluxes and carriers are subject to a wide range of natural and artificial conversion losses until they are spent to power electrical devices. This then enables energy services which improve human well-being and enable manufacturing and supply of a wide range of goods and services.

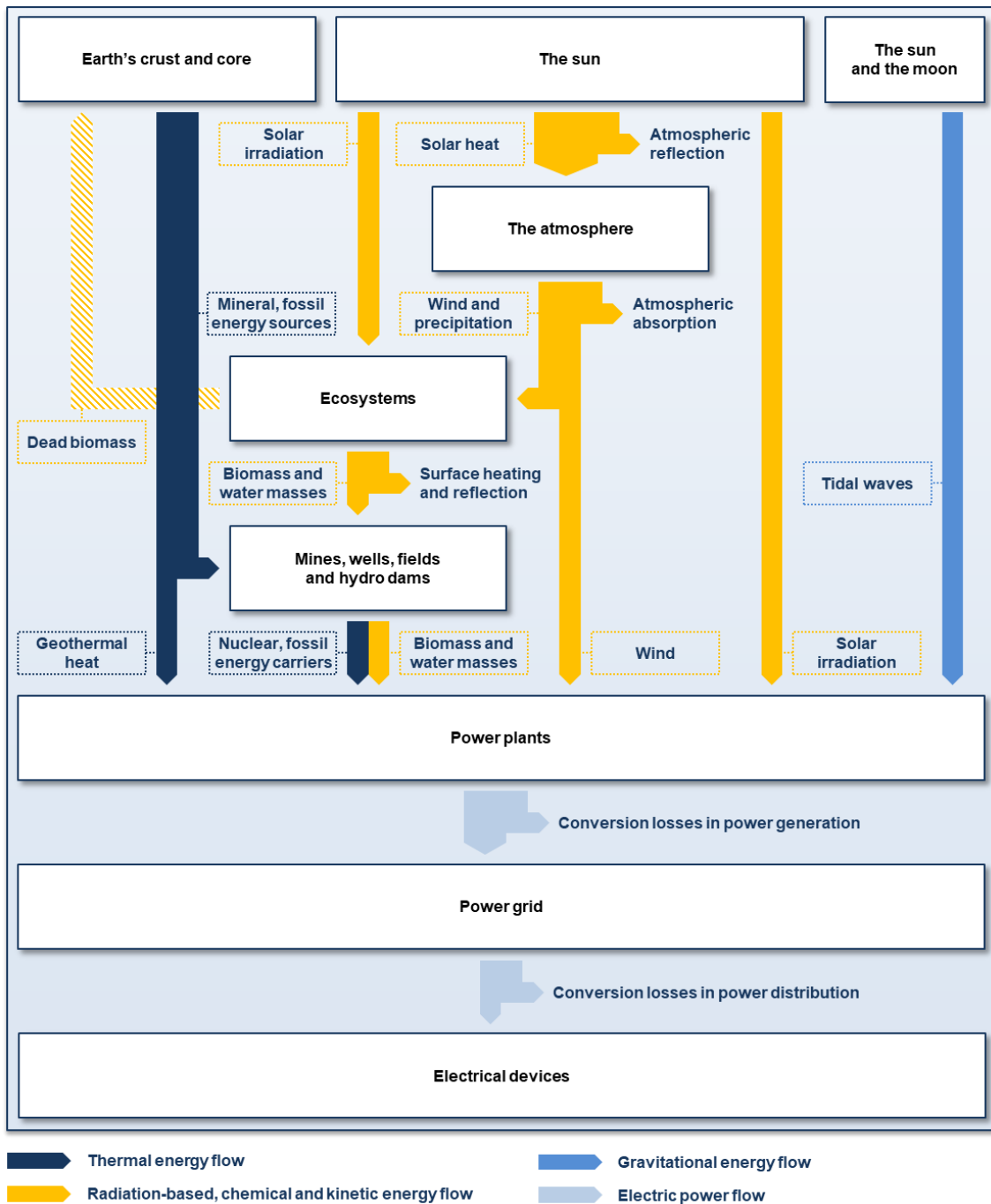


Figure 17: Energy flows in electric power systems

(Own elaboration)

This simplified depiction is, however, devoid of two features of Sankey diagrams. Firstly, quantitative metrics are absent. I have refrained from providing these, as such metrics are likely to vary across regions: Solar irradiation, for example, differs vastly between the arctic territories and the tropics. Alternatively, while fossil fuels are abundant in the Middle East, other regions are deprived of these precious energy carriers. Secondly, Sankey diagrams seek to quantify conversion losses. I did not provide these ei-

ther because conversion losses are subject to, among other things, the technologies deployed, as some technologies benefit from higher technical efficiency ratios than others (Petriz-Prieto, Rico-Ramirez, Gonzalez-Alatorre, Gómez-Castro & Diwekar 2016). Against this backdrop, I argue that quantitative data cannot be provided at the generic level of a framework. The quantitative data has to be analysed when operationalising the framework, or to be more specific, in the process of conducting sustainability assessments. Based on this analysis of energy flows, I am in a position to deduce criteria related to energy flows for sustainability assessments of power systems.

Against this backdrop, I propose to dedicate a set of criteria to measuring the natural occurrence of energy fluxes and energy carriers, since their availability also frames the extent of energy service delivery: Regions of limited energy fluxes or carriers will find it more difficult to provide energy services than, say, territories blessed with high levels of solar irradiation or vast deposits of fossil energy carriers. This can be attributed accordingly by considering criteria related to the natural occurrence of energy fluxes and carriers. Furthermore, I shall distinguish between inexhaustible energy fluxes and finite energy carriers to consider long-term availability, which is important when later looking into preserving opportunity spaces of future generations. I shall further split energy carriers into fossil and nuclear energy carriers and assign distinctive criteria to them, as their ecological impacts vary significantly.

I also propose to apply criteria to assess to what degree existing potentials of energy fluxes and carriers are already exploited: those regions where the majority of the potential has already been exploited will find it hard to further increase energy service delivery. Dedicating specific criteria to evaluating the current level of exploitation will allow for whether other measures, such as promoting energy efficiency, are to be explored to be put into perspective. For the same reason, I shall dedicate separate criteria to renewable energy fluxes and fossil and nuclear energy carriers.

While the above criteria cover natural aspects of energy flows in electric power systems, I still need to deploy criteria to measure the energy consumption of each energy service. These criteria will allow for an analysis of how energy is spent to improve human well-being and enable the manufacturing of goods and services. Furthermore, it will pave the way to assessing energy efficiency levels across the entire system. This, however, will require an additional criterion: I propose to complement these energy flow related criteria with a final control criterion on overall energy efficiency. This criterion

will enable the authors of sustainability assessments to rate the overall energy efficiency of the electric power system under review.

When applying the above criteria, those systems that primarily draw on renewable energy fluxes and manage to keep energy efficiency high across all stages of energy service delivery can be expected to do well – assuming that the goals of the sustainability assessment mirror the normative objectives of SD.³³ *Table 9* lists the proposed criteria for measuring the relevant stages of energy flows and energy conversion ratios. In terms of unit of measurement, I propose to measure all criteria related to the provision and consumption of energy fluxes and carriers in terajoules (TJ) (Kowalski, Stagl, Madlener & Omann 2009). This unit of measurement is often used by authors for similar analyses on energy systems. Likewise, I propose to apply the most frequently used metrics for electricity consumption of energy services, which are either kilowatt hours (kWh), megawatt hours (MWh), gigawatt hours (GWh) or terawatt hours (TWh) per year, depending on the system dimension. Since my framework is directed at assessing systems at aggregated levels, I shall apply TWh. Lastly, for the criterion directed at overall energy efficiency, I propose to calculate the ratio between exploited energy fluxes and carriers versus consumed electricity to determine overall losses.

Id	Criteria for energy flows	Exemplary unit of measurement
EF01	Provision of renewable energy fluxes	TJ per year
EF02	Provision of renewable energy carriers	TJ per year
EF03	Provision of nuclear energy carriers	TJ per year
EF04	Provision of fossil fuel-based energy carriers	TJ per year
EF05	Consumption of renewable energy fluxes	TJ per year
EF06	Consumption of renewable energy carriers	TJ per year
EF07	Consumption of nuclear energy carriers	TJ per year
EF08	Consumption of fossil fuel-based energy carriers	TJ per year
EF09	Energy use for lighting	TWh per year
EF10	Energy use for heating	TWh per year
EF11	Energy use for cooling	TWh per year

³³ Similar endeavours are already applied in practice. In Switzerland, for example, an approach was developed and set down in local legislation which seeks to minimise the energy end-use of citizens to a predefined level (Stulz, Tanner & Sigg 2011). Such approaches favour those energy fluxes and carriers for which power infrastructure secure high conversion efficiencies. This approach, however, ignores aspects related to energy service delivery, material flows or societal steering.

EF12	Energy use for cooking	TWh per year
EF13	Energy use for cleaning	TWh per year
EF14	Energy use for information	TWh per year
EF15	Energy use for communication	TWh per year
EF16	Energy use for entertainment	TWh per year
EF17	Energy use for recreation	TWh per year
EF18	Energy use for fuelling of mobility	TWh per year
EF19	Energy use for manufacturing of goods and services	TWh per year
EF20	Overall energy efficiency	%

Table 9: Criteria for energy flows for electric power systems

(Own elaboration)

A review of the criteria for energy flows combined with my previous work in section 9.1 on energy services, will allow the system to be evaluated in terms of a ratio on energy service delivery against energy efficiency. While such an analysis yields, without any doubt, interesting insights on how much energy is consumed to deliver energy services and which energy services are provided by the system, it needs to be further complemented with data related to the resource consumption and pollution emissions to create a comprehensive picture of the environmental effects caused by the system in providing its outputs. Accordingly, I shall proceed with a material flow analysis of electric power systems to be able to consider this missing ecological aspect.

9.3 Material flows

To accomplish the third task of this chapter, I shall analyse the resource consumption and pollution emissions caused by power infrastructure and electrical devices in power systems. Once more, I shall draw system boundaries in accordance with the holistic system depiction developed in chapter 8 and thereby draw the same scope definition as in the preceding sections. The goal of this section is to capture the relevant resources required to provide energy services and the critical pollutant emissions caused by power infrastructure and electrical appliances to define corresponding criteria. There is, for example, scientific evidence that the combustion of fossil fuels in thermal power plants is a major driver of global warming (IPCC 2007). Furthermore, scientists have discovered that the manufacture of refrigerators required for cooling purposes can contribute to the depletion of the ozone layer (Badr, Probert & O'Callaghan 1990). While this issue has been addressed by policies, some thermal power generation technolo-

gies are still known to contribute to the depletion of the ozone layer (Atilgan & Azapagic 2015; Brizmohun, Ramjeawon & Azapagic 2015). These examples highlight the relevance of capturing resource requirements and pollutant emissions across the entire transformation chain of electricity systems. This also justifies applying a holistic system scope to my task here. In terms of methodology to be applied, I shall revert to material flows analysis and life cycle assessments, as argued in section 7.3.

The first challenge encountered in this section lies with identifying which resources are vital for building and maintaining the technical components of electric power systems and what pollutant emissions are known to cause severe forms of environmental degradation. In order to answer this question, I shall revert to the huge body of existing literature on material flow analysis and life cycle assessments for electric power systems, or parts of systems, including more general studies related to sustainability issues in relation to this complex human-nature system. I shall structure the analysis on material flows into four categories:

- i) **Resource consumption.** The construction and operation of power infrastructure components and the manufacture of electrical devices requires non-renewable resources, such as metals, and renewable resources, such as wood or water, as well as derivatives of fossil fuels (Afgan, Carvalho & Homanov 2000; Gallego Carrera & Mack 2010; Hirschberg et al. 2005; Kowalski, Stagl, Madlener & Omann 2009; Onat & Bayar 2010).
- ii) **Emissions to the atmosphere.** Processes for mining resources, generating and distributing electricity to consumers, including the manufacture of power appliances, can cause severe pollution to the atmosphere, such as the release of greenhouse gases, chlorofluorocarbons or particulate matter (Atilgan & Azapagic 2015; Brizmohun, Ramjeawon & Azapagic 2015; Duncan et al. 2013; Raugeri & Leccisi 2016).
- iii) **Emissions to ecosystems.** Construction and maintenance of power plants and power grids as well as the assembly of electrical devices can have adverse effects on both ecosystems and human beings, including the distortion of ecosystems, eco-toxicity or reductions in life expectancy (Brizmohun, Ramjeawon & Azapagic 2015; Fearnside 2016; Hirschberg et al. 2005; Sheldon, Hadian & Zik 2015).

- iv) **Emissions to Earth's crust and core.** Some power generation technologies are known to cause land contamination and nuclear power requires long-term repositories for the storage of radioactive waste, while the disposal of this waste remains an unresolved issue (Hirschberg et al. 2005; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009).

In order to build and maintain the technical components of electric power systems, non-renewable resources are required. The main category of non-renewable resources required is metals and minerals³⁴ (Afgan, Carvalho & Homanov 2000; Hirschberg et al. 2005; Roth et al. 2009; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009) and some derivatives of fossil fuels (Afgan, Carvalho & Homanov 2000; Kowalski, Stagl, Madlener & Omann 2009; Sharma & Balachandra 2015). Furthermore, some renewable resources, such as wood or water, are used to build and operate facilities for the technical components of electricity systems (Gallego Carrera & Mack 2010; Grunwald & Rösch 2011; Kowalski, Stagl, Madlener & Omann 2009; Onat & Bayar 2010). Accordingly, *Figure 18* depicts the three types of resources consumed when building and maintaining the technical components of electric power systems as described above. In the upper part of the diagram, the components of the technical layer are displayed, while the lower part of the diagram contains the natural capacities of the ecological layer according to the holistic system representation created in the previous chapter. In the middle of the figure, material flows are shown to illustrate the way that the technical components draw on natural resources from ecosystems and the Earth's crust.

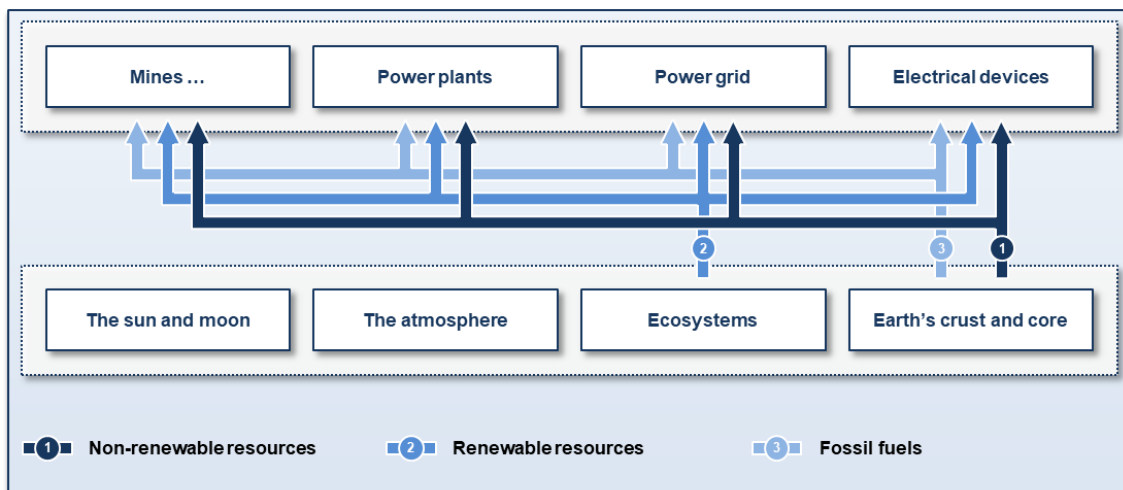


Figure 18: Resource consumption in electric power systems

(Own elaboration)

³⁴ Some of the key metals required are copper and aluminium (Afgan, Carvalho & Homanov 2000).

The diagram does not, however, yield quantitative information on how much resources are spent from the ecological layer, as this, as discussed in regard to energy flows in section 9.2, surely depends on the number and size of facilities in the power infrastructure and the usage of power appliances, which inevitably varies across systems.

Scientific evidence suggests that power infrastructure can cause four severe forms of pollution in the atmosphere: Firstly, the combustion of fossil fuels in coal- or natural gas-based power plants, for example, releases greenhouse gases to the atmosphere thereby fuelling global warming (Dombi, Kuti & Balogh 2014; Evans, Strezov & Evans 2009; Karmellos, Kopidou & Diakoulaki 2016). Secondly, the manufacture of refrigerators and the thermal combustion processes in power plants can contribute to the depletion of the ozone layer³⁵ (Badr, Probert & O'Callaghan 1990; Moussiopoulos 1990). Thirdly, fossil fuel-based power generation is known to emit sulphur oxides (SO_x) and nitrogen oxides (NO_x), which can cause among other things severe illnesses in human beings (Afgan, Carvalho & Homanov 2000; Dios, Souto & Casares 2013; Matteson 2014). Fourthly, thermal processes that are prevalent in, for example, coal- or natural gas-based power generation technologies, as well as the cultivation of biofuels, can cause particulate matter that may result in acute respiratory diseases in human beings (Grunwald & Rösch 2011; Shamzani Affendy, Nurul-Hidayah Nik Yahya & Alias 2013; Sharma & Balachandra 2015). Furthermore, processes related to the extraction of metals, minerals and fossil fuels can also cause emissions of particulate matter (Aneja, Isherwood & MOrgan 2012). *Figure 19* illustrates these four categories of pollution to the atmosphere caused by the technical components of electric power systems. Similar to the previous figure on resource consumption, the upper part of the diagram displays components of the technical layer in electric power systems, while the lower part depicts those of the ecological layer. Similarly, the arrows in the figure show what forms of pollution to the atmosphere are caused by the technical components of electric power systems. This depiction shows that power plants have a wide range of adverse effects on the atmosphere.

³⁵ While the ozone layer is regenerating due to a global ban of specific chlorofluorocarbons in consumer goods, some older power plants are still known to cause this type of emission.

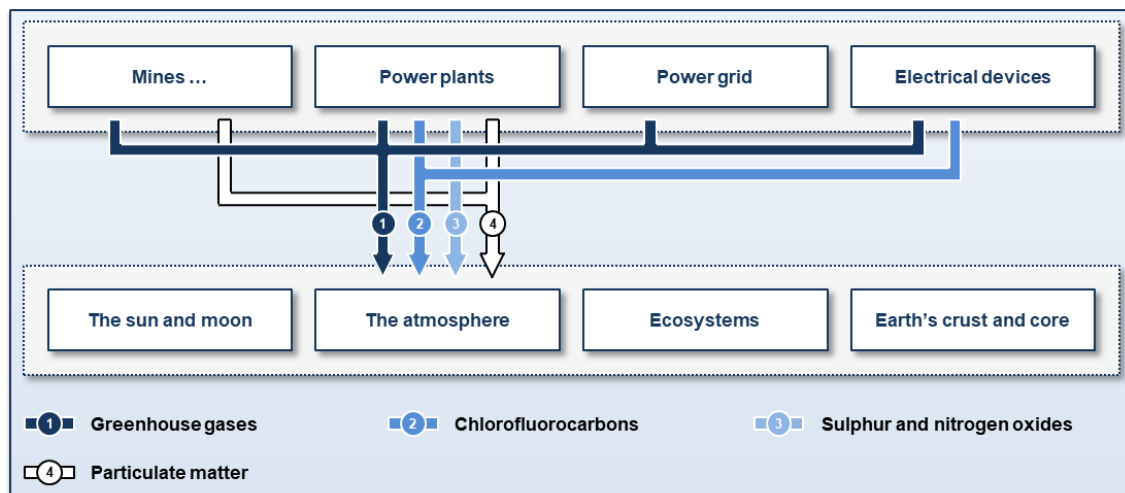


Figure 19: Emissions to the atmosphere in electric power systems

(Own elaboration)

Scientific evidence suggests that electric power systems can exert a wide range of effects on ecosystems and the life-forms inhabiting those systems, including human populations. First, the technical components of power infrastructure require land on which to build facilities. Additional land is often affected by waste and in some cases is rendered unavailable for other vital purposes³⁶ (Fthenakis & Kim 2009; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Ribeiro, Ferreira & Araújo 2013). Second, mining facilities, power plants and electricity grids not only take up land area but, especially in case of hydroelectric dams, may also distort ecosystems, sometimes severely impeding the delivery of ecosystem services (Kashef 1981). Third, there are known cases of losses in biodiversity resulting from the operation of biofuel farms, for example owing to mismanagement in agricultural practices, and power plants, owing to the fragmentation of ecosystems (Pedroli et al. 2013). Fourth, biomass farms often apply fertilisers to stimulate growth in energy carriers. Excessive use of fertilisers and the run-off of chemicals in power plants can result in eutrophication and acidification in rivers and lakes, thereby decreasing the water quality to the point where aquatic ecosystems are threatened and severe risks to human health arise (Hornung 1999; Jeswani, Gujba & Azapagic 2011). Fifth, other malpractices related to the cultivation of biofuels are known to potentially result in soil erosion or desertification, both of which are known to adversely affect food harvests (Vogel, Deumlich & Kaupenjohann 2016). Sixth, the erection and operation of some power generation and distribution technologies can cause eco-

³⁶ One could also consider land area as a natural resource rather than a form of pollution to ecosystems. However, scientific evidence suggests that some processes related to the extraction of fossil fuels, for example, can make vast areas of land unavailable for other uses (Baranzelli et al. 2015).

toxicity which increases the fragility of ecosystems and holds risks for human health (Fadeyi, Arafat & Abu-Zahra 2013). Seventh, scientific evidence suggests that some forms of pollution resulting from the operation of power infrastructure components reduce human life expectancy (Hirschberg et al. 2016). Eighth, nuclear power plants, hydroelectric dams and some power grid facilities in particular expose human populations to catastrophic risks; in the past accidents led to fatalities (Sovacool, Kryman & Laine 2015). Ninth, there are still concerns that human beings exposed to the electromagnetic fields of some power generation technologies, power lines and some electrical devices, face a greater risk of contracting potentially fatal diseases (Repacholi 2012). Accordingly, *Figure 20* depicts pollutant emissions caused to ecosystems and human populations stemming from the construction and operation of the technical components of electric power systems. This diagram depicts, in the upper part of the figure, the wide range of hazardous emissions caused by mining facilities, power stations, power grids and electric appliances to ecosystems, which are displayed on the lower part of the figure.

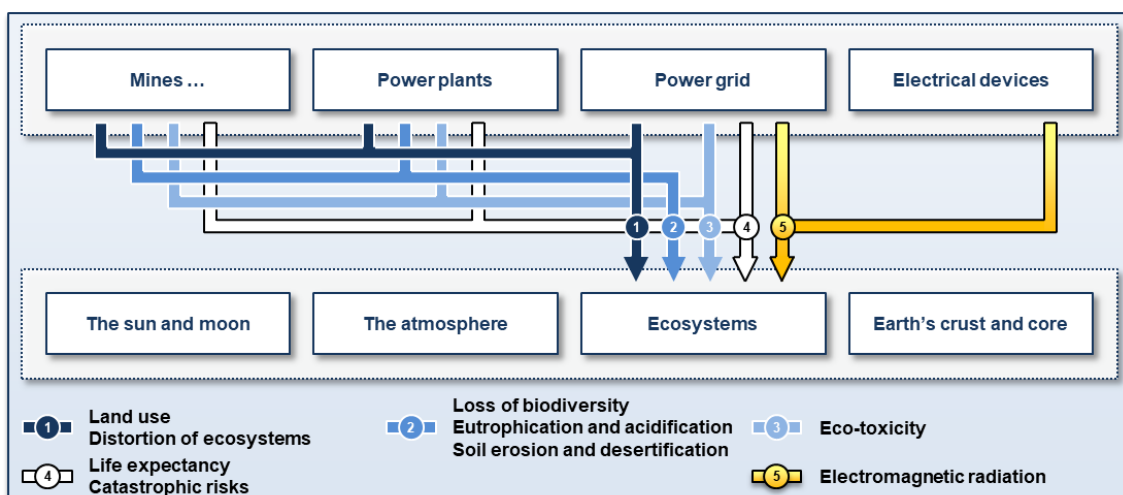


Figure 20: Emissions to ecosystems in electric power systems

(Own elaboration)

Research on the operation of nuclear power plants and mining facilities has identified two forms of major environmental degradation to the Earth's crust. Firstly, nuclear power plants produce radioactive waste which has to be stored in deep geological repositories. The required transportation and storage of spent fuel rods in repositories pose risks to human health and the environment in the form of nuclear radiation over a very long period of time (Thakur, Lemons, Ballard & Hardy 2015). Secondly, the excavations caused by mining for energy carriers and some of the power generation tech-

nologies in operation, such as nuclear power plants, are also known to hold risks related to land contamination or nuclear radiation (Laraia 2015). Against this backdrop, *Figure 21* displays the two severe forms of pollution caused mainly by nuclear power plants and mining to the Earth's crust and consequently human populations using the same diagram as used previously. Accordingly, this analysis emphasises that nuclear power is the main contributor to severe forms of pollution caused by electric power infrastructure to the Earth's crust.

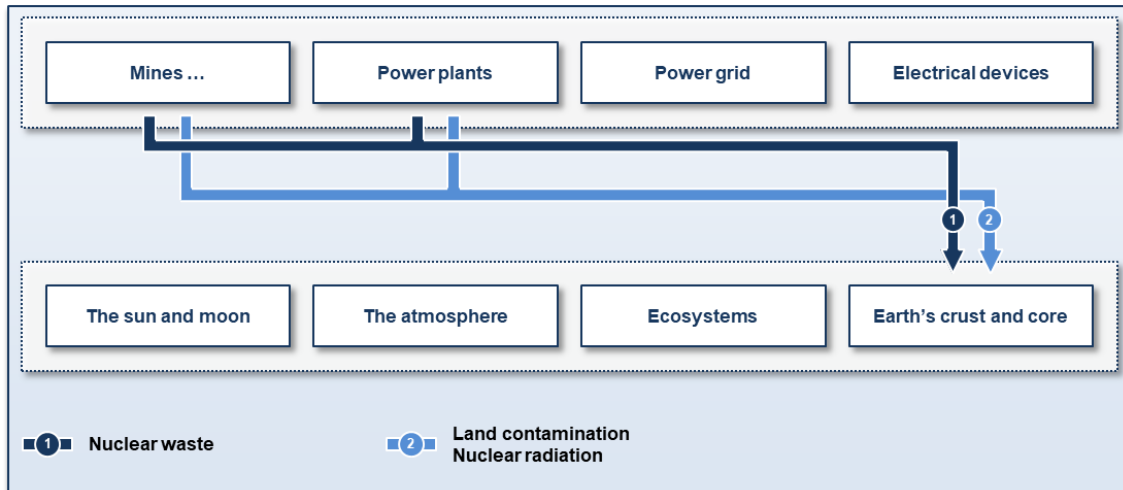


Figure 21: Emissions to Earth's crust and core in electric power systems

(Own elaboration)

In this section, I analysed in more detail which resources are consumed to establish and operate the technical components of electric power systems. Furthermore, I painted a holistic picture of the forms of pollution that are hazardous to human populations and the natural environment. Based on this analysis, I propose to systematically define a criterion for each identified type of resource and pollutant emission for sustainability assessments of electric power systems.

