The Economic Impact Model for Smart Distribution Grids



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The Economic Impact Model for Smart Distribution Grids

Master Thesis

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Executive Summary

Introduction

Over the next decades, a large-scale introduction of new energy technologies is expected, including renewable generation facilities (e.g. solar panels) and energy-efficiency systems (e.g. combined-heat power systems, electric vehicles). The distributed character of these technologies put new requirements on the power distribution grids. The grid must be capable of facilitating a bidirectional power flow, while supply and demand are less predictable. The concept of smart grids is seen as a promising way to support the future challenges of the grids. The DSO is designated stakeholder to take the lead in the smart grids development, since smart grids change the way the distribution grids will be operated and the main benefits of smart grids seem to affect the DSO. One major economic benefit of smart grids for the DSO is a higher utilization of the existing grid capacity, by load management. However, the complexity of smart grids, accompanied by the complexity of the distribution grids itself, makes it hard to make estimations on this benefit. An important complication is the high level of uncertainty surrounding the future distribution grid. It is for instance not clear how the energy system will develop over the years, and to what extent new technologies will be integrated.

This thesis attempts to give insight in the economic benefit of smart grids from the perspective of the DSO. The main research question is defined as: '*What is the economic value of smart power distribution grids from the perspective of the DSO, taking uncertainty in its future environment into account?*'. This research question is answered as follows. First, a system conceptualisation is made, which gives an overview of the problem situation of the DSO over the next three decades, and identifies the key aspects that are considered relevant. Second, the system conceptualisation is translated into a model that can be used for simulation. Third, the simulation experiments are done, and its results are observed and analysed. Finally, the conclusions and recommendations are defined based on the simulation results.

Medium Voltage Power Distribution System

The Medium Voltage Power Distribution System describes identifies the system boundary and its relation to the environment. It includes definition of the subsystems: the physical elements of the distribution grid. These are distinguished based on their function and technical character. The identified subsystems are high voltage stations, transport grid, distribution grid, and low voltage stations. The system goals is based on the DSOs objectives of economy and sustainability. The economic objective was defined as the minimization of total costs of the power distribution grid, including capex related to grid reinforcement, and opex related to energy loss. The DSOs objectives related to reliability and facilitation of a sustainable energy system, are treated as requirements. Four external influences are identified. Firstly, the energy-transition scenario describes what the energy system will look like, three decades from now. Secondly, the capacity demand development scenario describes how the capacity demand will develop over the years. Thirdly, the asset price scenario determines how the price of new assets will develop over the years, and fourthly, the electricity price scenario determines how the price of electricity will develop over the years. The DSO can affect the performance of the system by policies, which consist of strategies. Two strategies ate considered relevant: the smart grid strategy and the grid reinforcement strategy. The smart grid strategy defines if the DSO uses smart grids (or load management) to operate the grid. The grid reinforcement strategy defines the reinforcement approach of the DSO: either incremental or radical. This system conceptualisation gives insight in the scope of this research, and functions as the foundation for the Economic Impact Model for Smart Grids.

Economic Impact Model for Smart Grids

The Economic Impact Model for Smart Grids simulates how the system responds in different environmental scenarios under alternative policies. Its inputs are based on the external influences and policies, identified during system conceptualisation, and its outputs are based on the system goals. The model conceptualisation describes how the inputs lead to outputs, through a chain of causally related factors.

The model conceptualisation is based on the situation of one distribution grid asset, and can be described as follows.

Capital expenditures exist only if the asset is reinforced. If this the asset is reinforced, the capital expenditures are calculated for that year, based on the reinforcement type and the accompanying costs, both asset specific. The cost of the reinforcement type is influenced by the asset price scenario and the associated price increase in that year of reinforcement. The asset is reinforced if it is overloaded. An asset is considered overloaded if its load exceeds the load threshold. The load threshold is the maximal load of the asset without excessive reduction in lifetime and increasing risk of failure. The load is the quotient of the assets capacity demand and its nominal capacity. The capacity demand is related to the electricity demand during peak hours. The capacity demand of the asset is influenced by the energy-transition scenario and the capacity development scenario. The energy-transition scenario determines the capacity demand associated with the energy system 30 years from now. The capacity demand development scenario determines what the exact capacity demand is each year. The nominal capacity is the capacity of the asset as indicated by the manufacturer. If the asset is reinforced, its nominal capacity increases because it is replaced by an asset with a higher nominal capacity, or an asset is added to the configuration. The type of reinforcement and accompanying new nominal capacity is determined by the grid reinforcement strategy, either incremental or radical, which represent the realistic reinforcement options the asset engineer has.

