

## MASTER

### Regulating future distributed generation

distributed generation challenges for the Dutch distribution network : an exploratory research for the regulatory framework

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# Regulating Future Distributed Generation

*Distributed Generation Challenges for the Dutch Distribution  
Network; an Exploratory Research for the Regulatory Framework.*

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*This research is partly carried out at NMa/Energiekamer. However, any views expressed in this paper are those of the author(s) and do not necessarily reflect the views of the Dutch Competition Authority.*



## Preface

After travelling 31.000 kilometers in 5 months the final report for my master study Technology and Policy is finished. I might have underestimated the distance between Meppel and Den Haag, but I look back on my graduation project at the Energiekamer with great pleasure. It has been a challenging project in a dynamic sector. I admire the professionalism and expertise used by the Energiekamer to fulfill their role in this dynamic sector.

The report is the final report of my Master of Science program Technology and Policy. This program is very broad and focuses on applying technology and innovation for economic growth, sustainable development, and welfare. During my master I made the decision for innovation management as my specialization cluster. With my background in electrical engineering (bachelor), the Energiekamer has provided me with the perfect opportunity to combine the experience from my bachelor- and master program.

This research wouldn't have been possible without the support of my supervisors at the Energiekamer Hugo Schotman and Machiel Mulder. Special thanks go to Hugo Schotman, who was my mentor at the Energiekamer. He has been very supporting, enthusiastic and stimulating to work with. And of course, I would like to thank the people at the Energiekamer (Adriane, Edin, Fabien, Luuk, Marga, Mathieu and others) for their support and enthusiasm.

Further I like to express my gratitude to Geert Verbong (first supervisor, University of Technology Eindhoven), who has been very helpful with his expertise and enthusiasm. I also would like to thank my second supervisor of the University of Technology Eindhoven Greet Vanalme, for providing me with valuable information and support.

Further I really like to thank Karina, for here unconditional support and encouragement, and of course my parents. I hope my graduation will, in return, encourage my father to finish his MBA-study. Furthermore I like to thank my friends, who have been a great distraction in the weekends, and of course Alie, Klaas, Anne, Danny, Karin and Martijn, for their shown interest.

I hope this thesis will inspire further research in the field of further integration of DG in the Dutch electricity system and regulation.

Meppel, 4 September 2009

Bastiaan Meijer



## Summary

Distribution network operators (DNOs) are increasingly confronted with distributed generation (DG) units, which have to be facilitated by their networks. Facilitating these (renewable) DG units is important, as they can contribute to the climate goals set in among others the European 20/20/20 goals. Whether it is PV-panels, wind turbines, micro-CHPs or small scale biomass, the DNO is obliged to connect and facilitate the requested electricity transport. However, the rapid increase in DG-units already causes transport problems for some DNOs and is expected to become a bigger problem in the future. The office that regulates the distribution market, the Energiekamer, is closely involved and monitors developments in the market. This report intends to provide the Energiekamer with information on the possible development of DG, by describing different scenarios and the consequences of these scenarios for the distribution networks. The solution technologies for the distribution networks, deriving from the consequences, have been confronted with the regulatory framework.

From the energy transition, two decentralized scenarios and one centralized scenario have been identified, with variable DG developments towards 2030. This variation concerns the penetration level, the organization level, and the size of the DG units. The centralized scenario is characterized by a European super grid with a top-down electricity supply chain. The electricity is generated by large centralized production units, preferably renewable. In this sense one could think of PV-panels in the Sahara, wind turbines in the North Sea, and hydro turbines in Scandinavia. The consequences of the centralized scenario for the distribution network are relatively minor as the current structure (top-down) remains. The first decentralized scenario is named ‘plug and play’ and characterized by a low organizational level. Households are mainly responsible for the distributed generation, with PV-panels and micro-CHPs as the two main representative production types. The consequences of this scenario will mainly affect the LV-level, as the DG- sources of this scenario are mostly connected to this voltage level. The accessibility becomes a major issue as millions of households could supply the network, making the production of electricity highly unpredictable. The ‘fit and co-produce’ is the second decentralized scenario and characterized by the participation of large users. These users are connected to the MV-level in the electricity production field. Contrary to the ‘plug and play’ scenario the number of generation units is much smaller, but with an individual bigger capacity. In addition, the ‘fit and co-produce’ scenario is characterized by a high organizational level, meaning balancing takes place in local grids before interconnection with the distribution network takes place. These local grids are managed by special cooperations, which are not necessarily DNOs.

With regard to the consequences of the scenarios, the general problems of connecting DG are network losses, voltage quality (including voltage variation, frequency, and harmonics), reactive power, and protection. To deal with these problems four ‘solutions’ have been provided, from which the smart grid technology and grid reinforcement have been selected to be the most relevant. Large opportunities exist for the smart grid technology in the ‘plug and play’ scenario. In addition, this innovative technology is a necessity in the ‘fit and co-produce’ scenario. Grid reinforcement is the conventional solution and mainly applicable to the ‘plug and play’ consequences.

There is urgency in determining how smart grids will develop, as the two technological solutions (smart grid and grid reinforcement) are interrelated. When smart technology is applied, a grid does not require the same reinforcement as in the conventional situation.



In this research, smart grids are defined as *“the ability to balance on a distribution level without using interconnection but with storage, demand control and production control, and making optimal use of the connected DG capacity while maintaining voltage quality and reliability, and integrating ICT and new network technologies in the distribution system.”*

Demand control, as a balancing technique, refers to lowering demand for peak reduction, e.g. controlling the electricity demand of a freezer or air-conditioning. Production control refers to the increase and decrease of decentralized production. The decrease of production is limited to non-renewable sources. The increase of production refers to using the micro-CHP on a DNO's preferable moment in time. The possible surplus on heat, produced by the micro-CHP, could be stored for a different moment in time. This heat storage is one of the three identified types of storage. The other two types are electricity storage for peak shaving and electricity storage for improving power quality.

The MLP-framework is applied in analyzing the relationship between the regulatory framework and the smart-grid technology development. The MLP-framework consists of three levels: micro (niche), meso (regime) and macro (landscape). First of all, the landscape level refers to wider technology-external factors as environmental problems, increasing pervasiveness of ICT, oil prices, wars, and broad political coalitions. Secondly, the meso-level of the MLP consists of the socio-technical regime. In this regime the elements are linked that together fulfill electricity supply as a societal function, in which we focus on the distribution of electricity. Simplified, these elements represent: the actors involved in the socio-technical system, rules and institutions coordinate their behavior, and social-technical systems. Thirdly, novelties are generated in the niches (micro level), where they are protected or insulated from the normal market selection of the regime. These niches are often protected by strategic investments of companies or by subsidies.

In the socio-technical regime three analytical dimensions have been considered. The first analytical dimension is the socio-technical system. This system widens the existing innovation system, focusing mainly on production side, by encompassing diffusion and use of technology. Together the technology elements in the system fulfill the ‘electricity supply’ as a social function. The second analytical dimension is the actors, e.g. the end-user, DNOs, technology suppliers, energy service companies, and research institutions. These actors operate in the context of rules and influence the social-technical system by reproducing the elements and linkages of the system in their activities. The third and last analytical dimension is the rules and institutions. Their aim is to coordinate and structure the activities in the system. In this case the rules specifically refer to the regulative rules embedded in the regulatory framework. Within the socio-technical regime the focus is on the relation between the regulatory framework (rules) and the development of the solution technologies (smart grids and grid reinforcement) for the distribution networks.

The regulatory framework is divided into two types of regulation: direct and indirect. Direct regulation refers to the minimum conditions of the distribution network. These conditions especially refer to the Electricity Act and the Netcode. Indirect regulation has been defined as incentives given to the network companies. Based on these incentives the regulated company makes a consideration between efficiency and quality.

The relation between direct regulation and the smart-grid technology has been analyzed by determining the minimum conditions for a smart grid to break through. As with regard to the relationship between indirect regulation and the smart-grid technology, the reasons have been

investigated for a new technology to break through. In this case the smart-grid technology has to compete with the conventional grid reinforcement (which represents a thicker - or parallel cable and 'heavier' grid components). Five reasons for a smart grid breakthrough have been considered. The first reason is 'changes on a landscape level putting pressure on regime'. Reason two is 'internal technical problems undermining the trust in existing technologies'. The third reason is 'negative externalities and effects on other systems'. Reason four is 'changing user preferences'. The last reason concerns 'strategic and competitive games'. From these reasons the 'landscape change' and 'strategic and competitive games' have been analyzed in detail.

The 'landscape change' reason refers to a broad political coalition convinced of the necessity of smart grids for a sustainable, cost effective, and secure electricity system. Reasons for this coalition to stimulate (e.g. public support) the smart-grid technology are: no natural market appetite, no short-term benefits for a technology like smart grids, and no commensurate reward for a successful outcome of large deployment. As with regard to the 'strategic and competitive' reason, two key issues have been identified for indirect regulation: externalities for the DNO, and the technology innovation chain. The externalities refer to the DNOs costs of implementing smart grids that cannot be compensated by the DNOs benefits from smart grids. Such existence of externalities might be a reason for public support. Besides the two key issues for indirect regulation one should consider the regional differences, which seem to influence the competitive advantage.

The innovation chain is described by four stages: research, development, demonstration and deployment. The smart technologies are situated in the research and development phases, as desk studies are conducted and some pilot projects are set up. Furthermore, two innovation issues have been described concerning indirect regulation: the risk averse of DNOs, and a possible commensurate reward for successfully managing the innovation chain.



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## List of abbreviations

AC;	alternating current
APX;	Amsterdam Power Exchange
CE;	Committed to the Environment Delft (consultancy agency)
CHP;	combined heat power
DG;	distributed generation
DNO;	distribution network operator
DSO;	distribution system operator
ECN;	Energy Research Centre of the Netherlands
Energiekamer;	Dutch Office of Energy Regulation
EZ;	Ministry of Economic Affairs
FACDS;	flexible AC distribution system
FACTS;	flexible AC transmission system
GIL;	gas insulated line
HV;	high voltage level
IFI;	Innovation Funding Incentive
LV;	low voltage level
MLP;	multi-level perspective
MV;	medium voltage level
MVA;	mega voltage ampere
NMa;	Dutch Competition Authority
Ofgem;	Office of the Gas and Electricity Market (U.K. office of energy regulation)
PR;	program responsibility
PV;	photovoltaic
RPZ;	Registered Power Zones
S <sub>sc</sub> ;	feeding short circuit power in p



ST;	social-technical
TSO;	transmission network operator
TT;	technological transition
TU Delft;	Delft University of Technology
TU Eindhoven;	Eindhoven University of Technology
$U_L$ ;	voltage at point p
$U_{sc}$ ;	short circuit voltage
VPP;	virtual power plant
$Z_{sc}$ ;	line impedance

# 1 Introduction

## 1.1 Background

The Dutch electricity infrastructure is operated by eight Distribution Network Operators (DNOs) and one Transmission System Operator (TSO). These operators are respectively responsible for the middle/low voltage grids and the high voltage grid. The network operators are bound to the Electricity Act 1998 which is regulated by the Dutch Office of Energy Regulation: the Energiekamer. The task of the Energiekamer is to autonomously monitor the electricity market and let the market be as efficient as possible (NMa 2008).

## 1.2 Problem definition

The DNOs are believed to face a fundamental challenge ahead (Meeuwsen 2007, Scheepers et al. 2007). This challenge especially concerns Distributed Generation<sup>1</sup> (DG), which is regarded to be a problem for the distribution networks requiring a structural solution (NMa 2008, Scheepers et al. 2007, Creative Energy 2007). The source of the ‘DG problems’ can be found in the design of the distribution networks, which originally does not accommodate generation (Cossent et al. 2008). The urgency of the problems is underlined by current statistics<sup>2</sup>, which indicate a significant increase in DG. If one considers, in addition, the legal obligation of the operator to connect DG to its networks (DTe 2004), the relevance of finding a solution for the ‘DG-problems’ should be apparent.

The Energiekamer monitors the DG-problems, as it intends to look for a structural solution in cooperation with the DNOs and the Ministry of Economic Affairs (NMa 2008). However, the Energiekamer only considers the economic impact of an increase in DG on the network. The regulatory framework should be neutral vis-à-vis the technologies used (NMa 2008, DTe 2004). In this case the technologies mainly refer to the solutions for DG-problems. The justification of the assumption of neutrality is explored in this research. In addition, an attempt is made to provide options for change when the regulatory framework is not neutral. To explore the technologies for the distribution network that might be used in the future, different scenarios will be identified. The consequences of these scenarios will indicate the technologies used for DG-problems.

## 1.3 Research Question

The purpose of this research is to explore what the technical consequences are for the distribution networks in different scenarios and whether the regulatory framework is neutral towards the technologies used. In attempting to fulfill the purpose of this research the following research question has been defined:

*Which consequences do energy transition scenarios have on the distribution network, and is the regulatory framework neutral vis-à-vis the technological solutions for the distribution network?*

The main research question is relatively broad and is divided into three sections: the identification of the relevant energy transition scenarios, the consequences of the scenarios on the distribution network, and the neutrality of the regulation framework vis-à-vis the

<sup>1</sup> DG: ‘electricity production with a connection on a voltage level lower than 110kV’ (DTe 2004, p.5)

<sup>2</sup> <http://www.cbs.nl/nl-NL/menu/themas/industrie-energie/publicaties/artikelen/archief/2009/2009-2662-wm.htm>

technical solutions. By systematically answering the sub questions, there should be enough information within the three sections to answer the main research question.

Sub questions:

1. Which energy transition scenarios are relevant for the distribution networks?
2. Which technical consequences do the scenarios have on the distribution network?
3. Is the regulatory framework neutral vis-à-vis the technological solutions for the distribution network? And what could be changed if not?

## 1.4 Methodology

The first sub research question concerns, by considering various scenarios, the explanation of the possible unfolding of the energy transition. The outcomes of this question are different scenarios that describe how DG might develop in the future. Information for this first sub question is largely obtained by a desk study. The literature considered in the desk study are various scenario studies earlier conducted. Additional information is obtained from face-to-face interviews with experts of CE, TU Delft and TU Eindhoven. These interviews validate the selected scenarios from the literature.

The information to answer the second sub question is mainly taken from face-to-face interviews with experts and partly from a desk study. The experts are technical experts of DNOs, who are given the question what consequences the different scenarios have on their networks. In addition, the interview questions focus on the technical solutions they consider to prevent difficulties with their distribution networks and which possible hinder there might be for these solutions, e.g. in regulation.

Information to answer the last sub question is mainly obtained from face-to-face interviews with experts from DNOs, Energiekamer, ECN, CE and TU Delft. The information from the interviews will be used in a desk study. This desk study focuses on the relationship between regulation and the development of technological solutions for the DG-problems. Furthermore, the MLP analytical framework (Geels, 2004) will be used to analyze this relationship. As regards the second part of the last sub question, possible changes could be in both direct regulation (legislation and minimal standards) and indirect regulation (incentives).

## 1.5 Report overview

The next chapter provides an introduction to the Dutch regulation and distribution networks. Chapter 3 describes the selected energy transition scenarios. The consequences of the identified scenarios for the distribution networks are described in chapter 4. Chapter 5 focuses on putting the smart-grid technology concept into practice and attempts to give a practical definition to the concept. The last chapter describes the relationship between the smart-grid development and the regulatory framework, analyzed in the multi-level perspective (MLP) framework.

## 2 The Dutch regulation and distribution networks

### 2.1 Energiekamer

The Dutch Office of Energy Regulation (Energiekamer) operates as a chamber within the Netherlands Competition Authority (NMa) and is an autonomous administrative agency under the Ministry of Economic Affairs (EZ). The Electricity Act 1998 and the Gas Act are controlled by the Energiekamer and regulate operational activities relevant to the exploitation of the electricity and gas networks.

All network companies are regulated by the Energiekamer. As with regards to the Electricity Act (1998), the core activities of the Energiekamer are to safeguard general access to electricity networks, safeguard that tariffs and conditions concerning access and transport of different operators are not discriminating, and annually fixing access and transport tariffs for the regional electricity network operators. To conduct the activities for both the Electricity Act and Gas Act the Energiekamer consist of four departments: consumer market, trade and transport of electricity, trade and transport of gas and distribution networks. This research is conducted within the distribution network cluster.

### 2.2 Regulation

With the Electricity Act introduced in 1998, the restructuring of the electricity market was fully on its way in unbundling the vertically integrated utilities into production, transmission, distribution, and retail. Due to the monopolistic nature of their activities, the transmission and distribution operators' activities are kept regulated. Competition has been introduced in the production and retail activities. In regulating the network activities the DNOs are provided with incentives to make efficient investments and to efficiently operate the network while keeping a certain quality level. Besides these incentives, the economic viability of the network business should be guaranteed by regulation (Scheepers and Wals, 2007).

In this research we distinguish two types of regulation in the regulatory framework: direct and indirect. In principle the two regulation types have the same goal in ensuring efficient network operation and efficient long-term use of the electricity system (van Dijk, 2007). The difference between the direct and indirect regulation can be found in the means to come to the end. Direct regulation refers to the minimum standards applied on the distribution network, e.g. the Electricity Act and the Netcode (2007). Indirect regulation is defined as incentives given to the DNOs. Based on these incentives the operators make a consideration between efficiency and quality.

#### 2.2.1 Natural monopoly

Van Dijk (2007) describes a natural monopoly as one company that can supply the market with lower costs than two or more companies. In this sense, competition is out of the question as it is more efficient from costs perspective to have only one company. Caused by this natural monopoly characteristic, the transmission and distribution companies are subjected to sector-specific regulation.

Next to the electricity companies having a natural monopoly one can think of gas distribution, water distribution, airports and railroads. From these examples only the water distribution is not regulated. Airports and railroads are regulated by the Vervoerkamer, which

is the office of transport regulation. In this research we focus on the regional electricity distribution system, which is regulated by the Energiekamer.

## 2.2.2 Tariff Regulation

As with regards to the natural monopoly, the distribution tariffs charged by a DNO tend to be higher than socially optimal (Scheepers et al. 2007). However, by tariff regulation the social welfare can be increased due to lower pricing, higher demand and increased production. In this sense, regulation takes over the role of competition that is missing in a natural monopoly (van Dijk, 2007).

There are mainly two tariff regulation methods: rate-of-return and incentive regulation (van Dijk, 2007). Concerning rate-of-return regulation the regulator determines the tariffs the natural monopolist may charge. These tariffs are based on relevant costs and a reasonable return. In this way, the surplus on return is cut-off, minimizing the social welfare losses. However, there are no incentives for the monopolist to be cost efficient with this type of regulation. On the other hand rate-of-return regulation has enough incentive for investments and even over-investments could occur. This investment incentive refers to the cost of investment charged in higher tariffs for the end-user. When the costs are accepted by the regulator higher tariffs can be charged.

In The Netherlands, price-cap regulation is applied, which is a type of incentive regulation. In price-cap regulation, the tariffs cannot increase more than a certain percentage per year. The profit the regulated company can obtain is calculated from the difference between the return and the relevant costs. In this sense, the company is stimulated to be as cost-efficient as possible. Concerning the investments, this efficiency incentive could be a disadvantage as higher investment costs will directly influence the profit. On the other hand, this investment could be more cost efficient on the long term, meaning a higher profit at the end.

### 2.2.2.1 Incentive regulation- price cap for tariffs

The multiple year tariff cap indicate that the tariffs may not increase more than a certain percentage. This percentage is calculated from an inflation factor minus the efficiency factor, and, since 2004, plus the quality factor. Simplified, the higher the quality of the networks and the higher the operational efficiency, the higher the tariffs the DNOs can charge to the end-users. The price cap of the tariff can be calculated by the following formula (Methodebesluit, 2008):

$$TI_t = \left( 1 + \frac{cpi \pm x + q}{100} \right) TI_{t-1}$$

Where  $TI_t$  is the total revenue from tariffs in year t:  $TI_{t-1}$ , the total revenue from tariffs in year t-1:  $cpi$  the economy wide price level:  $x$  the efficiency factor and  $q$  the quality factor<sup>3</sup>. In addition, a DNO can make a proposition for a higher tariff when he faces an exceptional and considerable investment extending his distribution network.

Based on the Electricity Act, the so-called Methodebesluit describes methods of determine the x-factor, q-factor and a formula. For every individual regulated company the x-factor, q-factor and formula are determined for a period of minimum 3 years and a maximum of 5 years. Based on the x-factor, q-factor and formula every DNO sends its proposition of the

<sup>3</sup> In the Dutch case, the quality factor only applies to the distribution network (Hesseling and Sari, 2006).

tariffs in a so-called ‘tarievenvoorstel’. When the tariffs are approved by the Energiekamer they can be charged to the end-user.

### 2.2.2.2 Benchmark competition

To calculate the x-factor for every individual regulated company, yardstick competition (or benchmarking) is used. The yardstick competition principle makes a comparison between achievements of an individual operator with the sector average. As displayed in Figure 1, the tariff an individual DNO can charge depends on his efficiency performance in comparison to the overall sector.

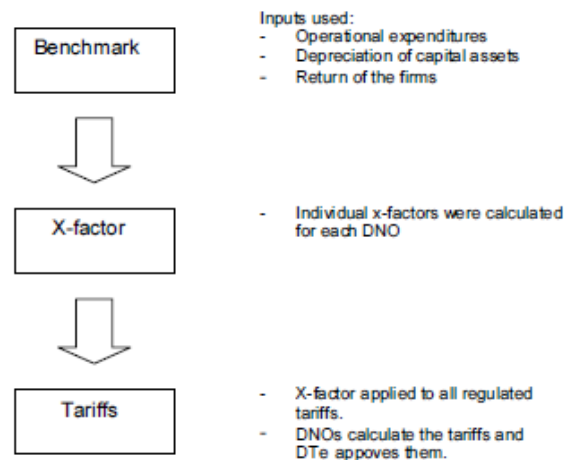


Figure 1, from benchmarking to tariffs through the x-factor, Wals et. al (2007)

The same process of benchmark competition applies to the q-factor. The q-factor prevents the so-called “race to the bottom” and makes sure that the quality is optimal. The “race to the bottom” refers to quality suffering under cost reduction.

### 2.2.3 Quality regulation

The 4<sup>th</sup> Benchmarking Report on Quality of Electricity Supply (CEER, 2008) describes three major aspects of electricity quality: continuity of supply, voltage quality and commercial quality. In this research the same distinction will be made and the definitions of the 4<sup>th</sup> benchmarking report will be adopted. As this thesis focuses more on the technical consequences of DG development for the distribution network the first two aspects of electricity quality are described in further detail. The commercial quality, referring to the nature and quality of customer services, will not be considered further.

The first aspect of electricity quality is continuity of supply, which is defined as the availability of electricity without an interruption of supply. Fewer and shorter interruptions refer to a better continuity of supply. For a DNO it is important to find a compromise between quality and efficiency (incentive regulation) and find an optimal supply. The second aspect of electricity quality is voltage quality, which is defined by the 4<sup>th</sup> benchmarking report as the usefulness of electricity when there are no interruptions. In practice, voltage quality is described as deviation from nominal values for voltage magnitude and the voltage wave shape. Peças Lopes et al. (2006; p.1191) describes it as follow: “*two aspects of power quality are usually considered to be important; transient voltage variations and harmonic distortion*”. In Varming et al. (2004) different aspects are described under power quality: short circuit power level, voltage variation and flicker, harmonics, frequency and reactive power.