In order to measure resource efficiency, I propose to dedicate distinct criteria related to the provision and consumption of each type of resource as identified above. I shall also apply the same procedure to each type of pollutant emission. Hence, I propose to apply a criterion to measure each type of pollution identified in this section. Furthermore, in order to evaluate whether pollutant emissions impede development processes, I shall also dedicate a criterion to each type of pollutant emission related to the ability of the environment or human beings to absorb or withstand those hazards. As for unit of measurement, I propose those units that are most frequently applied in the scientific lit-

erature and are commonly used. Accordingly, *Table 10* lists the proposed criteria related to material flows for sustainability assessments of electric power systems.

Id	Criteria for material flows	Exemplary unit of measurement
MF01	Provision of non-renewable resources	Tonne (t)
MF02	Consumption of non-renewable resources	Tonne (t)
MF03	Provision of renewable resources	Tonne (t)
MF04	Consumption of renewable resources	Tonne (t)
MF05	Provision of fossil fuels	Tonne (t)
MF06	Consumption of fossil fuels	Tonne (t)
MF07	Emission of greenhouse gases	Parts per million (ppm)
MF08	Absorption of greenhouse gases	Parts per million (ppm)
MF09	Emission of chlorofluorocarbons	Parts per million (ppm)
MF10	Absorption of chlorofluorocarbons	Parts per million (ppm)
MF11	Emission of sulphur and nitrogen oxides	Parts per million (ppm)
MF12	Absorption of sulphur and nitrogen oxides	Parts per million (ppm)
MF13	Emission of particulate matter	Micrograms per cubic meter ($\mu\text{g}/\text{m}^3$)
MF14	Breakdown of particulate matter	Micrograms per cubic meter ($\mu\text{g}/\text{m}^3$)
MF15	Use of land	Square kilometres (km^2)
MF16	Availability of land	Square kilometres (km^2)
MF17	Distortion of ecosystems	Ecosystem service delivery
MF18	Delivery of ecosystem services	Ecosystem service delivery
MF19	Losses in biodiversity	Taxonomic richness of a region
MF20	Biodiversity	Taxonomic richness of a region
MF21	Causes of eutrophication and acidification	Micrograms per litre ($\mu\text{g}/\text{l}$) and pH
MF22	Resilience to eutrophication and acidification	Micrograms per litre ($\mu\text{g}/\text{l}$) and pH
MF23	Erosion of soil and desertification	Tonnes per square kilometre (km^2)
MF24	Provision of soil	Tonnes per square kilometre (km^2)
MF25	Causes of eco-toxicity	Parts per million (ppm)
MF26	Absorption of eco-toxicity	Parts per million (ppm)
MF27	Reduction in life expectancy	Years of lives lost (YLL)
MF28	Life expectancy	Years
MF29	Increase in exposure to catastrophic risks	Probability multiplied by severity
MF30	Exposure to catastrophic risks	Probability multiplied by severity
MF31	Causes of electromagnetic radiation	Volts or Ampere per metre (V/m) (A/m)

MF32	Resilience to electromagnetic radiation	Volts or Ampere per metre (V/m) (A/m)
MF33	Causes of nuclear waste	Tonne per square metre (t/m) per year
MF34	Absorption of nuclear waste	Tonne per square metre (t/m) per year
MF35	Causes of land contamination/nuclear radiation	Parts per million (ppm), Sievert (mSv)
MF36	Resilience to land contamination/nuclear radiation	Parts per million (ppm), Sievert (mSv)

Table 10: Criteria for material flows for electric power systems

(Own elaboration)

My endeavour to systematically deduce criteria so far covers the output of electricity systems and the environmental burdens resulting from electric power systems. Applying these criteria to a sustainability assessment will allow the benefits provided by power infrastructures and electric appliances to be compared with the environmental degradation caused by the system under review. However, I am still missing one core element of the system to cover the basic feature of criteria for holistic sustainability assessments: criteria related to societal transformation processes. Hence, to accomplish my task in this chapter, I shall proceed by analysing societal steering processes for complex sustainability issues, such as transforming electricity systems to meet sustainability requirements.

9.4 Societal steering processes

One of the hallmarks of coupled human-nature system analysis is the recognition that complex socio-ecological systems, such as electric power systems, consist of a bio-physical, a social and a hybrid dimension. Thus, the process of creating the holistic depiction of electric power systems in the previous chapter revealed that, in sustainability assessments, it is not only technical power infrastructure, electrical devices and the natural environment that need to be considered, but also the actors social realm. In terms of scope definition, it therefore becomes apparent that both actors and their societal steering processes need to be considered in such schemes.

In order to determine and describe relevant actors and their actions, I shall draw on the theoretical background related to socio-ecological regimes and environmental governance. This approach allows the relevant actors to be described and depicts the way in which these actors agree on objectives for the development of complex coupled human-nature systems, such as electric power systems, and how their work shapes power infrastructure and determines the use of electrical appliances. In section 3.2, I ar-

gued that scholars perceive reflexive governance to be a prerequisite for dealing with today's sustainability challenges. Furthermore, I argued that I may delimit my focus on transformation aspects of governance. Accordingly, for this thesis, I shall assume that reflexive governance is in place and I shall focus on transformation aspects. My first challenge in this section lies in identifying the relevant actors in the system. Once this task is accomplished, I shall then proceed by elaborating the interrelationships between key actors and the critical interdependencies between these actors and the environment or technical components of electric power systems that are associated with steering the development of electricity systems.

Half a century ago, environmental governance often served the purpose of responding to severe forms of environmental degradation. Once the adverse effects of development on ecosystems or human health became apparent, policy makers and administrations put regulations in place that banned certain procedures or chemicals. More recently, environmental governance is perceived to cover a much broader scope and has become part of sustainability governance that seeks to evaluate the effects of policies and specific development projects prior to implementation as input for decision making through environmental assessments (Adelle, Jordan & Turnpenny 2012; Owens, Rayner & Bina 2004).

However, since key knowledge is today dispersed among different actors, these assessments are thought to also require the involvement of key actors outside of government institutions. In Western societies a broader sharing of responsibilities among researchers, policy makers and administrations, market actors and actors in civil society can be increasingly observed (Cheshire, Higgins & Lawrence 2007). Such a more cooperative mode of governance is thought to lead to a consideration of more of the relevant system elements in decision making and promotes public support for critical development endeavours (Lockwood 2010; Macnaghten & Urry 1998). Against this backdrop, I provide an overview of the above-mentioned key actors and their role in environmental governance:

- i) **Researchers.** In order to establish reflexive transformation governance that not only responds to environmental degradation but may also act preemptively, comprehensive analyses of energy and material flows as well as interdependencies with societal steering processes are likely to be required. Such research is traditionally carried out by scientists and seeks to advice

policy makers on the steering instruments to be deployed (Bilotta, Milner & Boyd 2014).

- ii) **Policy makers and administrations.** In represented democracies, bodies of elected representatives agree on areas for policy intervention and mandate administrative offices to implement policy steering instruments. Furthermore, government agencies operate infrastructure to deliver public services and deploy policy instruments to induce behavioural change (Dean 2010; McKee 2009).
- iii) **Market actors.** Manufacturers and suppliers of goods and services define business models to offer products and services to clients based on the regulatory framework. Customers express market choices and thereby influence the development of solutions by suppliers. Accordingly, suppliers respond to the demands of their customers in free markets (Govindan, Seuring, Zhu & Farrido Azevedo 2016).
- iv) **Civil society.** Organised institutional actors seek to influence policy development through participation in political processes. Their actions may be considered in policy decisions depending on the pressure they can exert on policy makers. Sometimes, they pursue their own initiatives to reach their goals (Eichbaum 1993).

Based on this general overview of the main actors and their roles, I am in a position to look into the second task of this section; that is, describing critical interdependencies in electric power systems. There are two key types of interdependencies in coupled human-environment systems: interdependencies among actors on the one hand and between actors and the environment or technical system components on the other. Depending on the complexity of the system, such as the number of actors involved, a huge number of interrelationships may exist. To accomplish my task at hand, I shall focus on those interrelationships that contribute to societal steering. Accordingly, I have to discuss the key aspects of change governance in more detail to then distil those interrelationships that are of relevance.

However, prior to doing so, I shall elaborate on the overarching challenge of transforming a complex human-environment system, such as an electricity system. Assuming a reflexive mode of governance is in place, then the process of transforming electricity

systems is the result of many actions on quite different levels. As the technical components of electric power systems are refined, dynamic interactions become increasingly important as actors need to integrate new technologies seamlessly into an already existing, intricately interwoven network of technical components. Each actor, such as a scientific research group or an operator of power infrastructure components is, however, a self-referential subsystem: they are likely to seek to optimise their own output and thus achieve a higher degree of specialisation. In doing so, they may create technological lock-ins. A tension could then emerge between the continuous self-optimisation of incumbents and the general perception that the system may no longer meet future requirements, such as accounting for limited ecological capacities.

Accordingly, in order to transform the technical layer of an electric power system, new components must be introduced and existing ones may have to be removed or altered. Such an endeavour can be achieved in two ways: either by welcoming new actors that have resources vital to the transformation of the system or by changing the value schemes of existing actors, for example through transformed business models, to contribute to the overarching objective of SD. Whatever the case, either way calls for some form of coordination in the sense of overall frame-conditions enabling collective action. *This* will enable a collectively organised transformation of energy and material flows towards common objectives.

To support the description of such governance as societal steering, I shall draw on the five structural elements of reflexive governance provided in section 7.6, elaborating key aspects of the structural elements to serve later as a basis to deduce social criteria referring to the instrumental features of SD for sustainability assessments of electric power systems. The emphasis is again on structural aspects of the social dimension. It is assumed that these structural, or functional, components are conditions for achieving collective action successfully. How they are further operationalised goes beyond the scope of my thesis:

- i) **Guiding principles of SD.** To enable collective action, researchers, policy makers and administrations, market actors and civil society actors that possess the knowledge and resources relevant to the future design of the system in question contribute to a common vision of the future. Such a vision is often captured in strategy papers developed and published by corresponding government agencies. According to the normative objectives of SD, the design of the technical functionality gives special consideration to ecological

capacities. In such contexts, scientists may provide the latest research on the system and share thoughts on adequate methodologies, such as how the normative requirements of SD may be operationalised. Suppliers and manufacturers share their technological and market experience, while environmental agencies can be expected to contribute environmental issues to be resolved. Government agencies are likely to facilitate the process of creating a common vision by providing respective discussion arenas and produce reports on potential scenarios and their implications.

- ii) **Steering rules.** Assuming that a fact-based approach is sought, then a set of operationalised objectives and steering rules can be deduced based on the guiding principles of SD. The latter is meant to serve as a focal point for implementation initiatives and is designed to ease the process of defining criteria and corresponding general goals. Here, researchers may propose methodologies for formulating objectives and steering rules, while government institutions are likely to transcribe commonly accepted objectives into laws. Civil society actors can be expected to seek to influence the translation of guiding principles into rules on behalf of their members. Once objectives are defined, they can be expected to serve as a basis for suppliers and manufacturers to develop corporate strategies and business models.

- iii) **Criteria and general goals.** In order to measure whether societal development is on track to meet the normative requirements of SD, criteria and general goals are defined and periodically evaluated. Scholars may propose criteria and general goals based on analytic approaches and advise the policy makers and government agencies who eventually decide on the criteria and goals to be used and monitored. Environmental agencies and sectoral unions can be expected to try to introduce their preferences into the definition of relevant criteria and general goals.

- iv) **Organisational set-up and steering instruments.** A structural set-up creates opportunity spaces for actors so they may contribute their part to the transformation of the system. Policy steering instruments are imposed to promote the accomplishment of mutually agreed objectives and thereby direct the development of the system. Scientists research options related to organisational set-up and policy instruments that promote the development of systems towards a more sustainable state, and advise policy makers who

decide on the final design of instruments and put them into force. Such changes in regulatory frame conditions may put pressure on suppliers and manufacturers to revisit their solutions portfolio. Organised institutional actors once again seek to influence instruments on behalf of their members.

- v) **Reflexive process.** Ideally, manufacturers and suppliers extract data from their technical components and conduct sustainability reporting geared to the criteria and general goals previously defined by policy makers and environmental agencies in order to share the latest data publicly. At the same time, researchers share their latest research on system components and dynamics. Policy makers incorporate knowledge obtained from reflexive processes into policy processes. Other actors, such as the media, sectoral unions and environmental agencies, can be expected to assume a reflexive role by paying special attention to dynamic interactions and observing system developments to process lessons learned and draw attention to the unforeseen consequences or developments that may oppose sustainability trajectories, thereby promoting a more profound understanding of the system.

Based on this overview of steering aspects of reflexive transformation governance, I am in a position to develop an overview of the responsibilities assumed by researchers, policy makers and administrations, market actors and civil society actors.

Accordingly, *Figure 22* depicts the five structural elements of socio-ecological regimes, in a system subject to reflexive governance of change, organised collectively to achieve a transformation of electric power systems involving those actors who possess in-depth knowledge of system components and have some form of responsibility in designing and implementing the future electric power system. This figure illustrates strong dependencies among actors to organise material and energy flows collectively in favour of human purposes, which plays a central role in transforming existing electricity systems to meet normative sustainability requirements.

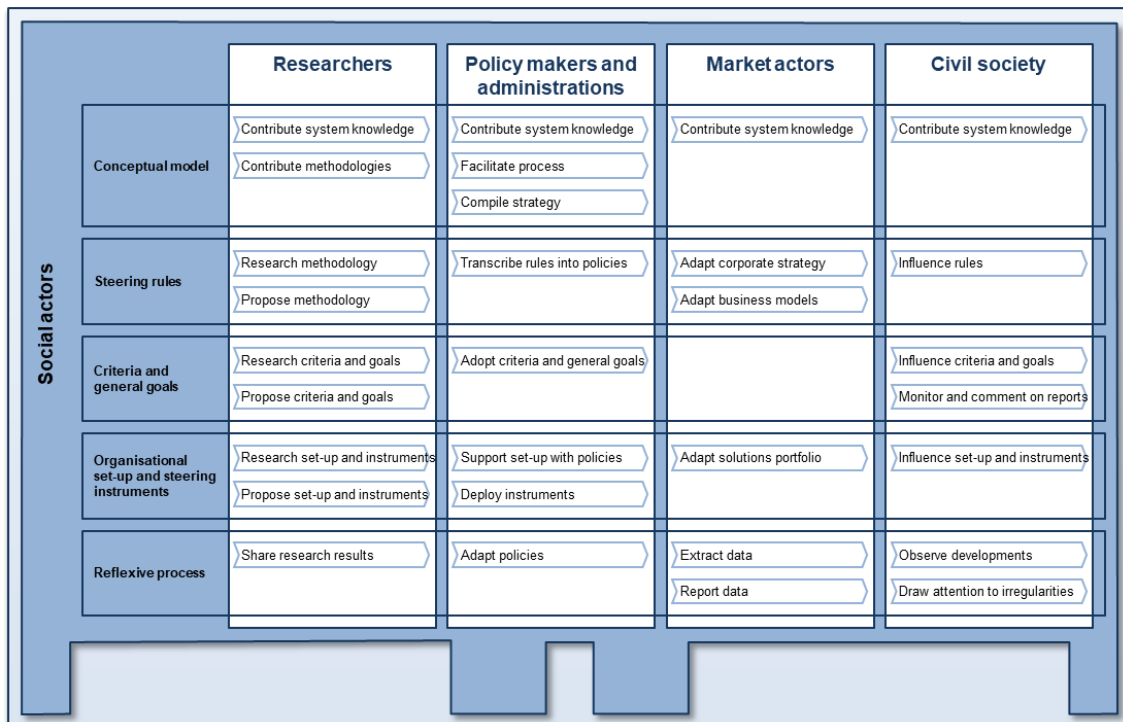


Figure 22: Governance components for collectively organising the power system.

(Own elaboration)

The description of the steering aspects of reflexive transformation governance serves as an ideal starting point to accomplish the task in this section: to systematically deduce criteria related to societal steering for sustainability assessments of electricity systems. I shall carry out this task based on the structural elements provided above.

In order for reflexive governance to work, a continuous process of increasing understanding of the system is a necessary precondition. Accordingly, I propose to define a set of criteria related to researching system components and their interdependencies. Moreover, I shall introduce a criterion to measure the contributions of non-scientific actors to building knowledge. Furthermore, I propose to add two criteria related to the role of state actors to produce strategies for the development of the electric power system and provide discussion arenas to exchange knowledge on reflexive governance.

As for the second structural feature, I propose to introduce a criterion related to scientific proposals for breaking down the overarching objectives of the guiding principles of SD into a set of rules. Furthermore, I shall define a criterion to measure the adoption of steering rules in policies and the involvement of civil society actors in the process of determining rules. Moreover, I shall dedicate a criterion to the adaptation of strategies and business models by manufacturers and suppliers.

For criteria and general goals, I shall define a criterion related to scientific proposals and another one for government agencies in order to define criteria and general goals and incorporate them into their policy framework. In terms of engagement of organised institutional actors, I propose to reuse to the previously defined criterion on the involvement of civil society, already defined for steering rules.

I propose a very similar set of criteria also related to the organisational set-up and steering instruments: One criterion to deal with scientific proposals and a second one related to deploying policies. For market actors, I propose to use a criterion related to the efforts of suppliers and manufacturers in adapting their solutions offering, while the generic criterion for civil society actors to influence structural elements of reflexive governance of change can also be reused for this structural element.

I shall dedicate one criterion to scientists' efforts to publish reports on system components, system interdependencies or other research related to societal steering and one to the role of government agencies to incorporate knowledge obtained from reflexive processes in policies. Furthermore, I propose to dedicate one criterion to evaluate the sustainability reporting of manufacturers and suppliers and a fourth criterion to the role of organised institutional actors on observing and commenting system developments outside of sustainability trajectories.

Accordingly, *Table 11* lists the above elaborated criteria that are defined to capture societal steering aspects in sustainability assessments of electric power systems.

Id	Criteria for societal steering processes
SS01	Research on system dynamics and interdependencies
SS02	Research on societal steering
SS03	Research on power infrastructure and electrical devices
SS04	Research on ecological capacities
SS05	Contribution of system knowledge and experiences gained
SS06	Compilation of divisional strategy and scenarios
SS07	Facilitation of arenas for public debates
SS08	Proposals on steering and instrumental rules
SS09	Adoption of steering and instrumental rules in laws
SS10	Involvement of civil society
SS11	Adaptation of strategies and business models

SS12	Proposals on criteria and general goals
SS13	Adoption of criteria and general goals
SS14	Proposals on organisational set-up and steering instruments
SS15	Adoption of organisational set-up and steering instruments
SS16	Adaptation of solutions offering
SS17	Publishing of scientific reports
SS18	Incorporation of findings into policies
SS19	Conducting of sustainability reporting
SS20	Monitoring of and commenting on system developments

Table 11: Criteria for societal steering processes for electric power systems

(Own elaboration)

By producing this last set of criteria related to societal steering processes, I have attained the goal of this chapter, namely, to systematically deduce a set of criteria for sustainability assessments of electric power system according to the system boundaries specified in chapter 8. Before moving on the next deliverable, I shall reflect on the scientific contributions of this chapter to the current debate on the operationalisation of sustainability assessments of electric power systems.

9.5 Conclusions

This chapter served the purpose of systematically deriving criteria for sustainability assessments of electricity systems in accordance with the scope framed by the holistic representation of electric power systems provided in chapter 8. To deliver this output, I drew on methodologies related to energy and material flow analysis, as well as reflexive environmental transformation governance. Against the backdrop of a multi-layered system representation, I systematically derived exemplary criteria which capture critical stages of energy, material and information flows in electricity systems.

At this point, I would like to emphasise that even systematic analyses may not be able to cover every detailed facet of complex systems, such as electric power systems. I am fully aware that such systems are not likely to be fully represented due to the vast scope of such systems. Furthermore, technological developments or the definition of the scope of the assessment may also have an impact on the outcome as the following example illustrates: In an electric power system where today private mobility is based entirely on fossil fuels and a transition to a system relying exclusively on electric cars is

successfully carried out, electricity consumption can be expected to rise substantially. My proposed framework would be able to capture both the increase in the delivery of the corresponding energy service and electricity consumption. However, other positive effects would remain unidentified: The resulting contributions of such a system transition to combatting global warming and the depletion of the ozone layer are in this particular case not grasped. This can be traced back to the fact that environmental degradation stemming from fossil fuel-based mobility is not part of the system scope. In contrast, distortions of ecosystems can be expected to increase if the rising electricity consumption is catered for by new hydroelectric power plant capacities. This new form of environmental degradation would, however, be detected by the sustainability assessment due to the system boundaries specified. The result could be interpreted as if the system had moved towards less sustainable trajectories, as some of the positive effects of the system transition lie outside of the scope of the sustainability assessment.

In this chapter, however, I did not strive to provide a universally applicable set of common criteria for sustainability assessments of electric power systems, but rather sought to demonstrate that a systematic approach is able to transparently identify relevant stages in the electricity system and derive criteria for sustainability assessments. This increased transparency eases the process of facilitating mutual learning on appropriate methodologies and system scopes.

With the results presented in chapters 8 and 9, I provided scientific contributions to the knowledge gaps related to the system in question for sustainability assessments of electric power systems. This was done to provide a basis for *evidence-based* decision making. Naturally, this raises the question how my contributions differ from the literature reviewed in chapter 4. At this point, however, I shall postpone such a comparative analysis to chapter 12, where I shall discuss my contributions in comparison to the research sample. I shall proceed by drawing attention in chapters 10 and 11 to the normative and instrumental aspects of SD and thereby strive to formulate general goals to the criteria identified in this chapter based on the guiding principles of SD. These contributions are expected to ultimately enhance *goal-oriented* decision-making support for the long-term development of key systems.

10 Steering rules

In order to formulate general goals for criteria that mirror the normative requirements of SD, one has to decide on an interpretation for the guiding principles. However, scholars generally agree that such interpretations are too ambiguous to guide policy making or for setting tangible goals for criteria in sustainability assessments (Holden & Linnerud 2007). Such interpretations are likely to offer broad objectives that point to societal development trajectories which may be subject to change (Van Zeijl-Rozema, Cövers, Kemp & Martens 2008), rather than, for example, precise caps for greenhouse gas emissions or maximum thresholds for resource consumption. However, as proposed in section 7.7, one could try to break down the normative cornerstones of a recent scientific interpretation of SD into mutually exclusive, but more tangible objective dimensions, and steering and instrumental rules. Such systematic multi-step deductive reasoning could facilitate a process that would sufficiently enrich the interpretation chosen and produce the specific goals to be used for criteria in sustainability assessments.

Accordingly, the purpose of this chapter is to enrich the normative features of the SD conception through such a sequential process: Firstly, I shall formulate a set of objective dimensions capturing the overarching normative essence of the interpretation of SD formulated in section 7.5. These objective dimensions will apply to electric power systems in order to later serve as a basis for producing general goals for criteria in sustainability assessments of power systems. Secondly, I shall derive more detailed steering and instrumental rules for each objective dimension. Thirdly, in the last section of this chapter, I shall formulate general goals for each criterion for sustainability assessments based on these rules. Throughout this process, I shall elaborate on and argue for each of the steps to shed light on how the normative notions of SD are ultimately translated into general goals for criteria in sustainability assessments.

While such endeavours are obviously prone to subjective interpretations and the result can be expected to vary among different authors, I deem this procedure valuable as it provides transparency on how the normative notions of SD are translated into goals for criteria in sustainability assessments. Furthermore, this process follows a systematic procedure that is less likely to succumb to biases. Lastly, in this chapter I shall focus on deducing steering rules and general goals for criteria that are related to the question *What should be sustained?* These goals will ultimately be complemented with instrumental rules and general goals for criteria on *How should this be sustained?* I shall produce the deliverables related to instrumental aspects in chapter 11.

10.1 Objective dimensions

The objective dimensions that I intend to deduce in this chapter have to meet three requirements. Firstly, they have to mirror the normative notions of SD to enable an evaluation of system data against predefined sustainability goals. In the absence of references to the normative requirements of the guiding principles, it remains contested whether a system that meets its general goals actually preserves opportunity spaces for future generations. There is, however, one well-known challenge associated with such approaches: the objective dimensions defined are likely to differ depending on the interpretation of the SD chosen. As argued previously, the ambiguous definition of SD provided by the *Brundtland Report* and independent application of related instruments in different countries have given rise to several distinct interpretations, ranging from ecological sustainability to focusing on societal steering aspects or the relevance of local specifics (Brand & Karvonen 2007; Hueting & Reijnders 2004; McCool & Stankey 2004). Against this backdrop, it becomes apparent that I have to base my work in this section on one specific interpretation of SD.

I shall draw on the interpretation presented in section 7.5: *Sustainable development aims to achieve well-being by considering ecological frame conditions, such as productivity and the resilience of ecosystems, that are vital for future human well-being, and the potential for societal transformation* (Burger et al. 2018).

Secondly, objective dimensions must be applicable to the system in question, which in my case is the electric power system. Modern societies rely on several key systems that provide outputs that are critical for human populations. Education systems, for example, seek to transfer knowledge from technical experts to individuals and thereby develop human capital. Accordingly, scientists and teachers argue that the function of the education system lies with generating and passing knowledge on to others (Cheng 2013). Today, energy flows are of lesser importance in education systems, as they only have a critical purpose in some types of learning methods, such as distance learning, and education subjects, such as information and communication technology (Fojtik 2015). In electric power systems, however, energy flows are a prerequisite for the system to perform its function of delivering energy services to improve well-being (Ahmad, Mathai & Parayil 2014). Against this backdrop, I argue that objective dimensions need to address the specifics of systems and that objective dimensions may vary across different systems. Furthermore, I argue that in order for objective dimensions to serve their purpose, they have to impose normative requirements on the functional elements

of the system in question, including their enabling and constraining factors. In electric power systems, the technical components are responsible for transforming natural energy and material flows into energy services through societal steering processes. Accordingly, I argue that objective dimensions for electric power systems will have to relate to these aspects of electric power systems in order to serve as a basis for operationalising SD through sustainability assessments.