Operational expenditures are caused by the assets annual energy loss and the electricity price in that year, determined by the electricity price scenario. The energy loss is depends on the asset specific energy loss character and its peak load.

Smart grids are expected to technically affect the power distribution grids in three ways. The first effect of smart grids is peak shaving. Peak shaving leads to a decrease of the capacity demand. Load management shifts non-time critical loads to off peak hours, which lowers the demand for peak capacity of the asset. The second effect is prolonged duration of peak loss. Energy loss is influenced by the height of the peak load and the duration of peak load. A more continuous load profile as a result of load management leads to a longer duration of the peak, and thus to higher energy loss. The third effect is the decreased load threshold. The load threshold is related to the heating character of power distribution. An asset can overloaded to a certain extend for a certain duration. The overload rate and the duration are based on stylized load profiles. However, load management changes the load profile. A more continuous load profile leads to a longer duration of peak load and thus lowers the load threshold.

A quantitative model was developed that is able to simulate multiple assets. The simulation activities are based on the conceptual model. The model uses data with asset information of five power distribution regions in the north and north-east of the Netherlands, including 50 high voltage stations, 2000 transport grids, 30.000 distribution grids, and 16.000 low voltage stations. The model was verified and validated by several tests.

Simulation results

Experiments of all environmental scenarios show that the total costs of operating the medium voltage power distribution grid over a time horizon of 30 years lay between €4.5 billion and €31.9 billion, with an average value of €13.5 billion. The net present value lies between €2.5 billion and €17.1 billion, with an average value of €6.9 billion. Based on this it can be concluded that future environmental scenarios have significant economic consequences for the DSO. Moreover, based on the wide range of values it can be stated that uncertainty in the DSOs future environment has a major impact on its economic objective. The source of uncertainty with the highest impact is the energy-transition scenario.

The radical grid reinforcement strategy is always more beneficial than an incremental one, since it decreases both capex and opex. The decrease in capex means that, apparently, the higher costs related to radical reinforcement are recovered by the additional nominal capacity it creates, leading to the postponement or even elimination of follow-up reinforcements. The decrease in opex can be declared by the fact that a radical grid reinforcement strategy leads to higher nominal capacity of the assets, thereby a lower peak load, and thus lower energy losses.

The impact of the smart grid strategy is less distinct, and differs in different energy-transition scenarios. A smart grid on strategy has a positive impact on the total costs in two out of three energy-transition scenarios. In order to understand why the impact of the smart grids on strategy on total costs differs in different energy-transition scenarios, a closer look is taken on capex and opex. The smart grids on strategy lead to capex savings in all three energy-transition scenarios. Purely based on capex, one would thus assume that the smart grid on strategy is always more beneficial. However, the smart grid on strategy leads to opex increases in all three energy-transition scenarios. This research identified three technical effects of smart grids on the power distribution grid.

In order to get a better understanding of the economic impact of smart grids, and why these differ in different energy-transition scenarios, the economic impacts of the isolated technical effects are analysed. Firstly, peak shaving leads in all energy-transition scenarios to significant total cost savings, as a result of both capex and opex savings. The capex savings can be explained by the decreased capacity demand as a result of load management, which leads to a lower need for reinforcements. Secondly, the increased duration of peak loss leads in all energy-transition scenarios to higher total costs. This impact is solely caused by opex increases, as this effect has no effect on capex. The increase of energy losses is explained by the fact that load management enables a more continuous load profile, which means that the duration of peak load is prolonged. Since the duration of peak load influences the energy loss, the energy losses are increased by smart grids. Thirdly, the decreased load threshold leads in all energy transition scenarios to a net increase of total costs. This impact is the result of a capex increase and an opex decrease. The capex increase can be explained by the fact that a decreased load threshold means that an asset is reinforced at a lower load, and thus earlier assuming that the load increases over the years as a result of the increasing capacity demand. The opex decrease can be explained by the fact that asset reinforcement coincides with a lower load as a result of a nominal capacity upgrade. More reinforcements lead to lower loads, and thus lower energy losses.

Based on these insights, it can be declared why smart grids are not always economically beneficial form the perspective of the DSO. The positive economic impact of smart grids on the total costs is mainly caused by peak shaving, and its capex saving characteristic. However, this impact is leveraged by negative economic impacts resulting from increased opex due to the prolonged duration of peak loss, and increased capex due to a lower load threshold. If the negative economic impact exceed the positive

impact, smart grids are not economically beneficial, which was the case in one of the three energy-transition scenarios.