### 2.2.3.1 Continuity of supply

In the Dutch case the quality is regulated through a q-factor. This q-factor is based on the quality of the output: continuity of supply (Hesseling and Sari, 2006). Hesseling and Sari (2006) argue that quality should be based as much as possible on output, instead of input or process, as the DNO is generally in a better position to make operational decisions. Quality indicators that characterize the continuity of supply of the electricity system should be in agreement with section 2, paragraph 1 of the Ministeriele Regeling “kwaliteitsaspecten netbeheer elektriciteit en gas”, (EZ, 2004) and are defined as follow:

- The duration of the interruption in minutes: the average time in minutes per year that no electricity is supplied to the consumer.
- The average period of interruptions in minutes: the average duration of an interruption in minutes.
- The interruption frequency per year: the amount of interruptions per year for a consumer.

### 2.2.3.2 Voltage quality

The voltage quality standards are explicitly described in the Netcode (2007). These standards are considered quality regulation on the input and not part of the q-factor (Hesseling and Sari, 2006). Despite voltage quality is not considered in the incentive regulation, interference is possible when necessary (e.g. when deviation from the standards occurs).

Voltage quality is defined as deviation from nominal values for voltage magnitude and the voltage wave shape. The voltage quality in normal condition should always suit the standards described in section 3.2.1 of the Netcode (2007), see Appendix I. The ‘power quality monitoring system’ project, commissioned by the DNOs, monitors the voltage quality by conducting tests at random. These tests indicate whether the quality is within the standards of the Netcode. The results of the project are supplied to the Energiekamer, as is obligated by article 3.3.4 of the Netcode. Five voltage quality aspects are described in the Netcode: frequency, slow voltage variation, fast voltage variation, asymmetry and harmonics. Remaining voltage quality aspects are described in NEN-EN 50160:1995.

The first voltage quality aspect is the frequency, which refers to the balancing of supply and demand. The rotation speed of synchronous generators, connected to the grid, is proportional to the frequency of the system and synchronized. The frequency might fall when the generators are slowing down due to an increase of electrical load. The equilibrium between instantaneous power consumption and production has to be maintained to keep the frequency on 50 Hz. The second aspect is fluctuating loads and / or production causing voltage variations on the network. This aspect is the main issue of complains regarding power quality. Fast voltage variation is called flicker. Slow voltage variation is not considered disturbing when it is within the -10% +6% tolerance band (Varming et al, 2004). The third aspect refers to the allowed asymmetry between the different phases in the 3-phase system. In the ideal situation the sine-wave of the network voltage is purely sinusoidal. The last aspect refers to the distortion of this fundamental sine-wave, which is a phenomenon called harmonics (Appendix III). The problem with harmonics is that it causes damage in different types of electrical equipment. Harmonics can also increase currents and cause possible destructive overheating in capacitors. (Varming et al, 2004).



### 2.3 The Dutch distribution networks

Typical technical aspects of the distribution network as grid topology, short circuit power and voltage variation are described in this paragraph. In addition, various voltage quality aspects are discussed.

A variety of electricity production units are connected to one of the five voltage levels of the Dutch electricity grid. These levels are displayed in Table 1, describing the voltage range, connection capacity, and network definition. The distinction between different voltage- levels derive from the Tarievencode Electriciteit (2009) of the Energiekamer.

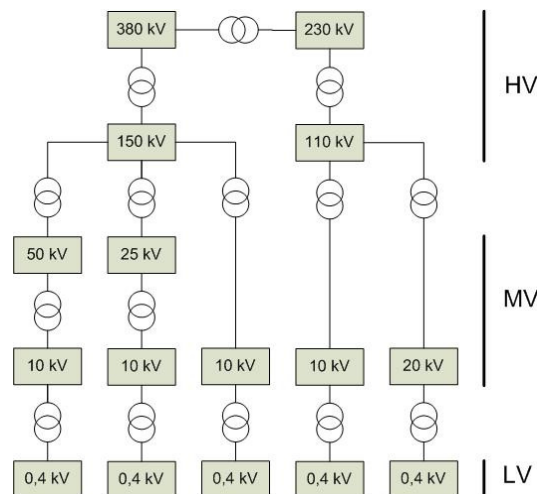
	Name voltage level	Voltage range	Network definition	Connection capacity
EHV	Extra High Voltage	380 - 220 kV	Transmission	>100MVA
HV	High Voltage	150 - 110 kV		
HMV	High Medium Voltage	50 - 25 kV	Distribution	>3,0 MVA, $\leq 100\text{MVA}^*$
MV	Medium Voltage	1 – 20 kV		>0,3 MVA, $\leq 3,0\text{ MVA}$
LV	Low Voltage	0,4 kV		$\leq 0,3\text{ MVA}$

\* If there is no High Medium Voltage available the connection will be realized on a HV or MV level.

**Table 1, definition transmission and distribution network, Tarievencode Electriciteit (2009)**

Table 1 shows that the distribution network and transmission network consist of respectively three and two voltage levels. This research will be primarily focused on the distribution network, as production units are considered decentralized when they are connected to a voltage level lower than 110kV (DTe, 2004). Furthermore, the smaller decentralized production units are defined as units connected to the LV level and the larger decentralized production units are connected to the HMV and MV level.

The current electricity network is characterized by a top down electricity flow. The top includes the EHV- and HV- level, connecting large producers and heavy consumers, from which electricity flows to lower levels. The smaller consumers are mostly connected to the MV and LV level, whereby households are primarily connected to the LV. Figure 2 provides a graphical representation of the total electricity network.



**Figure 2, schematic overview electricity network, Overbeek (1984)**



Difficulties might arise when producers are connected to the MV and LV level, as the original design of the distribution networks does not accommodate generation (Cossett et al., 2008). The distribution networks are not designed for a bi-directional flow; they are designed to supply the consumer top down (Ackermann et al., 2001). Problems also occur on transmission level, as the balancing becomes more difficult due to a large increase in low-controllable energy sources. A solution could be to lower balancing characteristics down the electricity supply chain and on distribution level. Such solutions will be considered further in the report.

### 2.3.1 Grid topology

The three design/operational principles that are applicable on the Dutch distribution network are: radial-, ring- and meshed shaped. In grid topology a distinction is made between design and operation. That the different grid topologies are not always designed and operated in the same way becomes clear when one considers the current Dutch distribution network topology.

Meeuwssen (2007) describes in his paper the dominant design principle of the Dutch HV-level being meshed and/or ring shaped, and the dominant operation principle also being meshed and/or ring shaped. On a MV level it is different; the dominant design is ring shaped and the dominant operation principle is radial shaped. The LV has a dominant radial shaped design principle and a radial dominant operational principle.

#### 2.3.1.1 Radial shaped

The radial shaped network topology is illustrated in Figure 3 and characterized by a one-way flow between the feeder and the load. A major disadvantage of the radial principle is that a failure in the network will disconnect all consumers attached to that ramification. This negative characteristic can be improved by implementing a section switch. This switch disconnects the point of failure in such a way that consumers before the fault can still be supplied.

The advantages of the radial principle are the simplicity and the relatively low cost of constructing the network. This radial shaped principle is commonly used in both the design and operation of the LV distribution level. In rural areas the radial shaped principle is also frequently used on MV-level, because of the low load-density. The load points are relatively far apart in rural areas, making multiple ways to feed the load inefficient (as with ring or meshed principle).

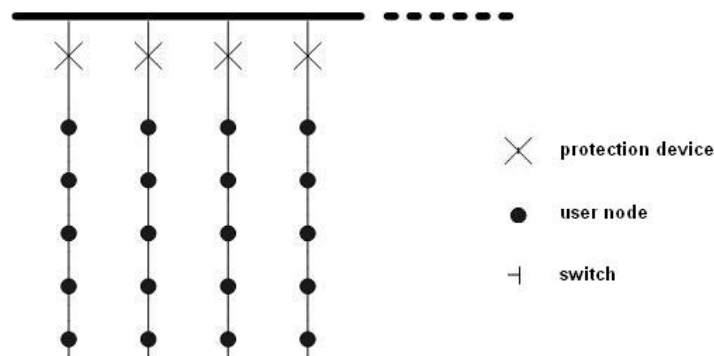


Figure 3, *radial shaped network*, Overbeek (1984)

### 2.3.1.2 Ring shaped

The ring shaped design (Figure 4) is commonly operated according to the radial shaped principle. This way of operating the ring shaped grid combines the advantages of the radial structure with the advantage of the ring-shaped structure. In other words the grid is relatively easy to protect and control, caused by the radial operation. In addition, it also allows a second way of electricity supply when a failure occurs, caused by the ring-shaped design. The ring-shaped design can be operated as a radial designed structure by sectionalizing switches. Ring shaped structures mostly occurs on a MV, but is also frequently used on a LV-level.

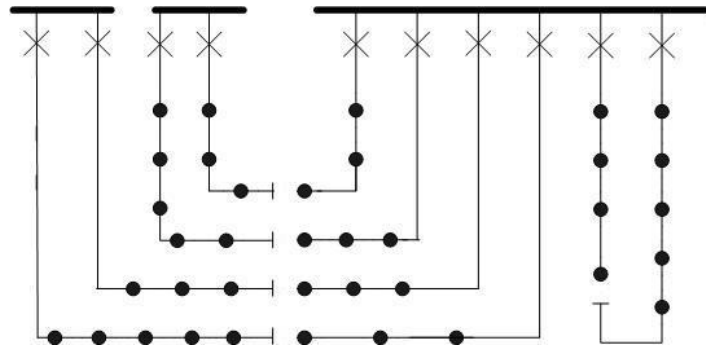


Figure 4, *ring shaped network*, Overbeek (1984)

### 2.3.1.3 Meshed shaped

To assure that the consumer is always supplied by electricity from more than two directions, a meshed structure (Figure 5) should be used. This type of network structure is frequently used on MV level in urban areas, characterized by a high load density. The meshed network structure also occurs sometimes on LV level in urban areas. The design and operation principle of the meshed structure differs most of the time. Frequently the advantages of the radial operation structure are combined with the advantages of the meshed design structure.

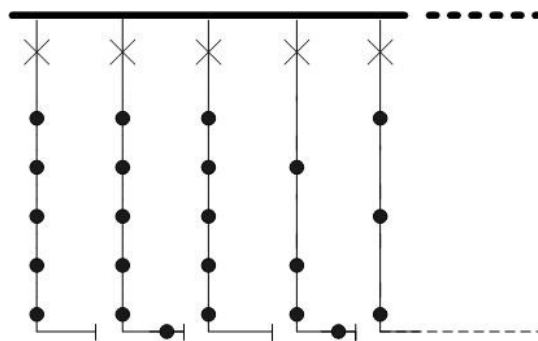


Figure 5, *meshed shaped network*, Overbeek (1984)

## 2.3.2 Transmission vs. distribution network

The transmission network and distribution networks are both facilitating electricity transport. Nevertheless these two network types have, in essence, a different purpose and a different design. The transmission network is originally designed to facilitate the connection with production units, where distribution networks are designed to supply the consumer. In this sense, the power flow in the distribution networks is one-directional, in contrast with the transmission network which deals with a bi-directional flow. Furthermore distribution

networks are usually radial designed and the transmission network meshed designed (Ackermann et al., 2001).

Two additional important differences between the two electricity network types are related to security and balancing. Both aspects will be described below from a transmission level perspective as they do not apply (at the moment) to the distribution networks.

### 2.3.2.1 Security

International accepted security standards are applicable on the design and operation of the transmission circuit. An example of these standards is the requirement of the transmission network to continue its function after a loss of a circuit due to a fault. This functionality can be obtained by using double circuit lines and operating in parallel. After a fault the remaining circuit should take over the load of the faulty circuit without being overloaded. The ‘N-1 secure design’ and the ‘N-1 secure operation’ determine that one of the N components may fail as the parallel circuit should take over. This secure operation is usually not replicated on the distribution network and ends at the HV/MV transformers (Meeuwsen, 2007)

### 2.3.2.2 Balancing

On a transmission level supply and demand are balanced to keep the system in equilibrium. The market based mechanism of programme responsibility (PR) is the basic principle behind transmission level balancing. The PR system is used in the Dutch electricity market since 1998 and allows different market players to trade electricity in an open market. Long term bilateral contracts are mostly used in trading power. About 12% of the trading occurs at the Amsterdam Power Exchange (APX), which is a day-ahead market operating with a price bidding system (Fрут et al., 2008). As electricity cannot be stored, the production and demand for electricity should always be in balance. To keep the balance, all PR parties have to exchange electricity exactly as described in their programme. This prognoses programme describes the expected amount of electricity traded between different market players, and has to be sent to the TSO.

Due to the uncertainties in the load profile of consumers, there is always imbalance to be settled by the transmission system operator. The settlement of imbalance is done on a basis of a price ladder bidding system, in which all electricity producers can make biddings for both positive and negative control capacity. The higher the imbalance is to be settled, the higher the imbalance costs will be.

To carry out the physical part of the ‘market based’ balancing, different balancing technologies can be considered. The balancing technologies on a transmission level are: production control, demand control and the interconnection with other countries. Another balancing option is storage, which is currently not used for balancing on any voltage level (Scheepers, 2008).

### 2.3.3 Regional differences

The Dutch electricity distribution networks are operated by eight DNOs, all responsible for managing their own distribution networks. These DNOs are: RENDO Netwerken, Cogas Infra en Beheer, Liander, Stedin, Westland Infra, DELTA Netwerkbedrijf, NRE Netwerk and Enexis. As shown in Figure 6, the DNOs are differentiated over the country with large regional differences. Especially regarding connection density there are large differences between a rural network in the north and an urban network in the west. Other regional differences refer to aspects as: the DG penetration level and grid topology. The difference between grid topology can influence the impact of a higher DG penetration level. Hence, the

regional differences should be taken into consideration when identifying the solutions for DG-problem in the scenario's consequences.

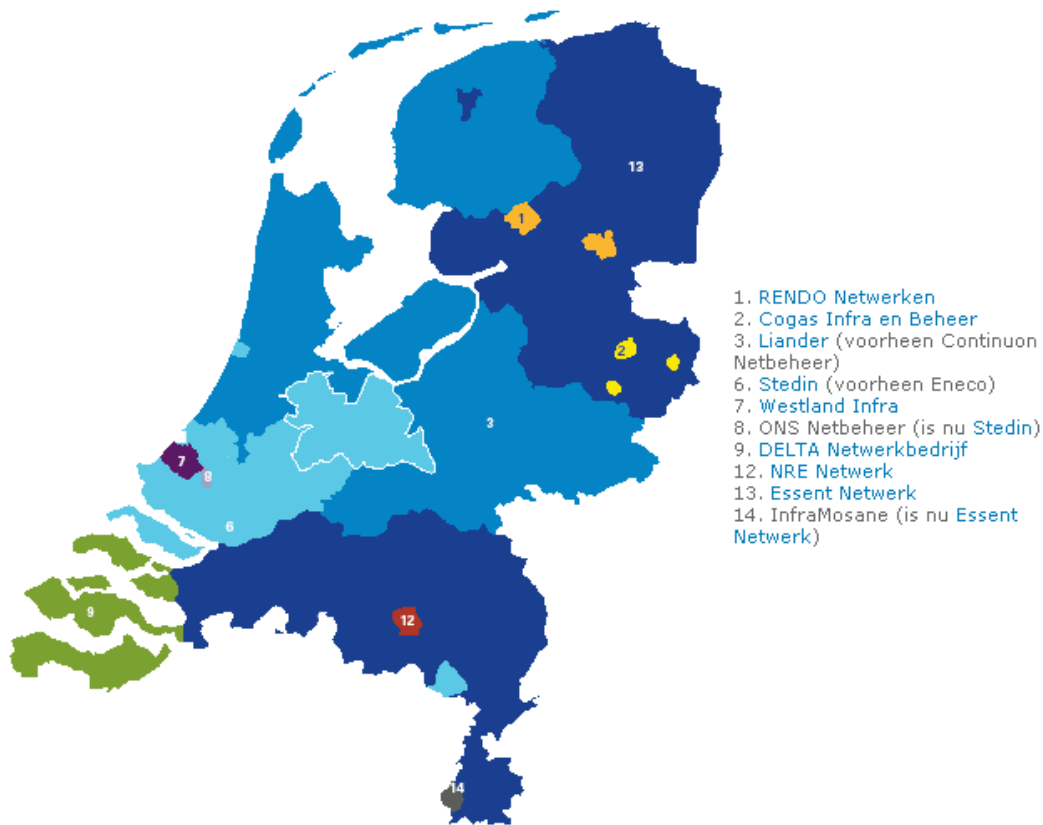


Figure 6, from [http://www.energieleveranciers.nl/page/pag\\_view.asp?pag\\_id=22091](http://www.energieleveranciers.nl/page/pag_view.asp?pag_id=22091)

### 2.3.4 Voltage drop

A significant problem for the current distribution network is the voltage drop. The point of connection is important for this 'drop', as the distance between the source and the load influences the voltage level, as can be seen in Appendix II. Generally, the longer the distance between the load point and the power source; the larger the voltage drops (Meeuwsen, 2007). This voltage drop in particular affects the rural areas, as the distances are generally larger than in urban areas. Another way of explaining the regional differences in voltage drop, is by relating it to the resistance of the line. This resistance is generally smaller for transmission- and urban distribution lines than for rural distribution lines. Reasons for the lower resistance, meaning a lower voltage drop, can be found in the thickness and cable length; when the cable section is smaller the resistance is higher and the losses are bigger (Ackermann et al., 2001).

#### 2.3.4.1 Short circuit power

According to Meeuwsen (2007), the short-circuit power is related to the voltage quality (except for the voltage frequency). In other words, the short-circuit power level highly influences the voltage quality, but is not a direct parameter. The short-circuit power level can be seen as a measure of the strength in a given point in the network or as the ability of the network to absorb disturbances (Varming et al., 2004).

In Figure 7 the equivalent model of any point in the circuit is displayed. In the model, point p is any point in the network;  $U_{SC}$ ,  $U_L$  and  $Z_{SC}$  are respectively the short circuit voltage, voltage

at point p and the line impedance. The short circuit power in p can be calculated by  $S_{SC} = U_{SC}^2 / Z_{SC}$ . Current variations in the line, causing a varying voltage drop over  $Z_{SC}$ , are directly related to the variations in the load and/or production in point p. The voltage in point p ( $U_L$ ), which is seen by all consumers connected to p, is equal to the difference between the short circuit voltage and the voltage drop over the line impedance  $Z_{SC}$ . Hence, when  $Z_{SC}$  is small, the voltage variation at p is small because the voltage drop is smaller, and the other way around. A low line impedance defines a strong grid; and a weak grid indicates a high line impedance and a high voltage variation (Varming et al., 2004 and Bayod-Rújula, 2009). In the MV and LV grid the lowest short circuit power levels can be found and logically the impact on voltage quality is the largest in these grid levels.

Summarizing, when the distance increases together with the impedance, the short circuit power becomes smaller and the voltage variation will be larger. In other words, the voltage variation will be higher when the distance between the power sources and the load point increases (Meeuwsen, 2007).

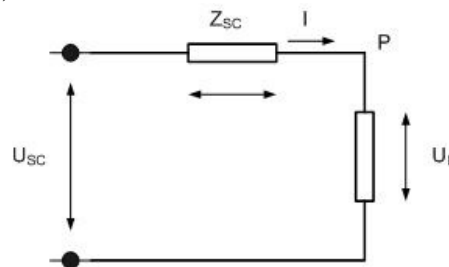


Figure 7, *equivalent model of any point in circuit*, Varming et al (2004) and Meeuwsen (2007)

### 3 Energy transition scenarios

The transition towards a sustainable energy supply system is argued to be ongoing and various scenarios are possible (Verbong and Geels, 2008). In this thesis the focus will be on the technical consequences for the electricity distribution network within different scenarios. Hence, before the consequences can be considered, the energy transition scenarios should be identified.

The energy transition scenarios used in this thesis will be developed in three steps. The first step consists of a desk study from which a rough distinction between scenarios will be made. The second step involves characterizing the scenarios that will be used in this thesis. The scenarios will be characterized in a qualitative and quantitative way. The final step is the validation of the quantitative description (in the form of a spreadsheet) by relevant literature.

The quantitative representations of the scenarios are based on capacity figures of Scheepers (2006) and utilization hours of the production units in general (Meeuwsen, 2007). By assuming a certain growth per year the figures for 2030 can be calculated. This quantitative representation will be used to identify the technical consequences of the distribution networks.

In paragraph 3.1 the relevant literature is described, presenting previous studies on energy transition scenarios. Paragraph 3.2 provides the assumptions of the identified scenarios. Paragraph 3.3 gives a qualitative and quantitative (spreadsheet) description of the three identified scenarios. The last paragraph presents the conclusion of this chapter.

#### 3.1 *Relevant literature for identifying the thesis scenarios*

The first step in identifying the scenarios is analyzing relevant literature of previous scenario studies. The focus of this analysis is on the DG development in the scenarios. The following relevant literatures are described below: WLO (2005), Meeuwsen (2007), TenneT (2008), Scheepers (2008) and Energie Rapport (2008).

##### 3.1.1 WLO (2005)

The WLO (2005) scenarios are considered trend scenarios of how the electricity market could develop. The time scope of the four WLO scenarios is 2040 and the scenarios are named: Strong Europe, Global Economy, Regional Communities and Transatlantic Market. The energy demand grows in all four scenarios and decentralized production will increase substantially. The sustainable production increases only in Strong Europe and Regional Communities, which are regarded to be the most progressive concerning DG. In these scenarios the DG-units are largely represented by combined heat power (CHP), without considering micro-CHP.

The electricity supply from CHP increases in all trend scenarios of the WLO until 2020. After 2020 the CHP development is variable between the different scenarios. The differences are caused by the development of: heat demand, electricity prices, and gas prices. As can be seen in Table 4, in the most progressive DG situation of WLO (2005), the decentralized capacity will reach 18.4 GW with a total production capacity of 43.8 GW. This means that centralized production represents 58 percent -and decentralized 42 percent- of the total electricity production capacity. In the most conservative scenario, centralized production represents 75 percent of the capacity and the remaining 25 percent is decentralized production.

### 3.1.2 Meeuwsen (2007)

Meeuwsen (2007) describes three different scenarios, which represent the various roads the electricity network may take towards a sustainable energy system. The scenarios are named: super grid, hybrid grid, and local grid. The super grid is the most central-orientated scenario and local grid the most decentralize-orientated scenario. These most ‘extreme’ scenarios considering DG (super and local grid) are particular interesting for this thesis.