Thirdly, there is generally agreement among scholars that the guiding principles of SD entail normative and instrumental aspects. While the features that safeguard opportunity spaces for future generations are directed at the question *What should be sustained?*, instrumental notions are directed at *How should this be sustained?* In order to cover both aspects, I shall need to draw up a set of rules that addresses both questions. For the sake of transparency, I shall divide my contributions on *What should be sustained?* and *How should this be sustained?* into two different chapters. I shall dedicate chapter 10 to setting goals related to *What should be sustained?* and thus I will postpone answering the other question until chapter 11. Against this backdrop, I shall formulate objective dimensions related to the question *What should be sustained?* for electric power systems by enriching the above-mentioned interpretation of SD into distinct objective dimensions. Accordingly, I shall proceed by formulating the objective dimensions related to the question *What should be sustained?*

The conception of SD seeks to establish a balanced approach to achieving development and environmental conservation (WCED 1987). In this thesis, I argue that electric power systems deliver the crucial energy services required to achieve human well-being and to enable the provision of goods and services. Accordingly, there is good reason to believe that if a society were to curtail the delivery of energy services that are essential to users, it would likely result in lower levels of human well-being (Ahmad, Mathai & Parayil 2014). Furthermore, the delivery of essential energy services does not lead to an erosion of the ecological capital per se; rather the technologies applied to deliver these are the things that are responsible for lesser or higher levels of environmental degradation (Afgan, Carvalho & Hovanov 2000; Evans, Strezov & Evans 2009; Roth et al. 2009; Stamford & Azapagic 2011). Against this backdrop, it is reasonable to argue that electric power systems will likely continue to provide energy services to serve human purposes in the future due to the effectiveness they exhibit in achieving human well-being. Accordingly, I shall dedicate the first objective dimension to the delivery of energy services in electric power systems:

1) *Provision of energy services to serve human purposes*

A hallmark of the guiding principles of SD is the recognition that current business practices and consumption patterns in industrialised nations erode global ecological capital thus creating the risk that future generations may no longer be able to meet their needs. Accordingly, it is thought that development patterns will have to change (Kemp, Parto & Gibson 2005; Meadowcroft 2011). Our planet produces a wide range of essential resources and services required for technologies, including power plants and electricity grids in electric power systems, to ultimately result in human well-being. In electric power systems, there are two distinct biophysical flows that draw on natural resources and serve human purposes: (i) energy flows (Sassoon et al. 2009) and (ii) material flows (Raj, Ghandehariun, Kumar & Linwei 2016; Şengül, Bayrak Aydınalp Köksal & Ünver 2016). Since SD imposes the obligation to preserve the ecological capital for future generations, I shall dedicate a specific objective dimension to both energy flows and material flows.

Energy flows can be classified into two distinct types: renewable and non-renewable energy fluxes or carriers. In this regard, the *Brundtland Report* proposed that societal development should take place only within the planet's ecological means (WCED 1987). Since non-renewable energy carriers are limited to their reserves or resources, such as in the case of coal (Thomas 2013), I argue that in electric power systems the priority should lie with exploring renewable energy fluxes and carriers. The latter cannot be exhausted and by tapping into the potential of this inexhaustible source of energy, no natural capital is irreversibly spent or made unavailable for future generations. Since electricity has become an indispensable fuel for modern societies to thrive (Ahmad, Mathai & Parayil 2014), however, I shall refrain from imposing a condition that fully prohibits the exploitation of non-renewable energy carriers. Accordingly, I argue that the second objective dimension should ensure that renewable energy fluxes or carriers are explored first before expending finite non-renewable energy carriers:

2) *Exploitation of renewable sources of energy before non-renewable ones*

Further, power infrastructure and electrical devices alter material flows by consuming resources such as metals or water. Exploiting these resources holds the risk of exhausting resource stocks (Afgan, Carvalho & Hovanov 2000; Gallego Carrera & Mack 2010; Hirschberg et al. 2005; Kowalski, Stagl, Madlener & Omann 2009; Onat & Bayar 2010). Furthermore, scientific evidence suggests that today some technical compo-

nents of electric power systems have an adverse effect on the atmosphere, ecosystems and the Earth's crust through pollutant emissions (Atilgan & Azapagic 2015; Brizmohun, Ramjeawon & Azapagic 2015; Duncan et al. 2013; Fearnside 2016; Hirschberg et al. 2005; Raugeri & Leccisi 2016; Sheldon, Hadian & Zik 2015). A key issue here is that the visible effects of these forms of environmental degradation are delayed: While current generations benefit from the improvements in human well-being attributed to the delivery of energy services, it is expected that future generations will encounter ecosystems with diminished service provision potential, such as extreme weather events stemming from global warming or nuclear radiation caused by nuclear power plants (Aliyu, Evangelidou, Mousseau, Wu & Ramli 2016; IPCC 2007). Since SD was specifically developed to counter such adverse developments in favour of future generations (WCED 1987), I shall formulate a third objective dimension directed at material flows. In line with the previously provided interpretation of SD, it will not, however, address issues related to resource scarcity only, but will also acknowledge more recently discovered increases in ecosystem fragility. Hence, it aims to secure resource efficiency and ecosystem services.

3) *Efficient resource consumption and the preservation of ecosystems*

These three objective dimensions encompass the key themes of the current scientific interpretation of SD (Burger et al. 2018): The first objective dimension aims to secure human well-being and the provision of goods and services for current generations, whereas the second and third objective dimensions are directed at securing a productive environment for future generations.

Accordingly, *Figure 23* depicts the functional components of electric power systems on the left-hand side, while the normative features of SD are shown in the upper part of the diagram. The figure highlights the fact that the objective dimensions relate to both the interpretation of SD and the functional elements of electric power systems with their enabling and constraining factors but excluding governance. Moreover, a brief summary of each objective dimension is provided in the white boxes.

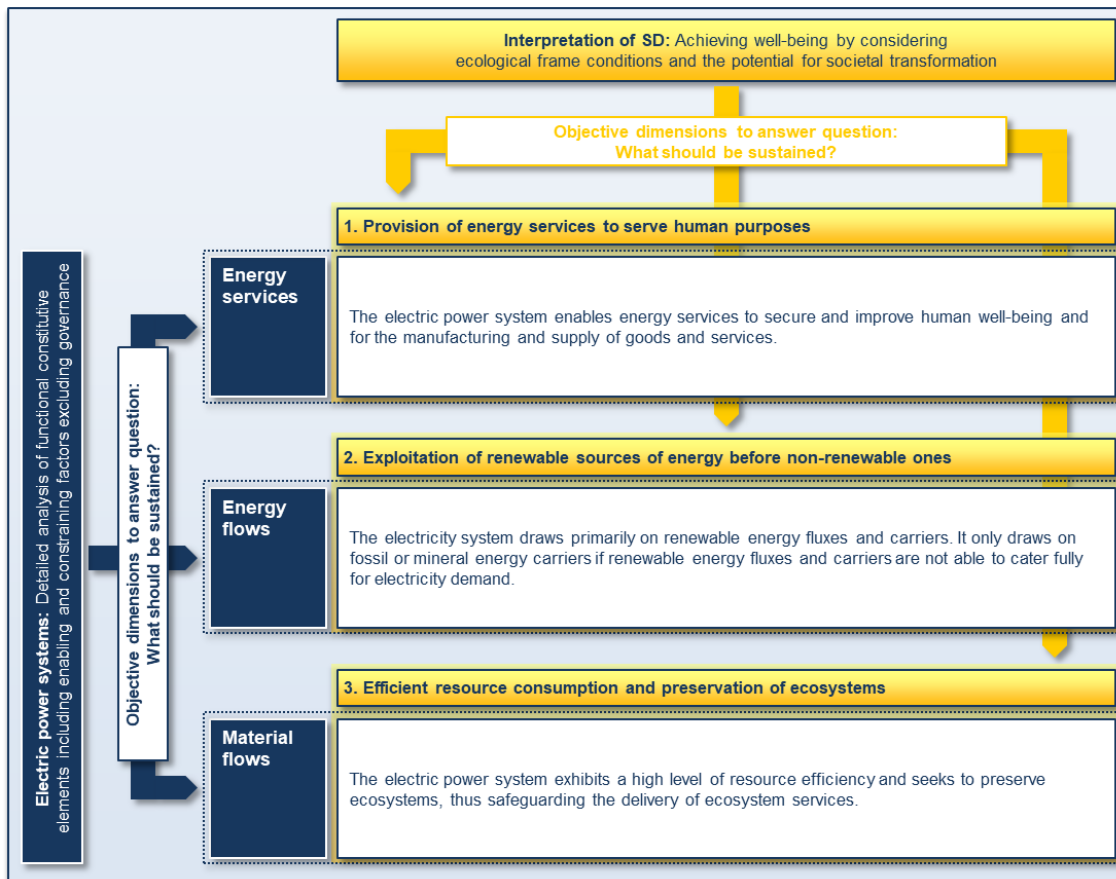


Figure 23: Normative objective dimensions for electric power systems

(Own elaboration)

In order to operationalise SD for electric power systems by means of a framework for sustainability assessments, these objective dimensions need to be translated with further interpretations into more specific steering rules. These rules then may serve as a basis for formulating general goals for criteria in sustainability assessments. Accordingly, I shall proceed by defining and arguing for a set of steering rules for each objective dimension.

10.2 Steering rules

To systematically define steering rules for sustainability assessments of electric power systems, mirroring those normative requirements of SD that are directed at the question *What should be sustained?*, I shall apply the same procedure to define objective dimensions. In order to formulate a set of steering rules applicable to electric power systems, I shall also draw on the detailed analysis of energy services, energy flows and material flows conducted in chapter 9.

In the previous section, I argued in favour of an objective dimension specifically directed at energy services: *Provision of energy services to serve human purposes*. Accordingly, I shall proceed by first dedicating a set of steering rules for those energy services that I deem relevant. As a starting point, *Table 12* displays the energy services provided by electricity systems that serve human purposes, as identified in chapter 9:

Energy service
Provision of lighting
Provision of heating
Provision of cooling
Provision of cooking
Provision of cleaning
Provision of information
Provision of communication
Provision of entertainment
Provision of recreation
Provision of fuelling of mobility
Provision of goods and services

Table 12: Summary of energy services

(Own elaboration)

At the same time, however, I will also draw on the previously selected interpretation of SD, which supports the normative requirement to ensure that future generations will also be able to achieve well-being (Burger et al. 2018). Hence, I argue that energy services will also be provided in the future as a result of the severe implications arising for individuals, government institutions and corporate enterprises should they become unavailable (Osman, Gachino & Hoque 2016).

Against this backdrop, I argue that the delivery of essential energy services also has to be evaluated in sustainability assessments to assess whether power infrastructure and electrical devices both refrain from eroding the ecological capital of Earth and contribute to societal development. This, however, begs the question as to whether all the above energy services are to be considered essential. Without going into a detailed discussion on the contribution of energy services to human well-being here, I argue that the vast majority of these services serve essential human purposes and I have already argued for their relevance in section 9.1. Human beings face various health-

related risk (Hajat et al. 2016; Hatvani-Kovacs, Belusko, Skinner, Pockett & Boland 2016; Ni et al. 2016) and scientific evidence suggests that the energy services of heating, cooling, cooking and cleaning help to safeguard human health. Similarly, the energy services of information, communication and fuelling of mobility have become extremely important in modern societies for cultivating contacts and organising collective action in a globalised world (Jones, Harms & Heinen 2016; Lee, Chen & Chan 2017). Moreover, the benefits of lighting to increase human productivity are widely acknowledged (Juslén, Wouters & Tenner 2007). Furthermore, the generic energy service directed at enabling manufacturing and provision of goods and services increases productivity and enables greater levels of process automation (Carpanzano & Jovane 2007). Against the backdrop of increasing populations, these contributions are often considered vital by scholars (Mollik, Rashid, Hasanuzzaman, Karim & Hosenuzzaman 2016). Since several scientific studies also highlight the relevance of recreation and entertainment for human health (Bartsch & Viehoff 2010; Buchecker & Degenhardt 2015), I shall also consider these energy services to be relevant.

Accordingly, I propose a set of steering rules related to the delivery of energy services. I shall, however, combine those energy services that serve similar purposes. More specifically, I propose to apply the following rules related to energy services, knowing that this is an open list that can be expected to change from time to time:

- 1.1 *Electric power systems enable the provision of lighting*
- 1.2 *Electric power systems enable the provision of heating and cooling*
- 1.3 *Electric power systems enable the provision of cooking and cleaning services*
- 1.4 *Electric power systems enable information and communication services*
- 1.5 *Electric power systems enable entertainment and recreation*
- 1.6 *Electric power systems provide for electric transport*
- 1.7 *Electric power systems enable the provision of goods and services*

I shall dedicate the first steering rule to lighting which among other things increases the number of hours in which individuals and workers may be active (Juslén, Wouters & Tenner 2007). I opt to merge energy services on heating and cooling into the same rule, as both alter the ambient temperature for the sake of comfort. Furthermore, I propose a rule related to cooking and cleaning since both energy services encompass a wide range of household appliances and aim to safeguard human health either by improving hygiene or in the proper preparation of food (Jarvis et al. 2016). Moreover, I

consolidate energy services for information and communication into a single rule, as such services draw on the same type of electric devices (Vorderer, Krömer & Schneider 2016). I also amalgamate entertainment and recreation into one rule as both energy services are thought to promote human health. Lastly, I dedicate one rule to electric mobility and another to the manufacturing of goods and services.

The next step encompasses drawing a set of rules related to those aspects of SD that are concerned with maintaining the ecological capital. In accordance with the second objective dimension *Exploitation of renewable sources of energy before non-renewable ones*, I shall produce a set of rules dedicated to energy flows.

According to the second objective dimension, power infrastructure and electrical devices should enable energy services without undermining the ecological capital of our planet. In terms of energy flows, I already argued in the previous section that renewable sources of energy should be given priority over fossil fuels or nuclear energy carriers. In other words, the potential of non-renewable energy carriers should only be utilised when, as a result of unavailability, excessive cost or lack of trade treaties with neighbouring states, renewable energy fluxes or carriers fail to enable the necessary power generation (Bigerna, Bollino & Micheli 2016; Rouhani, Niemeier, Gao & Bel 2016). While estimates on the extent of fossil and mineral fuels remain contested, their finite nature is unchallenged (Bauer et al. 2016; Shafiee & Topal 2009). Against this backdrop, I propose a rule that allows non-renewable energy carriers to be exploited the extent that they are in the future in principle substituted by renewable energy fluxes or carriers. Under this condition, future generations can still be expected to achieve human well-being.

Furthermore, attention needs to be paid to renewable energy carriers that can be over-exploited. Accordingly, I argue that the consumption of renewable energy carriers has to lie within regeneration rates. In cases of biomass power plants, for example, mal-practices in agriculture can cause severe forms of soil erosion potentially leaving the land unfertile for future generations as a result of nutrient losses (Ferreira, Panagopoulos, Cakula, Andrade & Arvela 2015; Merten & Minella 2013).

Moreover, I also argue that striving for a sustainable electric power system also requires aiming for the highest possible overall energy efficiency to minimise the need to tap into the potential of energy carriers. Nuclear power plants, for example, are for the time being only able to harvest a fraction of the energy stored in uranium. Expending

such energy carriers with today's technologies results in nuclear waste that still holds significant amounts of energy (Fiori & Zhou 2015; Gao & Ko 2014).

Accordingly, I suggest applying the following three steering rules related to energy flows in electric power systems to ensure that these rely mainly on renewable energy fluxes and carriers and exhibit as high energy efficiency levels as possible:

- 2.1 *Renewable sources of energy are exploited while non-renewable energy carriers serve as residual sources*
- 2.2 *The consumption of renewable sources of energy does not exceed regeneration rates*
- 2.3 *Electric power systems strive for highest possible energy efficiency*

The final task of this section concerns producing rules for material flows in electricity systems. These rules have to contribute to the third objective dimension: *Efficient resource consumption and the preservation of ecosystems*. It is common knowledge that SD strives to provide human well-being for both current and future generations. The interpretation chosen in this work recognises that current consumption patterns in Western societies are among other things a major driver of environmental degradation (Burger et al. 2018). These consumption patterns are broadly acknowledged to result in high levels of resource consumption and pollution (Duarte, Mainar & Sánchez-Chóliz 2013; Kalmykova, Rosado & Patrício 2016). Against this backdrop, I argue for a rule that imposes a critical threshold for resource consumption that corresponds to natural regeneration or recycling rates. Similarly, I argue for a second rule that prevents pollution from breaching a critical threshold as well (Bosello & De Cian 2014; IPCC 2007).³⁷

Furthermore, since SD seeks to safeguard human well-being for future generations as well, I argue that the catastrophic risks presented by components of the power infrastructure, such as nuclear power plants, should be mitigated as much as possible. Catastrophic events or accidents caused by these components are perceived as having long-lasting effects on both the environment and human health, including serious illnesses caused by exposure of nuclear radiation for example, which may affect the opportunity spaces of future generations (Beresford et al. 2016; Danzer & Danzer 2016).

³⁷ The idea behind this proposal is that scientists are in a position to determine tipping points for regenerative resource stocks and emission sinks. I acknowledge, though, that the most prominent examples of such thresholds, such as the climate change target of preventing an increase of global mean temperature of +2 degree Celsius, are merely a political consensus on appropriate risks to be borne by society.

Moreover, I argue that ecosystems, which among other things produce resources, should also be protected from the environmental degradation caused by the construction and operation of power infrastructure (Hamilton, Trimmer, Bradley & Pinay 2016; Saswattecha, Kroeze, Jawjit & Hein 2015). Likewise, emission sinks, which play a vital role in allowing for a high level of pollutant emissions to be tolerated, should also be conserved. In Borneo, deforestation caused by the production of palm oil for biomass energy is a prominent example of the environmental degradation of emission sink capacities caused by energy systems (Susanti & Maryudi 2016). The destruction of such ecosystems essentially imposes greater restrictions on fossil fuel-based power generation, assuming that global warming is sought to be prevented (IPCC 2007).

Lastly, there are ecosystems that should be protected from environmental degradation, as these ecosystems provide critical services for human well-being or are deemed to be of great intrinsic value³⁸ (Delgado & Marín 2016; Knüppe & Knieper 2016). Drawing on a more recent interpretation of SD (Burger et al. 2018), it becomes obvious that such ecosystems should not be made available for power infrastructure nor should they be adversely affected by pollution emanating from the technical components of the electric power system as they might impede opportunity spaces of future generations. Accordingly, I propose six rules for material flows to be applied in sustainability assessments of electric power systems:

- 3.1 *Consumption of resources does not exceed regeneration and recycling rates*
- 3.2 *Emissions caused by the power infrastructure remain within the extent of emission sink capacities*
- 3.3 *Actors face minimal risk exposure with regard to catastrophic events and serious accidents and illnesses*
- 3.4 *Resource stocks are shielded from the adverse effect of power infrastructure*
- 3.5 *Emission sinks are safeguarded against degradation caused by power infrastructure*
- 3.6 *Key ecosystems are protected from emissions emanating from the power infrastructure*

³⁸ Prominent examples are ecosystems containing fresh spring water, coral reefs with exceptionally high biodiversity or forests offering protection from windstorms, landslides, flooding or avalanches.

These rules aim to serve as a basis for deriving general goals for criteria in the next section. At this point, I would like to emphasise once again that the exemplary rules produced here are closely related to the interpretation of SD chosen in section 7.5 and the arguments proffered for what is essential to sustain. Should I have opted for a different interpretation of SD, then these rules could be expected to be different: A reduction of SD in environmental conservation, for instance, is likely to have led to the omission of the rules related to energy services. Furthermore, the rules depend on the system under review: The rules are not fully applicable or translatable to other systems delivering critical outputs to society, such as water supply or agricultural systems.

Figure 24 gives an overview of the proposed steering rules for electric power systems mapped to the corresponding objective dimensions. The diagram is based on the previous figure and shows the functional parts of the system on the left-hand side and normative aspects of SD in the upper part of the figure. Hence, the diagram highlights that steering rules are based on the SD model but directed at electric power systems.

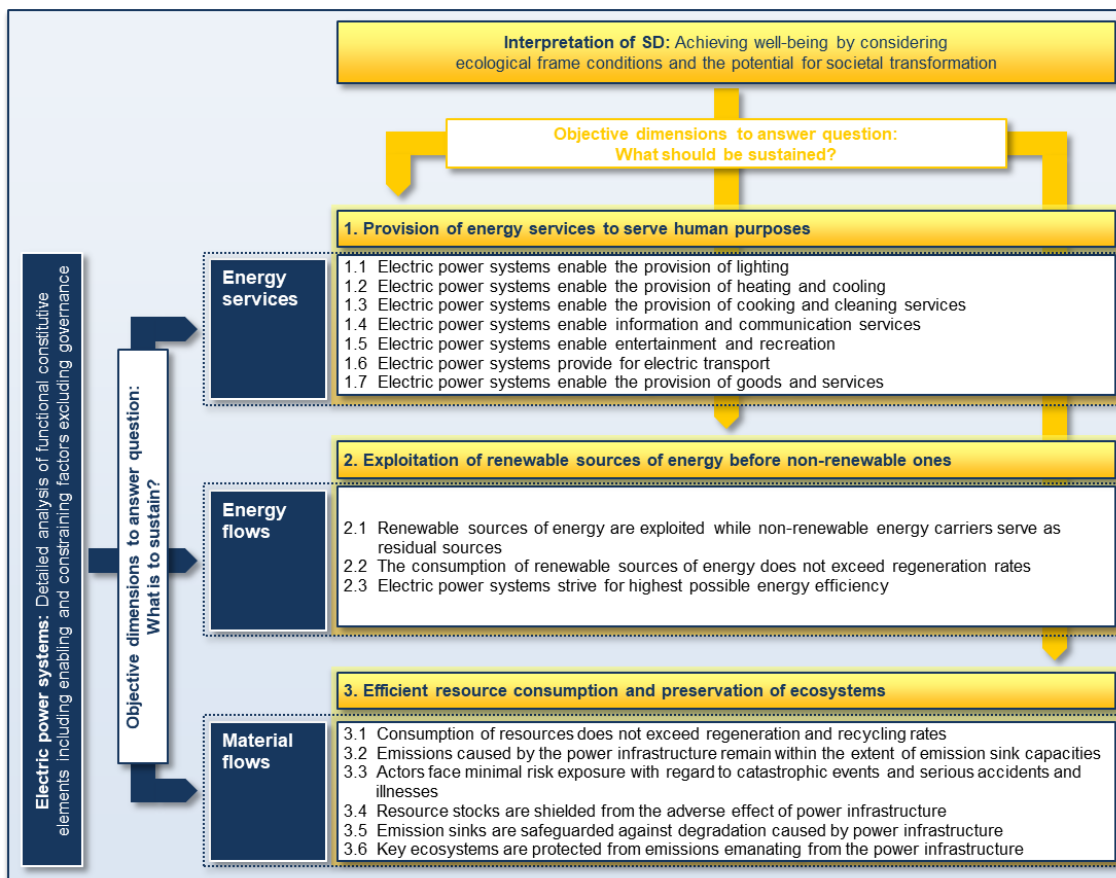


Figure 24: Steering rules for electric power systems

(Own elaboration)

With the contribution of this section and the previous work on analysing relevant flows in electric power systems, I have provided both the prerequisites for formulating general goals for criteria for sustainability assessments of electric power systems. In chapter 9 I systematically deduced a set of criteria for sustainability assessments of electric power systems framed according to the holistic system representation crafted in chapter 8. In this section, I formulated steering rules based on a current interpretation of SD. Accordingly, I shall proceed by formulating general goals for criteria based on the steering rules produced in this section. Once more I shall draw on the same approach.

10.3 General goals

Electric power systems serve the purpose of delivering energy services to private households, government agencies and corporate enterprises to improve human well-being and enable the provision of goods and services. In chapter 9, I identified those energy services that are considered essential in modern societies. In section 10.2, I then formulated a set of steering rules referring to energy services. These rules impose the condition that electric power systems should deliver energy services to their users in general. Since energy services are consumed based on demand, I shall refrain from specifying more detailed requirements, such as what quantity is to be provided. Accordingly, I shall neither formulate predefined quantitative goals for energy services to be met nor ranges of tolerance levels to be maintained. I shall merely stipulate that energy services are to be provided based on the demands of actors within the system.

I shall, however, introduce a restriction: at this point, I shall introduce a distinction between legitimate demand and luxury demand³⁹. Since the chosen interpretation of SD relates to the striving to secure human well-being for current and future generations (Burger et al. 2018) and the delivery of energy services requires finite natural resources or energy carriers (Afgan, Carvalho & Hovanov 2000; Gallego Carrera & Mack 2010; Hirschberg et al. 2005; Kowalski, Stagl, Madlener & Omann 2009; Onat & Bayar 2010), I argue that the system should primarily strive to meet legitimate demand. Against this backdrop, I shall introduce a corresponding condition based on the assumption that only a small fraction of the population benefits from luxury demand and scientific evidence suggests that luxury demand consumes vast quantities of energy and causes pollution

³⁹ For this thesis, I shall define legitimate demand as the demand for goods and services that are consumed in order to achieve human well-being in line with the previous interpretation of SD (Burger 2017). Based on this interpretation, a typical example of luxury demand in electricity systems are electrical heating systems for private swimming pools and saunas.

(Parker 2003; Mousia & Dimoudi 2015). Based on this restriction, *Table 13* lists the proposed criteria for energy services, as defined in section 9.1, with corresponding general goals based on the rules for energy services, as formulated in section 10.2.

Id	Criteria for energy services	General goals for the provision of energy services to serve human purposes
ES01	Provision of lighting	Meet legitimate demand for lux
ES02	Provision of heating	Meet legitimate demand to increase temperature
ES03	Provision of cooling	Meet legitimate demand to decrease temperature
ES04	Provision of cooking	Meet legitimate demand for calories and nutrients
ES05	Provision of cleaning	Meet legitimate demand to reduce pollution
ES06	Provision of information	Meet legitimate demand to obtain data
ES07	Provision of communication	Meet legitimate demand to exchange data
ES08	Provision of entertainment	Meet legitimate demand to obtain data
ES09	Provision of recreation	Meet legitimate demand for recreation
ES10	Provision of fuelling for mobility	Meet legitimate demand regarding kilometres covered
ES11	Provision of producing of goods and services	Meet legitimate demand to power devices

Table 13: Criteria and general goals for energy services

(Own elaboration)

To provide such energy services, power infrastructure draws on energy fluxes and carriers, converts energy into electricity and drives electrical appliances (Clough, Saad & Gould 2013). In section 9.2, I divided the sources of energy into four categories: renewable energy fluxes, which are provided infinitely, renewable energy carriers, which are produced according to regeneration rates (Twidell & Weir 2015) and both finite stocks of fossil energy carriers and nuclear energy carriers (Wiser 1999).