Conclusions

The main conclusion is that the benefit of peak shaving effect of smart grids cannot be translated one-on-one into economic value for the DSO. This research shows that under the assumption that the future environment of the power distribution grid is uncertain, the economic benefit of smart power distribution grids is not guaranteed. The reason is that the positive impact of peak shaving is leveraged by the increased energy loss, and accompanying opex. The higher opex are the result of assumptions on the technical effect of 'smart load profiles' on the power distribution grid. In the situation that the opex increase transcends capex savings, a the situation exists in which smart grids do not create a net economic benefit for the DSO. However, the in the situation that peak shaving is possible, the economic benefit of the DSO in terms of capex savings should not be underestimated.

An essential consideration of the DSO is if it should fully deploy smart grids, thereby lowering its capex, but increasing its opex. Or if it should fully reinforce its grids, thereby increasing its capex, but lowering its opex. Since the optimal policy is expected to lay somewhere in between, a logical next step would be to investigate where this optimum lies, so that the DSO can make well-argued trade-offs when designing the distribution grid of the future.

Recommendations

The first policy recommendation for the DSO is to consider a more radical grid reinforcement strategy. The second policy recommendation is to consider what their main driver behind smart grids is. If their main driver is economic benefit, this research can function as a starting point for advanced knowledge on the economic potential of smart grids. In order to improve its knowledge, it should further investigate the main sources of uncertainty that were identified in this research (and translated into suggestions for further research). By all means, the DSO should closely monitor the aspects related to the future energy system.

The recommendations for further research include validations of the assumptions that were made in this research and had a major impact on the economic potential of smart grids. The first suggestion concerns further research on the potential of peak shaving. Also, it is suggested to do more research on what the technical effect of a 'smart' demand profile is on the load profile of the power distribution grid assets. Furthermore, the knowledge on energy losses must be improved. Finally, it is important to investigate the impact of smart grids on the maintenance of the power distribution grids, which was beyond the scope of this research.

Finally, suggestions of further research for new insights are presented. Further insight is needed in the trade-off of load management and grid reinforcement. Also, estimations on the economic benefits of day-to-day operation of the power distribution grid are needed. Furthermore, it is important to investigate the economic impact of smart grids on the low voltage level of the power distribution grids. Finally, a study that integrates the costs and benefits of smart grids from multiple dimensions is needed to support decision makers on the road towards a more sustainable energy system.

Preface

Inspired by Marija Illic, I was looking for a thesis project related to smart grids in the summer of 2010. I was happy to receive an enthusiastic call from Remco Verzijlbergh, PhD candidate, on the opportunity of a research project in collaboration with Enexis, a large Dutch DSO. This thesis is the result of the research project, that started in October 2010.

Looking back, this research was an interesting journey in many dimensions. It was challenging to really understand the concept of smart grids, and moreover, to get comfortable with the power distribution grid and its electro-technical character. It was fun, and very interesting, to work closely with the colleagues of Enexis. This is where smart grids are put in practice!

The research would not have been possible without some people, who I would like to thank in special. Else Veldman, my supervisor at Enexis, who has safeguarded the substance of my work very carefully, and was always a very pleasant person to work with. Marinus Grond, my co-graduate-intern at Enexis and my 'electrical-engineering oracle', who was always open to answer my strange questions. Remco Verzijlbergh, who repeatedly energized me with his enthusiasm on smart grids, and gave me new directions of thought. Paulien Herder, my professor, whose straightforward approach gave a clear direction during rocky periods. Pieter Bots, who improved my research approach fundamentally every time we spent time. And last but not least – Zofia Lukszo, my first supervisor, who continuously believed in my potential, which deeply supported me.

Furthermore, I want to thank Han Slootweg, for giving me the opportunity to do this research project, and moreover, for his inspirational and sharp approach on smart grids.

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Mei Ling Tan

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM EXPLORATION

Over the past decade, energy issues have become more clear. One of the energy issues is our large-scale consumption of fossil fuels (i.e. coal, oil, natural gas), leading to depletion of their natural sources. The high dependence on fossil fuels leads to global power shifts, as most fossil fuels are located in political unstable areas. Emissions of fossil fuel processing leading to air pollution, exploration of fossil fuels is moreover done under dangerous labour conditions. Another important energy issue is climate change, the assumed reason behind increasingly dry areas around the equator, raising water levels and the high frequency of hurricanes. These issues have led to the idea that our current energy system needs a fundamental change.

A large part of energy is consumed in the form of electrical power. Currently, large-scale power plants generate power that is transported to the end-user by the electrical power grid. The grid can thus be seen as the essential linking between supply and demand. The electrical power system in its current form was introduced in the early 20th century. From this moment, generous investments have led to high coverage and high reliability infrastructures in most of Northwest Europe [1]. The current power system is thus the heritage of historic design choices over the past century. The system distinguishes a transmission system and distribution system. The transmissions system transports large amounts of electrical power from large-scale generation over long distances, and is managed by the transmission system operator (TSO). The distribution system receives power at transmission substations and delivers it to consumers. It is managed by the distribution system operator (DSO).

