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# Biomass or batteries

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# 1

# Introduction

*“The secret of change is to focus all of your energy, not on fighting the old, but on building the new”.*

*-Socrates-*

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Q8 Oils

## 1.1 General introduction

Humanity is on the verge of an energy transition, during which society gradually shifts from a dependency on fossil energy to different forms of renewable energy. This can be illustrated with global data from REN21 (2017) which shows that the decade from 2006 until 2016 has shown an exponential increase in installed capacity of solar photovoltaics and wind power. In addition, other forms of renewable energy technology (i.e. biomass conversion, geothermal, hydropower, ocean energy and concentrating solar thermal power) also show increases in installed capacity. About 10% of the final energy consumed originated from modern renewables in 2015 (REN21, 2017) against about 2% in 2005 (REN21, 2005). On the one hand, this rate of technological change is high, but on the other hand one can wonder if this pace is high enough to keep the global mean temperature increase below 2°C, or even below 1.5°C, as agreed upon in the Paris Agreement (United Nations, 2015). Therefore, it is of interest to explore current and potential developments in the energy system. In order to gain understanding of the drivers of change, this introductory chapter first goes back in time to the previous energy transition (i.e. the Industrial Revolution). It looks at technological change and the environmental problems accompanied with this technological change. Furthermore, it explores the development in scientific literature when it comes to understanding of environmental problems and it looks at the scientific insights regarding the drivers of change and the means to handle the environmental problems, before arriving at the main aim of this thesis.

## 1.2 The Industrial Revolution

Two and a half centuries ago, humanity was on the verge of a transition, which we now call the Industrial Revolution. This transition was made possible due to a substantial increase in the supply of energy (Fröling, 2009). Energy consumption was about 20 GJ · capita$^{-1}$ yr$^{-1}$ in 1800; the per capita energy consumption was about three times higher in 2016 and absolute energy consumption has increased twentyfold in this period (Grübler, 2004; IEA, 2016). This tremendous increase in energy consumption was made possible through a shift from flow to stock resources, in other words, a shift from biomass combustion to fossil fuel combustion (Fröling, 2009). Before the Industrial Revolution, the demand for mechanical energy was dependent on manual labour, draft animals, water and windmills alone. Chemical energy for heat and lighting purposes was available in the form of biomass and thus, society was dependent on natural flows of energy (Grübler, 2004). The availability of wood in England, where the Industrial Revolution initially took off, was much smaller than other European countries around 1800, due to high wood demand for material and fuel purposes (Hughes, 2009). This shows that the consumption rate was higher than the natural regeneration rate of biomass. The further development of the steam engine by James Watt in 1765 (Fröling, 2009) and its subsequent patent in 1769 (MacKay, 2008), which can be seen as the starting point of the Industrial Revolution (MacKay, 2008; Fröling, 2009) or energy transition, decreased the demand on wood for fuel purposes by substituting it with coal (Hughes, 2009). Thus, scarcity issues related to biomass were initially solved by shifting the demand for energy to another material system, whilst sustaining growth. Coal consumption and the associated emissions of carbon dioxide ($CO_2$) increased rapidly from this point forward (MacKay, 2008). Besides that, fossil fuel combustion is associated with other pollutants, such as sulphur oxides ($SO_x$) and nitrogen oxides ($NO_x$) (McKinney and Schoch, 2003). The wide availability of fossil energy, used in industrial processes, resulted in growing levels of pollution in abiotic ecosystem compartments such as, air, water and land (Hughes, 2009) in the second half of the nineteenth century. With these growing levels of pollution, the scale of the environmental effects increased over time. Coal is a major contributor to the formation of $SO_x$, due to the oxidation of sulphur at high temperatures. These substances result in air pollution on a local and regional scale. When reacting with water in the atmosphere, sulphuric acid is formed, which is better known as acid precipitation. This can disperse over hundreds of kilometres increasing the scale of pollution beyond national boundaries. Furthermore, the combustion of coal and liquid transportation fuels results in the formation of $NO_x$ due to oxidation of nitrogen in the air and the fuel when combusted. $NO_x$, just as $SO_x$, contributes to acid rain (McKinney and Schoch, 2003), which was first noticed in 1872 (Hughes, 2009). In addition, $NO_x$ contributes to the formation of smog, which is a local environmental problem, initially caused by the combination of smoke and fog. Nowadays, smog refers to secondary photochemical pollution from industrial sources, such as coal-fired power plants and liquid transport fuels (McKinney and Schoch, 2003; Hughes, 2009), where the $NO_x$ reacts with sunlight into the photochemical pollutant ozone (McKinney and Schoch, 2003). These environmental pollutions resulted in human health effects, deterioration of ecosystems and decreasing crop yields (McKinney and Schoch, 2003).