The development of a super grid is characterized by Meeuwsen (2007) as the increasing interconnection between European countries. Meeuwsen (2007) identifies the super grid scenario as one of three extreme diverging transition pathways towards a future electricity network. Key element in this scenario is the political decision-making on a European level, leading to one efficient internal European market. An increase in average size of the production units and a focus on large-scale renewable energy projects will stimulate the transition towards this European super grid. This super grid is achieved by fine-tuning and collaboration between the European TSOs. The figures in Table 2, representing the super grid scenario, show that decentralized production capacity is reduced to a zero percent contribution to the electricity supply in 2050.

		Type	Capacity [MW]	Utilisation [h]	Energy [TWh]
Large scale	Sustainable	Offshore wind	6.400	3.500	22,4
		Sustainable imports	2.000	4.000	8,0
	Not sustainable	LS biomass/waste	14.000	5.000	70,0
		Fossil fuel	8.000	5.500	44,0
		Base load (nuclear)	7.000	8.000	56,0
Small scale	Sustainable	Onshore wind	0	1.750	0,0
		PV	0	800	0,0
		SS biomass/waste	0	5.000	0,0
	Not sustainable	Micro cogeneration	0	2.500	0,0
Total			37.400	5.358	200,4
Sustainable			22.400	4.482	100,4
Not sustainable			15.000	6.667	100,0
Large scale			37.400	5.358	200,4
Small scale			0	n.a.	0,0

Table 2, *data super grid scenario 2050*, Meeuwsen (2007)

The other ‘extreme’ scenario is the local grid scenario, which is characterized by decentralized electricity generation. Despite the focus on decentralized generation, the electricity balance is kept in equilibrium with large scale generation units, providing a base load. The DG in this scenario is primarily represented by on-shore wind, solar cells, small-scale biomass, and micro-CHP. Furthermore, Meeuwsen (2007) describes a bottom up strategy for emission reduction and sustainable development; in contrast with the top-down strategy from an EU level in the super grid scenario. Table 3 provides the electricity production capacity figures for 2050, in the local grid scenario. The production types are classified as being large or small scale, and sustainable or not sustainable. The number of photovoltaic (PV) -panels and the number of micro-CHPs are remarkable. Both production types are relatively high and, assuming that the number of households will grow to 8 million, 75% of the households should obtain a PV-panel and 75% will cogenerate. Hence, a large number of households will have both a PV-panel and a micro-CHP in this ‘extreme’ scenario.



		Type	Capacity [MW]	Utilisation [h]	Energy [TWh]
Large scale	Sustainable	Off-shore wind	15.000	3.500	52,5
		Sustainable imports	0	4.000	0,0
		LS biomass/waste	0	5.000	0,0
	Not sustainable	Fossil fuel	8.200	5.500	45,1
		Base load (nuclear)	5.000	8.000	40,0
Small scale	Sustainable	On-shore wind	2.000	1.750	3,5
		PV	30.000	800	24,0
		SS biomass/waste	4.000	5.000	20,0
	Not sustainable	Micro cogeneration	6.000	2.500	15,0
Total			70.200	2.850	200,1
Sustainable			51.000	1.961	100,0
Not sustainable			19.200	5.214	100,1
Large scale			28.200	4.879	137,6
Small scale			42.000	1.488	62,5

Table 3, data local grid scenario 2050, Meeuwsen (2007)

Micro-CHPs are supplied by natural gas and used for house heating. The output of these micro-CHPs is largely depending on the seasonal temperature. This means a negligible output in the summer and a high output in the winter. In contrast, PV production seems to have a high output in the summer and a smaller output in the winter. This dependence of the season makes a base load inevitable. Two alternatives for base load are given: coal and nuclear. In addition, fossil fuel is used for peak generation to balance supply and demand. With a total capacity of 70.2 MW for 2050, from which 42.0 MW is decentralized, this is the most progressive scenario regarding DG.

### 3.1.3 TenneT (2008)

Similar to the Meeuwsen study, TenneT (2008) works with different scenarios to describe the variety in paths to a future electricity grid. TenneT describes four trend scenarios for 2030 and particular focuses on the transmission grid. TenneT's 'green revolution' and the 'sustainable transition' scenarios are characterized by a significant increase in DG. These decentralized production units are represented by both CHP and micro-CHP.

Make decisions on a European level is a characteristic of the 'green revolution' scenario of the TenneT (2008) study. The decentralized production is represented by: micro-CHPs at almost every household, PV-panels, and on-shore wind energy. In this scenario the development of the fuel cell is related to the car industry. The car industry is believed to stimulate the utilization of the fuel cell for micro cogeneration. In addition, solar, off-shore and on-shore wind energy will increase in this scenario. The other scenario characterized by a significant increase in DG is the 'sustainable transition' scenario. This scenario is the most progressive concerning CHP-capacity (Scheepers et al., 2007).

When considering the other scenarios of TenneT, which is done in Table 4, the decentralized capacity could grow to a maximum of 60% of the total production capacity. This is similar to the most DG progressive scenario of Meeuwsen (2007). In contrast, the percentage of decentralized production could only decrease to a minimum of 27 percent in 2030. Hence, it is assumed that even a highly centralized scenario will include a significant share of decentralized production capacity in 2030.

### 3.1.4 Scheepers (2008)

Scheepers (2008) considers four different scenario studies and provides an overview of how the future electricity production might develop. This overview is displayed in Table 4 and



makes a clear distinction between centralized and decentralized capacity. From Scheeper's paper one can conclude that there is no obvious trend in production, becoming mainly decentralized or centralized orientated, up to 2050. Therefore, all options of decentralized, centralized and hybrid scenarios are still open. The Energie Rapport (2008) has adopted this overview of Scheepers to indicate the development of decentralized production in the Netherlands (see section 3.1.5).

	2006	2020	2030	2040	2050
		Schoon & Zuinig	Visie2030	Welvaart en Leefomgeving (WLO)	Electricity networks of the future (Meeuwsen)
		(ECN & MNP)	(TenneT)	(ECN & MNP)	
<i>Elektriciteitsvraag</i>					
Groei per jaar**	-	1,5 - 2,1%	0% - 3%	0,5% - 1,7%	1,35%
Totale vraag	116 TWh	142 - 156 TWh	110 - 230 TWh	134 - 213 TWh	200 TWh
<i>Grootschalige productie</i>					
- Fossiel/ biomassa	14,4 GW	17,9 - 21,5 GW	12,9-20,9 GW	15,4 - 30,8 GW	8,2 - 22 GW
- Kernenergie	0,5 GW	0,5 GW	0 - 3 GW	0 - 6 GW	5 - 7 GW
- Wind op zee	0,1 GW	2,2 - 6 GW	1 - 6 GW	0 - 10 GW	6,4 - 15 GW
Totaal grootschalig	15,0 GW	23,2 - 24,2 GW*	15,7 - 25,2 GW*	19,1 - 30,8 GW*	28,2 - 35,4 GW*
<i>Decentraal</i>					
- Wind op land	1,5 GW	2,9 - 4 GW	2 - 4 GW	0 - 2,5 GW	0 - 2 GW
- Middelgrote WKK	5,9 GW	7,6 - 9,8 GW	7,3 - 9,3 GW	7,9 - 13,1 GW	
- Micro WKK			0 - 5 GW		0 - 6 GW
- PV	0,1 GW	0,1 GW	0 - 4 GW	<0,1 GW	0 - 30 GW
- Biomassa e.a.	0,4 GW	0,8 GW	0 - 4 GW	1 GW	0 - 4 GW
Totaal decentraal	7,9 GW	11,4 - 14,7 GW*	8,4 - 23,9 GW*	9,3 - 18,4 GW*	0 - 42 GW*
Totale productiecapaciteit	22,9 GW	35,6 - 37,8 GW	29,6 - 44,6 GW	33,1 - 43,8 GW	35,4 - 70,2 GW
Aandeel centraal	66%	61% - 68%	40% - 72%	58% - 75%	40% - 100%
Aandeel decentraal	34%	32% - 39%	27% - 60%	25% - 42%	0% - 60%

\* spreiding van het totaal in meerdere projecties; \*\* 1 terawattuur (TWh) is 1 miljard kilowattuur (kWh)

**Table 4, overview of various scenario studies, Scheepers (2008)**

As can be seen in Table 4, about one third of the electricity production is currently decentralized. The future development of decentralized production is however subjected to a large variation between (and within) the various studies.

### 3.1.5 Energie Rapport 2008

Three views of the Dutch government regarding the development of the electricity supply are described in the Energie Rapport 2008. The first view describes the Netherlands as the provider of flexible generated energy. This flexible energy supply is necessary due to large wind and solar energy capacity in Europe. The second view describes the Netherlands as a Smart Energy city characterized by a further increase in decentralized production units. In this view the development of DG (e.g. PV-panels, micro-CHP and biomass) plays an important role. Furthermore, the smart meter is an important aspect to increase the controllability of decentralized production units.

The third view is relatively centralized orientated: the Netherlands as the powerhouse of Europe. In this scenario the Netherlands has become a supplier of base load to the neighboring countries. The reason behind the development of a Dutch power house is, among others, the favorable position of large production units near the Dutch coast with a good access to cooling-water and coal supply from oversea. This scenario is further characterized by carbon storage, biomass and ongoing development of wind power. To facilitate this supply an increased interconnection capacity between European countries has to be realized in comparison to the current situation. The interconnection should be realized on an extra high voltage (EHV) or high voltage (HV) level.

### 3.1.6 Identified scenarios from literature

The relevant literature described above has provided a variety of scenarios, all with different assumptions and outcome. From these scenarios we make a rough distinction for this thesis between one centralized and multiple decentralized scenarios.

#### 3.1.6.1 Centralized scenario

The first energy transition scenario that we consider is characterized by centralized production. According to Scheepers (2008) the centralized production of electricity in the Netherlands could grow from fossil fuels (possibly in combination with biomass), off-shore wind farms, and possible nuclear power. This growth could even outcompete the increase in decentralized generation units. A large import from a European super grid is also possible in this scenario. Large solar power plants in southern Europe and hydropower from Scandinavia could be linked to the super grid and supply the Dutch electricity market (Meeuwssen, 2007).

#### 3.1.6.2 Decentralized scenarios

The decentralized scenarios represent the transition towards a large degree of decentralized production units facilitated by local grids. In this sense one could consider these scenarios the most progressive regarding DG. The decentralized scenarios take the following aspects into account: DG type (CHP, micro-CHP, PV-panels, on-shore wind, biomass), size (DG units connected to low voltage level or medium voltage level) and organization (producing individually or organized).

### 3.2 Assumptions thesis scenarios

This paragraph provides the assumptions for the identified thesis scenarios, which are in line with the research scope. One aspect of the research scope is the focus on increasing distributed generation (DG) as the driver for change in the distribution network. The basic principle from this focus is the production perspective used in identifying the thesis scenarios. However, by focusing on the production side a limitation of the research becomes apparent. The consumption side is more or less neglected, despite the major driver it could be in the near future, e.g. considering electric cars. Other conditions of the thesis scenarios are described below and concern the time scope and the decentralized matrix.

#### 3.2.1 Time scope

The scenarios studies described in section 3.1 have time scopes of respectively 2020, 2030, 2040 and 2050. The most reasonable time scope seems to be 2050, as the electricity networks have a life expectancy of minimum 40 years. Hence, one should beware of future developments, up to 40 years, when replacing the obsolete network. In addition, the vision of the Dutch government (Energie Rapport 2008) is to achieve a cleaner, reliable and affordable energy supply in 2050. Despite the reasons for 2050 being a reasonable time reference for the thesis scenarios the choice has been made to limit the time scope to 2030.

Testing whether the regulatory framework is neutral towards the consequences, in specific the technical solutions for the distribution network, does not necessarily require consequences up to 2050. In 2030 the direction of the energy transition is believed to be clearly visible, together with possible barriers in the regulatory framework. Hence, the choice between 2030 and 2050 is considered to be open for different arguments. The first argument favoring 2030 concerns the urgency of anticipating on the DG-problems, making 2030 a more valuable reference point. Secondly, 2030 is considered a 'halve way' milestone towards 2050 and a reasonable time reference point. The last argument is that 2030 is in agreement with the time

scope of the TenneT (2008) scenarios. This is considered to be important as the transmission and distribution network are highly interrelated.

### 3.2.2 Production perspective

As DG is the driver for change in the distribution network, the scenarios will be constructed from a production (centralized or decentralized) perspective. The development of the production side will be analyzed as it directly relates to the distribution network development.

There is a huge variety in electricity production units, all with different characteristics. From these characteristics two main parameters are considered important when identifying production types: [1] the unit size, the unit could be connected to the low-, medium- or high voltage level, [2] the controllability of the production unit. Low controllability means that the electricity supply of the production unit is difficult to predict and control. The different production types are placed in Figure 8, based on the two identified parameters.

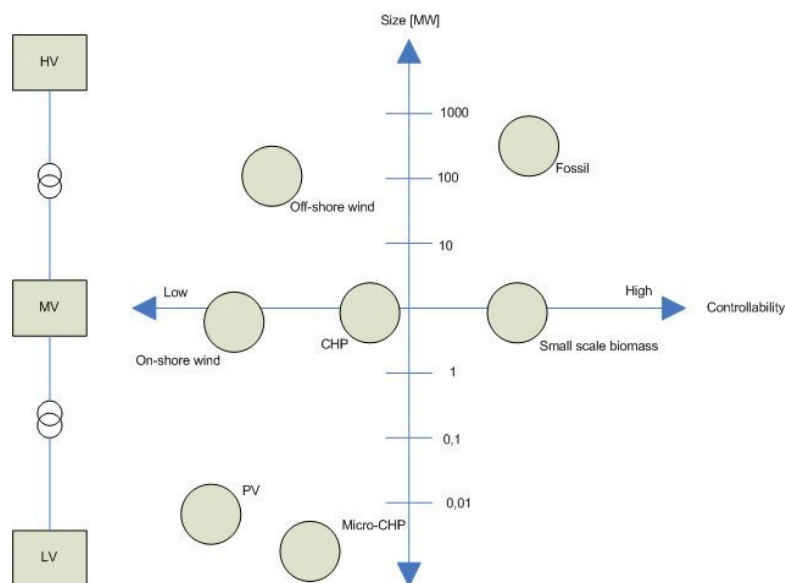


Figure 8, production units placed in graph based on controllability and size, Meeuwsen (2007)

A special comment regarding the off-shore wind turbines, which individual have the same size as the on-shore turbines; on sea the turbines are organized on remote areas and in this particular setting they could be regarded as one 'virtual' production plant (VPP). Considering this virtual power unit the off-shore wind turbines are connected to the HV-level; in contradiction the individual on-shore wind turbines are connected to the MV-level.

### 3.2.3 Demand perspective

This research adopts a 1.4 % electricity consumption growth per year for the period 2005-2030. This percentage is also used in the Energie Rapport (2008) and adopted from the IEA World Energy Outlook 2007. The 1.4 growth percentage suits the 0-3% variation of the different scenarios described in Scheepers (2008). In addition, it corresponds more or less to the 1.35% growth of the Meeuwsen paper. The growth in electricity consumption is assumed to increase with the same percentage (1.4%). However, we emphasize that this growth in domestic production and consumption is estimated. The ratio between import and export

could vary in the future, making the growth in domestic consumption and domestic production variable.

As regards the relevant literature, growth in electricity consumption is plausible. However, the specific growth percentage is believed to be uncertain. The electricity consumption is mainly depending on technological development and energy policy. Two examples of technological developments will be used in this report to illustrate the uncertainty in consumption growth: the electric car and the heat pump.

It has been argued that an electric car breakthrough will cause a tremendous increase in electricity consumption, far beyond the growth percentage assumed in this research. Different aspects as storage application of the vehicle and the need for a re-charge infrastructure will have huge technical consequences for the distribution network.

Similar to the electric car, heat pumps will have a significant effect on the distribution network from the consumption side. One respondent explained that a modern residential area might become entirely electrical (meaning no gas) and heat supplied by heat pumps. These heat pumps are sufficient to supply enough heat for 360 days; for the remaining 5 days additional electrical heating is required. Hence, for these 5 days only, the residents are dimensioned on 10 kW instead of the usual 2 kW. This implies huge consequences for the distribution network.

The electric car and heat pump technology indicate the uncertainty in electricity demand and the huge consequences for the distribution network from a consumption perspective. However, considering DG as the driver, these developments are not taken into consideration to limit the scope of this research. In addition, the problems arising from an increased penetration of DG in distribution networks is a current discussion in the Netherlands and for that reason this thesis fits that discussion.

### 3.2.4 Decentralized scenarios matrix

With the research primarily focusing on the distribution network and developments in generation, the decentralized scenarios are particularly important. As described earlier in paragraph 3.2.2, generation units have two main characteristics: unit size and controllability. These characteristics are translated into two parameters used in identifying the decentralized scenarios. The first parameter is the size of the decentralized production technology. A small size means connected to the LV-level and a large size means connected to the MV-level. The second parameter is the controllability, which is low when there is a low organization between production units. The organizational aspect is defined as follow: balancing supply and demand in a local grid before the interconnection with the electricity distribution network. The local grid can be managed by other parties (e.g. an organized residential area) than DNOs.

From the two parameters four decentralized scenarios can be identified, which are displayed in Table 5. From these decentralized scenarios two ‘extreme’ are identified: ‘plug and play’ and ‘fit and co-produce’. These scenarios affect respectively the low-voltage and medium voltage level, as the corresponding generation technologies are mostly connected to these levels.

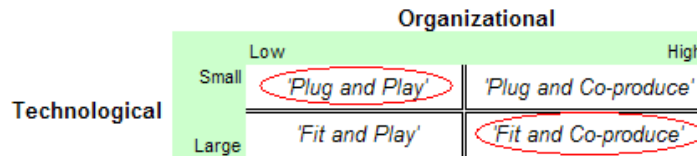


Table 5, matrix decentralized scenarios

The 'plug and play' scenario represents the situation where everyone could plug their generation unit on the LV-level and supply whenever they want. In the 'plug and co-produce' situation one could think of organizations like the building cooperation exploiting the generation units of their members, which results in a kind of micro-grid. This micro-grid is defined as a local grid where electricity demand and supply is balanced before the connection with the distribution network. In the 'Fit and Play' situation larger DG types are connected to the MV level by the DNO, and the supplier is allowed to supply at random. In the last situation the suppliers are organized in special cooperations. Hence, large VPP's could be realized. This cooperation takes place within a local grid, where the electricity is balancing before connected to the distribution network. Despite the variation in scenarios the choice has been made to test the regulatory framework vis-à-vis the two most extreme decentralized scenarios.

### 3.2.5 Spreadsheets for the scenarios

For the quantitative description of each scenario, the spreadsheet includes three sections: figures representing 2006, estimate growth percentages per year, and calculated figures representing 2030. The capacity figures of 2006 are from Scheepers (2008) and displayed in this report on page 32; Table 4. The utilization hours are from Meeuwsen (2007) and displayed in this report on page 31; Table 3. By multiplying the capacity figures with the utilization hours the energy production is calculated. To validate the utilization hours the calculated total energy production (light-shaded in Table 6) is compared to the total production indicated by the UCTE 2006 statistics, and ideally these figures are equal.

2006						2030					
	Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]	Growth [%]		Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]	
Centralized						Centralized					
Fossil/biomass	14,4	5500	79,2		0,0	Fossil/biomass	14,4	5500	79,2		
Nuclear	0,5	8000	4,0		0,0	Nuclear	0,5	8000	4,0		
Off-shore wind	0,1	3500	0,4		0,0	Off-shore wind	0,1	3500	0,4		
<b>Total centralized</b>	<b>15,0</b>		<b>83,6</b>	<b>65</b>	<b>0,0</b>	<b>Total centralized</b>	<b>15,0</b>		<b>83,6</b>	<b>65</b>	
Decentralized						Decentralized					
On-shore wind	1,5	1750	2,6		0,0	On-shore wind	1,5	1750	2,6		
CHP	5,9	1000	5,9		0,0	CHP	5,9	1000	5,9		
Micro CHP	0,1	2500	0,3		0,0	Micro CHP	0,1	2500	0,3		
PV	0,1	800	0,1		0,0	PV	0,1	800	0,1		
Biomass	0,4	5000	2,0		0,0	Biomass	0,4	5000	2,0		
<b>Total decentralized</b>	<b>8,0</b>		<b>10,9</b>	<b>35</b>	<b>0,0</b>	<b>Total decentralized</b>	<b>8,0</b>		<b>10,9</b>	<b>35</b>	
<b>Total production</b>	<b>23,0</b>		<b>94,4</b>	<b>100</b>	<b>1,4</b>	<b>Total production</b>	<b>23,0</b>		<b>94,4</b>	<b>100</b>	
Total production*			94,7		1,4	Total production			132,2		
Consumption*			116,2		1,4	Consumption			162,2		

\*UCTE 2006

Table 6, example spreadsheet

Concerning the CHP utilization hours, which are not provided by Meeuwsen (2007), CE Delft (2007) describes 1000 hours per year in which a CHP supplies the network. Whether these utilization hours change towards 2030 is considered by an expert of an independent

research agency. He argues that the utilization hours are determined by the peak hours, which are attractive to produce electricity. When nothing changes in the tariffs and the standards related to these peak hours, a large variation in utilization hours is unlikely. Assuming that nothing will change in the peak hour tariffs, this research adopts the 1000 utilization hours of the CHP for 2030.

The light-shaded growth percentages in Table 6 are based on the 1.4% increase in electricity production. Hence, the growth percentages of the centralized and decentralized electricity production are an estimation based on the characteristics of the individual scenario and the 1.4% growth percentage. When the light-shaded growth percentages are filled in, the sum of total production should correspond to the dark-shaded total production. This dark-shaded total production is based on a 1.4% increase of total production.

Now the light-shaded growth percentages are identified, the growth percentage for the individual production types can be estimated. These estimation figures should characterize the scenario in detail. From this growth percentage and the electricity production in 2006, the electricity production per generation type for 2030 can be calculated. In addition, by knowing the electricity production and utilization hours the capacity is calculated. This capacity should suit the possible development of generation types, as described in the next paragraph. Furthermore, the dark-shaded electricity production (83.6 and 10.9 GW) of the individual types should correspond to the light-shaded total electricity production as a validity check. In the last stage the capacity ratio is calculated for 2006 and 2030, which should correspond to the ratios described in Table 4.

### 3.3 Description of scenarios

In paragraph 3.1 a distinction is made between one centralized scenario and multiple decentralized scenarios, based on relevant literature. In paragraph 3.2 the decentralized scenarios are further identified by means of a matrix leaving two extreme decentralized scenarios: ‘plug and play’ and ‘fit and co-produce’. In this paragraph the three thesis scenarios will be qualitatively and quantitatively (spreadsheet) described. In Appendix IV an overview of the qualitative description is provided.

#### 3.3.1 Centralized scenario

The first energy transition scenario that we consider is characterized by centralized production. The centralized production units are facilitated by a so-called super grid. This scenario is assumed to be the most conservative one concerning DG. The electricity network of the centralized scenario is mainly characterized by a top-down structure, corresponding to the current situation. The major consequence for the electricity network will apply to the transmission network. As this research is based on the development of DG being the driver for change in the distribution network, there might be relatively little consequences. However, the relatively small consequences for the distribution network make this a useful test case when compared to different scenarios with relatively large technical consequences.