The liberalisation activities in the Netherlands led to separation of monopolistic (transport) and commercial activities (generation and supply)[1]. The role of the grid operators is therefore strictly limited to market facilitation by physically link producers to consumers, in an affordable and reliable way. It also means that every consumer and producer should be given unlimited access to the grid, within the given capacity limits. The distribution grid was historically designed to meet peak demand, using grid planning. The method uses historic demand data to make predictions on the future. The predictions include statements on how much when and where the grid capacity is needed, and in what way the need can be satisfied. The idea of dimensioning the infrastructure for peak conditions is the reason that the grids experienced overcapacity for many years. Together with the long lifetime of assets, this led to very little scientific breakthroughs and technological innovation in the field of power infrastructures.

There are some important developments affecting the distribution grid and the way the DSO operates today. One of them is aging assets, as the majority of the assets date back from the period 1960-2000, with a peak in the 1970s [1]. This means that the average age of an asset lays between 20 and 40 years. As the lifetime duration of a grid components is on average 30-40 years, the DSO is expected deal with high amount of replacement series over the next decade if it wants to retain its current reliability level. This may lead to an increased need for capital investments. At the same time, the DSO experiences the pressure of reliability and affordability. However, the ageing grids also increase the sense of urgency and create opportunities to consider new ways to operate the grids.

Another development affecting the distribution grid is energy-transition, the area of initiatives that support a more sustainable energy system: increasing the consumption of renewably generated energy,

[1] EU Directive 2003/54/EC

increasing efficiency of the overall energy system and lowering energy consumption. One of the key conditions for a sustainable energy system is the utilisation of renewable energy sources (as opposed to depleting natural sources). Technical breakthroughs in solar-, wind-, and hydropower systems enable more and more efficient ways to generate electrical power from natural resources. A higher share of renewables inevitably increases the role of electricity in our energy system, as renewable energy is directly converted into electricity. Renewable energy systems are by nature more suitable for small scale generation (i.e. residential), which means that the distribution grid will experience the intermittent nature or the natural sources. The second condition is increasing energy efficiency. Important developments that affects the grid is the increasing share of combined heat power systems (CHP) and electrification of heating and mobility. CHP systems enable consumers to generate electricity during heat generation from natural gas. Electrification of heating exists in the form of electrical power driven heat pumps. The introduction of electric vehicles is the energy efficiency response to mobility, as their well-to-wheel efficiency is higher than fuel driven cars. Although many initiatives consist with regard to the third condition (energy consumption reduction), the energy consumption is still increasing. Overall it can be concluded that in order to facilitate energy-transition, the distribution power grid must be capable of facilitating a bidirectional power flow, while supply and demand are less predictable.

The concept of *smart grids* is seen as a promising way to support the identified challenges of the power distribution grids. A definition is by the European Technology Platform [2] is: "Smart Grid is an electricity network that can intelligently integrate the behaviour and actions of all users connected to it – generators, consumers, and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety".

Although this definition is covering many principles of the smart grids, its general approach raises many questions. There is an high amount of definitions and ideas on smart grids, which makes the use of this term sometimes ambiguous. The main parallel between the different definitions is the use of information and communication technology (ICT) to enlarge the capability of the power grid. Potential benefits mentioned are facilitation of the bidirectional power flow, reduction of capital expenditures, reliability improvement, and a higher degree of involvement of the energy stakeholders, including consumers [3]. In terms of sustainability, smart grids will be able to facilitate the mass integration of small-scale energy generation from renewable resources, without the need for excessive grid reinforcement investments. From the perspective of the DSO, smart grids enable more active network management and load management. Active network management is possible by real-time information on the network status, and remote control of grid component. Furthermore, the ICT infrastructure supports real-time communication with producers, consumers and those that do both. This means that load, or demand, can be controlled. The electrification of heating and mobility increases opportunities for demand control, since these applications are less time critical (e.g. a car can be charged during off peak hours and a house can be heated during off peak hours)[4].

It is not surprising that designing and implementing such a technology that radically changes the way the system is operated today is extremely complex and has implications in many dimensions. Technology related challenges include the ICT infrastructure and its integration with physical systems of measurement, decision-making and control. Also, issues related to privacy as a results of the large scale data generation need to be solved. Moreover, smart grids are challenging from an institutional and organisational perspective, as it involves by definition the contributions of multiple stakeholders. The wide range of smart grid opportunities makes the decision-making even more difficult, as different stakeholders have different interests and desire different smart grid applications. Also, the infrastructural character of smart grids results in the fact that costs and benefits are indistinct, and often unevenly spread distributed amongst stakeholders. Therefore, a crucial question is who pays for and who benefits from smart grids.