In order to answer the question on what energy sources are to be exploited, I shall refer to steering rule *Renewable sources of energy are exploited while non-renewable energy carriers serve as residual sources*. This rule provides guidance on which sources of energy should be harvested and to what degree their potential should be exploited. Against this backdrop, I argue that the potential of renewable energy fluxes can be fully exploited without restriction due to their infinite availability. Furthermore, suppliers can tap into the potential of renewable energy carriers. However, and here attention needs to be paid to steering rule *2.2 The consumption of renewable sources of energy does not exceed regeneration rates*, based on this condition, electric power

systems should only draw from renewable energy carriers to the extent of their regeneration rates. If actors adhere to this rule, then renewable energy carriers may serve human purposes indefinitely. Accordingly, I shall define a general goal for the criterion on renewable energy carriers, that is, that such energy stocks are not to be depleted.

According to steering rule 2.1, however, fossil and mineral fuels should only be utilised whenever renewable sources of energy fail to generate the demanded quantities of electric power. The aim of steering rule 2.1 thus essentially lies in safeguarding as much of the non-regenerative fossil and mineral energy carrier stocks for future generations or until technologies are available with more efficient conversion rates (Hore-Lacy 2016). Should renewable energy fluxes or carriers not be able to cater for the electricity demand, then suppliers have to decide on using fossil or mineral energy carriers to bridge supply gaps. However, fossil fuel-based power generation has two distinct advantages over nuclear power:

- i) **Ecological impact.** Although scientific evidence suggests that the combustion of fossil fuels drives climate change (IPCC 2007), the adverse environmental impacts of nuclear power are considered by some politicians and researchers to be more long-lasting. As a result of radiation, the disposal of nuclear waste requires long-term storage of spent fuel rods in deep geological repositories (Edwards, Bindra & Sabharwall 2016). Moreover, nuclear power plants expose human populations to catastrophic risks and system failure (Lewis et al. 1979; Wheatley, Sovacool & Sornette 2016). Accordingly, there is a general perception that nuclear power passes significant costs and risks on to future generations (Kula 2015).
- ii) **Power generation flexibility.** Some generation loads of fossil fuel-based power generation technologies are more flexible than nuclear power or can also be used for heating purposes. Accordingly, they can more easily complement the erratic power generation of some power plant technologies that convert volatile renewable energy fluxes into power (Mikkola & Lund 2016).

Against this backdrop, I argue that considering the long-lasting effects of nuclear power and its limitations with regard to complementing renewable power generation, fossil fuels should rather serve as a last resort for power generation and not nuclear power.

While steering rules 2.1 and 2.2 provide guidance on answering questions on what energy fluxes and carriers should be exploited and to what extent, steering rule 2.3 *Electric power systems strive for highest possible energy efficiency* is directed at safeguarding the efficient use of sources of energy by aiming for the highest possible overall energy efficiency ratio. To measure system efficiency, scholars often resort to methods that compare total primary energy use against electricity consumed (Swing Gustafsson, Gustafsson, Myhren & Dotzauer 2016). While such methods clearly shed light on the overall efficiency of the power infrastructure, I propose to compare primary energy use with the provision of energy services to consumers to measure electricity consumption against the output of devices. In any case, implementing rule 2.3 allows for energy efficiency to be assessed and aims to reduce energy consumption. In practice, such approaches often result in partly crowding out fossil and mineral fuels due to their poor primary energy performance (Stulz, Tanner & Sigg 2011). Should this steering rule be attained, then other positive effects can be expected, as increased energy efficiency requires fewer natural resources and causes less pollution (Meyers, Schmitt, Chester-Jones & Sturm 2016). Steering rule 2.3 can be applied to each individual energy service and the power system as a whole in order to determine sources of inefficiency.

Based on this analysis, I am in a position to match steering rules with criteria on energy flows, as defined in section 9.2, to compute general goals for these criteria. Following the above line of reasoning, I propose to allow unlimited exploitation of renewable energy fluxes, while renewable energy carriers should be harvested in accordance with their regeneration rates. Furthermore, I propose to refrain from exploiting nuclear energy carriers to secure the delivery of energy services, and assign fossil fuels the role to serve as a residual source of energy in the case of a supply shortage. As for criteria related to the provision of energy services, I propose to strive for the highest possible output-to-efficiency ratio. Accordingly, *Table 14* lists the criteria for energy flows as specified in section 9.2 and general goals mirroring the requirements of rules 2.1 to 2.3.

Id	Criteria for energy flows	General goals for the exploitation of renewable sources of energy before the exploitation of non-renewable ones
EF01	Provision of renewable energy fluxes	No degradation of sources of energy fluxes
EF02	Provision of renewable energy carriers	No degradation of sources of energy carriers
EF03	Provision of nuclear energy carriers	No degradation of reserves
EF04	Provision of fossil fuel-based energy carriers	No degradation of reserves
EF05	Consumption of renewable energy fluxes	Unlimited use of energy fluxes

EF06	Consumption of renewable energy carriers	Use of energy carriers within regeneration rates
EF07	Consumption of nuclear energy carriers	Do not use at all
EF08	Consumption of fossil fuel-based energy carriers	Use of energy carriers only in the absence of renewable energy sources
EF09	Energy use for lighting	Attain highest possible ratio of lux/W
EF10	Energy use for heating	Attain highest possible ratio of degree Celsius/W
EF11	Energy use for cooling	Attain highest possible ratio of degree Celsius/W
EF12	Energy use for cooking	Attain highest possible ratio of kcal/W
EF13	Energy use for cleaning	Attain highest possible ratio of pollution cleaned/W
EF14	Energy use for information	Attain highest possible ratio of unit of data/W
EF15	Energy use for communication	Attain highest possible ratio of unit of data/W
EF16	Energy use for entertainment	Attain highest possible ratio of unit of data/W
EF17	Energy use for recreation	Attain highest possible ratio of hours/W
EF18	Energy use for fuelling of mobility	Attain highest possible ratio of km/W
EF19	Energy use for manufacturing of goods and services	Attain highest possible ratio of unit of output/W
EF20	Overall energy efficiency	Attain lowest possible conversion losses

Table 14: Criteria and general goals for energy flows

(Own elaboration)

In order to build and operate power infrastructure and electrical devices natural resources are spent (Afgan, Carvalho & Hovanov 2000; Gallego Carrera & Mack 2010; Hirschberg et al. 2005; Kowalski, Stagl, Madlener & Omann 2009; Onat & Bayar 2010). This begs the question: How many resources can be exploited without jeopardising development paths of future generations? In order to define a tolerable level for resource consumption, I shall refer to steering rule *3.1 Consumption of resources does not exceed regeneration and recycling rates*. This steering rule allows restrictions on resource quantities to be spent for the construction and operation of power infrastructure and electrical devices to be formulated: the exploitation of renewable resources, such as water or wood, should not exceed the regeneration rates, while the consumption of non-renewable resources, like metals, should not exceed the recycling rates.

While the previous steering rule regulates the consumption levels of natural resources, steering rule *3.2 Emissions caused by the power infrastructure remain within the extent of emission sink capacities* is directed at limiting the pollution caused by power systems. As elaborated in section 9.3, the technical components of electricity systems are

known to cause a wide range of pollutant emissions⁴⁰ (Atilgan & Azapagic 2015; Briz-mohun, Ramjeawon & Azapagic 2015; Duncan et al. 2013; Fearnside 2016; Hirschberg et al. 2005; Raugeri & Leccisi 2016; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Sheldon & Hadian 2015). Since some quantities of hazardous emissions can be broken down by emission sinks (Muñoz-Vallés et al. 2016; Vanhala et al. 2016), I argue that, to prevent long-term environmental degradation, the pollution emanating from these technical components should not exceed the absorption capacities of emission sinks.

Furthermore, the technical components of electric power systems also expose human settlements to further, more acute threats. These risks, such as exposure to catastrophic accidents, electromagnetic radiation, land contamination or nuclear radiation, can obviously have serious effect on human health (He, Wang & Huang 2008; Lewis et al. 1979; Nascimento Medeiros & Ganz Sanchez 2016; Wheatley, Sovacool & Sornette 2016). According to steering rule *3.3 Actors face minimal risk exposure with regard to catastrophic events and serious accidents and illnesses*, such risk exposure should be mitigated as much as possible. Steering rules *3.2* and *3.3* are also directed at maintaining a high level of human life expectancy. Accordingly, I shall define a general goal that life expectancy should not be adversely affected by electricity systems.

Moreover, the availability of natural renewable resources, such as timber or fibre, depends on the size of resource stocks and the regeneration rates. At the same time, non-renewable resources, like metals and minerals, do not regenerate naturally, but can be recycled recycling plants (Colling, Oliveira, Reis, Da Cruz & Hunt 2016; Foelster et al. 2016). While both types of resource stock comprise the ingredients required to construct and operate electricity systems, the stocks themselves may be under threat as a result of other development endeavours. Steering rule *3.4 Resource stocks are shielded from the adverse effect of power infrastructure* imposes the condition that these resource stocks must be protected from environmental degradation thus ensuring that future generations do not face situations where these valuable stocks are irreversibly depleted.

Emission sinks perform a vital service by breaking down pollutant emissions to levels where ecosystems and human health are not threatened. Prominent examples of such

⁴⁰ In section 9.3, I identified the release of greenhouse gases, chlorofluorocarbons, sulphur and nitrogen oxides and particulate matter, use of land area, distortion of ecosystems, losses in biodiversity, causes of acidification and eutrophication, soil and desertification and eco-toxicity as key pollutant emissions.

emission sinks are tropical rainforests and oceans, which, among other things, absorb greenhouse gas emissions and offer coastal protection (Daigle et al. 2016; Thomas 2017). These ecosystems display some level of resilience towards different types of pollution, including eco-toxicity, acidification and eutrophication (Pettit et al. 2013; Rougé, Mathias & Deffuant 2013). Steering rule *3.5 Emission sinks are safeguarded against degradation caused by power infrastructure* stipulates that emission sinks must be protected. Lowering the productivity of emission sink capacities could potentially lead to a decrease in the tolerable level of toxic substances thus threatening future development opportunity spaces (Salazar et al. 2016; Swann, Longo, Knox, Lee & Moorcroft 2015). Ultimately, meeting this rule will require finding solutions to protect relevant emission sinks from the adverse effects of human activities.

Ecosystems provide a wide range of services relevant to maintaining a productive environment and human well-being, such as the provision of food and freshwater, biochemical and genetic resources, regulation of climate, regulation of diseases, pollination, soil formation and nutrient cycling (BenDor, Spurlock, Woodruff & Olander 2017; Mouchet et al. 2017). While these ecosystems are today known to deliver crucial services to societies, some of them are in competition with key infrastructure projects. Hydroelectric power generation, for example, is known to cause problems in the Zambezi and the Nile river delta, as well as in parts of the Amazon and the Congo basin (Kashef 1981; Palmeirim, Peres & Rosas 2014). According to rule *3.6 Key ecosystems are protected from emissions emanating from the power infrastructure*, however, ecosystem services that are vital for environmental productivity and human well-being are to be safeguarded.⁴¹ Moreover, nuclear power plants expose human populations to risks, both as a result of their operation and the transportation and storage of nuclear waste (Benbow 1997). Based on rule *3.6*, human settlements must also be shielded from the risks emanating from the technical components of power systems. Since I have already argued against nuclear power in this section, I shall note here that nuclear waste is to be avoided at all costs.

Based on this translation of steering rules into general goals for criteria, *Table 15* displays those criteria formulated for material flows in section 9.3, including their general goals deduced in this section based on rules *3.1* to *3.6* which relate to material flows.

⁴¹ At this point, I would like to acknowledge that some ecosystems create additional value for human populations, such as spiritual and religious use, cultural heritage, aesthetics, recreational use and ecotourism, inspirational and educational use (Laband 2013; Willis 2015). Accordingly, some scholars argue that the technical components of electric power systems should also refrain from adversely affecting ecosystems that offer such value.

Id	Criteria for material flows	General goals for efficient resource consumption and the preservation of ecosystems
MF01	Provision of non-renewable resources	No degradation of resource stock
MF02	Consumption of non-renewable resources	Use within recycling rates of material stock
MF03	Provision of renewable resources	No degradation of resource stock
MF04	Consumption of renewable resources	Use within regeneration rates of material stock
MF05	Provision of fossil fuels	No degradation of reserves
MF06	Consumption of fossil fuels	As low as possible
MF07	Emission of greenhouse gases	Lower than absorption capacity of emission sink
MF08	Absorption of greenhouse gases	No degradation of emission sink
MF09	Emission of chlorofluorocarbons	Lower than absorption capacity of emission sink
MF10	Absorption of chlorofluorocarbons	No degradation of emission sink
MF11	Emission of sulphur and nitrogen oxides	Lower than absorption capacity of emission sink
MF12	Absorption of sulphur and nitrogen oxides	No degradation of emission sink
MF13	Emission of particulate matter	Lower than absorption capacity of emission sink
MF14	Breakdown of particulate matter	No degradation of emission sink
MF15	Use of land	None for protected areas; efficient use of others
MF16	Availability of land	No degradation of relevant land area
MF17	Distortion of ecosystems	Lower than absorption capacity of emission sink
MF18	Delivery of ecosystem services	No degradation of relevant ecosystem services
MF19	Losses in biodiversity	Lower than absorption capacity of emission sink
MF20	Biodiversity	No losses in relevant ecosystems
MF21	Causes of eutrophication and acidification	Lower than absorption capacity of emission sink
MF22	Resilience to eutrophication and acidification	No degradation of emission sink
MF23	Erosion of soil and desertification	Lower than absorption capacity of emission sink
MF24	Provision of soil	No losses in relevant soil
MF25	Causes of eco-toxicity	Lower than absorption capacity of emission sink
MF26	Absorption of eco-toxicity	No degradation of emission sink
MF27	Reduction in life expectancy	No reduction in life expectancy
MF28	Life expectancy	
MF29	Increase in exposure to catastrophic risks	Minimise risk to human health
MF30	Exposure to catastrophic risks	
MF31	Causes of electromagnetic radiation	Minimise risk to human health
MF32	Resilience to electromagnetic radiation	
MF33	Causes of nuclear waste	None

MF34	Absorption of nuclear waste	
MF35	Causes of land contamination/nuclear radiation	Minimise risk to human health
MF36	Resilience to land contamination/nuclear radiation	

Table 15: Criteria and general goals for material flows

(Own elaboration)

This set of general goals relating to criteria for material flow completes my task in this chapter of setting goals that mirror the normative requirements of the chosen interpretation on SD. However, before moving on to producing a similar set of goals related to instrumental aspects of SD, I shall summarise the preliminary conclusions on the endeavour carried out in this chapter.

10.4 Conclusions

This chapter served the purpose of conceptually reason for a set of exemplary general goals relating to criteria for sustainability assessments based on a detailed analysis of energy services, energy flows and material flows on the one hand, and a translation of the current interpretation of the normative requirements of SD on the other hand. The resulting general goals are directed at answering the question *What should be sustained?* Hence, they do not provide guidance for addressing aspects related to transformation governance.

In section 7.7, I proposed a multi-step procedure for, firstly, formulating objective dimensions based on a current scientific interpretation of SD. Subsequently, I produced a set of steering rules based on such objective dimensions to eventually translate the steering rules into more specific general goals for the criteria formulated in chapter 9. This process allowed me to argue and reason for a more detailed interpretation of the normative notions of SD and systematically derive more tangible goals for criteria.

While this transparent analysis enabled me to produce and reason for general criterion goals in sustainability assessments of electric power systems, I would like to emphasise that the results obviously depend on interpretations of SD. Accordingly, the deliverable of this chapter could have been very different had I chosen a different interpretation or put other arguments forward. However, at this point I would like to stress once more that my aspiration for this output did not lie with providing a universally applicable set of steering rules or general goals for criteria, but rather to demonstrate the benefits

of a more systematic approach. Like the deduction of criteria based on a detailed analysis of energy and material flows and the societal steering processes of electric power systems in chapter 9, I strive with this contribution to highlight the benefits of the transparency that such a procedure provides. The added value here lies with providing a basis for a discussion on how the rather abstract guiding principles of SD can be translated into more specific goals for policy steering instruments, such as sustainability assessments, which are designed so as to provide a basis for *evidence-based* and *goal-oriented* decision making.

The results presented in this chapter consist of a set of proposed steering rules and general goals for criteria in sustainability assessments of electric power systems. This begs the question, what similarities do they share with existing literature and how can discrepancies be explained? At this point, however, I would like to postpone such a discussion to chapter 12, where I shall discuss the scientific contributions made in chapters 8 to 11 as a whole to better highlight the overall benefits of the proposed framework.

The list of criteria for electric power systems with corresponding general goals defines the requirements that the system has to meet in the future in order for it to be considered sustainable. To meet these goals, a system transition will be required. This raises a further question: What are requirements for conducting such a system transition?

In order to answer this question, which is related to the instrumental aspects of the conception of SD, I shall proceed in chapter 11 by defining instrumental rules and general goals for criteria related to societal transformation processes. I shall thus draw on the more detailed layout of reflexive governance of change provided in section 9.4.

11 Instrumental rules

Today, societies are characterised by shared responsibilities among government institutions and other actors, and critical system knowledge is dispersed among various actors (Czada & Schimank 2000; Pahl-Wostl 2007). Against this backdrop it becomes obvious that transforming a complex human-environment system towards more sustainable trajectories requires collective action (Rhodes 1997). Furthermore, key literature on SD broadly acknowledges the need to actively direct development according to predefined sustainability objectives, as current consumption patterns are thought to erode ecological capital and threaten the opportunity spaces of future generations (UNCED 1992; WCED 1987). Accordingly, system development has to be actively steered to facilitate the organisation of various activities to meet these common goals.

Since the effectiveness of governance frameworks depends on the issues faced by the systems, I argued in section 7.6 that the instrumental requirements for conducting a transformation of electric power systems in industrialised countries can be obtained from reflexive transformation governance. Such governance is considered to be more appropriate for dealing with the complex sustainability challenges faced by electricity systems today, as recent scientific research has questioned whether traditional governance, consisting of forecasting, analysis and bureaucracy, is able to deal with modern sustainability issues (Newig & Voss 2010). I argued in section 7.5 that some instrumental requirements of the *Brundtland Report* may have to be enriched. Accordingly, I suggested drawing on a more encompassing interpretation of SD that accounts for recent scientific insights on reflexive transformation governance. Thus, I shall proceed by summarising key aspects related to the reflexive governance of change that are frequently mentioned in research on the governance of SD and are relevant for electric power systems:

- i) **Active steering.** Scientific evidence strongly support the fact that current development patterns in industrialised countries erode the ecological capital. To prevent long-term environmental degradation, changes in consumption patterns are deemed necessary (WCED 1987).
- ii) **Cooperation.** Modern societies are characterised by a high level of specialisation and key systems deliver essential outputs to private households, government agencies and enterprises. In order to operationalise SD, various actors are assumed to be required to contribute to the transformation of

those systems to more sustainable states. However, there are conflicting views among scientists on what form of participation best supports this process. Nonetheless, it remains uncontested that governments may no longer be able to prevent or remedy environmental degradation or societal problems without including and engaging other actors (Newig, Voss & Monstadt 2008).

- iii) **Reflexivity**. The deployment of new technologies is at risk of causing new environmental degradation or adverse societal effects. While the emergence of new risks cannot be prevented, reflexive processes that monitor system developments and trigger early responses will enable societal education and curb harmful developments in the early stages (Meadowcroft 2011).

At this stage, I shall assume that the points mentioned above are a prerequisite in order to enable successful system transitions to more sustainable states. Accordingly, I shall base my work on setting instrumental goals for criteria in sustainability assessments of electricity systems on the above features.

To systematically derive instrumental goals for criteria for sustainability assessments of electric power systems, I shall revert to the same multi-step procedure and structural features as applied in chapter 10. I shall first formulate a set of objective dimensions based on the above cornerstones of reflexive governance of change. These objective dimensions then serve as a starting point for systematically derive a set of instrumental rules. Based on these instrumental rules I can then reason for general goals related to social criteria in sustainability assessments of electric power systems that are directed at answering the question: *How should this be sustained?*

11.1 Objective dimensions

In order to enable objective dimensions to serve as a basis for translating the instrumental aspects of SD into more tangible goals for corresponding criteria, they must meet three requirements: Firstly, they have to relate to above key features of reflexive transformation governance. Secondly, they have to be applicable to the system under review, namely, electric power systems. Thirdly, they have to contribute to answering the question: *How should this be sustained?* Against this backdrop, I shall first formulate an objective dimension related to the general requirement to actively direct development.

The conception of SD acknowledges that current consumption patterns in industrialised countries may have to undergo changes as they are considered to be key drivers of severe forms of environmental degradation. The authors of the *Brundland Report* concluded that conducting business as usual is likely to lead to future generations no longer being able to meet their needs (Kemp, Parto & Gibson 2005; WCED 1987). Various research papers and political documents support that claim and reinforce the notion that more sustainable consumption patterns are likely to be necessary to sustain a productive environment for the future (Rees 1992; FSOS 2006). Against this backdrop, some scientists argue that societal development has to be actively directed towards sustainability objectives as new insights on the adverse effects of human-environment relationships are discovered (Meadowcroft 2011). Accordingly, I shall dedicate the first instrumental objective dimension to the pursuit of actively steering system development and instruments for implementation, such as policy instruments or new technologies, in accordance with the chosen interpretation of SD (Burger et al. 2018):

4) *Active steering of system development*

Most industrialised countries are today characterised by fragmented ownerships of key technical components of the electric power system and critical system knowledge is dispersed across various actors (Czada & Schimank 2000; Pahl-Wostl 2007). Since these actors tend to follow their own agendas in pursuit of their own interests, governments are no longer able to conduct such transformations without involving and engaging other actors (Stirling 2009). In response to this, the current scientific debate on SD governance explores various modes of transformation governance that may support system transitions under the above-mentioned conditions (Kemp, Parto & Gibson 2005; Lange, Driessen, Sauer, Bornemann & Burger 2013; Steurer 2010; Treib, Bähr & Falkner 2007; Van Zeijl-Rozema, Cövers, Kemp & Martens 2008). While thus far no consensus has been reached, there is agreement that in order to overcome sustainability challenges, the involvement and engagement of a wide range of actors is required, who may collectively collaborate in pursuing common goals (Driessen & Glasbergen 2002; Swyngedouw 2005). Government actors are thought to facilitate arenas in which key actors in the system come together to share system knowledge and explore pathways to attain sustainability objectives. To account for this, I shall specify an objective dimension that encompasses the requirement for collaboration between various actors:

5) *Collective organisation of work among various actors*

Since some of the current environmental and societal issues arose from the unintended consequences of the implementation of hitherto new power infrastructure technologies (IPCC 2005; Mahaffey 2015), many scholars argue that a reflexive process may play a key role in the future by monitoring system developments and the effects they have on both the environment and societal actors (Meadowcroft 2011). They further argue that in order to benefit as much as possible from specialised system knowledge, such a reflexive process also has to involve key actors, such as environmental agencies, grass-roots movements and the media, to foster mutual learning (Newig, Voss & Monstadt 2008). These actors are thought to independently monitor system developments, observe the effects on the environment resulting from the construction and operation of technical components and social organisation, and trigger the deployment of counter measures such as political initiatives or changes in business models (Foxon, Reed & Stringer 2009; Voss & Bornemann 2011). Accordingly, adverse developments are assessed by actors who do so according to their specialisation. Their findings should then be brought into a societal discourse that explores and potentially triggers changes. Against this backdrop, I argue that reflexive processes, which are particularly important in systems that have conflicting issues and goals, may have to be evaluated in sustainability assessments of electric power systems to identify whether a wide range of system knowledge is considered when deciding on priorities and goals. Accordingly, I propose to direct the third instrumental objective dimension at reflexive processes to foster learning and promote the adaptive capacities of the system under review:

6) *Reflexive process to ensure learning and adaptation*

These objective dimensions encompass the three key features of reflexive governance of change introduced in section 7.6. The first one is directed at the general feature of directing development. The second objective dimension accounts for the collective organisation of work involving different actors while the third is directed at establishing and running a reflexive process to increase system knowledge and the responsiveness of the system. Accordingly, *Figure 25* displays the instrumental objective dimensions and how they relate to the instrumental aspects of the chosen interpretation of SD.

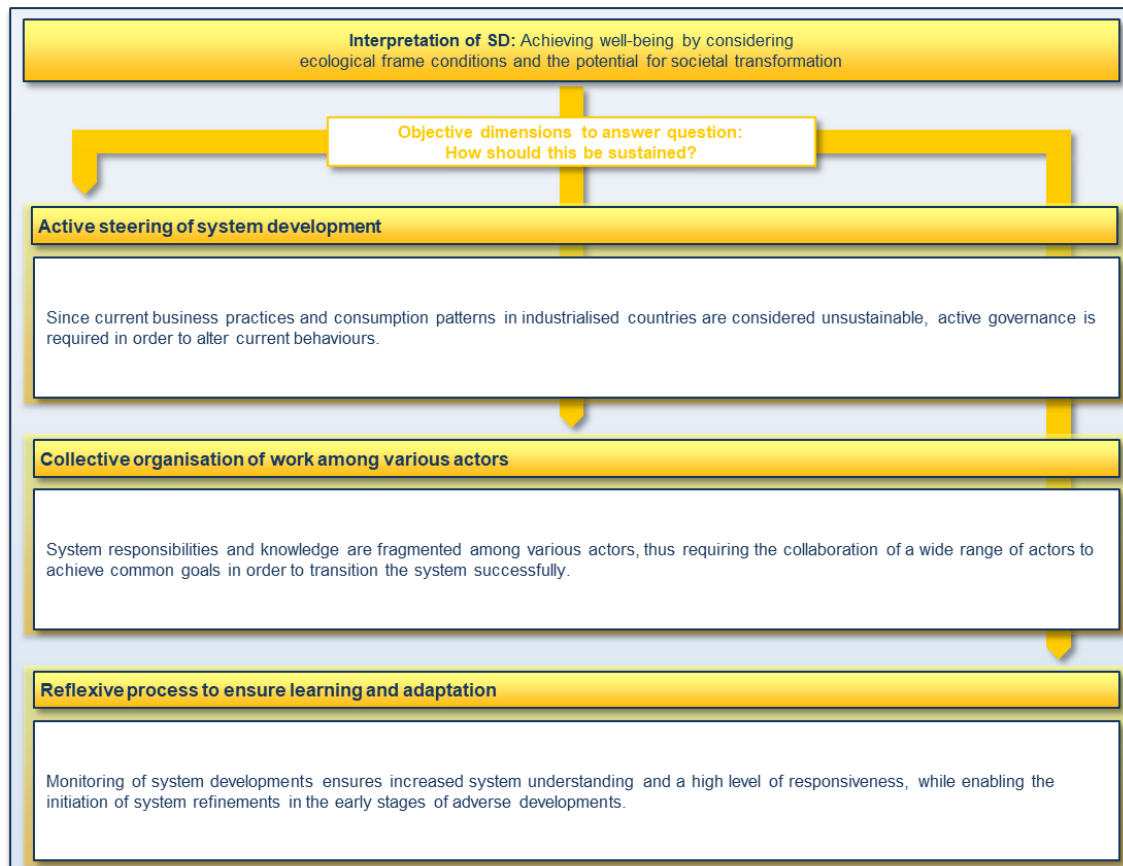


Figure 25: Instrumental objective dimensions for electric power systems

(Own elaboration)

I shall proceed by formulating a set of instrumental rules that is an enriched version of the instrumental objective dimensions presented in this section. Since such a multi-step procedure is prone to subjective views, I shall argue for my interpretations and provide my reasoning.