Besides environmental effects from fossil energy consumption, such as acid precipitation and smog, there are emissions of greenhouse gases (GHGs) affecting the mean temperature on a global scale. Arrhenius elaborated on the natural greenhouse effect, caused by the presence of water vapour and $CO_2$ in the earth's atmosphere in 1896, and calculated that a doubling of $CO_2$ would lead to a five centigrade temperature increase (Arrhenius, 1896). Arrhenius aimed to explain the coming and going of the Ice Ages and therefore wondered if changes in $CO_2$ concentrations could have occurred rapidly enough to be the driver for the Ice Ages. Despite this aim, the paper implicitly suggests there is a potential of fossil fuels to contribute to global warming, with the notion that the natural sequestration of $CO_2$, by weathering of limestone, is in the same range as the $CO_2$ emissions from coal combustion at that time (Arrhenius, 1896). Concentrations of $CO_2$ have risen from around 280 ppm before 1800 (Hughes, 2009) and surpassed 408 ppm in 2017 (Kuhns and Shaw, 2018). Current scientific evidence shows that human induced changes to the composition of the atmosphere have resulted in an increase of about 0.6°C compared to pre-industrial times (O'Neill et al., 2017). Global climate change is accompanied with risks, for which global mean temperature change is an often used indicator. Extreme weather events and rising sea levels are rather easy to comprehend as risks forthcoming from temperature change, due to increased evaporation and melting land ice. Other risks, mentioned by O'Neill et al. (2017), such as ocean acidification, deteriorating ecosystems, distribution of impacts and the possibility of large scale singular events (i.e. tipping points) are less straightforward to capture. Still, it is clear that the use of fossil fuels has global consequences that need to be addressed on several levels.

## 1.3 The need for an energy transition

Mitigation of climate change is on the global agenda, which is visible in the Paris Agreement where 194 countries and the European Union (EU) have expressed the ambition to pursue efforts to remain below a 2°C increase in global mean temperature (United Nations, 2015). Currently, about 170 countries and the EU have ratified the Paris Agreement (United Nations, 2016). Arriving in a state where the net emissions of GHGs are zero, by either using renewable energy, end-of-pipe solutions, such as the underground storage of GHGs, or a combination of both, requires substantial system change which is not a straightforward procedure. The timeframe available to stay below a 2°C increase can be illustrated with the so-called carbon budget. Total emissions of GHGs since the reference period (1861-1880) should remain below 2900 Gt $CO_2$ including non-$CO_2$ drivers (IPCC, 2014). The larger part of this budget is already consumed in the last 150 years. According to the IPCC (2014), the remaining budget was 1000 Gt $CO_2$ in 2011. At existing rates of 38.1 Gt $CO_2$ in 2011 (IPCC, 2014), a linear decrease to zero emissions should be achieved in exactly 45 years from now. In addition, technology is not the only function that affects the environmental impact. Ehrlich and Holdren (1971), describe the environmental impact as a straightforward linear relation, which is determined by the multipliers of population, and the per capita impact. The latter can be determined by the multiplication of per capita consumption and the impact of the technology used to foresee in this consumption. The United Nations project an increase of 2.2 billion in population up to 9.7 billion in 2050 of which the larger part is expected in Africa and Asia (United Nations, 2017), respectively a developing and transitioning continent. Consumption patterns in these regions can be expected to become more affluent and shift in the direction of consumption patterns in the most developed regions. According to MacKay (2008), per capita GHG emissions in Europe are roughly a factor three higher than Asia and a factor two to four in, respectively North and Sub-Saharan Africa. These simple numbers illustrate that an increase in absolute energy demand can be expected, whilst a decrease in energy related emissions is necessary. So far, increases in energy efficiency and renewable energy production have not been able to decrease the absolute energy consumption and emissions. Hence, the primary energy supply increased to 570 exajoule in 2015 (IEA, 2017) and the annual increment of 3.03 ppm $CO_2$ (Earth System Research Laboratory, 2018) was at an all-time high in 2015. Therefore, the technological assignment, to mitigate climate change, and realise system change on a global scale in such a short timeframe, is substantial.