1.2 PROBLEM DEFINITION

The DSO is designated stakeholder to take the lead in the smart grid concept development, since smart grids change the way the distribution grid will be operated. Furthermore, the main benefits of smart grids seem to affect the DSO. A thorough understanding of the costs and benefits is essential to take deliberate investment decisions. However, the complexity of the smart grid concept, accompanied by the complexity of the power distribution system itself, makes it hard to specify the benefits and costs.

Much is expected from one specific aspect of smart grids: the concept of demand control. In this concept, the DSO is able to control demand with the goal to structurally lower the need for distribution grid capacity. This is possible by shifting non-time critical loads from peak hours to off peak hours, lowering the need for capacity during peak hours by using more capacity during off peak hours. Lowering peak capacity leads to postponement or elimination of costly grid upgrades. This is expected to cause a significant economic benefit for the DSO.

Although this concept is very promising in theory, the DSO is left with some urging questions. What is the magnitude of the economic benefit? Does operating the grid closer and more continuously to its maximal capacity only lead to economic benefits? Or does it also coincide with additional costs? What are the main factors that determine this economic benefit? And to what extent depends the DSO on its environment? This research has the ambition to understand the economic impact of smart power distribution grids for the DSO. The next section describes the research objectives and questions.

1.3 RESEARCH OBJECTIVES AND QUESTIONS

This research has the objective to get insight in the economic impact of smart distribution grids, from the perspective of the DSO. However, this impact can only be analysed using forecasts on the future situation. Therefore, an understanding of the future environment of the DSO is needed. Then, the impact of future alternative policies (such as smartening the grid) can be analysed. Based on these analyses it can be concluded which policy is most beneficial in which environmental scenario.

To sum up, the research objectives are defined as:

- to understand how future environmental scenarios economically impact the DSO
- to understand how future policies – including smart grids - can lower the costs of the power distribution system, thereby creating an economic benefits for the DSO
- to make estimations of the economic impact of different environmental scenarios under alternative future policies by simulation

The research objectives will be achieved by answering research questions. The main research question is defined as:

'What is the economic impact of smart power distribution grids from the perspective of the DSO, taking uncertainty in its future environment into account?'

The following sub questions are formulated:

- *What are the economic consequences of future external influences on the power distribution system?*
- *What is the impact of alternative policies –including smart grids - on the total costs of the power distribution grid?*
- *Which future policies should the DSO implement in which future environmental scenarios?*

- *What are the most important sources of uncertainty related to the economic impact of smart grids from the perspective of the DSO?*

The answers to these questions are given in the Conclusion chapter.

1.4 RESEARCH APPROACH AND METHOD

This research takes a technical-economical approach, which means that it observes and analyses the economic consequences of technical aspects of the power distribution system. It observes a time horizon of 30 years. Reason is that most energy-transition related activities are expected to occur within this time horizon. Also, the power distribution grid assets lifetime is about 20-40 years. The research furthermore observes the Dutch power distribution grids, and limits itself to the medium voltage grid.

This research develops a method to determine the economic impact of smart power distribution grids. This method takes uncertainty, as perceived by the DSO, into account. The method can be described as a model-based decision support method, because it attempts to support decision making by the DSO, and uses a model to be able to get insight in the situation of the DSO. The first step of the method is the development of a conceptual framework for systematic treatment of uncertainty: the system diagram. This is conceptualisation of the system of interest of the DSO, and defines the boundaries of the system and its structure (i.e., the elements and relationships among these elements). The second step of the method is model development, based on the system conceptualisation. The focus of the modelling exercise is on the response of the system to outside forces (external influence changes or policy changes). Model development includes model conceptualisation (using a causal relation diagram) and translating the conceptualisation into a computer based model (MS Excel). After verification and validation of the model, the last step is of the method is to use the model for simulation. Experimentations with different model settings enables insight of the economic impact of smart power distribution grids [5].

This research includes the following research activities.

Literature study and desk research at the DSO were done to get an understanding of the power distribution system and the potential of smart grids. Literature study involved an evaluation of scientific articles, policy documents and position papers. The desk research at the DSO included evaluation of documents such as grid planning directives and economic statements, and interviews with distribution grid experts such as grid designers and business analysts.

A conceptualisation of the problem is made, using a *systems diagram*. The systems diagram is a representation of the system that is observed, its inputs (policies and external influences) and outputs (system goals). Furthermore, it shows the distinguished subsystems. In this research step the key aspects are identified and defined, giving a clear overview of the scope of the research.