Opposite to the decentralized scenarios the centralized scenario accounts for a small decrease in DG, indicating the disappearance of the driver for change in the distribution network. As a consequence the parameters in Table 5 are not applicable anymore. Hence, only one centralized scenario is considered. In this scenario the majority of production units are connected to the high voltage levels.



### 3.3.1.1 Spreadsheet centralized scenario

The quantitative representation of the centralized scenario is characterized by a high growth in centralized production and only a minor increase in decentralized production capacity, as can be seen in Table 7. Especially the off-shore wind increases enormously and the nuclear generated power stays behind. The ratio between centralized and decentralized shows a centralized orientated production scenario.

2006						2030				
	Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]	Growth [%]		Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]
Centralized						Centralized				
<i>Fossil/biomass</i>	14,4	5500	79,2		0,7	<i>Fossil/biomass</i>	17,0	5500	93,6	
<i>Nuclear</i>	0,5	8000	4,0		0,0	<i>Nuclear</i>	0,5	8000	4,0	
<i>Off-shore wind</i>	0,1	3500	0,4		19,0	<i>Off-shore wind</i>	6,5	3500	22,8	
									120,4	
Total centralized	15,0		83,6	65	1,5	Total centralized	24,0		119,4	71
Decentralized						Decentralized				
<i>On-shore wind</i>	1,5	1750	2,6		1,0	<i>On-shore wind</i>	1,9	1750	3,3	
<i>CHP</i>	5,9	1000	5,9		1,0	<i>CHP</i>	7,5	1000	7,5	
<i>Micro CHP</i>	0,1	2500	0,3		0,0	<i>Micro CHP</i>	0,1	2500	0,3	
<i>PV</i>	0,1	800	0,1		0,0	<i>PV</i>	0,1	800	0,1	
<i>Biomass</i>	0,4	5000	2,0		0,0	<i>Biomass</i>	0,4	5000	2,0	
									13,2	
Total decentralized	8,0		10,9	35	1,0	Total decentralized	10,0		13,8	29
						Sum	34,0		133,2	
Total production	23,0		94,4	100	1,4	Total production			131,8	100
Total production*			94,7		1,4	Total production			132,2	
Consumption*			116,2		1,4	Consumption			162,2	

Table 7, spreadsheet centralized scenario

The fossil/biomass generation type includes the more conventional generation units, such as coal and gas. In the Energie Rapport (2008) the gas and coal generators are considered to keep a significant role in the Dutch energy production. The government considers all options and allows investment in new centralized coal fired production units. With this investment it is essential to reduce the CO<sub>2</sub> emission by development of CO<sub>2</sub> capture. Considering the TenneT (2007) scenarios, the fossil/biomass capacity could vary between 12.9 and 20.9 GW in 2030. The figures of the TenneT study are adopted and represent the boundary in which the fossil/biomass capacity could develop. In the spreadsheet the fossil/biomass capacity grows to 17 GW, which suits the high capacity boundary and characterizes the centralized scenario.

The Dutch electricity production from nuclear sources is currently representing 4% of total production. This nuclear production is located at Borselle, which has a maximum life expectancy until 2033. This means that nuclear power will probably continue to play a role in the scenarios to 2030. In the Energie Rapport (2008) three scenarios are considered that consider the development of nuclear power units in the Netherlands. The first scenario is the possibility that no new nuclear units are build. The second scenario is the replacement of Borselle in 2033, which is logically not of interest for the thesis scenarios. The last scenario is, next to replacement of Borselle in 2033, the building of new nuclear power plants after 2020. Considering that two of the three scenarios account for a zero growth in nuclear capacity this research will include a zero growth. In addition, TenneT (2008) considers a growth in nuclear capacity from 0 to 3 GW. In their sustainable transition the growth is however zero, which will be adopted in this research.

The Energie Rapport (2008) describes the government's ambition to realize 6 GW off-shore wind capacity in 2020. This ambition also includes a 'stopcontact op zee', which implies an off-shore electricity grid connecting all turbines. In the TenneT (2008) scenarios the wind

off-shore capacity increases to a minimum of 1 GW and a maximum of 6 GW. In addition, according to Scheepers et al (2007) this could even growth to 9 GW. Hence, for this research the boundary is set on 1 GW to 9 GW. As can be seen in Table 7, the Off-shore wind capacity grows to 6.5 GW, which reasonable suits the higher boundary of this centralized production type.

A small increase in CHP and on-shore wind capacity is required in this centralized scenario to account for the small increase in decentralized production capacity. These two decentralized production units suit the boundaries of production development. The ratio between decentralized production and centralized production in the centralized scenario is 71% to 39%. This calculated ratio corresponds to the ratio of the ‘Super grid’ scenario, described by Meeuwssen. Furthermore it corresponds to the maximum DG orientated ratio of TenneT (2008) described in Table 4.

### 3.3.2 ‘Plug and play’ scenario

The ‘plug and play’ scenario is characterized by a large participation of households in the electricity production field. Their involvement implies that smaller units as micro-CHP and PV energy are important production units. In this scenario every household has the possibility to produce and supply their own electricity to the grid. The accessibility becomes a major issue as millions of households could supply the network, making the production of electricity highly unpredictable.

The matrix displayed in Table 5 indicates a low organizational aspect within the ‘plug and play’ scenario. This characteristic indicates that balancing on local grids, before connected to the distribution network, is unlikely. This characteristic excludes new concepts as the micro-grid and the VPP. All DG connections, in this scenario mostly on LV-level, are facilitated by the DNOs without third party interference. Every connection can produce at random and is compensated for the delivered electricity.

#### 3.3.2.1 Spreadsheet ‘Plug and play’ scenario

The quantitative description of the ‘plug and play’ scenario should indicate a huge increase in micro-CHP and PV, as a majority of households will produce electricity. The centralized production should also increase slightly, as it is assumed that off-shore wind expands. The quantitative description of the ‘plug and play’ scenario is given in Table 8 by a spreadsheet.

2006						2030				
	Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]	Growth [%]		Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]
Centralized						Centralized				
<i>Fossil/biomass</i>	14,4	5500	79,2		-0,5	<i>Fossil/biomass</i>	12,8	5500	70,2	
<i>Nuclear</i>	0,5	8000	4,0		0,0	<i>Nuclear</i>	0,5	8000	4,0	
<i>Off-shore wind</i>	0,1	3500	0,4		18,5	<i>Off-shore wind</i>	5,9	3500	20,6	
									94,8	
Total centralized	15,0		83,6	65	0,5	Total centralized	19,1		94,2	46
Decentralized						Decentralized				
<i>On-shore wind</i>	1,5	1750	2,6		4,0	<i>On-shore wind</i>	3,8	1750	6,7	
<i>CHP</i>	5,9	1000	5,9		1,0	<i>CHP</i>	7,5	1000	7,5	
<i>Micro CHP</i>	0,1	2500	0,3		17,0	<i>Micro CHP</i>	4,3	2500	10,8	
<i>PV</i>	0,1	800	0,1		18,5	<i>PV</i>	5,9	800	4,7	
<i>Biomass</i>	0,4	5000	2,0		4,0	<i>Biomass</i>	1,0	5000	5,1	
									34,9	
Total decentralized	8,0		10,9	35	5,0	Total decentralized	22,6		35,0	54
						Sum	41,7		129,2	
Total production	23,0		94,4	100	1,4	Total production			131,8	100
Total production*			94,7		1,4	Total production			132,2	
Consumption*			116,2		1,4	Consumption			162,2	

Table 8, spreadsheet ‘plug and play’ scenario



As explained in the centralized scenario paragraph (3.3.1) the fossil/biomass capacity could vary between 12.9 and 20.9 GW in 2030. As the ‘plug and play’ scenario is characterized by decentralized production units the relative low capacity of fossil/biomass production in the spreadsheet seems reasonable. With a capacity of 12.8 GW it fits the lower boundary of this centralized production type.

Considering the government’s ambition to realize 6 GW Off-shore wind capacity in 2020, this scenario will include a significant growth in this centralized production type (Energie Rapport 2008). The growth of on-shore wind capacity is influenced by ‘problems’ as: landscape view distortion, and social acceptance (‘Not In My Backyard’ problem) (EZ, 2008). As regards these problems, the on-shore wind capacity is not expected to extend further than 4 GW. In the Energie Rapport 2008 it is stated that on-shore wind capacity should grow from a 1.5 GW capacity to a total of 4 GW. In comparison, the TenneT (2008) scenarios indicate that on-shore wind will increase to a minimum of 2 GW and a maximum of 4 GW, which is adopted in this research. For this scenario the maximum boundary of 4 GW is used as the micro-CHP and the PV-panels cannot account for the total increase of decentralized capacity.

The development of micro-CHP seems highly uncertain, as the technology is not yet fully developed. Furthermore, as the heat demand from households is mostly in the winter, the micro-CHP electricity production is depending on the season. In the TenneT scenario the capacity of micro-CHP varies between the 0 and 5 GW. In the case of a total capacity of 5 GW the majority of households will own a micro-CHP. In Scheepers et al. (2007) the scenario figures of the TenneT study are corrected to a maximum micro-CHP capacity of 4 GW. The capacity boundary of 0 to 4 GW will be used in this research and the higher boundary correspond to the 4 GW of this scenario.

The electricity production from PV-panels is considered to be relatively expensive, but open to a fast development. The Energie Rapport (2008) explains that the Netherlands obtained a strong knowledge position and has currently reintroduced incentives for PV-panels. Hence, government stimulation is considered to play an important role in the development of PV capacity. In TenneT (2008) the PV capacity varies between the 0 and 4 GW. These figures have been corrected by Scheepers et al (2007) to a variation between the 0.5 and 6 GW, which is adopted in this research. The higher boundary of 6 GW matches the qualitative characteristic of the ‘plug and play’ scenario.

In TenneT (2008) the minimum capacity of decentralized CHP is 7.3 GW and the maximum capacity 9.3 GW, which implies that the CHP will increase in all scenarios. This capacity boundary is adopted in this research and the lower boundary should be met in the spreadsheet. Hence, the CHP capacity will increase with 1 % to a 7.5 GW. The ratio of 46 percent centralized and 54 percent decentralized capacity in this decentralized scenario correspond to the extreme ‘decentralized’ ratio figures of Table 4. In addition, this ratio clearly indicates the difference between this decentralized scenario and the centralized scenario.

### 3.3.3 ‘Fit and co-produce’ scenario

The ‘fit and co-produce’ scenario is characterized by the participation of large end-users connected to the MV-level in the electricity production field. Contrary to the ‘plug and play’ scenario, the number of generation units is much smaller, but with an individual bigger

capacity. Most important generation unit is the CHP in an industrial and commercial sentence, e.g. the CHP situated at greenhouses.

Furthermore, the ‘fit and co-produce’ scenario is characterized by a high organizational aspect, as indicated by the matrix in Table 5. Balancing supply and demand is taking place on a local scale and imbalance is compensated through the connection with the distribution network. Hence, DG production units situated near each other are organized before connected to the grid. New concepts as micro-grid and VPP fit the ‘fit and co-produce’ scenario.

### 3.3.3.1 Spreadsheet ‘Fit and co-produce’ scenario

The ‘fit and co-produce’ scenario is characterized by a large increase in CHP, but also in PV and biomass. It has been argued that the PV and biomass production technologies could be attractive for the companies as they might be used as ‘larger’ production units. The centralized production should also increase slightly, as it is assumed that off-shore wind increases. The quantitative description of the ‘fit and co-produce’ scenario is given in Table 9 by means of a spreadsheet.

2006						2030				
	Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity y [%]	Growth [%]		Capacity [GW]	Utilisation [h]	Energy [TWh]	Capacity [%]
Centralized						Centralized				
<i>Fossil/biomass</i>	14,4	5500	79,2		-0,5	<i>Fossil/biomass</i>	12,8	5500	70,2	
<i>Nuclear</i>	0,5	8000	4,0		0,0	<i>Nuclear</i>	0,5	8000	4,0	
<i>Off-shore wind</i>	0,1	3500	0,4		18,5	<i>Off-shore wind</i>	5,9	3500	20,6	
									94,8	
Total centralized	15,0		83,6	65	0,5	Total centralized	19,1		94,2	46
Decentralized						Decentralized				
<i>On-shore wind</i>	1,5	1750	2,6		4,2	<i>On-shore wind</i>	4,0	1750	7,0	
<i>CHP</i>	5,9	1000	5,9		2,0	<i>CHP</i>	9,5	1000	9,5	
<i>Micro CHP</i>	0,1	2500	0,3		0,0	<i>Micro CHP</i>	0,1	2500	0,3	
<i>PV</i>	0,1	800	0,1		18,5	<i>PV</i>	5,9	800	4,7	
<i>Biomass</i>	0,4	5000	2,0		8,0	<i>Biomass</i>	2,5	5000	12,7	
									34,2	
Total decentralized	8,0		10,9	35	5,0	Total decentralized	22,0		35,0	54
						Sum	41,2		129,2	
Total production	23,0		94,4	100	1,4	Total production			131,8	100
Total production*			94,7		1,4	Total production			132,2	
Consumption*			116,2		1,4	Consumption			162,2	

Table 9, spreadsheet ‘fit and co-produce’ scenario

As with the ‘plug and play’ scenario, the 12.8 GW fossil/biomass capacity fits the decentralized characteristic of the ‘fit and co-produce’ scenario. For the same reasoning the nuclear and off-shore wind are considered feasible capacity figures for this spreadsheet.

As with regards to the government’s ambition to realize 6 GW Off-shore wind capacity in 2020 this scenario will include a significant growth in this centralized production type (Energie Rapport 2008). As explained in the ‘plug and play’ paragraph the on-shore wind capacity boundaries of minimum 2 GW and maximum 4 GW are adopted in this research. As the ‘fit and co-produce’ scenario is characterized by large DG units the on-shore wind will increase to the maximum.

The PV-capacity varies between the 0.5 and 6 GW. The ‘fit and co-produce’ scenario accounts for a maximum increase of PV-panels as this generation type fits the large DG size characteristic. By combining large amounts of PV-panels the cooperations could produce significant large amount of electricity.

In the TenneT (2008) scenarios the minimum capacity of decentralized CHP is 7.3 GW and the maximum capacity 9.3 GW. This implies that the CHP capacity will increase in all thesis scenarios. Furthermore, Scheepers et al. (2007) describes that especially the CHP capacity has grown significantly in the greenhouse sector the last years. However, this growth is expected to disappear in the coming years, due to the development of competing options for heating (e.g. heat pumps). This indicates that the CHP capacity will grow, but only slightly. The capacity boundaries for this research are set on 7.3 to 9.3 GW. To the ‘fit and co-produce’ scenario the maximum capacity of 9.5 GW is applied.

The ratio of 46 percent centralized and 54 percent decentralized in the ‘fit and co-produce’ scenario, correspond to the ‘plug and play’ scenario. For consistency reasons this is considered convenient. With the same ratio for the two decentralized scenarios the focus is on the difference in generation size and organization, instead of a different DG penetration levels.

### **3.4 Conclusion**

Three scenarios have been identified for this thesis: the centralized scenario, the ‘plug and play’ scenario and the ‘fit and co-produce’ scenario. The identified scenarios correspond to relevant literature and have been described in a qualitative and quantitative way. It is assumed that the scenarios will have different consequences on the distribution network as the penetration level, type, size and organization level of DG differ substantially. In the next chapter we describe these consequences of the identified scenarios.

## 4 Consequences for the distribution network

This chapter focuses on the second sub research question: *which consequences do the scenarios have on the distribution network?* The information for this chapter derives from a desk-study and face-to-face interviews. The consequences will be described in four steps, which will be represented by four paragraphs. The first paragraph describes which general DG opportunities exist for the DNO. The second paragraph describes the general DG problems (challenges) for the DNO. Paragraph 4.3 provides the possible solutions for these problems. Paragraph 4.4 and 4.5 will consider the consequences which have been emphasized by the interviewees for the different scenarios. In the last paragraph the conclusion is provided.

### 4.1 Distributed generation opportunities for the distribution network

The 20/20/20 environmental policy goals are as follow: binding targets for 2020 to reduce greenhouse gas emissions by 20%, ensure 20% of renewable energy sources in the EU energy mix, and decrease primary energy use by 20% (COM, 2007). To realize these goals the further development of DG could play an important role (Energie Rapport, 2008). This role is empathized by the government's decision to subsidize the development of DG units (e.g. PV-panels and wind turbines). Hence, DG is an opportunity to reach the environmental goals, but what specific opportunities do exist for the distribution network? We will consider this question in this paragraph. In the next paragraph we will consider the specific challenges for the distribution network.

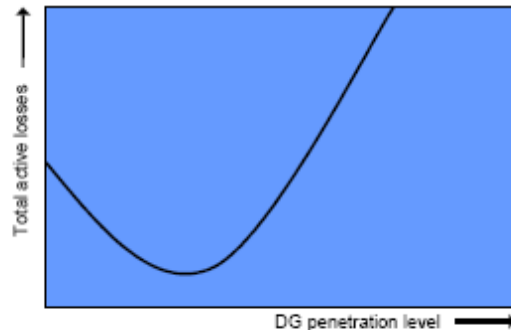
The first opportunity for the DNO in connecting DG in their distribution network is reducing transport losses. The transport losses can be reduced by decreasing the distance between the feeder and the load. This opportunity applies only to a certain DG penetration level, because for a higher penetration the losses increase again, as can be seen in Figure 9 (Scheepers and Wals, 2003). Due to the reduction in network losses, investments in the network can be postponed (Bayod-Rújula, 2009). Another benefit concerns the improvement of the voltage levels, in particular at the end of a distribution line where a voltage drop occurs (paragraph 2.3.4). Generally the connection of a DG source raises the voltage in the network and supports the voltage in areas where difficulties with voltage level exist (Bayod-Rújula, 2009). The last main benefit from DG sources in the distribution network is the increase in reliability. Not only can the energy dependence be reduced and a diverse energy portfolio build, also the self-supply characteristic of the DG can increase the reliability.

### 4.2 Distributed Generation challenges for the distribution network

The distribution network operator faces the most fundamental challenge ahead with the implementation of an increasing number of DG sources (Meeuwsen 2007, Scheepers et al. 2007). Bayod-Rújula (2009) describes the following aspect of this challenge: inverse energy flow, voltage control, management of reactive power, effective protection equipment and power quality. Similar aspects are described by different sources as Ackermann et al. (2001) and Meeuwsen (2007). The following challenging topics are selected to be the most significant: voltage quality (including voltage variation, frequency and harmonics), network losses, reactive power, and protection.

### 4.2.1 Network losses

The first opportunity we have described in paragraph 4.1 concerns reducing network losses. However, at a certain DG-penetration level network losses become a challenge instead of an opportunity. As the U-shape in Figure 9 illustrates, after a certain penetration level the network losses increase and becomes a DG- problem (Scheepers and Wals, 2003).



**Figure 9, variation of distribution losses due to DG penetration, Scheepers and Wals (2003)**

Cossent et al (2008) describes this relationship between DG penetration level and the network losses. Only with a low DG penetration level the DNO can benefit from the DG sources. A higher penetration level means higher network losses when the local production exceeds the local consumption. These higher network losses are the result of an increased distance between the feeder and the load. With a reverse flow the electricity has to ‘travel’ via a higher voltage level. The turn-over point to a disadvantage is relatively difficult to determine and can vary substantially, depending on local grid strength and local demand.

Quick adaption of production or consumption could increase the flexibility of the network (Scheepers, 2008). This need for flexibility argues for introducing the balance characteristic of the transmission level on the distribution level. By this balance characteristic on distribution level network losses might be reduced.

### 4.2.2 Voltage quality

#### 4.2.2.1 Voltage variation

When DG is supplying electricity to the distribution network, the DNO is faced with a voltage rise instead of a voltage drop. The difference between the voltage rise and the voltage drop is defined as the voltage variation (Appendix II). The voltage variation caused by the DG unit supplying or not, is experienced by all users connected near the unit. The voltage variation challenges are logically larger in rural areas as the distance between the load and the feeder is assumed to be larger than in urban areas.

#### A practical voltage variation problem:

Imagine a long distribution line in the city which, according to the Netcode, should maintain a voltage of 230 with a maximum variation of 10%. There is a possibility that at the end of the line the voltage is at its minimum: 207 V. For a DG to supply electricity at the end of this line he should generate a higher voltage than 207 V (no voltage difference, no power flow). In this situation it is for a DG unit no problem to supply the grid and it could even improve the voltage level. However, at the starting point of the cable, after the transformer, the voltage might be 253V. Hence, for a generator to supply the grid it should be above the 253V, which is not within the boundaries described in the Netcode (Appendix I).

#### 4.2.2.2 Harmonics

Harmonics refer to a distortion of the sinus-wave, which is further described in Appendix III. Harmonics are a result of non-linear sources (most DG-units are non-linear). When harmonics are accumulated on a LV level the voltage quality can be in danger. The harmonic can cause, among others, unreliable operation of electronic equipment, overheating capacitor banks, and breakers and fuses tripping (Meeuwssen, 2007).

#### 4.2.2.3 Frequency

The frequency problem refers to the balancing of supply and demand. The equilibrium between instantaneous power consumption and production has to be maintained to keep the frequency on 50 Hz. As can be seen in Figure 8 the DG-units are generally less controllable, meaning more flexible power sources are needed to maintain the frequency.

#### 4.2.3 Reactive power

The technical problems with reactive power management depend on the DG type. The type of DG-unit determines whether it is able to supply and absorb reactive power. Centralized power plants use synchronous generators, while decentralized technologies are often asynchronous generators. One of the operational characteristics that differ between the two is that asynchronous generators are not capable of providing reactive power. The asynchronous generators actually need reactive power from the grid. Options such as capacitors and power electronics converters could be used to overcome the disadvantages of DG asynchronous generators (Ackermann et al., 2001 and Bayod-Rújula, 2009).

#### 4.2.4 Protection

Bayod-Rújula (2009) describes that DG can cause decrease in the effectiveness of protection equipment. The lower effectiveness can create operational difficulties during a distribution circuit outage, as with 'island mode'. Lopes et al (2007) describes the same problem and indicate the need for anti-islanding protection. However, Lopes et al. (2007) argues that this is just one aspect of protection problems. Protection is also referring to: internal faults in generation equipment, protection of the faulted distribution network from fault currents supplied by the DG, and the impact of DG on existing distribution system protection.

One of the DNOs describes the island challenge as follow:

In a conventional situation parts of the grid could be cut off, giving the operator the opportunity for maintenance. However, with the introduction of decentralized production unit voltage might be applied on the grid during maintenance. A solution for this problem could be an electric device connected to the grid and the production unit, which tells the unit to stop supplying when there is no grid voltage detected. The only problem with this security is the chance two production units on the same network keep each other awake, creating a danger situation during maintenance. The only way to make sure the units do not supply the grid is by physically disconnecting the unit at each production side. Disconnect the production unit remotely could be an alternative when a smart meter is available.