11.2 Instrumental rules

To derive a set of instrumental rules for sustainability assessments of electric power systems based on the objective dimensions that contribute to answering the question *How should this be sustained?*, as defined in the previous section, I shall draw on the same procedure as applied to the formulation of steering rules in chapter 10. I shall also draw on the detailed analysis of societal steering processes elaborated in section 9.4 to ensure that the relevant actors and their activities are considered. I shall proceed by first producing a set of instrumental rules related to the objective dimension: *Active steering of system development*.

Assuming that society strives for a transition towards more sustainable electricity systems according to the interpretation of SD chosen in section 7.5, then different actors, namely, researchers, policy makers and administrations, market actors and civil society actors, must contribute collectively to a better understanding of the system (Newig, Voss & Monstadt 2008). My contribution in chapter 8 revealed strong interdependencies among different actors and between actors and the environment. Moreover, my initial review in section 2.3 highlighted the multiple challenges that power systems currently face. Against this backdrop, I argue that some research should be directed at promoting an understanding of the overall system to better comprehend the interrelationships between societal development and environmental degradation (Ahmad, Tahar, Muhammad-Sukki, Munir & Rahim 2016; Khan & Abbas 2016). There is good reason to believe that a sound understanding of system dynamics is a necessary precondition for undertaking system transitions. Conducting such transformations, however, also requires the deployment of a set of corresponding solutions, such as new technologies or policies. Accordingly, I argue that some research should be dedicated to discovering new clean technologies and developing steering instruments to alter unsustainable behaviours (Izadyar, Ong, Chong & Leong 2016; Podgornik, Sucic & Blazic 2016; Riesz & Elliston 2016). Against this backdrop, I propose to direct the first rule at research on system dynamics in electricity systems, new clean technologies and policy steering instruments that contribute to more sustainable electric power systems:

4.1 Scientists research system dynamics, technologies and behaviours

Once the sources of sustainability issues have been discovered and counter measures are identified by researchers, policy makers and administrations should deploy policy instruments that drive energy efficiency, promote renewable energy and smart grid technologies or, alternatively, penalise fossil fuel-based or nuclear power generation (Fouquet 2016; Thapar, Sharma & Verma 2016). Furthermore, incentives should be provided for consumers to alter their behaviour (Staddon, Cycil, Goulden, Leygue & Spence 2016). Such endeavours are likely to consist of a wide range of policy steering instruments to ensure that system transitions are carried out according to sustainability objectives (Pollitt 2012). Accordingly, I shall dedicate the second instrumental rule to the policy maker's endeavour to deploy policy steering instruments that drive a transition to more sustainable electric power systems:

4.2 Policy makers enact energy policy promoting renewable energy technologies and energy efficiency

The contributions of researchers, policy makers and administrations provide the frame conditions for the manufacturers of system components or electrical devices and the suppliers of electricity. While the chosen interpretation provides guidance on the necessity for a system transformation (Burger et al. 2018), one should not forget that electricity systems in industrialised countries already have an important responsibility. In section 1.1 I explained the importance of a stable and cost-efficient supply of electricity to consumers in modern societies (Hughes 1993). Since electricity is often used by electrical devices to meet rather basic needs (Bedir, Hasselaar & Itard 2013; Kavousian, Rajagopal & Fischer 2013), I argue that electricity utilities must continue to ensure a stable electricity supply for their consumer base free of discrimination.⁴²

4.3 Suppliers provide electricity to consumers in a reliable and non-discriminatory way

However, assuming that policy makers and administrations put regulations promoting clean technologies in place, then manufacturers and suppliers may have to alter their business models in accordance with such conditions (Bolton & Hannon 2016; Wainstein & Bumpus 2016). This essentially means that in those systems where there is to be a transition from a power infrastructure design that causes environmental and societal problems to one based on increased shares of renewable energy and smart grid technologies, suppliers have to redesign their business models. One should then be able to see changes in the product portfolio of or solutions offered by incumbents as well (Bolton & Hannon 2016; Govindan, Seuring, Zhu & Farrido Azevedo 2016). Accordingly, I shall stipulate a fourth instrumental rule to direct suppliers' efforts to adjust their business models in order to provide energy efficiency and clean energy solutions:

4.4 Suppliers develop business models and drive system transition through implementation

These four steering rules give a more detailed breakdown of the objective dimension *Active steering of system development*. They encompass three of the four key actors identified in chapter 8 that are thought to have a strong influence on the development of electric power systems. However, I in no way imply here that it is only the contribu-

⁴² Today, a large number of electricity suppliers in industrialised countries are still at least partly owned by governments. In such cases, governments are represented in key decision bodies and the development of power infrastructure is based on long-term political planning processes (Breeze 2014). Against this backdrop, it is often argued that electricity supply is provided as a public service.

tions of these actors that are deemed relevant for transforming electric power systems in terms of sustainability objectives. The opposite is true: civil society actors must be involved and engaged as they play an important role in society. This brings me to my next task in this section, which is related to defining instrumental rules for the fifth objective dimension: *Collective organisation of work among various actors*.

A hallmark of reflexive transformation governance is the recognition that system transitions require closer collaboration between governments and other actors (Steurer 2010). This raises questions on what measures policy makers and administrations need to implement to enable other actors to contribute. Against this backdrop and assuming that most systems have emerged from monopolistic structures and have so far been subject to traditional governance with limited participation opportunities, policy makers and government institutions may have to establish frameworks that allow access to political processes for a wider range of actors. Such a framework may have to grant participatory rights to civil society actors and market access for the suppliers of new technologies, as participation is broadly acknowledged to be a prerequisite for successful energy transitions (Van der Werff & Steg 2016; Yildiz 2014). This could be an essential feature, as the contributions of new actors, such as consumer agencies or the manufacturers of new technologies, might put consumers in a better position to drive the selection of technologies through market choice and, thus, organised institutional actors may more easily assume a reflexive role (Huh, Woo, Lim, Lee & Kim 2015; Vecchiato & Tempesta 2015). Accordingly, I propose to impose a rule to regulate policy makers' and administrations' efforts to foster participation and innovation:

5.1 Policy makers establish frameworks that encourage participation, innovation and dynamic system development

Since this instrumental rule encompasses rather broad themes of participation, innovation and system dynamics, I shall further specify its key contents to better enable a formulation of general goals later on:

- i) **Prevention of technological lock-ins.** This part of the instrumental rule assumes that a significant part of power infrastructure, such as fossil fuel or nuclear-based power generation, has to be replaced (Michelsen & Madlener 2016; Rehner & McCauly 2016). However, such an endeavour could potentially be undermined by the long life spans of infrastructure components, as incumbents are reluctant to incur financial losses resulting from the sunk

costs of existing infrastructure components and the deployment of additional renewable energy technologies reduces power prices. This conflict may result in path dependences, as incumbents refrain from investing in new technologies so long as existing components are not fully depreciated (Ellerman 1996). Accordingly, I argue that policy frameworks should offer incentives for the deployment of new technologies and that special consideration should be given to those that can be replaced within short timeframes. This will ease the process of replacing infrastructure components in the future whenever new scientific evidence suggests the need to substitute specific infrastructure components.

- ii) **Promotion of innovation.** Some scientists propose that such frameworks should encourage technical and business model innovation (Kang & Hwang 2016). It is important to provide incentives for innovation because the successful implementation of new technologies or business ideas is often subject to some degree of trial and error, discouraging incumbents as they fear financial losses.
- iii) **Market access.** Since new technologies are likely to be developed by new market actors, these actors may have to be admitted to markets which are today monopolies. This may require breaking open existing monopolies to expose the incumbents to competition (EPCEU 2009; Markard & Truffer 2006; Müller, Steinert & Teufel 2008).
- iv) **Access to political processes.** Some scholars argue that civil society actors should be accorded the right to monitor system developments, participate in processes related to the definition of future requirements for electric power systems and actively influence consumption patterns (Dryzek & Pickering 2017; Kong, Salzmann, Steger & Ionescu-Somers 2002). Independent parties may support societal debates by extracting and analysing data on system components, participating in discussion arenas or actively promoting resource-efficient lifestyles.

While policy makers and administrations can be expected to provide the necessary frame conditions to enable participation, the benefits of reflexive governance also, obviously, depend on the active engagement of non-government actors to promote mutual learning (Newig, Voss & Monstadt 2008). However, actors are known sometimes to

assume a perspective that is not neutral with regard to how the system should be developed for the greater good, and may be inclined to pursue their own interests according to own agendas (Stirling 2009). Accordingly, I shall dedicate a rule to imposing a condition that actors should actively contribute towards building system knowledge:

5.2 Actors contribute to increasing a collective understanding of the system and deducing measures

Thus far, my set of instrumental rules covers the essential features of active steering and the participation of reflexive transformation governance. However, I have not yet contributed instrumental rules for the features of reflexivity and adaptation. Accordingly, I shall proceed by formulating a final set of rules to also cover this third aspect.

Increased levels of participation, which are to be granted according to rule 5.1, can be expected to allow civil society actors to better assume a reflexive role. This might involve activities like monitoring the adverse effects of market behaviours or the deployment of new technologies on the environment (Kern & Rogge 2016). While identifying irregularities is a necessary precondition for resolving them, civil society actors may also have to introduce their findings into the public discourses or support consumers in their endeavour to reduce their environmental footprint (Kong, Salzmann, Steger & Ionescu-Somers 2002). Against this backdrop it becomes evident that a key benefit of reflexive governance is the level of involvement and engagement of the different actors in reflexive processes. Accordingly, I argue that it is worthwhile to deploy a rule for the engagement and involvement of civil society actors in reflexive processes in order to identify problems and contribute to further development of the system:

6.1 Organised institutional actors observe developments and collectively respond to irregularities

While above instrumental rule contributes to reflexivity, system adaptation is a key topic in transformation governance and it is strongly influenced by the technologies put in place; today, the technical lifespan of system components in power infrastructure, such as power plants or parts of electricity grids, can last more than half a century (IEA 2010). While this may have economic reasons, it also means that these technical components have to remain in operation for the remainder of their life span in order to avert sunk costs. Accordingly, some researchers argue that incumbent power suppliers in monopolies might be reluctant to invest in new technologies in order to safeguard their

previous investment (Dillig, Jung & Karl 2016). Relying exclusively on proven technologies may not only be expected to obstruct the deployment of new solutions, but also impedes innovation. Along these lines, one could argue that if we are striving to respond better to adverse developments in the future, then the only technical components that may be deployed are those that can be replaced quickly without causing financial losses. Accordingly, I propose to put a rule in place that promotes innovation and reduces the risk of path dependence:

6.2 Design of power infrastructure fosters innovation and prevents technological lock-ins

In this section, I argued for a set of rules that further detail the objective dimensions introduced in the previous section. Accordingly, *Figure 26* depicts those instrumental rules mapped to corresponding objective dimensions. These rules provide guidance on the requirements that governance has to meet in order to facilitate a system transition.

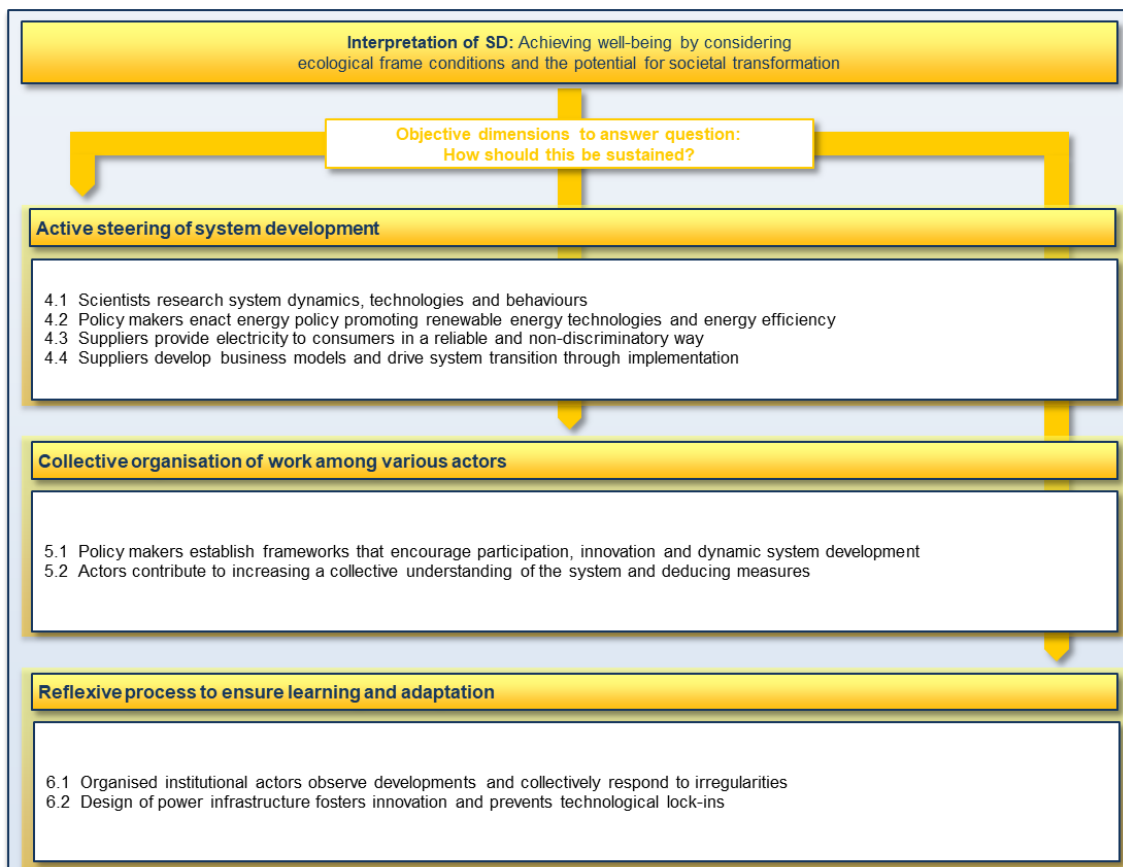


Figure 26: Instrumental rules for electric power systems

(Own elaboration)

I shall proceed with the last task of this multi-step endeavour to derive instrumental requirements for conducting system transitions; namely, a systematic definition of general goals relating to criteria for societal steering processes.

11.3 General goals

In chapter 8, I framed the scope for sustainability assessments of electric power systems in a way that considers the activities of actors that are deemed relevant in developing or operating power infrastructure and electrical devices. Based on this holistic system representation, I described reflexive transformation governance in section 7.6 as a basis to determine relevant social criteria for the sustainability assessments of power systems. At the same time, I translated a current scientific interpretation of SD into instrumental objective dimensions and rules in sections 11.1 and 11.2. It is now time to bring these functional and instrumental deliverables together. Accordingly, this section serves the purpose of matching the criteria relating to actors produced in chapter 9 with the instrumental rules formulated in this chapter to derive general goals for the aforementioned criteria. I shall structure this endeavour according to the identified actors and shall start by arguing for general goals for criteria related to researchers.

In section 9.4, I explained that researchers assume a central role in the development of electric power systems, which involves building knowledge on the systems as a whole, including an analysis of critical interdependencies. Furthermore, scholars research and develop new technologies, monitor and identify ways to alter consumption patterns and study policy steering instruments that are designed to induce change. Moreover, scientists promote dissemination of knowledge by publishing scientific reports.

According to instrumental rule *4.1 Scientists research system dynamics, technologies and behaviours*, some research should be dedicated to understanding human-human and human-environment interrelationships within electricity systems. Such research is relevant in order to better understand how actors shape the system to attain sustainability objectives and how human actions alter energy and material flows. Furthermore, some research should be carried out on appropriate modes of governance, policy instruments and organisational set-ups to direct system development in general and transformation towards sustainability trajectories in particular (Bilotta, Milner & Boyd 2014; Koontz, Gupta, Mudliar & Ranjan 2015; Wyborn 2015), as the chosen interpretation of SD highlights the relevance of actively driving development (Burger et al. 2018). Moreover, scholars should also consider the discovery of new renewable energy and

smart grid technologies to reduce the environmental impacts of power infrastructure. Such research should also involve technologies that enhance energy efficiency and analyse the drivers of electricity consumption to further reduce resource requirements and pollutant emissions (Jáñez Morán, Profaizer, Herrando Zapater, Andérez Valdaida & Zabalza Bribián 2016; Kalmykova, Rosado & Patricío 2016). These studies should be complemented with research on natural energy and material flows, including ecosystems and emission sinks, to better understand natural growth rates and tipping points related to emission sink capacities (Gunderson, Cosens & Garmestani 2016; Sassoon et al. 2009; Vanhala et al. 2016). Additional studies should be conducted on how interpretations of the normative requirements of SD can be operationalised. This may involve proposing steering and instrumental rules, criteria and general goals for sustainability assessments of power systems. Lastly, I argue that drawing on instrumental rule *5.2 Actors contribute to increasing collective understanding of the system and deducing measures*, scientists should also actively share their knowledge with other actors and collaborate on resolving the prevailing issues (Steurer 2010). Accordingly, *Table 16* lists the criteria for researchers, as elaborated in section 9.4, with general goals according to instrumental rules *4.1* and *5.2*.

Criteria for societal steering processes related to researchers		General goals for researchers
SS01	Research on system dynamics and interdependencies	Researchers focus on system analysis, human-human and human-environment interfaces
SS02	Research on societal steering	Researchers focus on reflexive governance and policy instruments to direct development
SS03	Research on power infrastructure and electrical devices	Researchers focus on renewable energy, smart grid and energy efficiency technologies as well as consumption behaviours
SS04	Research on ecological capacities	Researchers focus on energy flows, material flows and ecosystems including emission sinks
SS08	Proposals for steering and instrumental rules	Researchers propose steering and instrumental rules that contribute to the objectives of SD
SS12	Proposals for criteria and general goals	Researchers propose criteria relevant for the system and general goals in line with steering and instrumental rules
SS14	Proposals for organisational set-up and steering instruments	Researchers propose organisational set-up and instruments that promote system transition
SS17	Publishing of scientific reports	Scientists publish reports on renewable energy, smart grid, energy efficiency technologies and consumption behaviours

Table 16: Criteria and general goals for researchers

(Own elaboration)

In section 3.2, I argued that in reflexive governance, responsibilities are shared among various actors that may favour conflicting developmental paths. This can be expected to affect policy makers' and administrations' roles when striving to operationalise sustainability objectives.

Based on instrumental rule *5.1 Policy makers establish frameworks that encourage participation, innovation and dynamic system development*, policy makers and administrations should lay the foundations for other actors to contribute to more sustainable electric power systems. This rule essentially foresees that policy makers and administrations broaden the opportunity spaces for other actors by preventing the path dependence that result from technological lock-ins, thus promoting innovation and market access for new actors to accelerate the deployment of new technologies and grant access to political processes. These conditions are expected to enable other actors to contribute more easily. Despite instrumental rule *5.1* being rather abstract, I am still in a position to assign general goals to the criteria *SS05*, *SS07* and *SS10*: Policy makers and administrations are mandated to actively involve other actors to increase system knowledge and benefit from practical experience. Moreover, they establish arenas for public debates and reduce barriers for civil society actors.

To determine general goals for criteria *SS06*, *SS09*, *SS13*, *SS15* and *SS18*, I shall draw on instrumental rule *4.2 Policy makers enact energy policy promoting renewable energy technologies and energy efficiency*. According to this rule, government actors ought to craft strategies and scenarios that could potentially unfold in the future as a basis for mutually deciding on common development trajectories to meet the requirements of SD (Gormally, Whyatt, Timmis & Pooley 2016; Laugs & Moll 2017). In the previous section, I also argued that policy makers should implement steering instruments that promote or hinder specific technologies or market behaviours.⁴³ These policy instruments should consider scientific findings and practical experience and may be roughly separated into three categories: (i) instruments promoting those power generation and distribution technologies that are perceived to contribute to sustainability goals; (ii) another set of instruments providing incentives for consumers to change their behaviour (Dean 2010; McKee 2009); and (iii) more generic frameworks complied by policy makers defining the way suppliers and consumers interact in markets, such as market designs (Keles, Bublitz, Zimmermann, Genoese & Fichtner 2016). Referring

⁴³ I would like to emphasise that at this point only generic statements can be made on which areas policy makers can endorse policy instruments for promoting SD. An analysis of specific measures would have to be carried out on another level and thus lies beyond the scope of this thesis.

once more to steering rule 4.2, policy makers should also implement policy instruments that promote the deployment of renewable energy technologies and more energy-efficient lifestyles (Andor & Voss 2016; Johnston, Heffron & McCauley 2014; Pereira, Pereira & Rodrigues 2016; Wesseh & Lin 2016). However, since some renewable energy technologies provide electricity stochastically, smart grid technologies, enabling increased control over consumption loads, ought to benefit from the same mechanisms (Hossain et al. 2016; Reddy, Kumar, Mallick, Sharon & Lokeswaran 2014). Moreover, since the potential of cost-efficient renewable energy technologies may be limited in some regions, policy makers may be obliged to provide incentives to reduce electricity consumption (Jiang 2016; Ringel, Schlomann, Krail & Rohde 2016). Lastly, I argue that in order to meet steering rule 4.2 and be able to direct system development, policy makers may also have to define steering and instrumental rules as well as criteria and general goals for sustainability assessments and conduct such holistic evaluations to track whether the system is on a sustainable development path and implement policy instruments to respond to adverse developments. Accordingly, the last-mentioned conditions are a necessary precondition for operationalising a framework for sustainability assessments as proposed in this thesis. Based on this translation of instrumental rules into general goals for criteria for policy makers and administrations, *Table 17* provides an overview of the criteria and the general goals formulated in this section.

Criteria for societal steering processes related to policy makers and administrations	General goals for policy makers and administrations
SS05 Contribution of system knowledge and experiences gained	Policy makers and administrations involve key system actors to exchange knowledge and experience gained
SS06 Compilation of divisional strategy and scenarios	Policy makers and administrations craft strategies for electric power systems and develop scenarios that could potentially unfold
SS07 Facilitation of arenas for public debates	Policy makers and administrations establish arenas for public debates to increase system understanding by the public
SS09 Adoption of steering and instrumental rules in law	Policy makers and administrations translate steering and instrumental rules into laws to ensure that policies support objectives
SS10 Involvement of civil society	Policy makers and administrations establish frameworks enabling other actors to make a contribution
SS13 Adoption of criteria and general goals	Policy makers and administrations translate criteria and general goals into laws and conduct sustainability assessments.
SS15 Adoption of organisational set-up and steering instruments	Policy makers and administrations establish organisational set-ups and policy instruments that drive system transition towards the objectives of SD

*Table 17: Criteria and general goals for policy makers and administrations**(Own elaboration)*

In electric power systems, manufacturers of system components and electricity utilities decide on the technical designs of power infrastructure and electrical devices. Accordingly, market actors determine the provision of energy services and the levels of environmental degradation as well as the societal issues emanating from these technical components.

Market actors can be divided into manufacturers and suppliers on the one hand and consumers on the other. Consumers primarily respond to products offered by manufacturers and suppliers. Since the deployment of technologies is determined by market choice, the design choices of manufacturers and suppliers may have a resounding effect on society and the environment. Accordingly, electricity utilities face critical decisions today: they may either pursue a strategy focusing on the construction and long-term operation of power infrastructure to sell electricity or, alternatively, provide services enabling consumers to generate their own electricity. However, instrumental rules *4.3 Suppliers provide electricity to consumers in a reliable and non-discriminatory way* and *4.4 Suppliers develop business models and drive system transition through implementation* provide guidance on what objectives suppliers should pursue. Assuming that policy makers implement policy instruments promoting the deployment of renewable energy and smart grid technologies, manufacturers and suppliers should, in accordance with such regulatory and political frame conditions, increasingly invest in such technologies. Furthermore, new technological opportunities and regulatory frame conditions might enable suppliers to offer distinct product portfolios specifically designed to meet the individual demands of target customer segments. This could also involve new opportunities in the area of energy efficiency, thus reducing the energy consumption of consumers (Zvaigznitis, Rochas, Zogla & Kamenders 2015). Accordingly, I argue that the translation of instrumental rules *4.3* and *4.4* should result in changes to the business strategies and solutions offered by suppliers regarding the above-mentioned technologies. In order for policy makers to monitor the effectiveness of their frameworks and policy instruments, as imposed by instrumental rule *4.2*, suppliers should publish sustainability reports that shed light on the performance of system components (Higgins & Coffey 2016; Thijssens, Bollen & Hassink 2016). This information is required for other actors to contribute their part, for example for researchers to identify new re-

search opportunities or enable civil society actors to raise awareness on unsatisfactory developments. There is, however, an additional requirement related to instrumental rule *6.2 Design of power infrastructure fosters innovation and prevents technological lock-ins*: According to this condition, electric power utilities also have to consider the technical life span of technologies when deciding on specific investments. This rule essentially favours those technologies that depreciate quickly and reduces the risks of sunk costs for owners. *Table 18* displays criteria for market actors and corresponding general goals.

Criteria for societal steering processes related to market actors	General goals for market actors
SS11 Adaptation of strategies and business models	Manufacturers and suppliers adapt strategies and business models according to policies
SS16 Adaptation of solutions offering	Manufacturers and suppliers offer solutions in accordance with policies
SS19 Conducting of sustainability reporting	Manufacturers and suppliers publish reports on system components and their contribution to SD objectives

Table 18: Criteria and general goals for market actors

(Own elaboration)

In reflexive governance, civil society actors, such as environmental agencies or the media, assume reflexive roles. According to instrumental rule *6.1 Organised institutional actors observe developments and collectively respond to irregularities*, civil society actors are meant to monitor system developments, raise awareness on unsatisfactory developments and actively contribute towards changing household consumption patterns (Dryzek & Pickering 2017; Kong, Salzmann, Steger & Ionescu-Somers 2002). The response of such actors obviously also depends on their value systems, as actors are only likely to raise their voices if developments oppose their preferences and agendas. Some actors may also consider launching their own political initiatives to influence the development of the system (Eichbaum 1993). Against this backdrop, I argue that civil society actors should become actively involved in public debates and policy processes and should engage with consumers on energy efficient lifestyles. Accordingly, *Table 19* lists the criterion for civil society actors with a general goal according to the corresponding instrumental rule as outlined above.