The system conceptualisation is the foundation for model conceptualisation. A specification of the model is made, using a *causal relation diagram*. This diagram shows how inputs lead to outputs, through a chain of causal relations. The model conceptualisation is used to develop a quantitative model in MS Excel, that can simulate system behaviour: the Economic Impact Model for Smart Grids. The input data of this model origins from parallel research performed at the DSO.

The model is continuously verified and validated during model development, and further verified and validates based on dimension analyses, extreme values analyses and evaluation by experts. The verified and validated model is used for simulation. The design of experiments describes which experiments are planned to contribute to the research objectives. These experiments are done, using the model, and next analysed extensively. The results of the analysis lead to conclusions and recommendation.

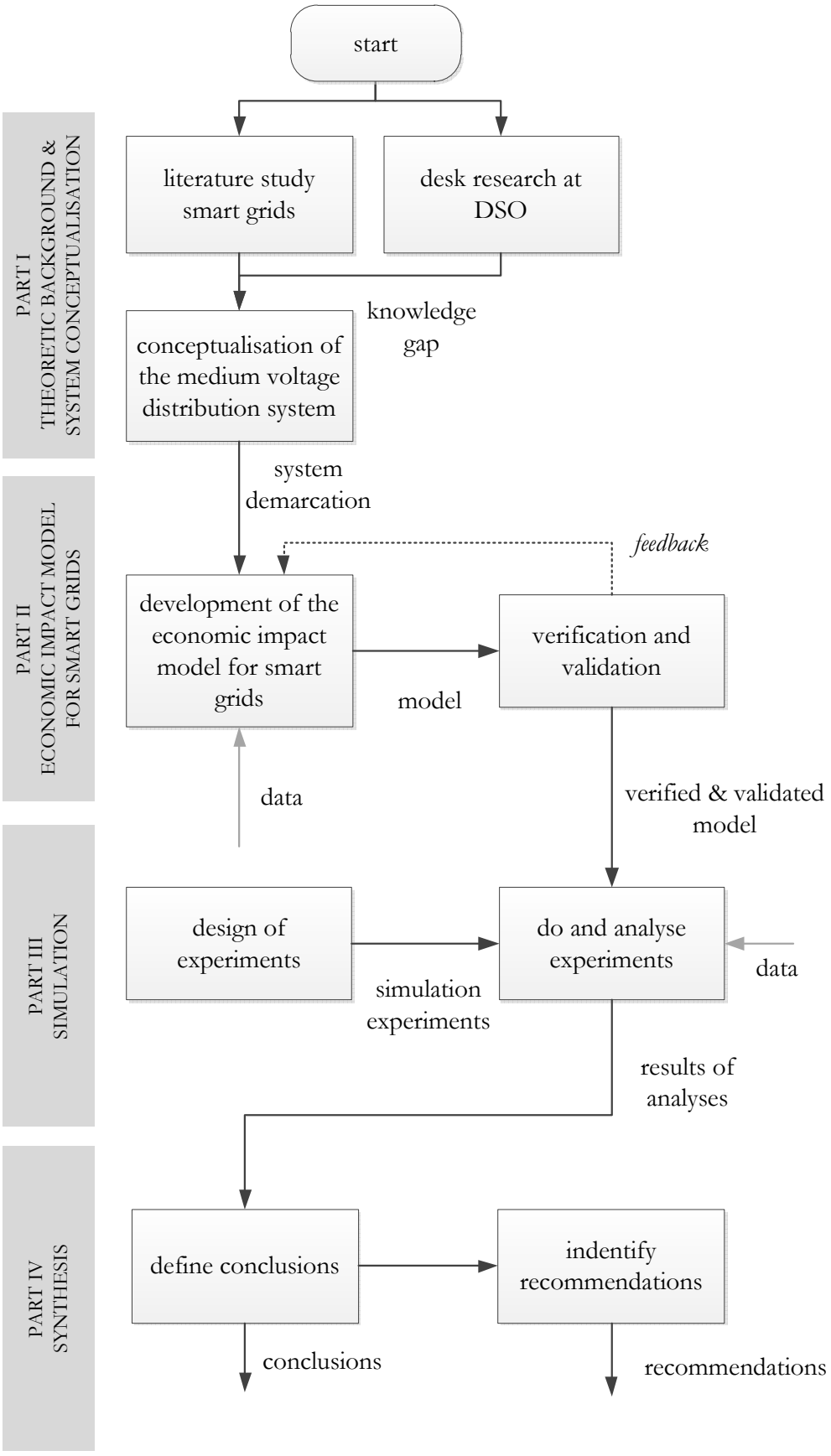


FIGURE 1 RESEARCH APPROACH

1.5 THESIS OUTLINE

This thesis consists of four parts.