### 4.3 Distributed generation solutions

After the challenges being defined, the solutions for the integration of DG units in the distribution network can be identified. Multiple sources explicitly mention the smart-grids concept, or refer to the necessity of grids being smarter, as the solution. These sources range

from the Energie Rapport (2008) and an EU paper<sup>4</sup> to various news paper articles<sup>5</sup>. Various DNOs confirm the interest in smart grids, but emphasize that it is a means to come to an end.

### 4.3.1 Smart-grids technology

An important technological solution deriving from the consequences of the ‘plug and play’ and ‘fit and co-produce’ scenarios is the smart-grid technology. Smartening the grid, more intelligence, ICT, interaction with end-user, smart meter and efficient use of the grid are terms mentioned by the interviewees referring to the smart grids. However, an exact definition could not be given and the technology is far from large scale deployment. Whether this deployment is hindered by regulation is analyzed in chapter 6. Before this analysis an attempt is made to define the smart-grid technology in chapter 5.

### 4.3.2 Alternative

Besides the smart grid as a consequence for both decentralized scenarios, the alternatives will be presented. Two alternatives follow from the interviews with DNOs; grid reinforcement and reconsidering power quality standards. A possible third option is ‘business as usual’ referring to the ‘fit and forget’ strategy in connecting DG-units (Scheepers et al., 2007). ‘Business as usual’ is characterized by the focus on the current top-down structure, not taking DG into account. Such an option applies to the centralized scenario, but is believed to be unfavorable in the decentralized scenarios as the current quality of supply and the voltage quality can no longer be guaranteed (unless the standards are reconsidered).

#### 4.3.2.1 Grid reinforcement

Grid reinforcement, e.g. thicker - or parallel cable and ‘heavier’ grid components, is the current way of solving possible transport problems caused by connected DG-units. The choice between grid reinforcement and smart grids cannot be made currently as the smart technologies are not yet available. Making the grid smarter could prevent the absolute need to enormously invest in additional grid reinforcement. Hence, grid reinforcement is an option but probably not the most favorable solution regarding economical benefits, for both society and the DNO.

#### 4.3.2.2 Voltage quality and reliability

The last alternative is the acceptance of a decrease in voltage quality and a less reliable electricity supply system. Grid reinforcement and other investments can be delayed when a lower reliability is accepted. The grid should currently be dimensioned on peak load and consumption. However, by allowing more interruptions the grid could be dimensioned lower with fewer investments. An argument for this alternative is the consideration of the Dutch electricity system being more reliable than other European countries, as can be seen in Figures 10 and 11. Not only is the frequency of interruptions low, also the duration of the interruptions is short.

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<sup>4</sup> EC (2006)

<sup>5</sup> See e.g. NRC Handelsblad zaterdag 11 april & zondag 12 april 2009, Wetenschap bijlage, ‘Een net in nood’; and De pers, 10 maart 2009, ‘Netbeheerders niet ‘innovatief’.



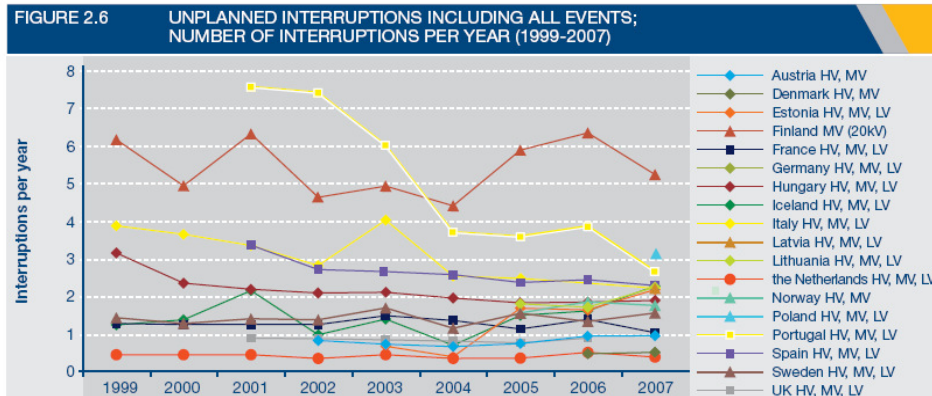


Figure 10, unplanned interruptions per year, CEER (2008)

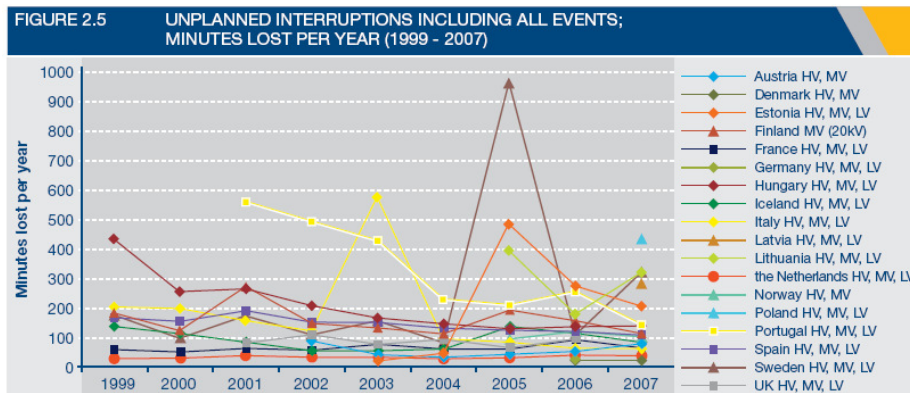


Figure 11, unplanned interruptions in minutes, CEER (2008)

Would it be an option to accept a situation where different connections have various reliability levels? It has been argued that a reliability differentiation would be very difficult as the LV-level is mostly radial. Hence, if the operator agrees to lower the reliability of a LV connection, it will affect all connections in that ramification.

As regards reliability, the DNOs emphasize their legal obligation to report faults and facilitate a network as reliable as possible. When a consumer is disconnected from the network, without his fault, he is compensated. Lowering the reliability as an alternative for smart grids is an unfavorable possibility for both society and DNOs.

In addition to the decrease in reliability, the end-user should also accept a lower voltage quality. As explained in paragraph 4.2.2 aspects of voltage quality as voltage variation, harmonics and frequency are under pressure.

#### 4.4 Consequences of the centralized scenario

One of the principles during the identification of the thesis scenarios was the focus on the production side; the development of DG as the main driver for change in the distribution network. In the centralized scenario this DG variable is very conservative; there is even a slight decrease in DG capacity. From this perspective the distribution network is not facing major re-adjustments. However, it is considered important to notice that the consumption side could still cause major changes in the distribution network. Especially the electric car and the heat pump have a significant effect when breaking through.



## 4.5 Consequences of the decentralized scenarios

The decentralized scenarios are the most progressive energy transition scenarios regarding DG development. Logically, the consequences of both scenarios for the distribution network will be substantial. Problems will refer mostly to keeping the balance between demand and supply, and solutions to two main technical options: grid reinforcement and smart grids.

To emphasize the fluctuation in electricity production capacity during a certain period, two ‘weather situations’ are used in describing the specific consequences of both decentralized scenarios. In situation 1 (‘maximum DG capacity’) all DG sources connected to the network use their maximum capacity to supply the grid. An extreme situation like this occurs during a sunny but cold day, where the PV-panels and micro-CHPs generate electricity and relative little electricity is consumed. In situation 2 (‘minimum DG capacity’) all DG sources connected to the grid do not use any capacity to supply the grid during a peak demand. A situation like this could occur on a cloudy hot day where the capacity of the micro-CHP and PV-panel cannot be fully used. The consumption of electricity is high due to air conditioning, freezers and fridges. The electricity for consumption is supplied top-down and the grid is considered entirely demand following at that moment in time.

The most significant remarks of the interviews with experts of DNOs are described below. These remarks concern the consequences of the two specific decentralized scenarios (‘plug and play’ and ‘fit and co-produce’). In addition, the remarks from interviews with experts of research institutions are taken into consideration. When needed, references are placed to relevant literature. The response of the interviews, concerning a specific scenario, is divided into: DG-problems and technical solutions used.

### 4.5.1 ‘Plug and Play’ scenario

The generation units in the ‘plug and play’ scenario are highly fragmented, as a majority of the households have their own unit. The consequences will particularly affect the LV level, as the household are connected to that voltage level. Besides the small ‘unit size’, the controllability of the units is low. Translating this controllability to the level of organization; the DNOs are facing a huge amount of uncontrollable generation sources. As organizational attempts are low, balancing is not applied on a local grid before connected to the distribution network. However, the possibility exists to apply balancing on a distribution level by the DNO. A practical alternative is reinforcing the grid to connect all decentralized production units. The grid will be dimensioned on the peak load/demand and a simultaneity factor.

#### 4.5.1.1 DG problems

In paragraph 4.2 four main DG problems have been identified: network losses, voltage variation, reactive power and protection. Below we give a description to what extent these problems occur in the ‘plug and play’ scenario.

First of all, the network losses in the ‘plug and play’ scenario. In situation ‘maximum DG capacity’ the local production exceeds the local consumption and the network losses will increase. In this sense, the capacity flexibility will be a significant problem. However, in situation ‘minimum DG capacity’ the distribution grid will be demand following by interconnection with a higher voltage level. As the connected party can plug and play at random, a time-differentiation in required grid capacity occurs. Secondly, the voltage quality can become a major problem in the ‘plug and play’ scenario. DG might induce voltage variations; a voltage drop will be experienced in situation ‘minimum DG capacity’ and a

voltage rise in situation ‘maximum DG capacity’. In addition, when all DG sources supply the grid the converters of these DG sources can increase harmonics. The last voltage quality aspect concerns frequency, which is affected when supply and demand are not in equilibrium. The third DG problem is reactive power. The difference between the two DG capacity situations requires the reactive power buffer in the grid to be very flexible. The last problem is protection, which is significant as the loads are unpredictable and the controllability is low. Especially the islanding problem can occur in this scenario.

#### 4.5.1.2 Solutions

The operators indicate that they do not explicitly know what consequences, for example, 1 million micro-CHP units will have on their network. However, pilot projects indicate that micro-CHPs will not cause severe problems due to their low capacity. A micro-CHP of 1 kW can in an extreme situation supply the net with a maximum capacity of 1kW. As the connection of a household is generally dimensioned on 1kW, no reinforcement is required. Difficulties arise when a household produces electricity with both a micro-CHP and a PV-panel. When, as in situation ‘maximum DG capacity’, the maximum capacity of supply exceeds the connection capacity, grid reinforcement is necessary. So far, DNO tests regarding DG problems in voltage variations indicate no severe problems, as the voltage variation still suits the voltage bandwidth.

No severe problems with the introduction of micro-CHPs, does not automatically imply that nothing has to change. There are opportunities for smart grids to realize a more efficient use of the distribution network. When a distribution network is 40-50 years old, its capacity might be fully used. Distribution networks are dimensioned on a certain peak demand and a 2% electricity consumption growth per year. Now their full capacity is reached investment might be postponed by using the micro-CHP to reduce the peak demand at 6 o’clock. In the winter this is relatively easy as people turn on their heating when arriving home from work. However, in the summer not much heating is needed. However, there is the opportunity to produce heat, e.g. warm water, and use it later that evening, e.g. for a shower. In this way the peak at 6 o’clock is reduced and investments in network reinforcement might be postponed.

Problems are likely to occur when both PV-panels and micro-CHP are situated at every household. As the peak load exceeds the peak demand the connection should be dimensioned on this peak load, which might indicate grid reinforcement. A smarter grid might prevent the grid reinforcement and make the grid more efficient, flexible and controllable.

#### 4.5.2 ‘Fit and co-produce’ scenario

The ‘fit and co-produce’ scenario is characterized by a large organizational level and DG sources being relatively large. The DG sources are mostly organized in local grids managed by special cooperation’s creating so-called virtual power plants (VPP). As with regards to the DNO, all organized DG sources are represented by one connection, most likely situated at MV-level.

When a smart meter is installed at this connection, the operator has the possibility to control its own system and monitor the separate local grid. In situation ‘maximum DG capacity’ the local grid is regarded as a VPP for the operator and in situation ‘minimum DG capacity’ the operator supplies electricity to the local grid. When the connection is made on a MV level the DNO should make arrangements with the involved actors regarding tasks and responsibilities for the separate local grid.

#### 4.5.2.1 DG problems

The impact of the situations ‘maximum DG capacity’ and ‘minimum DG capacity’ become less severe for the operator as the controllability increases and supply and demand are balanced before the meter. When a surplus or shortage is occurring in the local grid, the electricity is flowing to/from the MV-level. When these organized DG producers are connected to the HV-level the cooperation could be integrated into the electricity system of program responsibility. When the VPP is connected on the MV-level, communication issues become important.

The DG problems now apply mainly on the local grid, as demand and supply are balanced before the meter and a relatively small number of variable loads remains on MV-level. The small number of connections implies a low number of involved actors, which makes it easier to make arrangements.

#### 4.5.2.2 Solutions

This ‘fit and co-produce’ scenario is already emerging in certain areas with a high density of greenhouses and their CHPs, only without being highly organized. An example can be found in Berkel<sup>6</sup> where a MV distribution station is operated exclusively for greenhouses. But what happens when the gardeners go away, quit the CHP production, e.g. due to the arrival of a new heating technology? The grid reinforcement has a life expectancy of 40+ years, the CHP production might be there for only 5 years. Despite this difference in life expectancy the DNO is obligated to facilitate the production, making large investment for a possible temporally situation. A smarter network could be an answer to prevent these large grid reinforcements.

A typical phenomenon occurring with the electricity production of greenhouses is producing when the market prices are high, even when they don’t need the heat. In this situation the greenhouse becomes more of an electricity producer than a greenhouse. The surplus of heat is wasted to benefit from the high electricity prices. This creates a favorable situation when the objective is to increase the use of DG sources, but a highly unfavorable situation when the objective is to create a sustainable society. Hence, considering the focus in the Energie Rapport (2008) on the energy transition, a situation of producing electricity without using the heat should be prevented.

The local grid is organized and will be balanced before the connection with the distribution network, meaning a smart local grid is required. The major question marks for this local grid concern the tasks and responsibilities for the DNO. Could another organization than a DNO become responsible? Who is accountable for faults? By current regulation the owner should appoint the management of a local grid to a DNO, based on section 10 paragraph 3 of the electricity law.<sup>7</sup> Obtaining a release from this obligation and keep the grid under own management is granted by the Energiekamer when certain condition are met, described in section 15, paragraph 2 of the electricity law.

Within the organized local grid the balancing aspect seems hampered by direct regulation. Chapter 6 emphasises the relation between the balancing aspect and the regulatory framework (direct and indirect regulation).

<sup>6</sup> <http://www.stedin.net/pages/default.asp?PageID=39&Mainmenu=&MainmenuID=&Mainmenub=&MainmenubID=&ShowNieuws=12147&ModuleitemID=147>, accessed on 10-06-2009

<sup>7</sup> [http://www.energiekamer.nl/nederlands/elektriciteit/transport/overzicht\\_netbeheerders/index.asp](http://www.energiekamer.nl/nederlands/elektriciteit/transport/overzicht_netbeheerders/index.asp)

## 4.6 Regional differences

Regional differences play an important role in both scenarios ('plug and play' and 'fit and co-produce'). Especially when implementing smart technologies in the distribution network. The regional differences refer to grid topology, DG penetration level, and connection density (paragraph 2.3.3). The distribution network topology is in general radial operated, the design however might be ring- or meshed shaped. These differences in topology should be taken into consideration when considering smartening the grid. The DG penetration level might differ substantial as wind turbines are mostly situated in rural regions. The last variation between regions regards connection density, as rural areas have a lower connection density and different problems (voltage drop) in comparison to urban regions with a high connection density. These regional differences emphasize the difficulty in making the choice between a reinforced grid and implement smart technologies in a certain distribution network.

## 4.7 Conclusion

Regarding the solutions to deal with an increased penetration of DG sources two main directions seem to be of interest: grid reinforcement and smart-grid technology. The conventional way of solving transport problem on the grid is by grid reinforcement, e.g. thicker - or parallel cable and 'heavier' grid components. An innovative way to deal with this problem is by implement smart technologies that balance supply and demand.

From the consequences of the two decentralized scenarios the smart-grid technology is most emphasized by the DNOs and relevant literature, as a mean to come to the end of efficiently facilitating DG sources on a distribution level. As regards the 'plug and play' consequences the smart-grid technology turned out to be an opportunity to postpone investment in grid reinforcement. For the 'fit and co-produce' scenario the smart-grid technology is essential in creating an organized local grid. However, it becomes apparent that the technical practice is still far away from the smart-grid theory.

In principle the smart-grids concept refers to balancing on a local level, without affecting the current reliability and voltage quality. This definition of smart grids will be specified in the chapter 5. The relation between the two solution technologies and regulation will be analyzed in chapter 6.



## 5 Smart grids into practice; a definition

Smartening the grid, more intelligence, ICT, interaction with end-user, smart meter and efficient use grid are all terms mentioned by the interviewees referring to smart grids. However, an exact definition could not be given. It has been explicitly argued that a smart grid is a means to an end and not the end in itself. We consider it significant to define the smart-grid concept, enabling a profound analysis of the relation between smart-grid technology and the regulatory framework.

First, the smart-grid definitions in literature are considered, giving the idea of the technologies involved (5.1). Second, the smart-grid technology is put into practice by linking the characteristics of the smart grid to the practical examples derived from the interviews (5.2). Finally the conclusion is described in paragraph 5.3.

### 5.1 Literature definition of smart grids

Two papers are considered that provide smart grid definitions, as can be seen in the text boxes below. They are from respectively the European smart grids technology platform and ‘KEMA Consulting’, commissioned by the Ministry of Economic Affairs (Scott et al., 2008). The European smart grids technology platform defines it as follow (EC, 2006):

*“An electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supply. A smart grid, involving a combination of software and hardware allowing more efficient power routing and enabling consumers to manage their demand, is an important part of the solution for the future”.*

Scott et al. (2008) describes that there is no agreed definition internationally, but gives the follow suggestion, which is EPIC<sup>8</sup> adapted:

*“A smart grid generates and distributes electricity more effectively, economically, securely, and sustainably. It integrates innovative tools and technologies, products and services, from generation, transmission and distribution all the way to customers’ appliances and equipment using advanced sensing, communication, and control technologies. It enables a two-way exchange with customers, providing greater information and choice, power export capability, demand participation and enhanced energy efficiency”*

After considering these definitions the general purpose of the smart grid is relatively clear, but what does it mean in practice and which role does the DNO have? To answer this questions the smart grid is defined in terms of enabling technologies described below, adopted from the vision and strategy paper of the European smart grids technology platform (EC, 2006).

#### 5.1.1 Active distribution networks

In their vision and strategy paper for Europe’s electricity network of the future, the European smart grids technology platform describes an active distribution network. The active network is explained as today’s transmission grids characteristics revealed on the distribution network. In order words; going from a passive system towards an active distribution system, with

<sup>8</sup> Energy Policy Initiatives Center, University of San Diego School of law. <http://www.sandiego.edu/EPIC/>

similar control as the transmission system. Embedding such an intelligent control in the distribution network can lead to a maximum utilization of the grid.

An active distribution network refers mainly to system balancing, which is believed to be difficult in the distribution network due to the limited control capacity of several decentralized generation units. The control capacity is displayed in Figure 8, in which several DG units are placed in a graph. As can be seen only a small part of the total DG production capacity is flexible for system balancing. Their low controllability is illustrated by the sustainable power sources; no sun or/and wind means no power. An option to balance the system is to reduce the output of sustainable power sources by applying generation shedding instead of load shedding. However, this is considered less attractive from an environmental and economical point of view, as their potential is not fully utilized (Meeuwssen, 2007). Beside generation shedding three different balancing options could be identified: balancing with load demands, storage facilities and power exchange between different voltage levels (Scheepers, 2008).

### 5.1.2 Communication

ICT is considered to be essential for system balancing, making balancing aspects as data gathering, data processing, production control, storage facilities and consumption control possible. Reliable communication equipment should be integrated in the control system of the distribution networks. These communication facilities could enable grid automation, on-line services, active operation demand response and demand side management (Meeuwssen, 2007). The DNOs emphasize that such ICT integration in the distribution network could only be feasible when the smart meter breaks through.

When is a meter considered to be smart, is a relevant question for a technology that is considered to be the first step towards a smart grid. Should it only send data to the operator or should it be possible to disconnect on a distance? The government describes on their website<sup>9</sup> five main requirements to be fulfilled by smart meter technology. The first requirement is reading out the consumed and supplied energy at a distance, to improve operational management of the supplier, and customer's realization of their actual energy consumption and related costs. The second requirement is to connect and disconnect capacity on a distance. Such switching on a distance is to facilitate operational task realization DNOs, preventive disconnect during emergencies, disconnect during temporally unoccupied buildings, partly disconnection by default of payment, and to support certain pay methods as prepaid. The third is measuring and observing the quality of energy subtraction, for means of improvement operational management DNO and detection of leak, fraud, supply fluctuations etc. The fourth requirements are online interaction between consumer and supplier. This interaction is for: facilitating innovative product and services, to let the consumer react on market/ product and price development, and to support certain pay methods as pre-paid. The last requirement is quick response in controlling energy installations, by connecting with smart electronic facilities and DG-units, to facilitate consumption and production control.

### 5.1.3 New network technologies and power electronics

In the EC (2006) paper new network technologies and power electronics are mentioned separately as smart-grid enabling technologies. We argue that these two technologies can be treated together as network technologies. The EC (2006) paper refers to new network technologies as technologies that facilitate increased power transfers and losses reduction. Examples of such technologies are gas insulated lines (GIL) and the superconductivity

<sup>9</sup> <http://www.ez.nl/content.jsp?objectid=150297>



technology. GIL's<sup>10</sup>, are considered lines that house conductors in special gas, resulting in high load-transfer capacity. A different example given in the EC (2006) paper of a new network technology is flexible AC transmission systems technologies (FACTS).

According to Kechroud et al. (2007) problems in the distribution system caused by the DG could be solved by considering FACTS devices. These devices are new control devices as well as components like power electronics used in the transmission system for a better stability and provide power flow control. By using these devices on distribution level a flexible AC distribution system (FACDS) is created, in which three sub-groups could be classified: custom power devices, network operation controllers and DG interfaces. ICT and storage elements should be integrated in the network, enabling the best operation of FACDS being the solution for, e.g. voltage change, islanding, harmonic and blinding of protection. The specifications of FACDS depend, consider the regional differences in paragraph 2.3.3, on the DG penetration level and network design (e.g. radial, meshed).

The different technologies related to power electronics and new network technologies are not described further in detail. These technologies are considered to be in a research phase and might be applicable on the distribution network in the future. The DNOs confirm the interest in these technologies.