Criterion for societal steering processes related to civil society	General goal for civil society actors
SS20 Monitoring of and commenting on system developments	Civil society actors identify irregularities, influence consumption behaviour and initiate changes.

Table 19: Criteria and general goals for civil society actors

(Own elaboration)

In this section, I contributed general goals to criteria for societal actors based on a set of instrumental rules formulated based on an interpretation of SD. I shall conclude this chapter by briefly reflecting on the scientific contribution of this chapter.

11.4 Conclusions

This chapter served the purpose of systematically setting goals, related to the instrumental notion of the conception of SD, for criteria for societal actors in sustainability assessments of electric power systems. I applied a multi-step procedure to translate a current scientific interpretation of SD into three objective dimensions, a set of mutually exclusive instrumental rules and, ultimately, general goals for criteria.

Like chapter 10, I primarily strived to provide an exemplary set of instrumental rules and goals for criteria as a basis for scientific discussion. The proposed results obviously vary depending on the interpretation of SD and the decisions on which structural features of reflexive governance of change are deemed of importance. Moreover, the process of translating a rather abstract interpretation of the guiding principles of SD into more tangible goals clearly depends on subjective interpretations. Accordingly, the proposed results could differ: A governance framework that centralises ownership of all technical components and decision power with government actors, would hardly consider the contribution of other actors in political processes. In such regimes there would also be less need to grow system knowledge collectively as this may be expected to be almost fully borne by government actors. Nonetheless, I deem the results provided to be valuable since they might encourage a scientific discussion on the appropriateness of the chosen approach and an interpretation of relevant features of SD. I aimed to provide as much information and reasoning as possible to enable such a discussion.

Now that I have produced my deliverables, I shall proceed with a comparison of my results with the scientific contributions reviewed in chapter 4.

12 Comparative analysis

The review of the scientific state-of-the-art of sustainability assessments of electricity systems in chapter 4 revealed that today's contributions only partly encompass the system in question and are also often detached from normative and instrumental aspects of SD. However, evaluating the current or possible future performance of key features of electric power systems against predefined sustainability objectives is a crucial prerequisite for providing a comprehensive basis for *evidence-based* and *goal-oriented* decision making. In chapters 5 to 7, I argued that a broader range of hitherto neglected vital system properties can be taken into consideration by expanding the system scope to include more societal aspects and the provision of energy services. Such an extension of the system scope, however, requires an enrichment of the methodological base that today draws mainly on life cycle assessments, scenario analysis, expert interviews, multi-criteria evaluations and case studies. Against this backdrop, I argued in chapter 7 that to analyse power systems more systematically, sustainability assessments may have to be additionally based on detailed energy and material flow analysis, as well as methodologies related to environmental governance and scenario assessments. Moreover, I argued that in order to incorporate normative and instrumental features of SD into sustainability assessments, general goals may have to be formulated based on a current scientific interpretation of SD and the specifics of reflexive transformation governance may have to be considered. I proposed to draw on a multi-step procedure which allows system data to be placed into perspective with sustainability objectives. Accordingly, in chapters 8 to 11, I provided exemplary contributions to these hitherto missing features of sustainability assessments of power systems that strive to further empower this steering instrument to provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision making to direct system development.

This now begs the question, how do the exemplary results provided in chapters 8 to 11 differ from those of the proposals reviewed in chapter 4 and what parts of the *proposed framework* are confirmed by current sustainability assessments? Answering this question will also serve as a basis for exploring the strengths and weaknesses of the *proposed framework*. Accordingly, I shall dedicate this chapter to comparing the exemplary set of criteria, steering and instrumental rules as well as the general goals derived from the *framework for sustainability assessments* to those highlighted in the sustainability assessments reviewed in chapter 4. At this stage, however, I would like to point out that I will not go for an inductive improvement of my framework and one should

bear in mind the limitations of such an approach. I shall structure this analysis into three sections:

- (i) **Criteria.** A comparison of the criteria deduced from the *proposed framework* with the criteria for the research sample in chapter 4.
- (ii) **Steering rules and general goals.** A review of the steering rules and general goals proposed regarding criteria for the *framework for sustainability assessments* against the contributions of the research sample.
- (iii) **Instrumental rules and general goals.** A comparison of the instrumental rules and general goals regarding criteria for sustainability assessments according to the *framework for sustainability assessments* with reviewed contributions.
- (iv) **Conclusions.** A brief discussion on the most significant commonalities and differences identified as a basis for the concluding discussion in chapter 13.

I shall refrain from allocating a section to an analysis of the underlying system scope, since an extensive discussion was included in chapter 4 and served the purpose of framing the scope for sustainability assessments of power systems. I shall start by comparing criteria for sustainability assessments of electricity systems proposed by the framework with the contributions of the research sample.

12.1 Criteria

In chapter 4, I provided a summary of criteria themes proposed by the contributions of the research sample according to the structural features of sustainability assessments as elaborated in section 3.3. This endeavour was then directed at analysing which features of powers systems and the conception of SD are considered at an aggregated level in current sustainability assessments of electricity systems. Here, however, I am more interested in identifying small nuances between those criteria and indicators highlighted by the research sample and the criteria systematically deduced from the *framework for sustainability assessments* in order to critically reflect on the strengths and

weaknesses of the *proposed framework*⁴⁴. For the sake of readability, I shall provide four tables based on the structure used to deduce criteria; namely, energy services, energy flows, material flows and societal steering processes. In each table, the criteria that I systematically derived from the *proposed framework* are shown in sequential order on the left. Furthermore, I shall add a column on the right indicating roughly how often these criteria were highlighted by the contributions reviewed in chapter 4. In addition, at the bottom I shall list those criteria or indicators which were consistently proposed by several authors in the research sample but which I did not identify. Based on these overviews, I shall identify differences and explore strengths and limits of the *proposed framework* in relation to contributions made by the research sample.

Starting with an analysis of the criteria related to the output of electricity systems, *Table 20* lists exemplary criteria related to energy services obtained by applying the *framework for sustainability assessments* in chapter 9 and complemented with the criteria and indicators frequently proposed by contributions of the research sample.

Id	Criteria for energy services	Occurrence in research sample
ES01	Provision of lighting	None
ES02	Provision of heating	None
ES03	Provision of cooling	None
ES04	Provision of cooking	None
ES05	Provision of cleaning	None
ES06	Provision of information	None
ES07	Provision of communication	None
ES08	Provision of entertainment	None
ES09	Provision of recreation	None
ES10	Provision of fuelling for mobility	None
ES11	Provision of production of goods and services	None
ES01	Provision of lighting	Mentioned ≥ 10 times
ES02	Provision of heating	Mentioned ≥ 5 times
ES03	Provision of cooling	Mentioned ≥ 10 times

⁴⁴ While scientists agree that criteria aggregate indicators and indicators are used to extract specific data, in practice criteria and indicators are sometimes used interchangeably (Bruinen de Bruin et al. 2015; Myllyvitta, Holma, Antikainen, L  thinen & Leskinen 2012; Nguyen, Bonetti, Rogers & Woodroffe 2016; Papadopoulou & Antoniou 2014; Pollesch & Dahle 2015). In order to challenge the results of the *proposed framework* against as many aspects of the contributions as possible, I shall compare criteria derived from the *proposed framework* with the criteria and indicators of the research sample.

n/a	Access to electricity	Only mentioned once
n/a	Stability of supply	Mentioned ≥ 5 times
n/a	Capacity/availability factors of power plants or grids	Mentioned ≥ 5 times

Table 20: Comparison of criteria and indicators for energy services

(Own elaboration)

In chapter 9, I argued that electricity systems serve the purpose of powering electrical devices and thereby enable the delivery of energy services. Accordingly, I dedicated criteria to the provision of energy services. There is, however, a major challenge associated with measuring the benefits users obtain when consuming energy services: wasteful behaviour, such as leaving lights on without actually using them, cannot be identified by the chosen approach. Nonetheless, since energy services often serve vital purposes, such as enabling heating to safeguard human health or communication to cultivate social contacts, I deem the corresponding criteria to be very important (Baker & Rylatt 2008; Kipping & Trømborg 2015). However, none of the contributions reviewed in chapter 4 assigns criteria or indicators to measure the delivery of energy services. Instead, authors rather quantify financial investments to measure the benefits power systems create for societies and individuals (Afgan, Carvalho & Hovanov 2000; Heinrich, Basson, Cohen, Howells & Perie 2007; Karger & Hennings 2009; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Stamford & Azapagic 2011), employment opportunities and income generated (Afgan, Carvalho & Hovanov 2000; Dombi, Kuti & Balogh 2014; Grunwald & Rösch 2011; Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Matteson 2014; Maxim 2014; Ribeiro, Ferreira & Araújo 2013; Roth et al. 2009; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Stamford & Azapagic 2011). Furthermore, some authors assess electricity costs (Dombi, Kuti & Balogh 2014; Evans, Strezov & Evans 2009; Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Kowalski, Stagl, Madlener & Omann 2009; Matteson 2014; Maxim 2014; Onat & Bayar 2010; Ribeiro, Ferreira & Araújo 2013; Santoyo-Castelazo & Azapagic 2014; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Sharma & Balachandra 2015; Stamford & Azapagic 2011) to draw conclusions on the affordability of electricity for consumers.

While such criteria and indicators without question prove useful to assess the financial benefits or burdens electricity may impose, they exclude other important factors that determine whether power systems improve human well-being. Even in cases where electricity prices are low, some users may not be able to consume energy services due

to lack of access to electricity.⁴⁵ Only one contribution looks at access to electricity and electrification rates (Sharma & Balachandra 2015). Moreover, the technical limitations of power grids can result in an unstable power supply, potentially damaging electrical devices or even causing black-outs (Veloza & Santamaria 2016). Some authors acknowledge such issues by formulating distinctive criteria or indicators for evaluating supply stability or reliability (Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Maxim 2014; Ribeiro, Ferreira & Araújo 2013; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Santoyo-Castelazo & Azapagic 2014; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Stamford & Azapagic 2011). Furthermore, some authors highlight additional technical criteria or indicators for the availability or capacity of power generation or distribution technologies to measure security of supply (Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Onat & Bayar 2010; Maxim 2014; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Sharma & Balachandra 2015; Stamford & Azapagic 2011).

Complementing financial criteria or indicators with technical ones acknowledges a wider range of benefits and issues related to the delivery of energy services. However, there might still be other reasons, such as low education levels, as to why some consumers may not benefit from energy services (Ifegbesan, Rampedi & Annegarn 2016). Moreover, even if high incomes or many jobs are created, this does not guarantee that electricity systems do indeed deliver crucial energy services, such as heating or cooling (Kavousian, Rajagopal & Fischer 2013; Kipping & Trømborg 2015), to those who are in need of them. In contrast, measuring the consumption of energy services by users provides more accurate information on this subject.

Against this backdrop, I argue that measuring the delivery of energy services could be a promising way of ensuring that a wider range of known and new potential issues, which might prevent actors from drawing electricity from power grids, are considered. This approach faces new methodological issues, as the *proposed framework* requires detailed data on the electricity consumption of private households (Kavousian, Rajagopal & Fischer 2013). Today, however, the meters installed in private households rarely meet this requirement even in industrialised countries as a result of technical limitations and issues with data security (Barbosa, Brito & Almeida 2016). Furthermore, criteria for energy services still need to be accompanied by other criteria related to technical or political aspects: excessive consumption of energy services does not nec-

⁴⁵ In rural areas of emerging economies, some communities are still not yet able to enjoy the benefits of electricity supply to their homes (Sharma & Balachandra 2015).

essarily lead to satisfied consumers. Wasteful behaviours or inefficient electrical devices, for example, which expend precious electricity could also impede energy service delivery (Ishak, Sipan, Sapri, Iman & Martin 2016; Staddon, Cycil, Goulden, Leygue & Spence 2016). Hence, criteria for energy services need to be complemented with additional criteria, some of which will be further discussed in this section.

Accordingly, I summarise that the *proposed framework* has given rise to a new category of criteria measuring energy service delivery. When complemented with criteria relating to efficiency, criteria related to energy services are in a better position than current financial criteria and indicators to create a comprehensive picture of the benefits electric power systems provide to their customer base. Accordingly, these new criteria for energy services seem to be a promising addition to sustainability assessments of power systems. This comparative analysis, however, also shed light to a delimitation of the *proposed framework*: The underlying theoretical elements cannot assess individual consumption of electricity or energy services, as the framework is directed at providing aggregated criteria. Since studies of individual behaviour take place on a different level, it is not feasible to integrate such analyses without fundamentally re-engineering the *proposed framework*.

The subject of energy efficiency brings me to my next task in this section: comparing the proposed criteria for energy flows with those recommended in sustainability assessments of power systems reviewed in chapter 4. Accordingly, *Table 21* lists the previously deduced criteria for energy flows, while the right-hand column indicates how often the proposed criteria can be found in the contributions of the research sample. Furthermore, criteria and indicators frequently proposed in the research sample, but neglected by the *proposed framework*, are shown once more at the bottom.

Id	Criteria for energy flows	Occurrence in research sample
EF01	Provision of renewable energy fluxes	None
EF02	Provision of renewable energy carriers	None
EF03	Provision of nuclear energy carriers	None
EF04	Provision of fossil fuel-based energy carriers	Mentioned \leq 5 times
EF05	Consumption of renewable energy fluxes	Mentioned \leq 5 times
EF06	Consumption of renewable energy carriers	Mentioned \leq 5 times
EF07	Consumption of nuclear energy carriers	Mentioned \leq 5 times
EF08	Consumption of fossil fuel-based energy carriers	Mentioned \leq 5 times

EF09	Energy use for lighting	None
EF10	Energy use for heating	None
EF11	Energy use for cooling	None
EF12	Energy use for cooking	None
EF13	Energy use for cleaning	None
EF14	Energy use for information	None
EF15	Energy use for communication	None
EF16	Energy use for entertainment	None
EF17	Energy use for recreation	None
EF18	Energy use for fuelling of mobility	None
EF19	Energy use for manufacturing of goods and services	None
EF20	Overall energy efficiency	Mentioned \geq 10 times
n/a	Import of energy carriers	Mentioned \geq 5 times

Table 21: Comparison of criteria and indicators for energy flows

(Own elaboration)

In section 9.2, I argued that the natural occurrence of energy fluxes and carriers may vary across regions. While some regions are devoid of energy fluxes or carriers, others are blessed with vast deposits (Bauer et al. 2016). Accordingly, it is obvious that for regions with limited potentials, exploiting their scarce sources of energy may prove to be more difficult and pose further challenges to national transition plans. Against this backdrop, I concluded in chapter 9 that sustainability assessments have to consider the natural occurrence of energy fluxes and carriers. Furthermore, I argued that the provision of energy fluxes and energy carriers not only determines the level of well-being that may be achieved but also current consumption levels, as wasteful behaviours could potentially result in unjustified levels of consumption. Accordingly, I proposed in section 9.2 to also assess power consumption. The combined analysis of the natural occurrence of energy fluxes and carriers against electricity consumption allows the remaining untapped potentials to be computed.

This begs the following question: How should a society proceed if the potential of their renewable sources of energy is almost completely exploited? Reducing electricity consumption by making changes to lifestyles or increases in energy efficiency are not the only options: another alternative would, of course, be international trade to secure imports of clean electricity. Since the *proposed framework* does not take political borders

into account, however, it was not possible to propose criteria for international trade such as imports and exports.⁴⁶

To better understand the drivers of electricity consumption, I argued in chapter 9 that consumption of each energy service should be monitored. Moreover, since conversion of energy fluxes and carriers into electricity and its distribution to consumers is bound to have conversion losses and some electricity might be used wastefully by consumers, I argued in favour of also assessing overall system energy efficiency. All criteria together paint a holistic picture of the level of energy efficiency and, additionally, seamlessly complement the criteria for energy services previously discussed.

In terms of the natural occurrence of energy fluxes and carriers, few authors assign distinct criteria or indicators to assessing reserves of fossil fuels (Sharma & Balachandra 2015; Stamford & Azapagic 2011). The research sample does, however, show great interest in the political topics of imports and potential energy dependence on other countries (Kowalski, Stagl, Madlener & Omann 2009; Ribeiro, Ferreira & Araújo 2013; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Sharma & Balachandra 2015; Stamford & Azapagic 2011), which the *proposed framework* was unable to cover. Moreover, the contributions of the research sample often cover the theme of energy consumption as some authors quantify energy consumption at aggregated levels (Afgan, Carvalho & Hovanov 2000; Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Sharma & Balachandra 2015). None of the contributions, however, looks at quantifying the use of distinct energy services. In order to measure energy efficiency, many authors apply criteria or indicators related to overall energy efficiency or energy efficiency of power generation, distribution or supply (Afgan, Carvalho & Hovanov 2000; Dombi, Kuti & Balogh 2014; Evans, Strezov & Evans 2009; Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Matteson 2014; Onat & Bayar 2010; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Sharma & Balachandra 2015).

Similar to the review of criteria and indicators on energy services, the process of systematically deducing criteria from the *proposed framework* yielded new additional categories of criteria compared to the criteria and indicators in the research sample. While many assessments reviewed in chapter 4 examined energy consumption, the research

⁴⁶ International trade is also consistently brought forward as viable alternative by sustainability key literature (UN 2015; WCED 1987).

sample neglects the natural occurrence of renewable energy fluxes and carriers. Extracting such data is nevertheless a crucial prerequisite for drawing conclusions on how potentials can be further explored or whether the limits of domestic electric power generation are about to be reached (Duscha 2016; Juaidi Montoya, Ibrik & Manzano-Agugliaro 2016). An examination of energy consumption alone does not provide information on how much nuclear or fossil fuel-based generation can still be substituted with local renewable energy fluxes or carriers, nor does it give insight into whether efforts to increase energy efficiency are the only remaining option for reducing fossil fuel-based or nuclear power generation. This reveals another key strength of the *proposed framework*: the combined analysis of the natural occurrence of energy fluxes and carriers against consumption levels. While similar evaluations are frequently carried out, they have yet to be integrated into sustainability assessments and, thus, constitute a new field for sustainability assessments that may add vital information for decision makers.

Furthermore, none of the contributions analysed the consumption of energy services. Such data could prove useful for determining the energy intensity of specific energy services, thus providing a promising starting point for energy efficiency measures (Ahmadi-Karvigh, Becerik-Gerber & Soibelman 2016; Farinaccio & Zmeureanu 1999; Jones, Fuertes & Lomas 2015; Larsen & Nesbakken 2004). Accordingly, another benefit of the *framework for sustainability assessments* lies in considering the electricity consumption of each energy service across the entire value chain, which is deemed relevant by many researchers (Paiano, Lagioia & Cataldo 2013; Sugiyama, Honma & Mishima 2016). Such analyses of energy services might offer new insights on where to increase energy efficiency efforts. This, however, brings us to a shortcoming of the *proposed framework* which I mentioned while discussing criteria for energy services: additional data on the consumption of individual energy services is required in order to operate the framework in the field. Currently, however, only limited data is available that could be used in sustainability assessments. Nevertheless, this deficiency could at least be partly overcome by deploying smart metering technologies (Kavousian, Rajagopal & Fischer 2013).

To summarise, the comparison of contributions reviewed in chapter 4 with the criteria produced by means of the *framework for sustainability assessments* revealed two entirely new categories of criteria, namely, consideration of occurrence of energy sources and energy use for energy services. When applying the *proposed framework*, however, additional attention needs to be paid to political aspects: international cooperation to secure imports of clean electricity in energy flux-constrained systems might play a ma-

major role in combatting environmental degradation on a global level. The problem of incorporating this aspect into the *proposed framework* could be solved pragmatically by framing the geographical system scope according to political boundaries or multinational territories. Whatever the case, enhancing *the framework for sustainability assessments* so as to be able to cope with detailed import/export analyses among countries would require a significant extension of the methodological base using economic models. Since these models address different levels to those methodologies currently applied, I have doubts that such an extension could be done without substantially re-engineering the *proposed framework*.

I shall proceed by evaluating the proposed criteria for material flows against similar criteria and indicators proposed by current sustainability assessments of electricity systems. *Table 22* lists the previously deduced criteria together with comments on how often they are represented in the research sample reviewed in chapter 4.

Id	Criteria for material flows	Occurrence in research sample
MF01	Provision of non-renewable resources	Mentioned ≤ 5 times
MF02	Consumption of non-renewable resources	Mentioned ≥ 5 times
MF03	Provision of renewable resources	Mentioned ≤ 5 times
MF04	Consumption of renewable resources	Mentioned ≤ 5 times
MF05	Provision of fossil fuels	Mentioned ≤ 5 times
MF06	Consumption of fossil fuels	Mentioned ≤ 5 times
MF07	Emission of greenhouse gases	Mentioned ≥ 15 times
MF08	Absorption of greenhouse gases	None
MF09	Emission of chlorofluorocarbons	Mentioned ≤ 5 times
MF10	Absorption of chlorofluorocarbons	None
MF11	Emission of sulphur and nitrogen oxides	Mentioned ≤ 5 times
MF12	Absorption of sulphur and nitrogen oxides	None
MF13	Emission of particulate matter	Mentioned ≤ 5 times
MF14	Breakdown of particulate matter	None
MF15	Use of land	Mentioned ≥ 10 times
MF16	Availability of land	None
MF17	Distortion of ecosystems	Mentioned ≤ 5 times
MF18	Delivery of ecosystem services	None
MF19	Losses in biodiversity	Mentioned ≤ 5 times

MF20	Biodiversity	None
MF21	Causes of eutrophication and acidification	Mentioned ≥ 5 times
MF22	Resilience to eutrophication and acidification	None
MF23	Erosion of soil and desertification	Mentioned ≤ 5 times
MF24	Provision of soil	None
MF25	Causes of eco-toxicity	Mentioned ≤ 5 times
MF26	Absorption of eco-toxicity	None
MF27	Reduction in life expectancy	Mentioned ≥ 5 times
MF28	Life expectancy	None
MF29	Increase in exposure to catastrophic risks	Mentioned ≤ 5 times
MF30	Exposure to catastrophic risks	None
MF31	Causes of electromagnetic radiation	Mentioned ≤ 5 times
MF32	Resilience to electromagnetic radiation	None
MF33	Causes of nuclear waste	Mentioned ≤ 5 times
MF34	Absorption of nuclear waste	None
MF35	Causes of land contamination/nuclear radiation	Mentioned ≤ 5 times
MF36	Resilience to land contamination/nuclear radiation	None

Table 22: Comparison of criteria and indicators for material flows

(Own elaboration)

In section 9.3, I explained that altering energy and material flows in power systems to serve human purposes also brings about unintended consequences in the form of resource depletion and pollution. Against this backdrop, the regeneration rates of renewable resource stocks and ecological emission sinks are known to play a key role in breaking down pollution and preventing long-term environmental degradation and, thus, potentially severe damage to human health.

Scientists and political leaders argue that some severe forms of environmental degradation, such as global warming, the depletion of the ozone layer, deforestation and the exhaustion of resource stocks, can be expected to negatively affect future generations and they conclude that energy systems in general and power systems in particular are, among other crucial infrastructure systems, the key drivers eroding the ecological capital (Atilgan & Azapagic 2015; Brizmohun, Ramjeawon & Azapagic 2015; Goodenough et al. 2016; IPCC 2007; Susanti & Maryudi 2016; Zikos & Hagedorn 2017). Against this backdrop, I argued earlier that sustainability assessments of power systems need to evaluate depletion rates of resource stocks in relation to their regeneration or recycling

capacities and that hazardous pollution should be compared with the capacities of emission sinks.

A comparison of the proposed criteria for resource provision and consumption derived by the *proposed framework* with those of the research sample reviewed in chapter 4 reveals strong similarities among criteria for the consumption of natural resources. Most contributions contain corresponding criteria or indicators (Afgan, Carvalho & Hovanov 2000; Hirschberg et al. 2005; Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Roth et al. 2009; Santoyo-Castelazo & Azapagic 2014; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009) including fossil fuels. However, none of the studies seeks to quantify resource stocks or regeneration rates. In the absence of such data, decision makers will find it more difficult to determine the reach of resource deposits or the maximum sustainable yield rates. There is one notable exception though: *Matteson* (2014) introduces an indicator for resource conservation.

In terms of pollutant emissions, virtually all authors consider key forms of environmental degradation except for those that initially state that their focus is exclusively on social indicators. Global warming, land use, toxicity to aquatic ecosystems and risks to human health are among the most frequently mentioned (Afgan, Carvalho & Hovanov 2000; Dombi, Kuti & Balogh 2014; Evans, Strezov & Evans 2009; Grunwald & Rösch 2011; Heinrich, Basson, Cohen, Howells & Perie 2007; Hirschberg et al. 2005; Jeswani, Gujba & Azapagic 2011; Karger & Hennings 2009; Kowalski, Stagl, Madlener & Omann 2009; Matteson 2014; Onat & Bayar 2010; Ribeiro, Ferreira & Araújo 2013; Roth et al. 2009; Rovere, Borghetti Soares, Basto Oliveira & Lauria 2010; Santoyo-Castelazo & Azapagic 2014; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Sharma & Balachandra 2015; Stamford & Azapagic 2011). However, none of the scholars put an effort into quantifying the tolerable thresholds of the emission sinks that prevent environmental degradation. One has to be aware, however, that such thresholds or tipping points constitute political consensus related to catastrophic events.

The above results show that the *proposed framework* is once more able to propose new meaningful categories for criteria: it allows for the capture of key resource deposits including regeneration or recycling rates. This data is vital as some resources, such as metals and water, are necessary preconditions for constructing and operating electric power infrastructure and are becoming increasingly scarce (Goodenough et al. 2016; Zikos & Hagedorn 2017). Furthermore, those resource requirements that are frequently covered by the research sample are also considered by the *proposed framework*. As

argued above, both growth and consumption-related criteria are required to determine the amount of resources that is spent today and how much is carried forward to future generations. Without both types of resource-based criteria, decision makers will find it difficult to grasp the impact of their decisions on the development paths that ought to be pursued. If decision makers know that current consumption patterns lie beyond regeneration rates or lead to an exhaustion of critical resource deposits, then they might be inclined to opt for a different development path than if they had not known.

In terms of pollution, the *proposed framework* also highlighted a new category of criteria that is absent in the research sample: the natural capacity of ecosystems or human bodies to break down pollutant emissions (Moreira & Pires 2016; Weissert, Salmond & Schwendenmann 2014). The proposed framework is also able to identify almost all of the criteria and indicators found in the contributions reviewed in chapter 4: the research sample contains very few additional pollutant emissions which are proposed only once, such as noise and the visual impairment of landscapes (Gallo, Fredianelli, Palazzuoli, Licitra & Fidecaro 2016; Sedoff, Schott & Karney 2014). These exceptions shed light on another weakness of the proposed approach: since the *proposed framework* is based on a stringent analysis of energy and material flows for the biophysical part of the system, problems stemming from sources other than energy and material flows remain undetected. There was no way that the *proposed framework* could have led to the discovery of criteria related to noise or aesthetics. However, this flaw could be easily remedied by adding theoretical elements that cover other aspects, such as those mentioned above. In the case of noise, for instance, an additional methodology could be used that is directed at measuring sound in decibel and which evaluates the measurement against tolerable levels for human beings. This would then ultimately result in adding an additional methodological step to the existing methodological base of the *proposed framework*: in addition to energy and material flow analysis sound measurements would also be carried out for all the technical components of the system. Accordingly, I perceive an extension of the proposed framework that covers the additional aspects of noise or aesthetics to be feasible by expanding the methodological base.