Part I includes background information on smart grids, and a conceptualisation of the system of interest. Chapter 2 presents the background information on smart grids, based on literature review and desk research at the DSO. Chapter 3 introduces the Medium Voltage Power Distribution System, which is the definition of the system of interest. During this part of the thesis the research scope is defined.

Part II introduces the Economic Impact Model for Smart Grids. Chapter 4 presents the model conceptualisation, using a causal relation diagram. Chapter 5 describes the model, by definition of its structure, verification and validation. The results of this part of the thesis is a verified and validated model, that can be used for simulation.

Part III includes the results of simulation using the Economic Impact Model for Smart Grids. Chapter 6 presents the results and analysis of experiments. Chapter 7 presents the results of further exploration of the impact of smart grids. The result of this part is insight in system behaviour, in specific its response to smart grids.

Part IV comprises synthesis based on the research efforts. Chapter 8 presents the conclusions by definition of answers to the research question. Chapter 9 includes recommendations, including policy recommendations for the DSO and suggestions for further research.

PART I BACKGROUND INFORMATION & SYSTEM CONCEPTUALISATION

CHAPTER 2 SMART GRIDS

2.1 GENERAL APPROACHES

As is true for any truly transformative technology, smart grids are widely debated. Analysis of different definitions shows that the key similarity amongst different definitions is the application of information and communication technology (ICT) to power grids on a large scale [3]. This also resonates in a definition by McDonald, who talks about the set of *advanced digitally based technologies* that can be attached at the boundary of generation and transmission, and all the way through the grid across the meter and into the home [6]. Though most definitions include the essential contribution of multiple stakeholders the grid owners and in particular the DSO, are at the centre of the debate [2].

In order to avoid misunderstanding, it is important to differentiate between smart grid concepts and approaches. Literature mentions three different concepts: the grid oriented concept, the market oriented concept, and the system oriented concept [3]. This is important because each concept serves different goals, affects different stakeholders in different ways and requires different technological solutions. The grid oriented concept only concerns the grid operator. Goals of smart grids are reducing investments in grid reinforcement, optimizing lifetime and failure risk of grid components, and supporting outage restoration.

The goals of smart grids can be captured by economic and technical efficiency, increased sustainability, improved reliability of supply and increased customer services . These cover the smart grids values mentioned in literature, though often differently formulated. The Electric Power Research Institute identifies four comparable fundamental categories of benefits: economic, reliability environmental, and security and safety [7]. Most authors mention smart grids as the best response to an affordable, reliable and sustainable future energy system. To this regard, Veldman introduces smart grids as the feasible solution to continue reliably delivering electricity and to facilitate the integration of distributed generation without excessive investments [1]. Other researchers also refer to smart grids as the most cost-effective alternative to heavy investments due to grid upgrades [8]. Others propose that it is fundamentally impossible to meet the energy and environmental objectives set by the society without transforming smartening the current grid operation. They introduce smart grids as the enabler of just-in-context (JIC), just-in-time (JIT) and just-in-place (JIP) actions [9]. This research takes a closer look at the principle of load flexibility. The basic idea is that the operation of the distribution grids can be optimized, and maximal utilization of al resources connected to them can be achieved. Some researchers go even further and move from smart grids to a 'wireless grid'. In their perspective, the current energy system with transport of power is inefficient, expensive and unnecessary. They envision an energy system without central generation units, and without transmission and distribution grids. Distributed generation and load balancing will make power distribution unnecessary [10].

In relation to the above context, this research assumes that smart grids is enabled by ICT, though it does not take any observations of this ICT system into account. Also, this research takes a grid oriented approach, looking at the value of smart grids from the perspective of the DSO. Though smart grids potentially coincide with a wide range of benefits, this research is furthermore in search for the economic benefits.

2.2 LOCAL DEVELOPMENTS

Figure 2 shows the drivers for smart grids in different global areas. The introduction of renewable energy systems and aging assets are the most important drivers for European smart grids, while losses reduction and reliability improvement are the main drivers in South America. The diversity of drivers means that the

effectiveness of smart grids is location specific. It is therefore important to determine the local value of smart grids [11]. The local grid situation, is often caused by historic grid design choices [1]. In order to estimate the value of smart grids, it becomes thus important to look at the local situation of the power grid. This means not only at a continental level, but also at a national level, or even regional level. Smartening the grid is complicated due to the huge diversity of installed assets in the Netherlands only [12].