## 5.2 A smart-grid definition for the distribution network

Based on the desk-study and the face-to-face interviews, local balancing is identified as the key indicator of a smart grid. The following definition is obtained:

*The ability to balance on a distribution level without using interconnection, but with storage, demand control and production control, and making optimal use of the connected DG capacity while maintaining voltage quality and reliability, and integrating ICT and new network technologies in the distribution system.*

Balancing on a distribution level refers to local grids on LV and MV-level. These local grids refer not only to a residential area and an industrial zone, but also to a local distribution grid connecting these residential areas and industrial zones.

Based on the above definition, Appendix V describes a smart-indicator. This indicator is an attempt to judge a particular distribution network on its 'smartness'. Currently balancing is exclusively a responsibility of the TSO and this characteristic might be transferred to the distribution level. The possible transfer of balancing techniques from transmission- to distribution level will be considered individually below, after a short description of the balancing system applied on transmission level.

### 5.2.1 Balancing on transmission level

The market based mechanism of programme responsibility (PR) can be seen as the basic principle behind transmission level balancing. As electricity cannot be stored, the production and demand for electricity should always be in balance. To keep the balance all PR parties have to exchange electricity exactly as described in their programme. These prognoses programmes concerning electricity transport are sent to the TSO based on article 5.1.1.1 and 5.1.1.2 of the Netcode (2007). In addition, based on article 5.1.1.1.a.1, the connected parties with a capacity more than 60 MW have a so called "biedplicht". This "biedplicht" obligates the party to offer, by means of a bid, variable capacity to the TSO. Parties with a capacity similar or less than 60 MW could offer on a voluntarily basis. When all prognoses are

<sup>10</sup> [http://tdworld.com/mag/power\\_gas\\_insulated\\_line/](http://tdworld.com/mag/power_gas_insulated_line/)



collected by the TSO he determines whether transport problems could be expected, based on 5.1.1.6 of the Netcode. When a transport problem seems to occur, the TSO take measurements to solve the problem. The procedure of solving a transport limitation is described in article 5.1.1.8 of the Netcode. In this procedure section c of 5.1.1.8 refers to the “biedplicht”, in which the TSO sends a request to the connected parties to produce more/less or consume less. When new problems seem to occur after solving the original transport problem the TSO can restrict the connected parties based on article 5.1.1.8.a. This means that transport prognoses are not accepted when leading to new network problems.

There is always imbalance to be settled by the TSO, caused by the uncertainties in the load profile of end-users. When a transport problem occurs in an acute situation, the TSO uses the same procedure described in 5.1.1.8, according to 5.1.1.9. The last article that is considered in this description is 5.1.1.10, which determines that the TSO is authorized to obligate the producer to produce more or less and obligate the consumer to reduce the transport request in a case of threatening large faults (NMa, 2009). Hence, to carry out the physical part of this ‘market based’ balancing, different balancing technologies can be considered. The balancing technologies on a transmission level refer to adapting production to demand, lowering consumption and the interconnection with other countries. Another balancing option, not currently used, is storage (Scheepers, 2008).

Now four balancing techniques have been identified: demand control, production control, interconnection and storage. Considering the definition of smart grids, the distribution network might use these techniques to make optimal use of the production units that are connected. One balancing techniques seem not applicable on the distribution network; interconnection with foreign countries is not likely to occur. However, the distribution network is inter-connected with higher voltage levels. This interconnection is already applied on the current distribution network as the electricity is supplied top-down. The four distribution balancing techniques will be described below.

### 5.2.2 Interconnection

The first balancing technique is interconnection with higher voltage levels as currently applied on distribution level. Electricity is flowing from a higher voltage level supplying the demand on a lower level. Situations might occur where electricity is flowing the other way around due to a surplus on local decentralized production. This reverse flow is unfavorable regarding the increase distance between the feeder and the load (via a higher voltage level). When the distance increases it results in increasing network losses.

### 5.2.3 Demand control; decrease

Demand side management on distribution network might be possible by varying the transport capacity available for the end-user. However, contrary to the transmission level the distribution network is largely radial operated; so the individual customers cannot have variable connection capacity. When the network is operated according to the meshed structure it might be possible. Considering the radial structure, the DNOs responded that opportunities could be found in switch off specific equipment as freezers and air-conditioning to decrease demand. Caution is particularly important when this balancing technique is applied, as Big Brother-like situations should be prevented. When the user agrees with a variable transport capacity (switching off specific electrical equipment) the DNO might use it as a balancing technique.

## 5.2.4 Production control; decrease and increase

As emphasized in the description of balancing on transmission level, production side control could be used as a balancing technique. Applying the same transmission production control mechanism on the distribution network (with prognoses-programmes) might be possible in the ‘fit and co-produce’ scenario, considering the relatively little number of organized actors involved. In the ‘plug and play’ scenario working with prognoses programmes seems out of the question, considering the enormous amount of actors involved. Concerning production side management on distribution level the distinction is made between decrease production and increase production.

### 5.2.4.1 Decrease of production

Decrease of production can be used to make sure the boundaries of the network capacity are not crossed. This might be possible by controlling DG sources on a local level. The decrease of production applies to the non-renewable DG-units, considering the importance of renewable DG-units for environmental goals (described in paragraph 4.1). A financial agreement could be made to compensate the producer for not producing. This compensation is paid by the DNO as he could postpone reinforce investment when the boundaries of its grid capacity are not met.

Would a user be willing to generate less and be compensated for it? To answer this question we consider the user’s intention to generate electricity and supply the grid. It has been argued that there are two intentions: earning money or being idealistic. The former is the most likely. Hence, when a CHP owner wants to produce, the operator has the opportunity to pay the price and shut down the CHP when it is optimal for the network.

### 5.2.4.2 Increase of production

Large opportunities seem to exist for this balancing technique, especially related to the micro-CHP. Controlling a micro-CHP gives the DNO the opportunity to apply peak shaving. In this case the following situation is considered; a distribution network that is 40 to 50 years old with a fully used capacity. This network has been dimensioned on a certain peak demand and a 2% electricity consumption growth per year. Now his full capacity is reached, investment might be postponed by using the micro-CHP in reducing the peak demand at 6 o’clock<sup>11</sup>. However, in the summer the generated heat is not required at that moment. In this situation the opportunity exist to store the heat, e.g. warm water, and use it later that evening, e.g. for a shower. In this way the peak at 6 o’clock is reduced and network reinforcements or other investment might be postponed.

## 5.2.5 Storage

The electricity production from sustainable DG sources is mostly depending on the weather, as wind turbines and PV panels are respectively depending on the wind and the sun. Hence, there is hardly any profile in electricity production. The characteristic of storage units to absorb a surplus during windy or sunny days and deliver on cloudy or windless days is an attractive one. We argue that storage can be an attractive option for both commercial companies and network operators. For commercial reasons storing inexpensive off-peak power can be lucrative in satisfy peak demand with an assumable higher electricity price. For a network operator the focus lies on peak reduction and increasing voltage quality.

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<sup>11</sup> Consider paragraph 4.5.1.3

Storage for peak reduction by the operator can be obtained by electricity storage for demand peak reduction, electricity storage for production peak reduction, and by heat storage during peak demand. By these storage options the operating costs can be reduced (Schainker, 2005). Voltage quality improvement by storage application is characterized by short term electricity storage. With storage for quality the voltage can be fine-tuned and the frequency can be controlled to expected levels. Now we will describe the three application of peak reduction and the one application for voltage quality in detail.

#### **5.2.5.1 Electricity storage for demand peak reduction**

By using storage facilities, charged during off-peak, the peak can be reduced before the maximum capacity of the grid is reached. Hence, by situating the storage units close to the end-user the network can be relieved and investments be postponed. There are four main principles identified that can store this relatively large amount of electricity: pumped hydroelectric storage (PHS), compressed air energy storage (CAES), battery storage and hydrogen energy storage (Meeuwsen, 2007 & Schainker 2005). A possible future storage facility that requires special attention is the use of batteries in electrical driven vehicles. The electric car has an enormous storage potential, as 80-90% of the car stands still on average.

#### **5.2.5.2 Electricity storage for production peak reduction**

During production peak moments, when the DG sources fully supply the grid and there is relatively little demand, storage units could be used to lower the peak. The same main storage principles used for demand peak reduction are applied in storage for production peak reduction. The peaks in production and consumption are never simultaneously and stored electricity during production peaks can be used during demand peaks.

#### **5.2.5.3 Heat storage for peak reduction**

Earlier the balancing technique regarding increasing production has been described, which in particular focussed on the micro-CHP and heat storage as an important condition. The heat could be stored in a boiler or in the ground. The heat storage technique is not fully developed yet and requires further attention. This heat storage goes beyond the distribution network and might not be the responsibility of a DNO.

#### **5.2.5.4 Energy storage for power quality**

Meeuwsen (2007) describes that short term storage facilities (seconds to some minutes) are especially applicable on the power quality applications. These applications refer to fine-tuning the voltage and control the frequency to expected levels. Schainker (2005) provides three main storage facilities that are used for power quality applications: superconducting magnetic energy storage (SMES), flywheel energy storage and super-capacitor energy storage.

### **5.3 Conclusion**

The balancing techniques, production control, consumption control, and storage are considered the practical elements defining the smart grid. Reliability and voltage quality are important aspects when implementing the smart grid. The balancing techniques interact with ICT and new network technologies creating an active distribution network.

In the next chapter we will investigate whether the regulatory framework is neutral vis-à-vis the identified technological solutions (smart grid and grid reinforcement). The smart-grid definition is used in the analysis of possible barriers in direct and indirect regulation for

the smart-grid technology. In this sense, the smart-grid balancing techniques will be tested versus the regulatory framework.



## 6 Regulation versus the solution technologies

In this chapter the last sub question is considered: *is the regulatory framework neutral vis-à-vis the technological solutions for DG-problems? And what could be changed if not?* Gathering information to answer this question is done by analyzing the relationship between the regulatory framework and the two identified solutions: smart-grid technology and grid reinforcement. When smart-grids development is hampered by regulation the organization level of DG development remains low. This favors the conventional grid reinforcement in the ‘plug and play’ scenario and the centralized scenario.

Paragraph 6.1 describes the interrelatedness between the two identified solution technologies. In paragraph 6.2 the MLP-framework is described, which will be used to analyze the relationship between the regulatory framework and the development of solution technologies. In the sub paragraphs of 6.2 we explain the general idea behind the MLP-model. In paragraph 6.3 possible barriers in direct regulation are described. Paragraph 6.4 emphasizes the controversy between smart-grid technology and grid reinforcement. The last paragraph describes the possible reasons for the smart-grid technology to break through, particular concentrating on indirect regulation.

### 6.1 The interrelated solution technologies

The conventional way of solving transport problems on the grid is by grid reinforcement, e.g. thicker or parallel cables and ‘heavier’ grid components (as considered in 4.3.2.1). An innovative way to deal with transport problems is to implement smart technologies that make more effective use of the existing grid. Transport problems on distribution level can occur when the demand increases or by an increasing penetration of DG-sources. To illustrate the controversy between grid reinforcement and the implementation of smart technologies, we consider this example of a respondent: when a new residential area is equipped with heat pumps it is facilitated by the DNO with a 4 times reinforcement grid in comparison to the ‘current’ dimensioning. When smart technologies are applied, this reinforcement factor might be reduced to 2 times the conventional grid strength. In this sense, smart technologies make the grid more efficient.

The contradiction between these two ‘solutions’ indicate the urgency of making decisions concerning the development of smart grids. The respondents explain that when an obsolete network is reinforced or newly constructed, the grid capacity has to be dimensioned. The capacity of the grid is calculated by a 2% electricity growth per year and the condition to still facilitate a peak demand over 40 years. One can imagine that a cable can be over-dimensioned in the future, considering a smart-grid breakthrough. When this occurs the cable is not fully utilized.

### 6.2 Multi-level perspective

How does a technological transition (TT), e.g. the transition towards a smart grid, comes about? Geels (2002; p.1257) explains “*TT’s are defined as major technological transformations in the way societal functions as transportation, communication, housing, feeding are fulfilled.*” In this research the electricity supply is the societal function, specifically focused on the distribution supply system. The multi-level perspective (MLP) framework is illustrated in Figure 12, consisting of three levels: landscape (macro), regime (meso) and niche (micro) level.

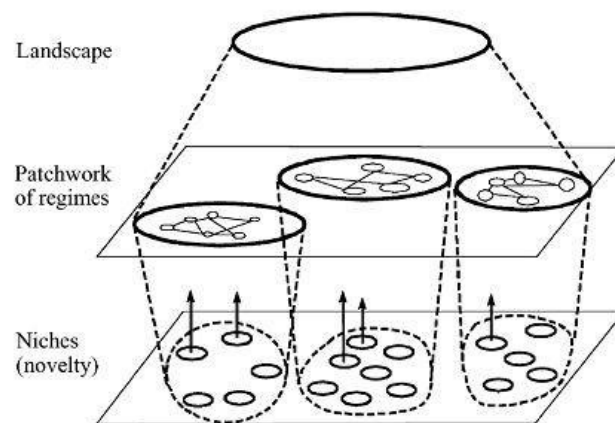


Figure 12, MLP-model with three analytical levels, Geels (2002, p.1261)

### 6.2.1 Landscape level

The socio-technical (ST) landscape refers to wider technology-external factors and can be seen as a context for the interactions of actors. Examples of external factors in the landscape environment are cultural and normative values, environmental problems, the process of European integration, increasing pervasiveness of ICT, oil prices, economic growth, wars, emigration, and broad political coalitions (Geels, 2002 & Meeuwsen, 2007).

Developments on a landscape level that are particularly important for the centralized scenario are the security of energy supply and climate change. The security of supply is threatened by global competition and geopolitical instability (Verbong and Geels, 2008). This pressure is faced internationally, by more cooperation on a European level. The control of the electricity system will shift to a European level characterized by a top-down structure.

For the decentralized scenarios a diversity of landscape factors are identified that put pressure on the regime. These factors refer to further liberalization, climate change and ICT development (Elzen et al. 2002), to high energy prices, energy scarcity and increasing CO<sub>2</sub> emission (Verbong & Geels, 2008 and EZ, 2008).

### 6.2.2 Niche level

Novelties are generated in the niches where they are protected or insulated from the regime's normal market selection. In the niche the rules are not clear cut even as relationships between actors. Strategic investments of companies or subsidies often provide the protection for these novelties, e.g. the smart-grid technology (Geels, 2002). In addition, the niche provides the space to build: a social network supporting the innovation, a supply chain and a user-producer relation. The user-producer relationship is particularly important for the smart-grid technology as will be explained in paragraph 6.1.3.2, describing the user as an important actor.

### 6.2.3 Regime level

The meso-level of the MLP is representing the socio-technical regime in which dimensions are linked, together fulfilling a societal function. Simplified, these analytical dimensions are respectively the social-technical system, the actors involved in the socio-technical system, and the rules and institutions coordinate their behavior (as can be seen in Figure 13).

Change of incremental nature is continuously occurring in regimes, based on existing socio-technical configurations. In this research the socio-technical regime is in the domain of electricity. It is characterized by centralized fossil-based top-down supply chains, network operators, rules for network connection and transmission pricing, increasing competition, and concentration across national borders (Meeuwssen, 2007).

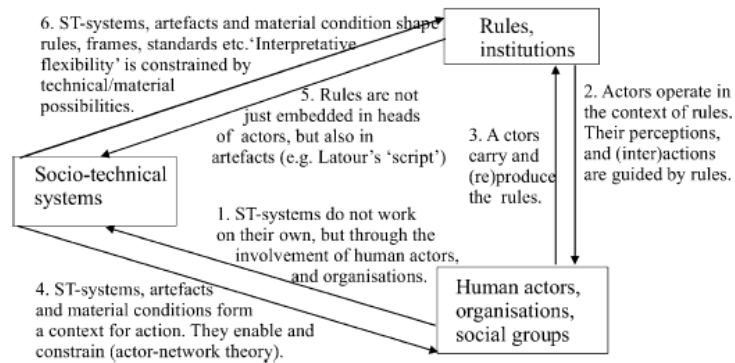


Figure 13, *three interrelated analytic dimensions*, Geels (2002, p.903)

The stability of an existing technology is accounted for by the meso-level of ST-regimes. Based on the regimes knowledge and capability, technical solutions are produced for problems of the existing regime, e.g. the DG-problems. By reproducing the current system the interaction between the three elements create a so-called 'lock-in', which can be breached by developments in the upper and lower levels. However, the alignment of the regime to an existing technology makes it hard for an innovation to break through (Geels, 2002). Considering the conventional way of solving capacity problems we assume that grid reinforcement is the technology lock-in and smart grid is the technology that could breakthrough when a 'window of opportunity' is created.

#### 6.2.3.1 Social-technical system

The first analytical dimension in the regime is the socio-technical system. This system widens the existing innovation system, focused mainly on the production side, by encompassing diffusion and 'use of technology' (Geels, 2004). Technology is a crucial element in the ST-system and a distinction between sub-functions as production, distribution and 'use of technologies' is made. As can be seen in Figure 14, these sub-functions are fulfilled by necessary resources as artifacts, capital, labor, cultural meaning, and regulation.

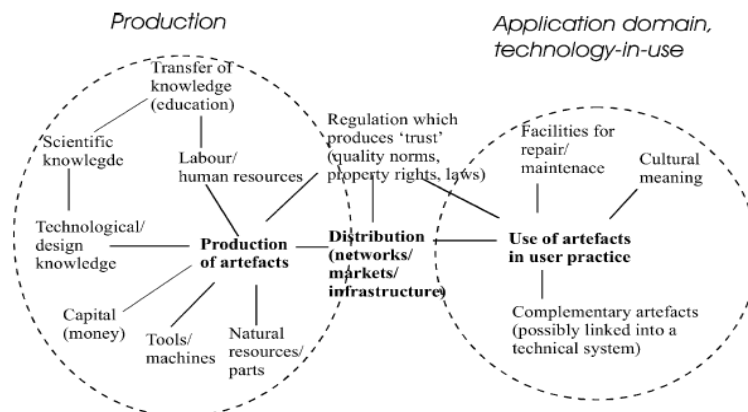


Figure 14, *the basic elements and resources of socio-technical systems*, Geels (2002, p.900)



### 6.2.3.2 Human actors, organizations, social groups

The second analytic dimension is the various actors, organizations and social groups (all together defined as actors) involved in the social technical regime. In this section we considered the actors, characterized them and describe their role in the energy transition to a decentralized future electricity supply system. In addition, the role of the actors is considered concerning the balancing techniques.

The user is defined as connected to the electricity grid requesting the transport of electricity for consumption and/or the sale of generated electricity. Changing aspects for the users are among others: in-house generation, ability to sell electricity, freedom in choosing a supplier, and maybe real time tariffs (EC 2006). All these change aspects will broaden the user's expectation regarding services and connectivity. The 'plug and play' scenario is characterized by changing user expectations for households and in the 'fit and co-produce' expectations mostly change for the companies. Concerning the different balancing techniques the role of the users varies between the techniques, but their acceptance is crucial. Especially concerning production and consumption control, the end-user is (voluntarily) confronted with technology that takes over in-house control, e.g. disconnecting the freezer or increasing production of the micro-CHP. The users need to accept these technologies in order for the smart grid to breakthrough.

The electricity network companies should, together with other actors, fulfill the users' expectations by conducting the necessary investments for power quality and system security in an efficient and cost effective way (EC, 2006). As this research focuses on the distribution network we consider the DNOs as the electricity network companies. As regards the balancing techniques, the DNOs might use them to facilitate the connected DG-sources as efficient as possible, maintain voltage quality, or maintain reliability. The implementation of the balancing techniques will make the DNO more of a DSO; a distributed system operator. When this transition takes place and the DNO becomes a DSO, coalitions will change. The operator shall to a higher level cooperate with the end-users, suppliers of ICT, TSO etc.

Technology suppliers will be key players in achieve effective deployment of their developed innovative smart solutions. These solutions refer to the network-, demand- and generation side, both centralized and decentralized. We concentrate on the network and the developments to provide open access, long-term value, and integration with the existing infrastructure (EC, 2006). As regards the balancing techniques, the ICT supplier will especially have an important role in the transformation of the DNO into a DSO. Concerning production control the supplier of e.g. DG – sources could cooperate to develop a controllable micro-CHP and for consumption control a controllable freezer. A shared vision between the operator and the technology supplier is also needed for storage; to ensure a strategic deployment in the existing infrastructure.

The energy service companies will have to satisfy the growing need of users, as they are the interface between the electricity system and the users. In order to incorporate the balancing techniques the user should be involved in the strategic deployment of the smart grid with help of the energy service companies. These companies are the intervening party between the DNO and the end-users.

Research institutions play an important role in the development of smart-grid technologies and the way they are implemented in the electricity system. As stated by the European technology platform smart grids (EC, 2006); without research there will be no innovation and

without innovation there will be no development. Cooperation between universities, research centers, utilities, manufactures, regulators and legislators is required for successful development of the smart-grid technology.

### 6.2.3.3 Rules

The general phenomena ‘rules and institutions’ aim to describe is the coordination and structuration of activities (Geels, 2004). As regards their corresponding aim, institutions and rules are regarded similar. Rules will be the general term used in this report for this third analytic dimension.

Three different kinds of rules have been identified: normative, cognitive and regulative (Geels, 2004). This thesis particularly focuses on the regulative rules in relation to the distribution network. The other two rules will be shortly addressed. First, the normative rules refer to values, role expectations, duties, rights, and responsibilities. There is a social pressure to become ‘part of the group’ and the basis of legitimacy is morally governed. In this sense, the normative rules describe how the actor is supposed to behave. Secondly, the cognitive rules refer to the cognitive capacity of human beings. These rules are embedded in the head of the actors. Furthermore the cognitive rules have been characterized by priorities, problem agendas, beliefs, bodies of knowledge, and jargon/language (Geels, 2004). Finally, the regulative rules are explicit formal rules, which regulate interactions and constrain the behavior of the actors involved. Geels gives the example of government regulations which structures the economic process. As regards the regulative rules we focus on the regulatory framework, which refers to the formal rules for direct and indirect regulation.

In the hierarchy of the regulatory framework’s formal rules the directive 2003/54/EC (ED, 2003) of the European Parliament and the Council is the top (NMa 2009b). It describes the common European rules for the internal market in electricity. This directive is implemented in the Dutch Electricity Act, which has been enabled in July 2004. Lower in the hierarchy are the secondary rules; including ministerial regulation, policy rules, codes and more. The codes refer to the technical codes (netcode, meetcode and systeemcode), the tariffs code (tarievencode), and the information code (informatie code).

As with regard to direct regulation rules, we focus on the Dutch Electricity Act and the Netcode (2007). The Netcode is a regulation that describes the conditions of the way DNOs and end-users act regarding: the network operation, the connection to the network, and the electricity transport on the network. As regards indirect regulation, we have been focusing on the Electricity Act, in particular article 41, paragraph 6. This article describes the incentive for the DNOs to find a balance between efficiency and quality.