Besides climate change, there is another argument on a global scale in favour of system change, namely resource depletion. Hughes (2009), mentions that in England at the start of the Industrial Revolution, forests were being depleted in order to foresee in demand for fuel. These national issues were then resolved by substitution of wood with coal and expansion, by importing resources from colonies (Hughes, 2009). There are limits to expansion as addressed by Malthus (1872) in relation to population growth and the availability of arable land. The same holds for other resources, such as fossil fuels. Recent estimates for the ratio of reserves over production for oil, coal and natural gas are, respectively 50, 153 and 52 years (British Petroleum, 2017). The aforementioned timeframe of 45 years is therefore not only driven by the 2°C climate ambition, but also by the decreasing availability of fossil resources, since further expansion is not an option. The limits related to the use of stock resources were mentioned by Arrhenius in 1920 when he emphasised that coal fields will be exhausted after a certain time. “When this calamity will happen, and the probability of the discovery of substitute sources of energy, are questions of vital importance” (Arrhenius, 1920). The risk related to the dependence on an exhaustible stock resource, was emphasised by Hubbert’s peak theory (Hubbert, 1956). His peak theory argues that production of a resource will follow a bell-shaped curve, or a normal distribution. This means that at a certain point in time, the production levels of a resource will stagnate and subsequently decline. Hubbert did not see this resulting in a calamity, since he expected a lot from nuclear energy as a substitute source of energy. It was not until the publication of Limits to Growth, commissioned by the Club of Rome (Meadows et al., 1972) that environmental issues and resource depletion became more widely recognised as global risks. By recognising the global impacts of fossil energy use related to climate change and resource depletion it became clear that the existing system in which energy and materials were consumed was not sustainable on the long term. In addition, the current consumption of energy and materials is still not sustainable, since it shows a close connection to the business as usual scenario from Limits to Growth (Turner, 2014), resulting in resource shortages, overpopulation and global pollution (Meadows et al., 1972). The Brundtland report “Our Common Future” (Brundtland, 1987) can be regarded as a moment in time after which atmospheric pollution, resulting in global climate change, adjusted the discussion about the design of the energy system and formed the basis for the need for an energy transition.

The focus of environmental problems has historically been on direct effects and specifically on acute (e.g. acid rain and smog) instead of chronic effects (Holdren and Ehrlich, 1974). Meanwhile, the large scale use of fossil fuels has manifested two chronic environmental effects, resource depletion, due to the use of stock resources and climate change, due to the emission of GHGs. Whilst, the acute effects of pollution on a local, regional, national scale and beyond due to the use of fossil fuels still exist, the chronic effects gain more attention. The major shift from flow to stock resources formed the origin of these two environmental externalities, which affect the global environment. The term environmental externality is an economic concept that refers to "[…] uncompensated environmental effects of production and consumption that affect consumer utility and enterprise cost outside the market mechanism" (United Nations, 1997). These environmental externalities became to some extent known in literature more than a century after the start of the Industrial Revolution (Arrhenius, 1896; 1920) and it took roughly another century before the social cost of these environmental externalities became widely recognised as a global risk (Meadows et al., 1972; Brundtland, 1987). In summary, the need for an energy transition is clear. Both chronic effects guarantee the future occurrence of an energy transition, willingly or unwillingly.