To summarise, a major strength of the *proposed framework* lies in recognising the relevance of both resource stocks and emission sinks, including their regeneration or absorption rates: should a society opt to refrain from jeopardising opportunity spaces for future generations, then consumption will have to lie within the reach of regeneration or recycling rates. The same rule would also apply to pollutant emissions and emission sinks: human populations can strive for development so long as the pollution absorp-

tion threshold of the environment is not breached. In order to enable such conscious decisions, corresponding data is required, and this is another key strength of the *proposed framework*: it provides the categories for accessing essential data on resources and emissions as well as natural limits. Against this backdrop, I argue that the *proposed framework* offers a distinct advantage over those sustainability assessments reviewed in chapter 4 as it provides data on resource consumption and emission levels including their regeneration and absorption rates. Accordingly, it allows thresholds for sustainable yields to be identified and this additional information might prove useful to decision makers in determining policy goals or in case of conflicting priorities.

Finally, I shall conclude this section with a comparison of the proposed criteria for societal steering processes and the social aspects assessed in the contributions of the research sample. *Table 23* contains criteria derived from the proposed framework, while the right-hand column contains information on how often a criterion is mentioned by the research sample. Since the contributions of the research sample did not consistently reveal new societal criteria, the list only contains criteria highlighted in the *framework for sustainability assessments*.

Id	Criteria for societal steering processes	Occurrence in research sample
SS01	Research on system dynamics and interdependencies	None
SS02	Research on societal steering	None
SS03	Research on power infrastructure and electrical devices	Mentioned ≤ 5 times
SS04	Research on ecological capacities	None
SS05	Contribution of system knowledge and experiences gained	None
SS06	Compilation of divisional strategy and scenarios	None
SS07	Facilitation of arenas for public debates	None
SS08	Proposals on steering and instrumental rules	None
SS09	Adoption of steering and instrumental rules in laws	None
SS10	Involvement of civil society	None
SS11	Adaptation of strategies and business models	None
SS12	Proposals on criteria and general goals	None
SS13	Adoption of criteria and general goals	None
SS14	Proposals on organisational set-up and steering instruments	None

SS15	Adoption of organisational set-up and steering instruments	Mentioned ≤ 5 times
SS16	Adaptation of solutions offering	Mentioned ≤ 5 times
SS17	Publishing of scientific reports	Mentioned ≤ 5 times
SS18	Incorporation of findings into policies	None
SS19	Conducting of sustainability reporting	Mentioned ≤ 5 times
SS20	Monitoring of and commenting on system developments	None

Table 23: Comparison of criteria and indicators for societal steering processes

(Own elaboration)

In section 9.4, I outlined the importance of identifying the key actors and their activities in sustainability assessments of power systems. In societal steering processes, various actors agree on the long-term development objectives of power systems through negotiation and deliberation. The resulting consensus imposes requirements on the design of power infrastructure and thereby determines which power generation and electricity grid technologies will be deployed by electricity utilities or which types of electrical devices are used by consumers. These decisions inevitably affect the productivity of the environment and thus also determine opportunity spaces for future generations. Accordingly, I argued in favour of dedicating criteria to the efforts of key actors in sustainability assessments. Against this backdrop, the *proposed framework* yields a set of criteria directed at researchers, policy makers and administrations, market actors and civil society actors, and the roles they assume in reflexive transformation governance.

The vast majority of sustainability assessments of power systems reviewed in chapter 4 looks at social aspects. This already includes the indicators on job opportunities or income mentioned previously, which I took the liberty of discussing in the context of criteria for energy services. While the research sample so far contained criteria or indicators that were suggested several times, a huge variety of criteria and indicators is proposed for actors in the social realm. One contribution recommends indicators related to justice (Kowalski, Stagl, Madlener & Omann 2009), while others propose indicators on risks (Gallego Carrera & Mack 2010; Maxim 2014; Roth et al. 2009; Santoyo-Castelazo & Azapagic 2014; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009). Two authors dedicate indicators to accidents (Schenler, Hirschberg, Burgherr, Makowski & Granat 2009; Stamford & Azapagic 2011), while others propose indicators for themes like social cohesion (Evans, Strezov & Evans 2009), corruption (Stamford & Azapagic 2011), innovation (Gallego Carrera & Mack 2010; Karger & Hennings 2009), intergenerational issues (Santoyo-Castelazo & Azapagic 2014) and participation (Gallego Car-

ra & Mack 2010; Schenler, Hirschberg, Burgherr, Makowski & Granat 2009). Unfortunately, background information on how authors choose their criteria and indicators is not provided, although authors sometimes state that they relied on expert interviews or literature to decide on which indicators to choose.

The variety of recommended indicators was somewhat unexpected, as there is much common ground among scholars on key social aspects of SD; for instance, scientists and politicians agree that research plays a crucial part in identifying new sources of environmental degradation and developing appropriate remedies (Bilotta, Milner & Boyd 2014). Furthermore, there is a common understanding that policy makers and administrations have a pivotal role to play in implementing policies and frameworks to alter behaviours that erode the environment (Dean 2010; McKee 2009). Moreover, manufacturers and suppliers are broadly perceived to deploy business models and technologies based on policy frame conditions (Govindan, Seuring, Zhu & Farrido Azevedo 2016). Lastly, there is also broad agreement among scientists and policy makers that civil society actors should monitor system development and play a more prominent role in reflexive processes by collectively organising action (Eichbaum 1993). Against this backdrop, I argued in chapter 11 that sustainability assessments should also cover these actors and their activities. Ultimately, both the broad consensus on social aspects of SD among scientists and political leaders, as well as the high variability of proposed social criteria for sustainability assessments of electric power systems, make a strong case for a systematic approach.

The *proposed framework* does exactly that – it enables a systematic analysis to identify key actors, crucial interfaces between actors and the environment, as well as analyses of their activities. By drawing on the *proposed framework*, I was able to generate a well-structured set of criteria for each actor. Some of the proposed criteria are also present in the contributions of the research sample, such as policy (Sharma & Balachandra 2015), competition and markets (Sharma & Balachandra 2015), periodic publications (Sharma & Balachandra 2015), creation and development of knowledge on new technologies (Karger & Hennings 2009) and market concentration (Gallego Carrera & Mack 2010). However, the other criteria derived from the *proposed framework* are not represented in the research sample.

Since this may seem at first to be modest support for the *proposed framework*, I shall highlight the benefits of the proposed criteria for societal steering processes. Firstly, the *proposed framework* allows a set of criteria to be generated that focuses on key actors

in the system and their activities; this is required in order to define goals and develop the system. As such, this set of criteria is more consistent than the loose assortment of social aspects in current sustainability assessments of electric power systems. Secondly, since key actors and their activities are represented, decision makers may obtain data on which actors actively support transition processes and which hamper the envisioned development. Should, for instance, power suppliers refrain from deploying renewable energy technologies or neglect energy efficiency efforts, then this becomes apparent through the analysis of such criteria. However, there is also an obvious limitation of the *proposed framework* related to underlying assumptions on how a society is organised. Since criteria on societal development are based on the assumed framework of reflexive transformation governance, proposed criteria only serve their full purpose in regimes where such governance is indeed in place. In regimes that fundamentally oppose the assumed governance, the set of meaningful criteria could look different. In fully centralised governments, for example, non-state actors may be expected to contribute very little if at all.

12.2 Steering rules and general goals

Only one of the contributions reviewed in chapter 4 strived to translate the normative features of SD into a set of rules (Grunwald & Rösch 2011). The substantial principles of the IFSD approach and the steering rules of the *proposed framework* are on the same level and seek to provide answers to the question: *What should be sustained?* Accordingly, the steering rules of the *proposed framework* can be compared to the substantial principles of the IFSD approach. The contribution of *Grunwald and Rösch*, (2011) however, refrains from further enriching substantial principles to derive goals in regard to criteria for sustainability assessments of power systems.

This represents another essential benefit of the *proposed framework* as such goals further support the process of operationalising SD. In this section, I shall therefore compare the steering rules deduced from the *proposed framework* with the substantial principles of the IFSD approach, as proposed by the contribution of *Grunwald and Rösch*, (2011) in order to identify and explore differences between the two.

I shall start the discussion of steering rules by listing those of the *proposed framework* and comparing them with the substantial principles of sustainable development proposed by *Grunwald and Rösch* (2011). Accordingly, *Table 24* contains the steering rules of the *framework for sustainability assessments* in sequential order on the left-

hand side, matched to the substantial principles of the IFSD approach advocated in the scientific paper of *Grunwald and Rösch* (2011) on the right side. Those substantial principles for which the *proposed framework* did not yield corresponding steering rules are placed at the end of the table.⁴⁷

Framework for sustainability assessments Steering rules	IFSD approach Substantial principles
1.1 Electric power systems enable the provision of lighting	-
1.2 Electric power systems enable the provision of heating and cooling	Protection of human health Securing the satisfaction of basic needs
1.3 Electric power systems enable the provision of cooking and cleaning services	Protection of human health Securing the satisfaction of basic needs
1.4 Electric power systems enable information and communication services	Equal access to education, information and an occupation
1.5 Electric power systems enable entertainment and recreation	-
1.6 Electric power systems provide for electric transport	-
1.7 Electric power systems enable the provision of goods and services	-
2.1 Renewable sources of energy are exploited while non-renewable energy carriers serve as residual sources	-
2.2 The consumption of renewable sources of energy does not exceed regeneration rates	-
2.3 Electric power systems strive for highest possible energy efficiency	-
3.1 Consumption of resources does not exceed regeneration and recycling rates	Sustainable use of renewable resources Sustainable use of non-renewable resources
3.2 Emissions caused by the power infrastructure remain within the extent of emission sink capacities	Sustainable use of the environment as a sink
3.3 Actors face minimal risk exposure with regard to catastrophic events and serious accidents and illnesses	Avoidance of unacceptable risks
3.4 Resource stocks are shielded from the adverse effect of power infrastructure	-
3.5 Emission sinks are safeguarded against degradation caused by power infrastructure	-
3.6 Key ecosystems are protected from emissions emanating from the power infrastructure	-
-	Autonomous self-support
-	Compensation for extreme differences in income and wealth
-	Conservation of nature's cultural functions
-	Conservation of social resources
-	Conservation of the cultural heritage and of cultural diversity

⁴⁷ I outlined the cornerstones of the IFSD approach in section 7.6 (Kopfmüller 2001).

-	Just distribution of natural resources
-	Participation in societal decision-making processes
-	Sustainable development of real, human and knowledge capital

Table 24: Comparison of steering rules and substantial principles

(Own elaboration)

The first notable difference clearly lies in the different scopes applied to both contributions: the IFSD approach provides a set of substantial principles universally applicable across all key systems (Grunwald & Rösch 2011). In contrast, the *framework for sustainability assessments* is specifically geared to electricity systems. This is a strength of the *proposed framework* since steering rules with corresponding general goals facilitate an easier operationalisation of sustainability assessments of electric power systems. The IFSD approach, however, requires further steps to translate substantial principles into goals for the criteria for sustainability assessments of power systems. This also hints at a challenge one may face when putting the *proposed framework* into practice: for every critical system a dedicated set of steering rules and general goals has to be formulated. Should such an endeavour be carried out for several systems, then some extra effort is likely to be required to align the steering rules and general goals of different systems in order to ensure they mutually support rather than contradict each other and cohesively contribute to overarching sustainability objectives. Nonetheless, as argued throughout this thesis, in order to create sustainability assessments with general goals for criteria that mirror the normative features of SD, system-specific steering rules are required to provide a basis for *goal-oriented* decision-making support.

Secondly, the *proposed framework* yields steering rules dedicated to the output of power systems, namely, energy services. The more aggregated contribution of *Grunwald and Rösch* (2011), however, refrains from doing this. Their more general substantial principles are directed at the benefits provided by key systems. The substantial principles of ‘*protection of human health*’ or ‘*securing the satisfaction of basic needs*’, for example, cover similar aspects of well-being as energy services for ‘*heating and cooling*’ or ‘*cooking and cleaning*’. Furthermore, the steering rule related to the energy service of ‘*information and communication*’ and the substantial principle of ‘*equal access to education, information and an occupation*’ are also directed at similar themes, although obviously at different levels. Accordingly, both approaches seek to set goals that are related to societal development. However, there are also interesting differences here: while the *framework for sustainability assessment* contains a steering rule related to the ‘*provision of goods and services*’, the IFSD approach refrains from

providing a substantial rule related to the output of businesses or economic development. Moreover, there is no substantial principle related to '*mobility*', which may be traced back to its release date: the IFSD approach was originally published in 2001 when electric mobility was still in its infancy. This further emphasises the importance of regularly reviewing and updating steering rules and general goals as changes in political or technological frame conditions occur.

Thirdly, the *proposed framework* entails a set of steering rules related to energy flows. This comes as no surprise, as the framework is developed based on the example of electric power systems. It is, however, a surprise to find that the IFSD approach does not uphold any substantial principles related to energy in spite of ongoing discussions on the environmental degradation caused by energy systems. Accordingly, another benefit of the *proposed framework* lies in its recognition of the relevance of considering key system flows depending on the system applied.

Fourthly, there are strong similarities among steering rules related to resource deposits and emission sinks in the *proposed framework* and the substantial principles of the IFSD approach. Both approaches foresee evaluating resource consumption and pollution in terms of the capacity of the environment to produce resources and break down pollution (Grunwald & Rösch 2011). This procedure is also very much in line with the work carried out by the Enquete Commission in 1998 for Germany (EK 1998). This commonality may be explained by the fact that all systems need to draw on some resources and cause emissions. Accordingly, both the more aggregated IFSD approach and the electricity system-specific steering rules of the *proposed framework* consider them. The IFSD approach, however, provides also an additional substantial principle on the subject of natural resources: '*conservation of nature's cultural functions*'. Since the *framework for sustainability assessments* is based on an analysis of energy flows, material flows and societal steering processes, cultural aspects of the environment are not subject to analysis. This shows a limitation of the *proposed framework*, as its results are, as already mentioned in the previous section, strongly related to methodologies used to derive criteria and general goals. This deficiency could be remedied, like the aforementioned criteria related to noise and aesthetics, by adding an additional theoretical element to the *proposed framework* that considers this aspect of ecological capital. Hence, this additional aspect could be covered by expanding the methodological base using approaches related to the cultural value of ecosystems.

Fifthly, both approaches acknowledge the potentially catastrophic risks that may stem from electric power infrastructure. While I introduced steering rule *3.3 Actors face minimal risk exposure with regard to catastrophic events and serious accidents and illnesses*, the IFSD approach entails the principle of *Avoidance of unacceptable risks*.

Some of the substantial principles of sustainability proposed by *Grunwald and Rösch* (2011) not only address the question of *What should be sustained?*, but also aspects related to answering the question: *How should this be sustained?* This involves, among other things, the substantial principles on *'Participation in societal decision-making processes'*, *'Autonomous self-support'* and *'Compensation for extreme differences in income and wealth'*. The *proposed framework*, however, considers these themes under the subject of instrumental rules. Accordingly, I shall proceed with a review of instrumental rules and general goals for social criteria in sustainability assessments of power systems.

12.3 Instrumental rules and general goals

Similar to the subject of steering rules and general goals in sustainability assessments, only the contribution of *Grunwald and Rösch* (2011) reviewed in chapter 4 provides a set of instrumental principles that addresses the same subject as the instrumental rules of the *proposed framework*. Against this backdrop, I am once more only able to compare the instrumental rules of the *proposed framework* with the instrumental principles for their contribution. This endeavour will, however, also prove valuable for gaining insights on the results of the *framework for sustainability assessments*. I shall start this endeavour by listing the instrumental rules of the *proposed framework* on the left-hand side of *Table 25* and match them to the instrumental principles of the IFSD approach used in the scientific paper of *Grunwald and Rösch* (2011), on the right-hand side. Those instrumental principles of the IFSD approach which are not covered by the *proposed framework* are listed at the bottom of the table. Furthermore, those substantial principles that are not covered by steering rules are shown in brackets.

Framework for sustainability assessments Instrumental rules	IFSD approach Instrumental principles
4.1 Scientists research system dynamics, technologies and behaviours	
4.2 Policy makers enact energy policy promoting renewable energy technologies and energy efficiency	

4.3 Suppliers provide electricity to consumers in a reliable and non-discriminatory way	
4.4 Suppliers develop business models and drive system transition through implementation	
5.1 Policy makers establish frameworks that encourage participation, innovation and dynamic system development	(Autonomous self-support); (Participation in societal decision-making processes); Self-management; Self-organisation
5.2 Actors contribute to increasing a collective understanding of the system and deducing measures	Balance of power
6.1 Organised institutional actors observe developments and collectively respond to irregularities	Society's reflexivity; Society's ability to respond
6.2 Design of power infrastructure fosters innovation and prevents technological lock-ins	
-	Internalisation of external social and environmental costs; Adequate discounting; Restrictions on debt
-	Fair international economic relations; Encouragement of international cooperation
-	(Compensation of extreme differences in income and wealth); (Just distribution of natural resources)
-	(Sustainable development of real, human and knowledge capital)
-	(Conservation of social resources)
-	(Conservation of the cultural heritage and of cultural diversity)

Table 25: Comparison of instrumental rules

(Own elaboration)

The instrumental rules of the *proposed framework* are based on reflexive transformation governance and thus assume that current sustainability issues are characterised by unclear goals, as well as a decentralisation of critical system knowledge and decision power, as described in section 3.2. Against this backdrop, it seems obvious that the proposed instrumental rules address critical stages of the operationalisation of SD. In contrast, the instrumental principles of the IFSD approach are not only directed at governance of change, but also contain additional financial and political principles (Kopfmüller et al. 2001). Since the instrumental rules of the *proposed framework* are exclusively derived from reflexive governance of change without features of economic models or political processes, it is not possible to introduce economic or political conditions to be met. While I fully acknowledge the relevance of economic and political aspects in achieving transitions towards more sustainable states and the frequent mention of this in the key sustainability literature (UNCED 1992; WCED 1987), the *proposed framework* cannot consider such aspects as a result of its methodological base. Indeed, economic models are clearly on a different level to that of reflexive transformation governance. Thus, accommodating both levels would vastly increase the complexity of the *proposed framework*. Accordingly, I doubt that economic models could be

easily incorporated into the *proposed framework*. However, there are also notable differences between the instrumental rules of the proposed approach and the instrumental principles of the IFSD approach on a more detailed level.

Firstly, the *proposed framework* contains instrumental rules related to the contributions of scientists, policy makers and administrations, as well as market actors: *4.1 Scientists research system dynamics, technologies and behaviours*, *4.2 Policy makers enact energy policy promoting renewable energy technologies and energy efficiency*, *4.3 Suppliers provide electricity to consumers in a reliable and non-discriminatory way* and *4.4 Suppliers develop business models and drive system transition through implementation*. The IFSD approach does not contain principles related to these actors.

Secondly, both approaches provide rules and principles on the subject of participation: *Grunwald and Rösch* (2011) dedicate a set of substantial and instrumental principles to ‘*Autonomous self-support*’, ‘*Participation in societal decision-making processes*’, ‘*Self-management*’ and ‘*Self-organisation*’. However, the instrumental rules of the *proposed framework* assume that such conditions are already met and specify the obligation of policy makers to ensure that *5.1 Policy makers establish frameworks that encourage participation, innovation and dynamic system development*. While the higher level of specificity on this theme is a strength of the *framework for sustainability assessments*, it also sheds light on a weakness: the *proposed framework* can only be applied to those cases in which a majority of the electric power infrastructure is already in place and there is reflexive governance to conduct a system transition. Hence, it is less suitable for emerging economies that have not yet installed any power infrastructure. Since reflexive governance is a necessary precondition for both SD and the *proposed framework*, the latter cannot be further developed to cope with other modes of governance.

Thirdly, both approaches examine the subject of power albeit with a different focus. The IFSD approach dedicates a generic instrumental principle to ‘*Balance of power*’. In contrast, the *proposed framework* implies balance of power by introducing the instrumental rule that actors should contribute collectively to an encompassing understanding of the system and a definition of steering instruments: *5.2 Actors contribute to increasing a collective understanding of the system and deducing measures*.

Fourthly, there are, however, strong similarities between the reflexivity approaches as both dedicate instrumental rules or principles to this subject. While the IFSD approach upholds principles of ‘*Society’s reflexivity*’ and ‘*Society’s ability to respond*’ on a more

general level (Grunwald & Rösch 2011), the *proposed framework* introduces a more specific instrumental rule. Accordingly, ‘*Society’s reflexivity*’ is broken down into the rule of *6.1 Organised institutional actors observe developments and collectively respond to irregularities*, thus emphasising organisational aspects of reflexivity. Furthermore, the *proposed framework* ‘*society’s ability to respond*’ is more closely related to technical components of power systems: *6.2 Design of power infrastructure fosters innovation and prevents technological lock-ins*. This narrower definition seems appropriate as another instrumental rule is already directed at societal reflexivity. To summarise, both approaches dedicate instrumental rules or principles to the subject of reflexivity and there seems to be agreement on the relevance of this subject in the context of operationalising SD.

Lastly, there are also two substantial principles related to justice, proposed by the IFSD approach, that are absent in both lists of rules in the *proposed framework*: ‘*Compensation of extreme differences in income and wealth*’ and ‘*Just distribution of natural resources*’ (Grunwald & Rösch 2011). The *proposed framework* does not contain any specific rules on justice as meeting the specified steering rules should, to the best of the current scientific knowledge, lead to the conservation of a productive environment for future generations. Along these lines, meeting the rules specified above should safeguard intergenerational justice. The subject of intragenerational justice, however, is very complex and would require a more detailed analysis of societal aspects in order to be covered by the *proposed framework*. Since such analyses are carried out on different levels, I doubt that they may be easily integrated into the *proposed framework*. Accordingly, this aspect cannot be adequately captured by the *framework for sustainability assessments*.

The findings of sections *12.1* to *12.3* are based on an evaluation of sustainability assessments of electric power systems against the structural features of the proposed framework and specific contributions that aim to fill the current knowledge gaps. However, as initially outlined with this thesis I strive to provide a *framework for sustainability assessments* that can be applied universally to complex coupled human-environment systems. Accordingly, I still need to draw conclusions on the strengths and weaknesses of the *proposed framework* on a general level in order to accomplish this task.

12.4 Conclusions

The comparative analysis revealed strengths and shortcomings of the *framework for sustainability assessments*. In this section, I shall summarise the key findings, highlighting those contributions that may stimulate the current scientific debate on how to enhance sustainability assessments to provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision support in the development of critical systems.

Firstly, the *proposed framework* is based on proven theoretical elements that allow for a systematic identification of criteria for complex coupled human-environment systems. The exemplary results for electric power systems show that applying a holistic system scope leads to the identification of crucial new criteria involving, among other things, an analysis of energy services, hitherto absent in sustainability assessments. As such, applying the *proposed framework* leads to a more holistic set of criteria that allows for evaluating whether the system contributes to the improvement of human well-being and the safeguarding of ecological productivity. Furthermore, almost all of the previously identified criteria were also produced by the *framework for sustainability assessments* with a few exceptions. Although some of these exceptions could be remedied by expanding the theoretical base of the *proposed framework*, it may not be feasible to incorporate others as they relate to other levels.

Secondly, criteria deduced using a structured and transparent approach are likely to be less susceptible to criticism relating to bias, as the additional transparency of applied methodologies provides reasons as to why certain criteria are proposed and others are not. This transparency can be expected to facilitate discussions on appropriate approaches and methods for sustainability assessments. Such discussions are likely to promote the continuous refinement of methodologies.

Thirdly, the design of the *proposed framework* fits well with reflexive transformation governance because it allows applied methodologies to be modified and new ones to be introduced as scientific knowledge on the critical features and interfaces of the system under review grows. Accordingly, the *framework for sustainability assessments* can co-evolve with research and be further developed as new insights on the system or crucial interdependencies among components or other key systems are gained.

Fourthly, for the first time, the *proposed framework* introduces general goals for criteria in sustainability assessments based on a current scientific interpretation of SD and

previously deduced system criteria. This systematic approach ensures that goals correspond to the normative features of SD, as opposed to participatory endeavours, including expert interviews, that will find it difficult to guarantee that choices of criteria or goals mirror such normative requirements. This additional normative feature represents an entirely new scientific contribution for sustainability assessments. It expands current information on system performance by incorporating sustainability goals, thus enabling decision makers to evaluate system data against predefined objectives mirroring the guiding principles of SD.

Fifthly, once normative goals are directly fitted to criteria in sustainability assessments, the assessments no longer serve a purely descriptive purpose. Rather, they then provide an analysis of areas in which the system deviates from predefined sustainability goals and evaluates contributions to SD. Accordingly, the *proposed framework* provides a basis on which decision makers may spot areas of immediate concern through ex post analysis and potential future adverse developments based on ex ante analysis. Furthermore, the *proposed framework* allows decision makers to identify intervention points for policy measures. These are fundamentally new features that the *framework for sustainability assessments* provides to decision makers.

Sixthly, a systematic translation of the guiding principles of SD into general goals for criteria can be expected to serve as a solid basis for challenging current scientific interpretations of SD. The conception of SD faces criticism for being ambiguous or not specific enough to operationalise. However, if we try to translate the normative cornerstones of SD into more tangible rules, then this also provides practical examples for steering and instrumental rules that can be further discussed. I expect this transparency to stimulate scientific discussion on how to operationalise SD based on practical experiences.

Seventhly, the framework also introduces a new theme for sustainability assessments related to governance. The deduction of instrumental rules based on reflexive transformation governance allows potential issues hindering the operationalisation of SD to be pinned down. This aspect has been, at least according to the research sample, hitherto underrepresented in sustainability assessments of power systems.

To summarise, the *proposed framework* consists of theoretical that are geared to specific methodological challenges. While the current contributions seem to focus on comparative technology assessments often enhanced with a set of social indicators, the

proposed framework expands the underlying system scope and integrates normative and instrumental aspects of SD. It thereby adds new layers of transparency to the system under review and the way in which SD is interpreted. Ultimately, it seeks to empower sustainability assessments to provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision making in the future by facilitating an evaluation of the system under review against sustainability objectives. As such, it not only proposes an incremental refinement of the existing features of sustainability assessments, but also extends its scope with fundamentally new dimensions to be able to better respond to today's highly complex sustainability issues.