## 6.3 Possible barriers in direct regulation

By describing the MLP framework the relationship between the regulatory framework and the solution technologies has been partly exposed. Now we can specify this relationship and determine whether the regulatory framework hinders the solution technologies and what can be done about it. As with regard to the regulation framework, the distinction has been made between direct and indirect regulation (paragraph 2.2). In this paragraph we focus on direct regulation and paragraph 6.4 will focus on indirect regulation. In addition, this paragraph focuses specifically on the conditions in direct regulation for a smart grid to breakthrough. These conditions will indicate where possible barriers exist for the smart-grid technology. As regards grid reinforcement, it has been argued by respondents that this conventional solution

for DG-problems is not hindered by direct regulation; grid reinforcement is already largely deployed.

Basically we attempt to answer the following question in this paragraph: to which conditions should the direct regulation comply, allowing a large deployment of smart technologies on distribution level? To answer this question all three balancing techniques will be considered. An indication will be given to which direct regulative rules they seem to conflict. We describe only an indication as rules are interpretable. Correspondence between the DNOs and the regulator should clarify what is legally possible and whether adjustments are necessary.

### 6.3.1 Demand and production control

In this paragraph three balancing techniques with similar possible barriers in direct regulation will be described: decrease in demand, decrease in production, and increase in production. The first balancing technique is decrease in demand, from which four possible barriers have been identified. These barriers are only based on a first analysis in this thesis of the Electricity Act and the Netcode (2007). Further research is recommended to validate the barriers. The first barrier concerns the limit accessibility of the distribution network, and the other three barriers concern the arrangements for end-user. As regards the first barrier, the NMa (2009) describes the availability of sufficient transport capacity and the accessibility to the electricity network, essential parts of a good functioning electricity system. This accessibility of the distribution network is limited by decrease in demand. However, when the grid manager within reasons has no capacity available for the transmission requested, he is not obligated to do so (see text box). So, when a DSO is short in grid capacity could he apply decrease of demand? Is this within reasons? Further research should determine whether the limit accessibility is an actual barrier.

#### ***Section 24, paragraph 4 of the Electricity Act:***

- (1) The grid manager shall be required to make an offer to any person who requests such in relation to the transmission of electricity, making use of the grid managed by him, and at tariffs and subject to conditions, in accordance with paragraphs 5 and 6 of this chapter.
- (2) The requirements, referred to subsection (1) shall not apply in so far as the grid manager within reason has no capacity available for the transmission requested.
- (3) The grid manager shall refrain from any form of discrimination in relation to those to whom he has an obligation, as referred to in subsection (1).

According to Section 24 of the Electricity Act, the DNO must make an offer for any person who requests the transmission of electricity. However, is it allowed to stimulate a person to not request transport on a for a DNO unfavorable moment? It has been argued that the end-user could be stimulated by actively involve him in the electricity system and offered a contract that compensates for a lower transport accessibility. In this sense the end-user gets a compensation for allowing the DSO some in-house control. The possibility exists for the end-user to let its freezer and air-conditioning controlled by the operator. A compensation contract to execute the production control may not by any means affect the comfort level of the user.

Three barriers have been identified that might hamper an arrangement (compensation contract) with the end-user. The first barrier is no conditions could be found in the Electricity

Act and Netcode (2007) that legitimacy a compensation contract. It seems that all connections on LV should correspond to the ones described in article 3.1.2 of the Netcode (2007). Secondly, the compensation contract should be offered to the end-user via a third party: the electricity supplier (license holder). This contract has to be combined with the capacity tariff, which is charged to the end-user via the supplier. The supplier receives the money and pays the DNO for the requested electricity transport. The capacity tariff is a yearly fixed sum, from which the height depends on the connection's size. Implementing an arrangement (e.g. a compensation contract) will affect this capacity tariff and agreements with the supplier should be made. The last barrier refers to point 3 of the text box: every end-user connected to the distribution networks should be offered a 'compensation contract', as the DSO must refrain from any form of discrimination. Hence, even in network that are facing no difficulties, the compensation contract should be offered.

The second balancing technique is the decrease in production, which again limits the accessibility of the electricity network. As with the decrease in demand, further research should determine whether this is an actual barrier. The largest barrier for decrease of production seems the discrimination of non-renewable decentralized production; only the non-renewable DG-units will be decreased with this balancing option (described in paragraph 4.1). The discrimination of this type of DG-units is illegal, as can be seen in the text box (point 3). Besides the accessibility and discrimination, an arrangement with the end-user implies barriers in direct regulation. Implementing such an arrangement might be hampered by the same three possible barriers as with the consumption decrease: no legal conditions, no allowance of discrimination, and no-direct relationship with end-user.

The last balancing technique considered in this paragraph is production increase. With this technique the DNO asks the end-user to produce electricity, in order to reduce peak demand. The same three possible barriers, as described for the decrease in production and demand, might apply to this balancing technique. From these barriers the 'no allowance of discrimination' needs additional explanation; the decentralized producers that are connected to a weak grid will be profit more from this agreement than producers connected to a strong grid.

### 6.3.2 Storage

Two options for storage by the DNO are considered in paragraph 5.2.5: store energy for peak reduction and storage for voltage quality. The storage for peak reduction consists of three types: demand peak shaving, production peak shaving, and heat storage. As regards the peak shaving storage, the DNO can charge during off-peak and deliver during a peak. Cooperation between the DNO and a commercial party seems necessary; buying and selling the electricity at a, for the DNO, preferable moment in time. The commercial party has to be involved as the DNO is legal not entitled to incorporate in paying or selling electricity (consider Section 17, paragraph 2 of the electricity law in the text box below). The DNO might have the opportunity to maintain the storage facilitate and hire it to commercial parties. The task and responsibilities around storage should be very clear, especially when the electric car with its storage potential breaks through.

As with regard to storage for voltage quality (part of the performance), there seems to be a legal basis considering section 17, paragraph 2 (a) of the Electricity Act. However, no conditions could be found in the Electricity Act and Netcode that explicitly legitimacy the use of storage by a grid operator (e.g. a DNO).

***Section 17, paragraph 2 of the electricity law:***

The grid manager, or a legal entity in which the grid manager has a participating interest, as referred to in section 24(c) of book 2 of the Netherlands Civil Code, may not supply goods or services resulting in competition between them and third parties, unless this relates to carrying out activities in respect of:

- (a) the performance of the duties referred to in sections 16(1) and 16(2), either for himself or for other grid managers, or on behalf of third parties entitled to use a grid.
- (b) the construction, management or maintenance of cables and pipelines outside of buildings for the transmission of gas, heat, cold or water; or
- (c) the provision and maintenance of grids for the use of related services by third parties.

**6.3.3 Tasks and responsibilities**

Considering the ‘fit and co-produce’ scenario, an additional dimension concerning task and responsibilities is applicable, as the local organized grid faces uncertainty. Who is responsible? Who is accountable for faults? By current regulation the owner should appoint the management of a separate grid to a DNO, based on section 10 paragraph 3 of the electricity law.<sup>12</sup> Obtaining a discharge from this obligation and keep the grid under own management is granted by the Energiekamer when certain conditions are met, described in section 15, paragraph 2 of the Electricity Act. These ‘certain conditions’ should be tested vis-à-vis a local balanced grid.

**6.4 Possible reasons for a smart-grid breakthrough**

The possible barriers for the smart-grid technology in indirect regulation will be identified in this paragraph. As regards the grid reinforcement, the relation between indirect regulation and the deployment of this conventional solution is part of a current discussion. For that reason we focus on the smart-grid technology. In paragraph 6.1.4 we have explained that reproducing the current system by interaction between the three elements in a regime creates a technology ‘lock-in’. Considering the conventional way of solving transport problems we assume that grid reinforcement is this technology locked in. The smart grid is the technology that may breakthrough, when a window of opportunity is created. However, what could be the reason for the smart grid to breakthrough? And when the conditions in direct regulation are met, is indirect regulation hampering a breakthrough? These questions are addressed in this paragraph.

Radical novelties, which the smart grid is considered to be (EC 2006), can break through when a ‘window of opportunity’ is created by tensions and miss-alignment for different reasons. The reasons described below are based on Geels (2004) and will be linked to the development of smart grids and possible barriers in indirect regulation.

- *Changes on landscape level putting pressure on regime*; concerning this reason we argue that it is important to make the distinction between landscape pressure creating opportunities for DG and landscape pressure creating opportunities for smart grids. Basically the increase penetration of DG can be facilitated by the conventional way of grid reinforcement or by smart grids. The landscape pressure, creating opportunities for smart grids, can come from broad political coalitions.

<sup>12</sup> [http://www.energiekamer.nl/nederlands/elektriciteit/transport/overzicht\\_netbeheerders/index.asp](http://www.energiekamer.nl/nederlands/elektriciteit/transport/overzicht_netbeheerders/index.asp)

- *Internal technical problems undermining the trust in existing technologies*; the shared perception and placement on problem agendas is important and not just the existence of technical problems. These technical problems might refer to the problems arising with the further penetration of DG units. For the breakthrough of smart grids we do not consider this a significant reasoning, as it has been argued that the trust in the conventional grid is not yet decreasing.
- *Negative externalities and effects on other systems*; pressure on the regime might be caused by health risk, safety concerns, environmental impact etc. Concerning the conventional way of dealing with electricity transport no negative externalities seem to exist. Positive externalities might exist for the smart grid when implemented by the DNO. We describe these externalities further in paragraph 6.4.2.1.
- *Changing user preferences, the established technologies might have difficulties to meet them*; the change in user preference might be caused by cultural changes, price changes and policy measures (such as taxes). In this sense, if one considers subsidizing PV-panels, the user preference for renewable energy can increase by policy measurements. Concerning the distribution network, we believe that the end-user does not care how he is connected to the grid. However, a smart grid is likely to influence the user preferences. Involving the end-user into the energy system facilitated by smart grids is believed to be important and essential in the large scale deployment.
- *Strategic and competitive games*; competitive advantage can be achieved by new technologies. Investments in R&D are a necessity for these new technologies. Most R&D is incremental, but companies can also invest in radical innovations by sponsoring a particular niche which, in their view, has a strategic potential. In addition, a domino effect can be created as companies watch and react to each other's strategic moves. Obtaining competitive advantage vis-à-vis competitors is the generally idea behind benchmarking and the Dutch indirect distribution regulation. By further development and large scale deployment of smart grids, DNOs can achieve competitive advantage. This is a possible reason for the smart technology to breakthrough.

When the radical novelty breaks through it enters the competition with the existing technology. Whether the novelty replaces the existing technology depended on wider changes in user practice, politics and social acceptance (Geels, 2004). Eventually a new regime and system will arise. From the five above mentioned reasonings we select the 'landscape change' and 'strategic and competitive games' to be the most likely, as argument in the short description of the reasons. In addition, these reasons are in conflict concerning possible incentives for smart-grid development, as will be explained below.

#### 6.4.1 Change on a landscape level

In the European technology platform smart grids (EC, 2006) it is stated that the European internal market, security and quality of supply, and the environment are factors that should be accommodated by future grids. The overall goal is to supply sustainable, secure and competitive energy. In Figure 15 the different factors are displayed, in which the European internal market is the first factor. The internal market promotes economic growth and plays a key role in the EU's competitiveness strategy. Encouragement of efficiency and spur on technological progress and innovation is to be achieved by increased competition, from which the citizens can benefit due to lower prices and wider choice. The second factor is



security and quality of supply, which is important as modern society is depending on it. The security, reliability, and quality of supply are threatened by the uncertainty of fossil fuel supplying countries and the ageing infrastructure. By investment in infrastructure, it can be developed and renewed with innovation solutions. The last factor concerns the environment, which is under treat as greenhouse gases cause a climate change. The most cost-effective technologies and measures have to be used; enabling the EU to meets its targets under the Kyoto protocol and beyond (EC, 2006).

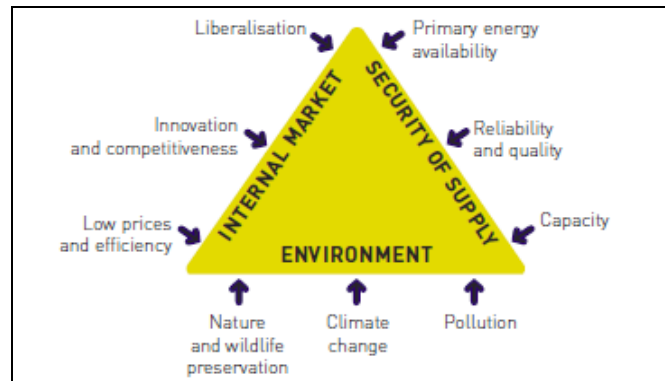


Figure 15, *driving factors in the move towards smart grids*, EC (2006)

In the SET-plan towards a low carbon future (COM, 2007) it is stated that Europe needs to act now to deliver this sustainable, secure and competitive energy. The challenges on climate change, security and competitive are interrelated to create the energy supply system of the future.

As regards the environment, we argue that climate goals are not a direct driver for the implementation of smart grids. However, the renewable DG sources that might be facilitated by smart grids are a direct driver. The smart grids on their own are not essential to achieve the climate goals; the DG sources could also be facilitated in a conventional way. The climate goals are considered an indirect driver for smart grids. The DNO is faced with an increase penetration of DG sources and should make the decision to facilitate it in the conventional way of grid reinforcement or use the opportunity to integrate a new innovative way and develop smart grids. Concerning the internal market, smart grids seem to become the most cost effective way to facilitating DG. This should be made explicit by comparing the financial benefit of the smart-grid versus the grid reinforcement. Concerning security of supply the smart grids do not seem to guarantee a more secure network than the conventional grid.

COM (2007) explains that the energy innovation process, including smart grids, suffers from unique structural weakness. This weakness refers to the long lead times to large deployment of an energy technology. This long lead time is caused by: the scale of investment needed, lock-in effect in social technical regime based on carbon-based infrastructure investment (grid reinforcement), imposed price caps, and network connection challenges. In addition, the large scale deployment of new energy innovations is hampered by the commodity nature of energy; smart grids do not provide 'better' energy services. Another issue imposing the weakness of the innovation process concerns the social acceptance of the smart grid. This weakness can lead to up-front integration cost to convince the user of the innovative technology. COM (2007) concludes that there is no natural market appetite and no short-term benefits for a technology like smart grids. From this reasoning public intervention and

support of energy innovation is believed to be justified and necessary. Hence, when the statements of the COM (2007) report are considered and when a broad political coalition favoring smart grid is formed, public support is required.<sup>13</sup>

### 6.4.2 Strategic and competitive reason

Considering the benchmarking model described in paragraph 2.2.2.2, the DNOs should be as efficient as possible to obtain competitive advantage. Based on obtaining this advantage the DNO decides whether a smart grid is more efficient than grid reinforcement. From this perspective the indirect regulation seems to stimulate innovation; the smart grid will be developed and deployed by the DNOs to obtain competitive advantage. However, in paragraph 6.4.2.1 and paragraph 6.4.2.2 we identify two arguments that oppose the statement of the smart grid being stimulated by competitive advantage: the existence of smart grid externalities for a DNO and the innovation process. These arguments indicate barriers in the indirect regulation for the deployment of smart-grids. However, the arguments are based on the interviews conducted in this thesis. Further research should validate these barriers.

In addition, a point of attention for indirect regulation concerns the regional differences, described in paragraph 2.3.3. These are expected to affect the competitive advantage that can be reached. These differences are: connection density, DG penetration level, and grid topology. The DG penetration level affects the competitive advantage as some distribution networks face more DG-units than others. When every DNO connects, within reasonable limit, the same amount of DG the costs are calculated to the end-user (benchmarking model). However, when the DG penetration varies heavily the costs of connecting might be calculated to the producing end-user. Another option can be to socialize the costs of DG connection. The variable costs of connecting DG units is part of a current discussion (also concerning grid reinforcement), and not considered in this thesis in further detail.

As with regard to the two other regional aspects (connection density and grid topology), the respondents emphasized the importance of considering these aspects. However, no detail explanation could be given of how these regional aspect influence the implementation of smart grids. Further research is required to indicate to what extend smart-grid technologies are the best option for a particular distribution network. One could imagine that a smart grid might not be the most cost- efficient solution in a distribution network with a low connection density (rural area). Furthermore, implementing a smart grid in a radial network is expected to differ from implementing in a meshed network.

#### 6.4.2.1 The existence of externalities

The first possible barrier for smart grids being stimulated by competition is the existence of externalities for the DNO when implementing smart grids. COM (2007) explains that society tends to receive the immediate benefits of smart grids instead of the buyers, being the DNOs. When the costs are not entirely covered by the benefits the smart grid is unlikely to be a favourable option for DNOs. When such externalities can explicitly be proven, it might be a reason for public support. The benefits of other parties should explicitly come from the smart grid as an innovative alternative for the conventional way of connecting users. The social benefit of smart grids in connecting renewable DG units is not considered as such a benefit,

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<sup>13</sup> Note; we believe the argumentation described in the SET-plan remains relatively vague as it is not clear where the argumentation is based on, e.g. practical examples. No specific explanation is given why the regulatory framework is locked-in, and how that could be prevented.



as the units can also be connected in the conventional way. Below we give a short indication of the benefits and cost for the different parties involved. A profound analysis is required to determine whether public support is justified.

The first party that might benefit, other than the DNO, is the end-user. The user benefits derive from ‘production increase’ (balancing technique), as the user produces during high electricity prices when their capacity is needed. In addition, the user benefits from ‘consumption control’, which can deliver him a lower electricity bill. The second party is the TSO, which benefits from smart technologies implemented on distribution level in keeping the electricity system in equilibrium. Despite the balancing on distribution level the TSO still has to balance on a transmission level and supply shortages to lower voltage levels. Close cooperation with the DSO will be required. The third party that might benefit is the research institutions, which play an important role in the development of smarter technologies. The last party that might benefit is the energy service companies. They benefit from the ‘production and consumption control’ by offer new services as energy saving software, automatic on/off switch and real time energy use displays.

The smart-grid benefits of the DNO mainly refer to effective use of their grid and postponement of grid reinforcement. When reinforcement seems necessary, the grid might be dimensioned on a lower capacity by using smart technologies.

Storage facilities can be a large cost as they are assumed to be relatively expensive. Concerning the other two balancing techniques (consumption and production control), the costs mainly refer to ICT. Especially the data control is assumed to be a large cost.

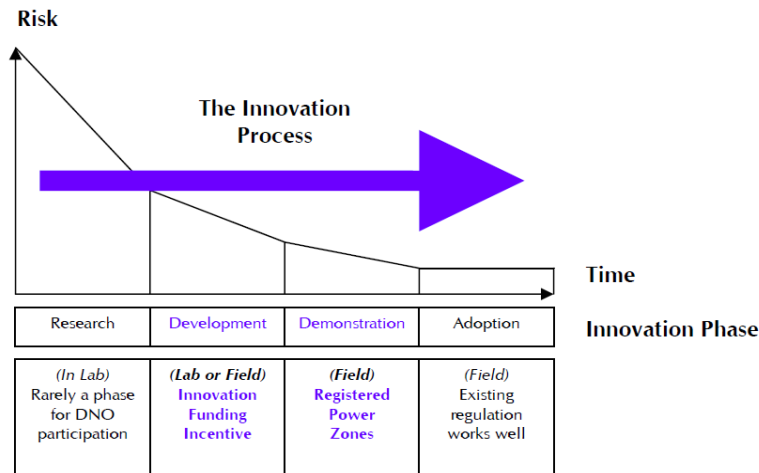
#### 6.4.2.2 Innovation

The second possible barrier for smart grid being stimulated by competition concerns the technology innovation progress (also referred as innovation chain). In this research we consider the simplified way of describing the innovation chain by four stages: research, development, demonstration and deployment (Scott, 2008). From the interviews the smart technology is situated in the research and development phases, as desk studies are conducted and some pilot projects are set-up. Hence, before the smart-grid technology can compete with the conventional way and breakthrough, relatively large investments in development and demonstration are necessary (Scott, 2008).

We argue that concerning the ‘competitive and strategy’ reason for breaking through, it is important to understand the different phases in the innovation chain and the risks involved. We identify two innovation issues for the distribution network sector. First of all, the sector is considered relatively risk averse. This risk aversion might be more of a normative rule (described in paragraph 6.1.3.3), as modern society is depending on electricity. As new technologies are accompanied with risk, not all technologies concepts that are placed under smart grids will succeed. In addition, the current Dutch distribution networks are highly reliable as can be seen in Figures 10 and 11. Replacement with a new technology should not affect this reliability, indicating the importance of the demonstration phase. The second innovation issue refers to the risk taken in the early stage of development. From a commercial organization point of view, the large investments are only made when a commensurate reward for a successful outcome can be received. The risk taken in the early stage of development should be compensated by the possible high reward in large scale deployment. It is possible that the DNO is unable to obtain a commensurate reward that is comparatively

to the risk taken. A solution can be an innovation incentive mechanism for successfully manage innovation.

In the UK regulation, the innovation process of distribution networks is stimulated by two inventive mechanisms: Innovation Funding Initiative (IFI) and Registered Power Zones (RPZ). (MacDonald, M. 2004, Ofgem 2003) These two incentives mechanisms are respectively applicable on the development and demonstration phase within the innovation process model, as can be seen in Figure 16.



**Figure 16, IFI and RPZ placed in the innovation process, Ofgem (2003)**

The research phase is considered to be the domain of research institutions, manufactures and university, possibly sponsored by the DNOs. It is unlikely that this phase is undertaken by the DNO itself. In the development phase effective inputs from users is required to let the development activities meet the real world. Most technical challenges and product testing will be addressed in this phase. The DNO is required to deliver financial commitment to focus the development activities on a particular user (e.g. company, household, small DG, large DG etc.) and network (e.g. radial, meshed, low connection density etc.). The IFI has a particular application in the research phase. In the demonstration phase, the DNO is essential and the RPZ is operating. In this phase a full simulation takes place to experience the conditions on an operational power system. This experience is essential for the confidence of a widespread deployment in the adoption phase. Whether the incentives will be effective and how these two incentives can be applied in the Dutch regulation system is recommended for further research.

By fostering the development and demonstration phase in the innovation process the smart-grid technology could develop in the niche. Whether the smart grid is largely deployed depends on the DNO's decision to adopt the technology in facilitating the DG units or stay with grid reinforcement.

## 6.5 Conclusion

Information to answer the third research sub question has been gathered by analyzing the possible development of technologies (as grid reinforcement and smart grids) in a MLP. In this MLP we have particularly focussed on the relationship between the smart-grid technology and the regulatory framework. From this information we conclude that the regulatory framework is not neutral vis-à-vis the two solution technologies. This conclusion

is based on the assumption that the three arguments described below are valid. These arguments indicate barriers in the regulatory framework for the deployment of smart-grids. However, we emphasize that the arguments are solely based on the interviews conducted in this thesis and an additional desk-study. Further research should validate these barriers.