## 1.4 Carbon lock-in and sustainability transitions theory

Again, after two and a half centuries, humanity is on the verge of an energy transition. However, changing the energy system is not a straightforward procedure. In order to understand the inertia of the energy system, one should go back in time and consider the work of Adam Smith, the author of "The Wealth of Nations" in 1784. He can be argued to be the founding father of our modern economic system, driven by increasing returns to scale. Whilst these increasing returns have clearly contributed to the wealth of modern economies, there is a drawback. Arthur (1989) shows that increasing returns can result in a technological lock-in, which is not definitely the optimal alternative and not easily changed. In addition, Unruh (2000) argues that these increasing returns to scale have been the driver for a carbon lock-in of modern economies and that, as a result of this, there are market and policy failures hampering the introduction of renewable energy technology. Hence, the existing fossil energy system is established in a techno-institutional context, where the institutions were adjusted over time to stimulate the increase of the fossil energy system. Nowadays, these institutions hamper the diffusion of renewable energy technology (Unruh, 2000). Besides institutions, there are other factors contributing to this lock-in. Such factors can be, organisational, industrial, societal and technological (Unruh, 2002). The energy transition is a challenge, due to carbon lock-in, since it is comprised of a variety of factors requiring change.

Shifting from fossil to renewable energy can be done by changing the resource use on the consumption or the production side. On the production side, a variety of renewable energy sources is available (e.g. solar, wind, hydro, geothermal or biomass). On the consumption side such renewable energy sources have to foresee in the supply of energy suitable for electric appliances, heating and cooling and transportation. All the available technologies have their own specific characteristics and with that, their own advantages and disadvantages. From a technical and environmental perspective, hydropower is able to respond to fluctuations in demand and supply, but also affects land use. In addition, local geographic circumstances determine the suitability of hydropower (Yüksel, 2010; Ellabban et al., 2014). This is illustrated by the large differences in the share of inland energy consumption of hydropower within the EU. In Austria and Sweden this share is over 10%, whilst the EU average is 1.8% (Eurostat, 2018). Solar energy can contribute to the supply of heat and electricity (Ellabban et al., 2014), but is limited by the amount of solar irradiation at different geographic locations and daily and seasonal cycles.

Besides that, storage of electricity is still technologically challenging. There are multiple promising technologies available for electricity storage, but they are currently not implemented on a large scale (Lund et al., 2015). Just as solar energy, wind energy is free of charge and potentially infinite but it is subject to variation in wind speed, affects land use and has storage issues (Lund et al., 2015). Geothermal energy has an advantage over wind and solar, since it can continuously supply energy. Besides that, it supplies heat instead of electricity, which is a large part of the energy demand in households, almost 80%, (Eurostat, 2017) and industrial processes, about 70%, in the EU (Fleiter et al., 2017). Furthermore, geothermal energy contributes for 0.4% to the EU energy consumption (Eurostat, 2018), meaning that when implemented on a large scale, new supply grids have to be installed at the cost of existing grids.

Biomass as an energy source is argued to be abundant and renewable (Ellabban et al., 2014). In addition, biomass is the only renewable carbon carrier and thus offers complementary opportunities to the current carbon lock-in. It can be combusted in order to produce heat and power and it can be converted with a variety of technologies into liquid or gaseous fuels and building blocks for the chemical industry (McKendry, 2002a; 2002b). Thus, biomass as a primary energy carrier matches with the supply and demand side of the current energy system. The perception of biomass as a renewable resource is visible in the EU's energy policy (European Commission, 2012) and in its renewable energy statistics, which shows that almost two-thirds of the renewable energy was derived from biomass and renewable waste in the EU28 in 2016 (Eurostat, 2018). Biomass is regarded as a flow resource within the bioeconomy strategy (European Commission, 2012). The regeneration rate of biomass is much higher than the regeneration rate of fossil resources, which justifies an approach towards biomass as a flow instead of a stock resource. This legitimates its application as a renewable resource. However, scarcity issues may arise due to high expectations for biomass as a substitute resource for fossil carbon, possibly resulting in an imbalance between supply and demand or resource depletion. Hughes (2009), showed that this was already a reality in England in the first decades of the Industrial Revolution. Biomass should be cascaded based on economic value as presented in figure 1-1 (European Commission, 2012), where the highest value is at the top of the pyramid and the lowest value at the bottom; for the physical quantities the inverse holds. This should result in more efficient use of materials and waste streams. The cascade, however, shows continued linear consumption, by combustion of biobased liquid transport fuels and application of biomass for electricity and heat, which does not overcome possible scarcity issues.