13 Discussion

The comparative analysis in chapter 12 yielded a number of new scientific insights for sustainability assessments in general and for power systems in particular. At the end of the previous chapter, I argued that these new features could provide a more comprehensive basis for decision-making support for the long-term development of key systems in industrialised countries. However, the discussion in chapter 12 also shed light on some of the limitations of the *proposed framework* that can be traced back primarily to the set of applied theoretical elements. Furthermore, to reap the maximum possible benefits when operationalising the *proposed framework*, additional research is required to remedy some of the newly identified knowledge gaps. While the previous chapter provided critical insights on the strengths and limitations of specific parts of the *proposed framework* based on a review of the exemplary contributions for power systems, I shall dedicate this chapter to a more general discussion of the *framework for sustainability assessments*. I shall structure this discussion into three sections:

Firstly, I shall go back to the research question stated in chapter 6 and explore to what degree I was able to meet the aspirations I originally formulated by discussing the results in relation to the research question. Furthermore, I shall explore to what extent I was able to fill the knowledge gaps identified in chapter 5. I shall therefore argue for why I believe that I have accomplished my main tasks and for what parts I deem additional efforts necessary.

I shall then draw attention to the potential criticism that the *proposed framework* may not be fully in line with the hallmark of democracies, which seeks to involve various actors in societal steering and decision making: Since the *proposed framework* constitutes an analytical scheme based on a set of theoretical elements, it may not be immediately clear as to how it accounts for active stakeholder involvement. This would be in stark contrast with recent research on SD and participation, however; during the past decade, research on SD governance has broadly considered stakeholder involvement and engagement as a necessary precondition for the operationalisation of SD (Bond, Viegas, Coelho & Selig 2010; Gastil & Black 2008). Accordingly, I shall defend the *proposed framework* against such a potential criticism in section 13.2 by highlighting how it assumes and integrates active actor involvement and engagement; after all, it is based on reflexive transformation governance. I shall also point out which features indeed refrain from drawing on participatory elements and rather rely on analytic approaches based on the key literature on scientific sustainability.

In section 13.3, I shall explore further research opportunities identified in the process of comparing the *proposed framework* with current contributions by revisiting the comparative analysis in chapter 12. While additional research is required in order to fully operationalise the *proposed framework*, some of these new research tasks might also provide crucial results for related research endeavours. Research on the consumption of energy services or electricity is a key starting point for designing effective policy steering instruments to promote more sustainable lifestyles. This example illustrates that additional research on missing data for the *proposed framework* might create synergies with other important research endeavours.

Based on this structure, I shall proceed with a review of the deliverables provided by this thesis in terms of the research questions originally formulated in chapter 6 and then continue with an analysis of my contributions to each of the research gaps identified in chapter 5.

13.1 Review of results

In chapter 6, I formulated the research question of this thesis against the backdrop of shortcomings in the current sustainability assessments of power systems, as identified in chapter 4, and the corresponding knowledge gaps discussed in chapter 5. These analyses led to the recognition that current sustainability assessments of power systems comprise comparative technology assessments rather than constituting comprehensive evaluations of key systems against predefined sustainability objectives. Accordingly, I chose to direct the research question at the overarching question:

How should sustainability assessments be designed methodologically to provide a basis for evidence-based and goal-oriented decision making on the long-term development of key systems?

In order to answer this research question, two essential conditions have to be met. These two conditions refer to providing a comprehensive basis for *evidence-based* and *goal-oriented* support for decision making on the long-term development of key systems. Here, I shall look firstly at providing *evidence-based* data and then discuss contributions to *goal-oriented* support for decision making.

Throughout the thesis, I have argued in favour of basing critical development decisions on relevant current and potential future data on the system in question. Furthermore, I

argued that this data has to display the relevant properties of power systems, from the natural occurrence of energy fluxes, carriers and natural resources to the provision of energy services. My argument is based on the assumption that the risk of erroneous decision making caused by the omission of relevant data can be reduced by assessing the entire life cycle of energy services. Moreover, I emphasised the importance of considering societal steering processes that determine the goals the system has to meet and the technical design of key systems.

Accordingly, in order to meet the criterion on providing a basis for *evidence-based* decision support, I argue that decisions on the future long-term development of key systems must be directly informed by relevant empirical data on key system features. The *proposed framework* provides a basis for that: it frames the scope and defines key criteria to extract relevant data on key system properties and presents it to decision makers. This information is composed of both data on the current system performance to identify issues of immediate concern and data on potential future states to indicate possible future issues. Furthermore, the *proposed framework* is a conceptual scheme that is composed of a set of theoretical elements to facilitate the extraction and interpretation of relevant data. Thus, the *framework for sustainability assessment* indicates the type of data that is deemed relevant according to latest scientific research.

Unfortunately, as noted at several stages throughout chapter 12, not all of this data is readily available today and additional research is required to close newly identified knowledge gaps. Nonetheless, since I directed the research question towards proposing a methodological design for a *framework for sustainability assessments* and not a set of data for a specific system, I deem this condition of the research question to be met. However, I would like to point out once more that identifying key system data and defining criteria have to be understood as an ongoing process. For example, new political or technological developments may raise or reduce the importance of specific system components and distributed power generation may impose new requirements on electricity grids (Bush 2014; Del Rio & Unruh 2007; Liu, Zeng & Liu 2011). Accordingly, the exemplary criteria produced in chapter 9 are not to be understood as a final list, but are likely to change in the future as new scientific evidence reveals new insights on critical system components.

I further argued that the development of key systems for sustainability trajectories can only take place if sustainability objectives are defined beforehand and that these have to mirror the normative requirements of SD. Without this crucial step, it is by no means

clear whether a system is on track towards a more sustainable state. In chapter 4, I then concluded that the majority of proposals lack reference to exactly such normative sustainability objectives and thereby obstruct *goal-oriented* decision making. This brings me to the second condition for evaluating whether the research question has been answered.

In previous chapters, I argued in favour of directly relating criteria for sustainability assessments to general goals formulated based on a recent scientific interpretation of SD. Such an approach ensures that, in sustainability assessments, an evaluation of the system performance against sustainability goals can be directly conducted. In chapters 10 and 11, I provided exemplary goals for the criteria for sustainability assessments of power systems, which are crucial for directing development according to sustainability objectives. In contrast to other proposals where goals are determined through expert interviews, benchmarking processes or public polls, I derived an exemplary set of rules and general goals for criteria in sustainability assessments of power systems based on a current scientific interpretation of SD. Thereby, I expanded the scope of sustainability assessments for the first time to also encompass the normative and instrumental requirements of the guiding principles of SD.

However, the resulting rules and general goals strongly depend on the underlying interpretation of the conception of SD, as already noted on several occasions. Accordingly, the formulated rules and general goals also have to be understood as an exemplary set, because the interpretation of SD may vary significantly depending on the regime in place and the value systems of a society. This will inevitably also transcend the domain of rules and general goals which is based on such a normative foundation. However, like the proposal on criteria, I did not attempt to provide a universally applicable complete set of rules and goals here, but rather used the *proposed framework* to produce exemplary results that are meant to stimulate a fruitful discussion on the appropriateness of interpretations of SD and the methodological base of the *proposed framework*. However, since the research question is directed at providing a methodological design and not at producing a final list of general goals and rules, I also deem the second condition of the research question to have been met.

After having reflected on my contribution in relation to the broader research question, I shall proceed by evaluating my deliverables for each knowledge gap that I promised contributions for in chapter 5.

The first knowledge gap originates from the wide range of criteria and indicators proposed by the contributions of the research sample. Against the backdrop of the huge variability in the proposed criteria and indicators, ranging from mostly applying ecological indicators to looking exclusively at societal aspects, I suggested that a comprehensive analysis of the systems under review is required to first identify relevant system components. Accordingly, I crafted an exemplary holistic system representation of electricity systems in chapter 8 based on coupled human-environment system analysis. Such endeavours have been carried out before, but not to frame the scope in sustainability assessments of power systems. Compared to the contributions of the research sample, the proposed system scope not only succeeds in identifying relevant categories, but also considers new key aspects of the systems hitherto neglected: Firstly, the system representation structures the system into social, technical and ecological dimensions and identifies key system components consistently mentioned in the literature on electricity systems or reflexive transformation governance. Furthermore, it considers data across the entire transformation chain including electrical devices. Secondly, the applied approach identified the delivery of energy services as the key output of electricity systems. Despite serving an important purpose, this is a fundamentally new area to be considered in sustainability assessments: although SD strives to balance societal development and environmental conservation, surprisingly few of today's sustainability assessments of power systems look at the output of power systems. Accordingly, my contribution in chapter 8 not only provided a well-structured and holistic depiction of electricity systems and is based on a scientific scheme that is rarely used in sustainability assessments, but also proposed entirely new dimensions that allow sustainability assessments to evaluate the output of the system against environmental burdens.

The review of the research sample in chapter 4 not only highlighted the disagreement on system scopes among authors of sustainability assessments, but also revealed a strong heterogeneity among criteria and indicators within categories, such as resource requirements or pollution. In chapter 5, I then took this diversity to be an indication of a further lack of consensus on the relevant stages of system flows that should be subjected to the analysis. Accordingly, I conducted an exemplary analysis of energy and material flows including societal steering processes in chapter 9. The goal of this endeavour was to identify those stages of flows that are deemed important and therefore have to be captured in sustainability assessments. I applied a set of distinct methodologies to describe the different stages of system flows across the previously identified system components. The results consist of a list of proposed criteria for sustainability

assessments. Most of the identified criteria are also found in the individual contributions of the research sample. Some of these analyses have been conducted before and my results are consistent with those of such studies. The detailed analysis of electric power systems, however, also drew attention to fundamentally new categories of criteria hitherto neglected. A new set of criteria on energy services is obviously worth mentioning along with entirely new categories of criteria related to the natural occurrence of energy fluxes and carriers, deposits of resource stocks and estimated capacities of emission sinks. The combined review of ecological regeneration versus consumption rates and pollution emissions against emission sink capacities now allows maximum sustainable yield rates and tolerable limits in sustainability assessments to be determined. Accordingly, estimations on thresholds can henceforth be used in sustainability assessments to determine whether opportunity spaces for future generations are threatened. This deliverable is also consistent with work done on environmental management rules. While indicators are one of the basic features of sustainability assessments, I refrained from systematically deriving a set of exemplary indicators, as these would be likely to vary across regions and jurisdictions. Nonetheless, the proposed approach facilitates an evaluation of system data against ecological boundaries in contrast to drawing on subjective expert interviews. The deliverable for this knowledge gap provides a fundamentally new feature of sustainability assessment that represents a key step towards providing a basis for *evidence-based* decision making.

My initial analysis in chapters 4 and 5 revealed another shortcoming in today's sustainability assessments of power systems: such assessments often refrain from drawing on exploratory scenario assessments to compute potential future states of the system. While such forward-looking analyses shed crucial light on how the system might develop, I did not provide exemplary results on this basic feature, as sophisticated system models and scenario assessments of power systems are today frequently provided in policy contexts. Moreover, since the basic feature of ex post analysis was well represented in the research sample, I decided against providing scientific contributions on these subjects.

In chapter 5, I identified shortcomings in today's sustainability assessments of power systems related to providing a basis for *goal-oriented* decision making: Hardly any scientific proposal contained goals that mirrored the requirements of SD for criteria, thus impeding evaluations of system data against predefined sustainability goals in general. Against this backdrop, I vowed to systematically formulate exemplary general goals for criteria in chapters 10 and 11 based on a current scientific interpretation of SD and a

systematic multi-step procedure. The resulting general goals are at least partly found in one contribution of the research sample, which is based on the same procedure but draws on a different interpretation of SD. Setting goals for criteria in sustainability assessments constitutes another entirely new field for sustainability assessments and enables them to evaluate system data against sustainability objectives. Henceforth, sustainability assessments will be founded on a more comprehensive basis to inform decision makers on areas of immediate concern or potential adverse developments, as both system data and sustainability targets are provided. Since the goals are based on an interpretation of SD, decision makers instantly gain insights on the system performance in relation to sustainability objectives. This approach, thus, provides a basis for *goal-oriented* decision making and complements the deliverables on criteria to provide a comprehensive and holistic picture for decision makers. I did, however, also refrain from systematically producing an exemplary set of target values for the indicators, as such target values are likely to vary depending on the principles, values and norms of a society and are agreed through negotiation and deliberation in modern democracies.

Lastly, I would like to add that I put effort into providing transparency on how I produced my exemplary deliverables. My hope is that the information on how I produced the exemplary deliverables for sustainability assessments of power systems encourages scientific discussion on appropriate methodologies or the relevant basic features of sustainability assessments to further improve this important steering instrument. Once more, I would like to emphasise that the results presented in chapters 8 to 11 are exemplary contributions and these results are likely to differ depending on the system scopes, applied methodologies and subjective interpretations in the key literature.

This brings me to the last point in this section, which is related to expectations regarding instruments for decision support. Such instruments are sometimes expected to present decision makers with a single best or optimal solution. While this certainly holds true for many scientific endeavours, I would like to draw attention to the fact that sustainability assessments seek to inform decision making on the long-term development of key systems. Such systems are characterised by high levels of complexity and a necessary precondition is the involvement of a wide range of actors to deliver the output of the system. One aspect I would like to point out here that requires consideration is that in order to obtain agreement on objectives, interests need to be balanced through negotiation and deliberation. Accordingly, without going into a detailed discussion here, one cannot expect a single best solution from the *framework for sustainability assessments*. Against this backdrop, it becomes obvious that the *proposed frame-*

work does not question the key hallmarks of democracies to involve and engage actors in societal decision making, but rather promotes the integration of active stakeholder involvement and engagement. To further demonstrate this, I shall dedicate the next section to exploring how the *proposed framework* integrates participation.

13.2 Participation and operationalisation of the framework

As mentioned in the previous section, missing data currently prevents a full implementation of the *framework for sustainability assessments*. However, it would be too short-sighted to base a decision on the implementation of such a comprehensive steering instrument only on the availability of data. The *proposed framework* comprises a scientific contribution and primarily strives to contribute to the scientific discussion on how sustainability assessments could be further developed to cover hitherto neglected features and provide a more comprehensive basis for *evidence-based* and *goal-oriented* decision-making support. In this section, however, I shall draw the attention to another crucial aspect of operationalising SD, namely, participation. In this thesis, I refrained from arguing for appropriate forms of participation. This might have been surprising to observant readers given the vast attention the subject of participation is given in scientific discussions on the operationalisation of SD (Cent, Grodzińska-Jurczak & Pietrzyk-Kaszyńska 2014; Doelle & Sinclair 2006; Hartley & Wood 2005; O'Faircheallaigh 2010; Stirling 2009).

Today, there is broad consensus among researchers on SD and political leaders that the cornerstones of SD need to be embedded in national and local policies in order to drive transitions towards more sustainable states (UN 2015; UNCED 1992; UNCSD 2012; WCED 1987). In parallel, there is also agreement that in order to reflect societal values and gain public acceptance for long-lasting implementation efforts, some form of active stakeholder involvement and engagement is required. This is further emphasised in democracies, where actor participation is deemed an unquestionable hallmark of modern societies. However, the review of the research sample in chapter 4 revealed wide-ranging proposals for the way actors should be involved. At the one extreme, scholars suggest delegating the decision on which criteria should be evaluated or what objectives are to be pursued fully to the public or public representatives (Ribeiro, Ferreira & Araújo 2013), while at the other end of the continuum, researchers perceive the participatory element to be reduced to obtaining knowledge from actors (Bond, Viegas, Coelho & Selig 2010; Gastil & Black 2008).

In this thesis, I did not strive to contribute to identifying appropriate forms of participation to operationalise sustainability assessments. Rather, I proposed a scientific framework that might be perceived to question some aspects of participation. However, I without doubt agree that successful transitions of key infrastructure systems towards more sustainable states require the active involvement and engagement of various non-state actors. This is why I based the *proposed framework* on reflexive governance of change; this considers the active involvement and engagement of non-state actors in societal decision making as a necessary precondition. Scientists, for example, play a key role in researching systems, technologies, policy instruments and consumption behaviours. Furthermore, market actors develop business models and solutions offerings to meet the demand of their customer base. Moreover, civil society actors monitor system developments and trigger public discussions when irregularities occur. These examples affirm that in the assumed governance framework non-state actors have to play their part in order to achieve system transitions.

I also hinted at several points that not all problems may be resolved by adopting a single best solution or reverting to expert opinion. I ended the previous section, for example, by recognising that conflicting priorities are likely to arise and have to be resolved through negotiation and deliberation to balance the system. Moreover, it is not only the assumed governance that is based on active participation, but also some of the exemplary deliverables directly related to actor involvement. For example, I formulated instrumental rules *5.2 Actors contribute to increasing a collective understanding of the system and deducing measures* and *6.1 Organised institutional actors observe developments and collectively respond to irregularities* to secure active actor involvement and engagement.

Accordingly, while my goal was to demonstrate the additional benefits stemming from applying a broader system scope and reverting to a wider range of scientific methodologies to provide a basis for *evidence-based* and *goal-oriented* decision-making support, I obviously do not intend to imply that sustainability assessments can be implemented without the contributions of non-state actors. On the contrary, I deem it a necessary precondition to involve actors in order to achieve successful system transitions.

However, in contrast to some of today's sustainability assessments of electric power systems, I also strongly support based goals on scientific interpretations of SD. There is a general agreement among scientists and politicians that oft-cited key literature on the conception of SD or sustainability issues is based on broadly acknowledged scien-

tific evidence, such as the drivers of climate change or issues with the long-term disposal of nuclear waste. In my view, this consolidated scientific knowledge on human-environment issues cannot be adequately substituted with interviews with selected actors. Ignoring such crucial scientific findings would strongly oppose one of my key arguments backing the *proposed framework*: the relevance of providing a basis for *evidence-based* decision support for the development of key infrastructures. Against this backdrop, I argue that the operationalisation of sustainability assessments requires an adequate mix, with decisions being based on scientific evidence on the one hand, and involving and engaging actors on the other. This, obviously, is a complex task and contributing to the identification of appropriate forms of participation clearly lies beyond the scope of this thesis. Here, I merely wish to point out that the *proposed framework* is designed to fit seamlessly with reflexive governance in democratic regimes without restricting the rights of the public or individuals.

Lastly, I would like to touch on another important aspect related to knowledge transfer: Empirical studies suggest that implementing sustainability projects may have the benefit of mutual learning between scholars and involved actors: on the one hand, participating actors increase their understanding of the long-term environmental effects caused by their daily activities, while on the other hand scientists gain insights on the particular issues faced by the stakeholders involved (Hertin et al. 2009; Jha-Thakur, Gazzola, Peel, Fischer & Kidd 2009). Without going into a detailed discussion on this complex subject here, I would like to add that implementing the *proposed framework* may also prove valuable for closing some of the knowledge gaps between the research community and the public.

Ultimately, in order to provide a scientific contribution to identify appropriate forms of participation for operationalising sustainability assessments, additional research is required that explores themes of governance and SD in democracies. This brings me to the final part of my thesis. My endeavour to create a *framework for sustainability assessments* has led to the discovery of new knowledge gaps. Some of them need to be filled to fully benefit from an implementation of the *proposed framework*, while others might be worthwhile pursuing on their own. I shall therefore dedicate the last section to exploring additional research opportunities.

13.3 Further research opportunities

The discussion on the strengths and limitations of the *proposed framework* in chapter 12 revealed a number of new knowledge gaps on key electricity research topics, such as the need for a better understanding of the consumption of energy services and the electricity consumption patterns of private households, as well as the lack of life cycle assessment data on components of power grids and electrical devices. Accordingly, I shall summarise the most prominent new research opportunities which I identified throughout the process of developing and discussing the *proposed framework*.

I have already discussed one new knowledge gap rather extensively in section 12.1. This is related to the hitherto relatively modest knowledge on the consumption patterns of electricity and energy services by private households (Farinaccio & Zmeureanu 1999; Larsen & Nesbakken 2004). The lack of such data constitutes a key issue for research directed at the design of steering instruments to promote energy efficiency and alter consumption behaviours in general. Since the electricity consumption patterns of individuals are currently not fully understood, some of the drivers of electric power consumption also remain unclear. Until recently, this lack of knowledge could be partly explained by technical limitations: private households were traditionally equipped with meters that continuously count electricity consumption. In order to obtain the count for a specific date, an employee had to access the meter and read the count from the meter itself. A year later the worker would do the same once more and then the previous count was subtracted from the new one to calculate the annual aggregated electricity consumption. Today, however, the global trend of digitalisation has given rise to more sophisticated metering technologies and power suppliers increasingly install smart meters, especially for businesses with high levels of electricity consumption. While various types of smart meters with different features exist, it is safe to say that most versions are able to measure electricity drawn from power grids more frequently, for example every 15 minutes. Furthermore, measurements can be read electronically so that data usually is available often in real time. This more detailed data can be expected to allow researchers to obtain more detailed electricity consumption profiles of private consumers, thus revealing more information related to their consumption patterns. In order to determine the drivers, however, additional research is likely to be required.

Private households, however, are reluctant to approve smart meter installations, mainly for security reasons. On the one hand, they are cautious that their consumption data might be sold to aggressive marketing agencies, thus potentially flooding them with

unwanted advertising campaigns. On the other hand, consumers fear that hackers might study their consumption load profiles to determine optimal time frames for robberies. Should researchers seek to benefit from more detailed electricity consumption data on private households, they have to treat these concerns seriously and find solutions that negate the risks for consumers. One may expect a number of benefits to arise from more detailed consumption load profiles for research: an intelligent software program with data on devices might be able to indicate which devices were in use. Furthermore, such consumption data could be expected to provide valuable insights on intervention points for policy steering instruments. Should, for example, excessive electricity consumption of lighting applications be identified, tailor-made feedback could be given to users (Podgornik, Sucic & Blazic 2016). Accordingly, a detailed study of electricity consumption patterns would not only generate data valuable for the operationalisation of the *proposed framework*, but might also create additional benefits for other research or for policy makers seeking to design more effective steering instruments.

The review of the scientific state-of-the-art of sustainability assessments of power systems in chapter 4 also highlighted that current contributions are somewhat biased towards power generation technologies. In order reap the greatest possible benefits from an operationalisation of the *proposed framework*, additional life cycle assessment data on power infrastructure components and electrical appliances is required. Some components of power grids seem to have been less frequently subject to detailed scientific analyses and, thus, only limited data on their resource requirements or environmental impacts is today readily available. This data could, however, become particularly relevant as power grids play a pivotal role in balancing power generation with consumption. Should the shares of erratic solar and wind-based power generation increase in the future, this key process to prevent blackouts may be expected to become more challenging (Sharma & Saini 2015; Warren 2014). In such cases, power grids will increasingly have to be able to respond within moments to shifts from strong excess power generation to shortages of power supply, for example on days with scattered cloud cover. In order to cope with such dramatic changes in generation loads, electricity grids are expected to require more automated energy flow measurement and steering technology.

This begs the question how such a transition in power distribution technologies affects resource requirements, as the way resource requirements change when societies opt for a transition to more renewable energy and smart grid technologies remains unclear. This also applies to certain types of electric appliances. While some devices, such as mobile phones or laptop computers, have been subject to extensive analyses, other

more basic installations, including ventilating systems or ovens, have not been as frequently subject to holistic cradle-to-grave life cycle assessments. This data deficiency would have to be remedied in order to generate as many benefits as possible from applying the *proposed framework*.

One of the hallmarks of the *proposed framework* is the consideration of both the functional aspects of the system and the normative requirements of SD. In this thesis, I was able to demonstrate how a scientific interpretation of SD can be translated by means of a multi-step procedure into general goals for criteria for sustainability assessments of power systems for the first time. As elaborated in chapters 10 and 11, I chose one specific interpretation of the guiding principles of SD to carry out this endeavour. During this process, I was only able to hint at the severe implications the selection of the interpretation could potentially have. Accordingly, one could now strive to further demonstrate this effect by first choosing, for example, a strongly ecology-oriented interpretation and one that focuses on social aspects and then systematically translate these interpretations into general goals for criteria. Such an endeavour is likely to confirm that while the functional cornerstones of the system can be expected to remain roughly the same, the selection of two different normative foundations may lead to two different sets of general goals for criteria. Against this backdrop, I argue that the choice of interpretation of SD strongly influences the direction the system development should take, since this interpretation serves as a basis for deriving general goals for criteria. I would expect such an analysis to further stimulate the scientific discussion on what key systems should strive to sustain.

Moreover, I would like to touch on another key challenge that the authors of sustainability assessments frequently face: sustainability assessments are designed to provide a comprehensive basis for decision making on the long-term development of key systems. As explained in section 13.2, such a process is likely to involve negotiation and deliberation. Against this backdrop, it is not by chance that authors often encounter conflicting results, where not all goals can be reached simultaneously without concessions. While my contribution provided a set of exemplary criteria and general goals for sustainability assessments of power systems, the *framework for sustainability assessments* does not provide a solution on how to determine appropriate weightings. The framework is designed to systematically provide the categories for identifying relevant data and offers a basis for discussing goals. How decision makers eventually come to a decision based on this information, however, lies beyond the scope of this thesis. Nonetheless, I would like to emphasise that I am fully aware of the challenges associ-

ated with weighing criteria and goals. Furthermore, I acknowledge that the *proposed framework* does not offer systematic procedures for weighing criteria or corresponding general goals to determine single best solutions. Accordingly, I acknowledge that additional research on this subject is required before the *framework for sustainability assessments* can be applied in the field.

Lastly, the vast scope of power systems and the complexity of SD allowed me to only create the *proposed framework* conceptually, which is fully in line with the originally formulated research question. While I would have thoroughly enjoyed seeing it come to life by putting it into practice, this has not yet been possible owing to the aforementioned deficiencies and challenges. While I could have processed data on specific parts of the system in question, I would have then been unable to reap the benefits of considering the entire system, as well as the normative and instrumental requirements of SD, which I advocated so passionately throughout the thesis.

Once the above data deficiencies and challenges have been resolved, a new research opportunity could lie with applying the *proposed framework* in the field to gain further insights. While I am confident that the theoretical foundation has given rise to a robust scientific instrument to provide a comprehensive basis for *evidence-based* and *goal-oriented* decision-making support, I acknowledge that often practical experience proves invaluable for finalising instruments and tools because it validates underlying assumptions in the field.

Assuming that my arguments hold true, the *framework for sustainability assessments* should serve well in providing a comprehensive basis for *evidence-based* and *goal-oriented* decision making on the long-term development of critical systems in modern democracies. Since putting the *framework for sustainability assessments* into practice, clearly lies, as mentioned above, beyond the scope of my work here, I will have to postpone such an endeavour and leave it as my final opportunity for further research.

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