The first argument concerns barriers for the smart-grid technology in direct regulation. These barriers have been identified for every individual balancing technique. One barrier concerned every balancing technique: no explicit legal conditions to explore the technique. Production control (consisting of production increase and production decrease) has additional barriers in decrease accessibility, no allowance of discrimination, and no direct relation between DNO and end-user. In addition, the decrease in production has a barrier in discriminating non-renewable DG. Demand control has barriers in decrease accessibility, no allowance of discrimination, and no direct relation between DNO and end-user. As regards storage, there is a barrier in DNOs being not entitled to incorporate in paying or selling electricity. In addition, there is uncertainty concerning the tasks and responsibilities of storage. These barriers in direct regulation are based on a first analysis (desk-study) of the Electricity Act and the Netcode (2007). Further research is recommended to validate these barriers in direct regulation.

The second argument concerns externalities for a DNO when implementing smart grids. This means that the benefits of smart grids can not sufficiently be internalized by the DNOs to compensate the costs. In this sense, indirect regulation contains a barrier for obtaining competitive advantage from deploying smart grids.

The third argument refers to the two innovation issues in indirect regulation: the risk adversity of DNOs and the commensurate reward of successfully managing the innovation process. As regards the commensurate reward; the reward might not be comparatively to the risk taken by the DNO.

Assuming that the regulatory framework is hampering the smart-grid technology, what could be changed? We argue: legal conditions for the balancing techniques, allowance of specific 'positive' discrimination and arrangements between supplier and DNO. In addition, the tasks and responsibilities in balancing techniques on distribution level should be clearly defined. A situation in indirect regulation where the costs cannot be compensated by the benefits for a DNO might be corrected by public support. Concerning the innovation issues in indirect regulation innovation incentives could be created, as in the UK with IFI and RPZ.

## 7 Conclusion

In this thesis three sub research questions have been systematically answered, providing the information to answer the main research question:

*Which consequences do energy transition scenarios have on the distribution network, and is the regulatory framework neutral vis-à-vis the technological solutions for the distribution network?*

In answering the first sub question: *which energy transition scenarios are relevant for the distribution networks?* the centralized, ‘plug and play’ and ‘fit and co-produce’ scenarios have been identified. These three scenarios are relevant as they represent extreme DG developments. These developments mainly concern penetration level, organization level and size of the DG units. The consequences of these scenarios can be tested vis-à-vis regulation.

The second sub question is: *which technical consequences do the scenarios have on the distribution network?* The centralized scenario appears to limitedly influence the distribution network and is not analyzed in this thesis in further detail. However, the consequences of the two decentralized scenarios are significant. The possible solutions for DG-problems in the decentralized scenarios strongly focus on the smart-grid technology concept. In both ‘plug and play’ and ‘fit and co-produce’ scenario, the smart-grid concept is considered as an important means to come to the end of efficiently facilitating DG sources. However, it has become apparent that the smart grid is a promising technology, but far away from large scale deployment. Large investments are needed in further developing the smart-grid technology. A, by the DNOs justified, alternative for solving the DG-problems is conventional grid reinforcement.

To analyze which role regulation plays in the development of the solution technologies we have investigated how the smart grid can breakthrough and which role the regulatory framework plays in this breakthrough. To enable such an analysis, the smart-grid technology concept is defined in a ‘practical’ way. In this sense, the smart grid has been characterized by balancing on a distribution level. By making optimal use of the local DG-units the interconnection is to be used as little as possible (depending on the DG penetration level). The balancing on the distribution level should be conducted by storage, production control, and consumption control. Furthermore, the smart grid should maintain voltage quality and reliability, and make optimal use of ICT and new network technologies.

The stability of grid reinforcement being the conventional technological solution for DG-problems is accounted for by the meso-level in the MLP-framework. This stability can be considered a technological ‘lock-in’. When the smart-grid technology breaks through, it can compete with the locked in technology. How the socio-technical system will develop depends on the involvement of the actors (e.g. users, electricity network companies, technology suppliers, energy service companies and research institutions) and rules (e.g. direct and indirect regulation).

With the smart grid being defined and analyzed in the MLP-framework, the third sub-research question can be considered: *is the regulatory framework neutral vis-à-vis the technological solutions for the distribution network? And what could be changed if not?* In answering the last sub research question the following solution technologies will be analyzed:

smart grid (innovative technology) and grid reinforcement (conventional technology). In principle, the regulatory framework should be neutral versus these technologies. As with regards to the regulatory framework we have distinguished two types of regulation: direct and indirect. Direct regulation refers to the minimum standards applied on the distribution network. Indirect regulation has been defined as incentives given to the network companies. Based on these incentives the company makes a consideration between efficiency and quality.

In answering the third sub research question we conclude that the regulatory framework is not neutral vis-à-vis the two solution technologies. This conclusion is based on the assumption that the two main arguments described below are valid. These arguments indicate barriers in the regulatory framework for the smart-grid technology. Hence, assuming that there are no barriers for grid reinforcement, the regulatory framework is not neutral vis-à-vis the two solution technologies. However, we emphasize that the arguments are solely based on the interviews conducted in this thesis and an additional desk-study. Further research is recommended to validate these barriers.

The first main argument concerns possible barriers for the smart-grid technology in direct regulation. These barriers have been identified for every individual balancing technique. One barrier relates to every balancing technique: no explicit legal conditions to explore the technique. Production and demand control (consisting of production increase and production decrease) have additional barriers in decrease accessibility, no allowance of discrimination, and no direct relation between DNO and end-user. As regards storage, there is an additional barrier in DNOs being not entitled to incorporate in paying or selling electricity. Besides these barriers, there is uncertainty in the tasks and responsibilities the DNOs have in production control, consumption control and storage. Especially the tasks and responsibilities concerning storage are significant to determine. The possible barriers in direct regulation are based on a first analysis (desk-study) of the Electricity Act and the Netcode (2007). Further research is recommended to validate these barriers.

The second main argument refers to possible barriers in indirect regulation. These barriers have been identified from the two reasons ('landscape change' and 'strategic and competitive games') we selected for the smart-grid technology to break through. The first reason is 'landscape change', which refers to a broad political coalition convinced of the smart-grid's necessity. When the smart grid is not developed and deployed by the market itself, the coalition could decide for public intervention (e.g. support of innovation). Arguments for an intervention are: no natural market appetite, no short-term benefits for a DNO, and no commensurate reward for successfully manage the innovation process. Hence, a barrier from a landscape reason is that there is no public support for smart grids. The second reason is 'strategic and competitive games', which refers to obtaining competitive advantage vis-à-vis competitors. By further development and large scale deployment of smart grids, DNOs can achieve competitive advantage. In principle, this is a valued reason and no barriers exist in indirect regulation for a smart-grid's breakthrough. However, two arguments have been identified that oppose the statement of smart-grid technology being stimulated by competitive advantage. Based on these two arguments we conclude that there are barriers for the smart-grid technology in indirect regulation. The first argument concerns externalities for a DNO when implementing smart grids. In this case, the benefits of smart grids cannot be sufficiently internalized by the DNO to compensate the costs. The second argument refers to the two innovation issues in indirect regulation: the risk aversion of DNOs and the possible 'low'

reward of successfully managing the innovation process. As with regards to this ‘low’ rewards, it might not be sufficient in comparison to the risk involved.

Assuming that the regulatory framework contains barriers for the smart-grid technology, what could be changed? We argue that when the barriers are validated by further research the specific adjustments to regulatory framework can be determined. An indication of possible adjustments: legal conditions for the balancing techniques, allowance of specific discrimination, arrangements between DNO and end-user, clearly defined tasks and responsibilities for balancing techniques, socializing smart-grid costs, and innovation incentives.

## 8 Recommendation for further research

Chapters 3 and 4 describe respectively the three identified scenarios and the consequences of these scenarios on the distribution network. We recommend a more detailed analysis of the consequences for the different distribution networks. In this case, the thesis was focused on the overall consequences, without considering the regional differences in distribution network described in paragraph 2.3.3. In further research the regional differences (in net topology, connection density and DG penetration level) should be taken into account. Furthermore, investigating the DG’s connection costs in different distribution networks is recommended for further research. In this sense, the variable connection densities and grid topologies seem to influence the required investments. A smart grid may not be the most efficient solution in every distribution network.

An indication of barriers in direct regulation for the smart-grid deployment is described in paragraph 6.3. Only a first analysis of barriers in the Electricity Act and the Netcode (2007) has been made. Further research is recommended to validate these barriers for the following balancing techniques: production control, consumption control and storage.

In paragraph 6.4.2.1 we described that when the benefits of the smart grids might go to other parties, while the cost are accounted for by the DNO, it might reason public support. This reasoning could not be fully investigated in this research. A profound analysis of all cost and benefits of smart grids is considered to be necessary. In addition, the type of public support might be investigated, e.g. socialization of the costs or subsidizing innovation?

The last recommendation for further research refers to paragraph 6.4.2.2, describing the innovation process. By fostering the development and demonstration phase in the innovation process the smart-grid technologies could be made ready for large scale deployment. Further research is recommended to validate the two innovation issues for the distribution network sector. In addition, whether the UK’ incentives are effective and how the two incentives can be applied in the Dutch regulation system is recommended for further research.



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## Appendix I, voltage quality

Quality aspect	Criteria
Frequency	<p>50 Hz +/- 1% throughout 99,5% any year.</p> <p>50 Hz +4% / -6% throughout 100% of the time.</p>
Slow voltage variation	<p><b>Grids <math>U_n \leq 1\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>U_n</math> +/- 10% for 95% of the in 10 minutes average values during 1 week.</li> <li><math>U_n</math> +10% / -15% of all average values in 10 minutes.</li> </ul> <p><b>Grids <math>1\text{kV} &lt; U_c &lt; 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>U_c</math> +/- 10% for 95% of the in 10 minutes average values during 1 week.</li> <li><math>U_c</math> +10% / -15% of all average values in 10 minutes.</li> </ul> <p><b>Grids <math>U_c \geq 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>U_c</math> +/- 10% for 99,9% of the in 10 minutes average values during a 1 week consideration period.</li> </ul>
Fast voltage variation	<p><b>Grids <math>U_n \leq 1\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>\leq 10\% U_n</math></li> <li><math>\leq 3\% U_n</math> in situations without break-down production, large consumers or connections</li> <li><math>P_{LT} \leq 1</math> during 95% of the in 10 minutes average values during a 1 week consideration period.</li> <li><math>P_{LT} \leq 5</math> of all in 10 minutes average values during a 1 week consideration period</li> </ul> <p><b>Grids <math>1\text{kV} &lt; U_c &lt; 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>\leq 10\% U_c</math></li> <li><math>\leq 3\% U_c</math> in situations without break-down production, large consumers or connections</li> <li><math>P_{LT} \leq 1</math> during 95% of the in 10 minutes average values during a 1 week consideration period.</li> <li><math>P_{LT} \leq 5</math> of all in 10 minutes average values during a 1 week consideration period</li> </ul> <p><b>Grids <math>U_c \geq 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>10\% U_c</math></li> <li><math>3\% U_c</math> in situations without break-down production, large consumers or connections</li> <li><math>P_{LT} \leq 1</math> during 95% over the in 10 minutes average values during a 1 week consideration period.</li> <li><math>P_{LT} \leq 5</math> of all in 10 minutes average figures during a 1 week consideration period</li> </ul>
Asymmetry	<p><b>Grids <math>U_c &lt; 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li>The inverse component of the voltage lies between 0 and 2% of the normal component during 95% of the '10 minutes measurement periods' per week.</li> <li>The inverse component of the voltage lies between 0 and 3% of the normal component during all measurement periods.</li> </ul> <p><b>Grids <math>U_c \geq 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li>The inverse component of the voltage <math>\leq 1\%</math> of the normal component during 99,5% of the in 10 minutes average values during a consideration period of 1 week.</li> </ul>
Harmonics	<p><b>Grids <math>U_n &lt; 35\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li>The relative voltage per harmonic is smaller than in the norm mentioned percentage for 95% over the in 10 minutes average values. For harmonics not mentioned apply the smallest figures from the norm.</li> <li><math>T_{HD} \leq 8\%</math> for all harmonics un to and including the 40<sup>e</sup>, during 95% of the time.</li> <li>The relative voltage per harmonic is smaller then <math>1 \frac{1}{2} \times</math> in the norm mentioned percentage for 99.9% over the in 10 minutes average values.</li> <li><math>T_{HD} \leq 12\%</math> for all harmonics un to and including the 40<sup>e</sup>, during 99.9% of the time.</li> </ul> <p><b>Grids <math>35\text{kV} \leq U_c &lt; 110\text{kV}</math>:</b></p> <ul style="list-style-type: none"> <li><math>T_{HD} \leq 6\%</math> for all harmonics un to and including the 40<sup>e</sup>, during 95% over the in 10 minutes average values during a consideration period of 1 week.</li> </ul>

	<ul style="list-style-type: none"><li>• <math>T_{HD} \leq 7\%</math> for all harmonics up to and including the 40<sup>e</sup>, during 99.5% over the in 10 minutes average values during a consideration period of 1 week.</li></ul> <p><b>Grids <math>U_c \geq 110\text{kV}</math>:</b></p> <ul style="list-style-type: none"><li>• <math>T_{HD} \leq 5\%</math> for all harmonics up to and including the 40<sup>e</sup>, during 95% over the in 10 minutes average values during a consideration period of 1 week.</li><li>• <math>T_{HD} \leq 6\%</math> for all harmonics up to and including the 40<sup>e</sup>, during 99.5% over the in 10 minutes average values during a consideration period of 1 week.</li></ul>
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**Netcode (2007)**

## Appendix II, Voltage drop

The point of connection is relatively important for the voltage drop as can be seen in Figure 17. The line describing the large electricity extraction represents the voltage drop and, as one can see, the voltage drops as the distance between the source and the load increases. In general the longer the distance between the load point and the power source, the larger the voltage drops.

When DG units are connected to the distribution line, the voltage deviation could increase tremendously. Consider the situation where the user at the end of the line experiences the difference between large electricity injection and large electricity extraction. This represents the difference between only consumption (low voltage profile) and full DG feeding (high voltage profile). This difference in voltage is experienced by all user connected near that point in the distribution network.

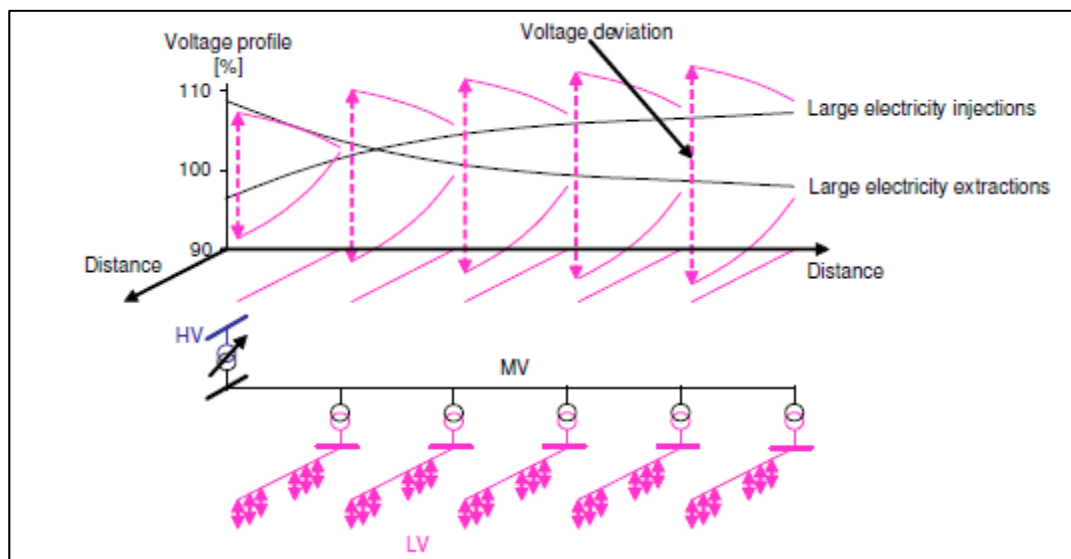


Figure 17, *voltage deviation*, Meeuwsen 2007



## Appendix III, Harmonics

The sine waves of the voltage and currents in a power circuit are frequently not pure. Despite the usual satisfactory waveform of the line voltage, the fundamental current waveform can be badly distorted. This distortion can be caused by: non-linear loads, magnetic saturation in the cores of transformers, switching actions of thyristors, PLC, and electronic ballast. Due to these harmonic currents the voltage distortion is indirectly generated (Wildi, 2006).

A harmonic distortion occurs in integer multiples of the fundamental frequency (50 Hz), which is by definition the lowest frequency. The other waves, such as the 2nd Harmonic with  $2 \times 60 = 120$  Hz and the 3rd Harmonic of 180 Hz, are called harmonics (Figure 18). The sum of a fundamental voltage and a harmonic voltage implies a non-sinusoidal waveform. The magnitude of the harmonics determines the degree of distortion. Logically a square wave could be composed of a fundamental wave and an infinite number of harmonics (Wildi, 2006).

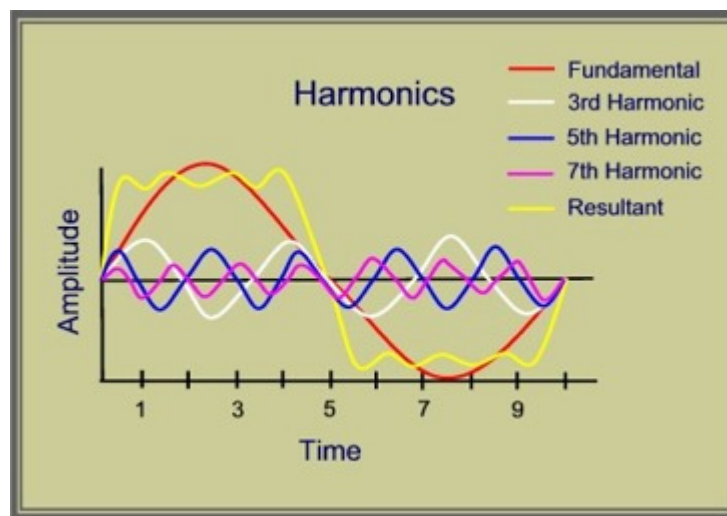
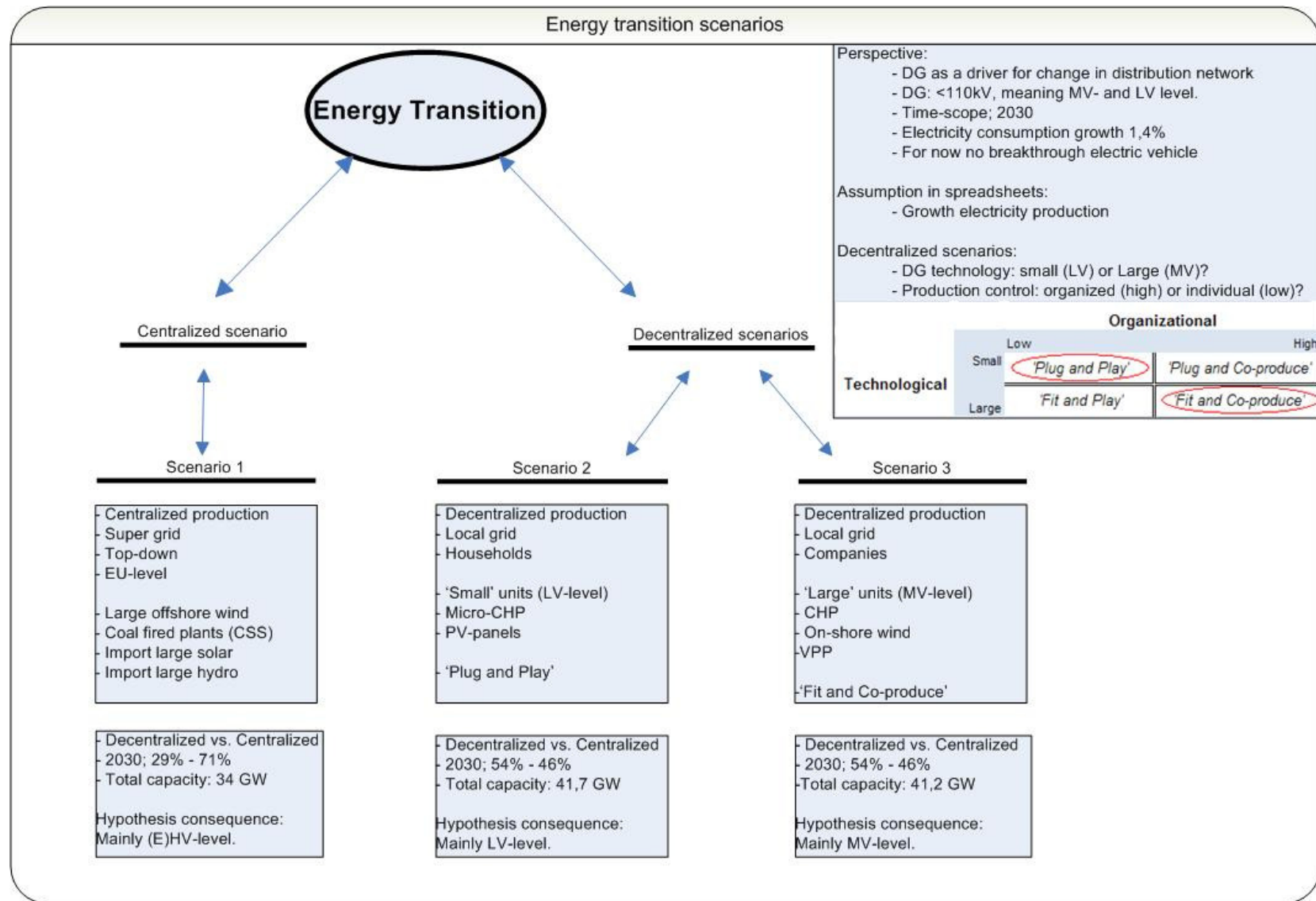


Figure 18, the fundamental sinus wave and the harmonics, derived on 29-07-2009 from <http://www.hersheyenergy.com/harmonics.html>

## Appendix IV, overview scenarios



## Appendix V, smart-indicator

The following smart-grid definition has been described in this thesis:

*“The ability to balance on a distribution level without using interconnection, but with storage, demand control and production control, and make optimal use of the connected DG capacity with maintaining voltage quality and reliability, and integrating ICT and new network technologies in the distribution system.”*

By using the DG units as efficient as possible the distribution networks should be as autonomous as possible. The key issue is to balance on a local scale and make less use of the interconnection with other voltage levels. The objective of this example is to put the smart indicator into practice.

Grid	A	B	
DG-capacity	7	9	KW
DG-supply	6	6	KWh
Demand	10	10	KWh
Interconnection	4	4	KWh

Two grids are under consideration in this example, both with the same demand at a random moment in time. The DG penetration level (capacity of combined DG-units, measured in KW) differs between the grids. The grids make limited use of the interconnection, but are not considered equally smart. Grid A makes smarter use of the available DG capacity than grid B.

Grid A can be smarter than Grid B by making use of balancing techniques as demand control, production control and storage. Storage is considered DG- supply and not DG-capacity. When a DG-unit charges a storage unit, it does not supply the grid.

This smart-indicator should give an idea of how a grid can be judged on its smartness. A further elaboration of the smart-indicator is recommended for further research.