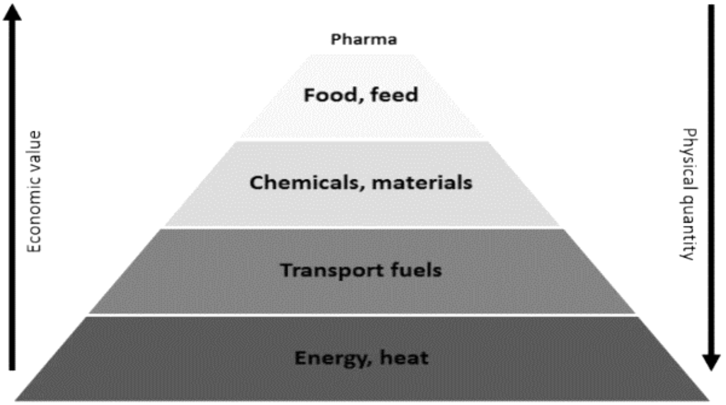

Figure 1-1: Overview of economic cascading of biomass in a bioeconomy (based on Lange et al., 2012).

Global projections on the longer term for the potential of primary biomass have large margins varying from 33 to 1135 EJ · $yr^{-1}$ in 2050 (Hoogwijk et al., 2003). The review by Laugs and Moll (2017) shows that the future projections for biomass based on thirty quantified energy scenarios vary roughly between 120 and 250 EJ · $yr^{-1}$ in 2050. Compared to 48 EJ in 2005 (Heinimö and Junginger, 2009) roughly a two to fivefold increase is expected. This suggests, that at best, biomass can partially foresee in the future energy and material demand for carbon. Substituting fossil with renewable carbon, whilst refraining from system change, is the current trend. Hence, biomass is often applied for electricity, heat, green gas or liquid fuels, which are all complementary to the existing energy system and in the lower part of the biomass cascade (figure 1-1). Complete substitution of fossil carbon with renewable carbon is not obvious given the annually available quantities. In addition, it is questionable whether increasing quantities of biomass for energy can keep up with the absolute increase in energy demand. This can be illustrated with the transport sector in the EU. The total number of passenger vehicles has increased with 4.5% between 2011 and 2015 (ACEA, 2017). The share of biofuels mixed with conventional transportation fuels fluctuated around 5% in the same timeframe (Flach et al., 2017). Biofuels are an institutional solution for carbon lock-in, but currently, the net effect when it comes to mitigating climate change is about zero. Besides this, electrification of private transport is occurring in the EU as an alternative for the use of conventional and biofuels. Despite only 0.15% of the private transport fleet being electric and only representing 1.2% of new sales in 2015, the absolute quantities sold show a strong increase (EEA, 2016). Continuation of this trend, with an increasing scale of application and increased dependency on lithium for batteries, may alleviate pressure on conventional and biofuels and address climate change, but may also be accompanied with scarcity and shifting geographic resource dependency.

Even though environmental effects, such as climate change and depleting resources, are understood for half a century, the share of renewable energy was only 13.2% in the energy mix of the EU28 in 2016 (Eurostat, 2018). When aiming to overcome the factors contributing to carbon lock-in and the inertia of the existing energy system, understanding of the drivers or processes involved in system change is recommended. Gaining understanding of such drivers can be done by looking at previous transitions. Historic analyses of transitions have led to a variety of frameworks related to sustainability transitions theory; the Multi-Level Perspective (MLP) on sustainability transitions and the Technological Innovation System (TIS) are the ones most frequently applied (Walrave and Raven, 2016) to analyse change. The MLP aims to explain the socio-technological dynamics in transition and the TIS aims to explore the dynamics of diffusion of a technological innovation into a system by setting a number of pre-conditions. Reflecting on historic transitions by means of sustainability transition frameworks can contribute to understanding the dynamics of transition and be a starting point to overcome the stage of carbon lock-in.

The previous energy transition, can be considered emergent (Geels, 2011). Beck et al. (1994), argue that when the perception of environmental problems changes from “a problem of the world surrounding us” to an “institutional crisis of industrial society itself”, self-reflection is needed when looking at further technological development. This requirement of a shifting perception of global environmental problems from chronic to acute is in line with Holdren and Ehrlich (1974) and Unruh (2002) who argues that external forces are probably required before action is undertaken. Waiting for the occurrence of external forces or large scale singular events as elaborated by O’Neill et al. (2017) is a substantial risk. The second part of the statement by Beck et al. (1994), addressing self-reflection is, however, already occurring. First, the current energy transition is shaped around the concept of sustainability, where sustainable development is defined as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Thus, the current energy transition is goal-oriented instead of emergent. Second, sustainability transitions theory analyses the processes involved in system change. When change is not emergent, but goal-oriented with the collective good being regarded as the desired outcome, guidance is required. Geels (2011), argues that the factors that need to be taken into account to analyse and steer sustainable transition are, technology, politics and its resulting policy, economics and culture or norms. This shows that in order to steer change towards the collective good, there is more than a technical and resource issue alone that needs to be resolved; societal aspects, organisational aspects, new norms, new structures and processes and powerful agency of the incumbents, should be taken into account in order to guide the energy transition. Here, it is argued that, whilst environmental problems are generally regarded as “a problem of the world surrounding us” there is reflection on technological development and how the energy transition should be guided. Independent of the perception of environmental problems, the insights from sustainability transitions theory can contribute to the guidance of the energy transition by finding the best strategies, at different stages of the energy transition in order to steer change along the desired pathway.

## 1.5 European energy policy

Guidance of the energy transition, especially since it is goal-oriented towards sustainability, which can be regarded as a collective good, requires policy. Policy is of importance to guide the energy transition, since it provides the context and direction in which the energy transition takes place. The EU has signed the United Nations Paris Climate Agreement, together with 174 countries (United Nations, 2016). A clear vision on what should happen may therefore be expected from the EU. In 2015, the Energy Union was introduced which aims to provide “secure, sustainable, competitive and affordable energy” (European Commission, 2015a). Competition can be regarded as a precondition for the affordability of energy. Therefore, the main energy policy from the EU revolves, around three objectives, namely security of supply, affordable energy prices and sustainable energy consumption (European Commission, 2015a; 2017a). Keppler, (2007) explains the presence of internal friction within these three objectives with his unsolved triangle of European energy policy (see figure 1-2). Simply optimising the three aspects of this triangle does not work, which can be illustrated with two examples. First, currently low coal prices have a positive effect on security of supply and economic competitiveness, but it has a detrimental effect on the environmental objectives. Second, intermittent renewable power may meet the environmental objective and in some cases result in economic competitiveness, but storage issues still put a burden on security of supply.

Alkemade et al. (2011) explain that there is a conflict between innovation and transition policy by arguing that “[…] policy […] may not only be misaligned but may even conflict as transition policy focuses on stimulating the new and phasing out the old whereas innovation policy often focuses on sustaining the old”. Kivimaa and Kern (2016) argue that “[…] policy mixes favourable to sustainability transitions need to involve both policies aiming for the ‘creation’ of new and for ‘destroying’ (or withdrawing support for) the old”. Therefore, the effect of innovation on the energy transition is unsure due to this internal friction within the European policy objectives. Despite this, innovation plays a key role in the concept of the Energy Union. Hence, the European Commission advocates in its Energy Union communication that a new strategy for research and innovation is required and that an innovation driven transition provides space for economic growth (European Commission, 2015a).

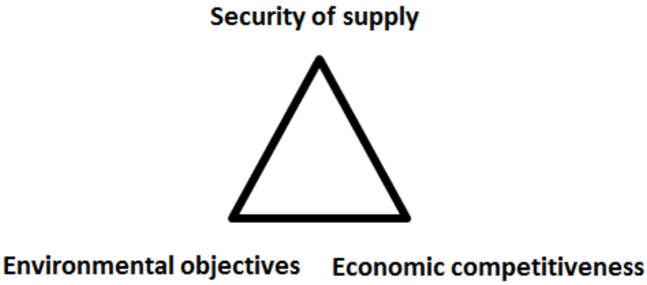

Figure 1-2: The unsolved triangle of European energy policy (based on Keppler, 2007).

The energy transition should lead to structural change of the existing system in order to overcome the challenges of climate change and resource depletion. Therefore, the question is whether the pace at which policy driven innovation manifests itself and introduces change to the incumbent system is enough, to mitigate the global environmental effects of climate change and resource depletion. Or alternatively phrased, is the pace at which policy driven technological innovation manifests itself and introduces change to the incumbent system, enough to prevent a global change of perception, from a chronic to an acute problem, by external forces or large scale singular events?

## 1.6 Aim and scope of the thesis

The need to change the energy system is clear, climate change and resource depletion. Availability of the required resources to realise this change in the required timeframe is insecure. The perception of climate change as a chronic problem and the need for a goal-oriented approach towards the collective good, do place the incentive for guidance of change on a governmental level. System change is not only a governmental matter when it comes to responsibility, but the EU can take a strong responsibility for the energy transition. The existing strategies imply that the EU is also willing to take such responsibility. However, the future contribution of technological innovations, in line with proposed European strategies, to the energy transition is insecure and therefore worth exploring.

Therefore, the main aim of this thesis is to explore the potential contribution, of some current and possible future technological innovations, to the energy transition.

This resulted in the following overarching research question: to what extent do some current and expected future technological innovations, contribute to the energy transition?

This thesis aims to explore the effect of technological innovation on the energy transition in the context of resource dependency and climate change. As elaborated, there are multiple challenges related to overcoming carbon lock-in. Whether technological innovation is enough to overcome carbon lock-in and address resource dependency and climate change in the required time frame is explored by analysing three technological innovations. It continues with four result chapters and finalises with a general conclusion. Chapter 2 addresses the challenges in the transportation or mobility sector. It explores material scarcity and shifting dependencies in the private transportation sector by means of a chain analysis, where lithium availability for electric vehicle batteries in private transportation was explored, with an emphasis on substitution of lithium in other sectors.

Subsequently, chapter 3 zooms in on the lower part of the biomass cascade in the bioeconomy strategy. This was done by a chain analysis exploring biomass co-combustion in a coal-fired power plant, which is currently a trend in the Netherlands. This is the second technological innovation discussed in this research and it analyses the implications of biomass co-combustion for electricity production by adjustments of existing coal conversion technology, set against the indicators of the Renewable Energy Directive (European Commission, 2009).

When regarding biomass as a potentially scarce resource, deliberate application of biomass is necessary. Biomass gasification technology is a potential future innovation, since the technology can convert biomass to basic gaseous molecules (Speight, 2015). These molecules can be converted to synthetic natural gas, a green gas suitable for injection into the existing natural gas grid. Large scale application of biomass gasification is the third innovation discussed in this research. Chapter 4 is applied to gain insights in the effect of large scale green gas production. It analyses the environmental impact and energy performance of a green gas supply chain when it replaces 1% of the current natural gas consumption in the EU28. In perspective, this 1% corresponds with half of the currently required quantities of natural gas in the Dutch residential sector for the supply of heat.

The Dutch residential sector is largely dependent on low caloric natural gas for the supply of heat. Biomass gasification with green gas production can theoretically play a large role in this sector when shifting to a more sustainable heat supply. However, this is a developing technology; its diffusion into the energy system is subject to a number of factors and its successful contribution to supply heat for the Dutch residential sector within the required timeframe, is unsure. In addition to exploring technological potential, this research focuses on the opportunities and barriers of biomass gasification from a socio-technological point of view to find if the current green gas ambitions are feasible. Thus, chapter 5 is applied to explore a case where the feasibility of the diffusion of biomass gasification for green gas, applied in the Dutch residential sector, is analysed.

Finally, chapter 6 provides the general conclusion and discussion. This chapter is applied to summarise the potentials and limitations of the explored technological innovations to contribute to the energy transition and answer the main research question. Additionally, the final chapter reflects on the results and aims to provide some recommendations for the explored innovations and some general recommendations for the energy transition.