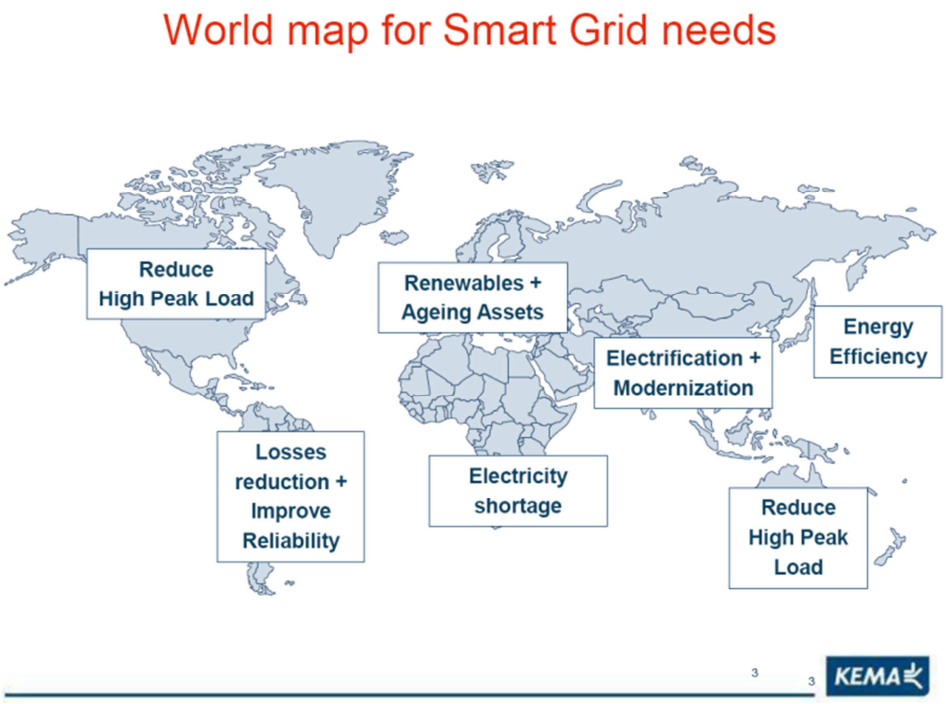


FIGURE 2 WORLD MAP FOR SMART GRIDS NEEDS [13]

Distribution grids across Europe also exhibit considerable difference in design. However, the fundamental architecture of the grids has much in common since they were often constructed at the same time. Since aging assets is a typical challenge faced by the grid operators, the European Union puts heavy emphasis on the development of a European Smart grid. The European Technology Platform Smart Grids sees smart grids as an innovative response to ensure cost-effective investment. As very significant investments are required over the next decades, now is the time to incorporate new solutions when planning asset renewal [2]. Though much is expected of smart grids, they are not expected to totally eliminate the investments needed in the European power infrastructure. It is forecasted that an additional €390 billion is needed over the next three decades, about €90 billion in transmission and €300 billion in distribution grids [14]. The World Energy Outlook made the same estimation resulting in an investment size of €144 billion for transmission, and €436 in 2050 [15].

One of the major research tasks stated by the European Union is to get more insight in power grid investment planning, thereby assessing and quantifying the generic business case for smart grids. There is a lack of knowledge on how to respond to multiple drivers and environmental uncertainties that will affect investment choices in the future. The aim is to support decision making by offering solutions for addressing multiple (and sometime concurrent) smart grids drivers. The defined targets that must be weighted are costs, the degree to which sustainability is facilitated and reliability. They furthermore mention the need for new tools to evaluate risk and social-economic based asset management [2].

The vision of the Dutch Taskforce Intelligent Grids is that the introduction of smart grids is not urgent, though inescapable [16]. They have estimated the costs of a Dutch smart grid system on roughly €6 billion. The societal benefits due to lower consumer energy bills are estimated on €10 billion in 20 years. This does not include the potential benefits of deferred and eliminated grid investments. They assume that 10% more efficient grids will lead to €4.2 billion savings. Overall, based on early assumptions and taking into account uncovered benefits, the taskforce expects larger benefits than costs for a Dutch smart grid. It is stated that investments in smart grids may be more beneficial for society than investments in grid reinforcements. The taskforce explicitly states the difficulty in adequately calculating the costs and benefits, though well-founded estimations on the costs and benefits are needed to get insight in the business case of smart grids [16].

In relation to the above context, this research takes a closer look at the Dutch power distribution grids. Insights of this research have the potential to be translated to other North-western distribution grids, carefully taking local circumstances into consideration. Location specific analysis is the only way to estimate the actual benefit closer to reality. Though rough estimations on grid related investments are made by European and Dutch governments, there exists a lack of more detailed understanding of future investments and the potential of smart grids accordingly.

2.3 Economic benefit for the DSO

The Dutch DSO is increasingly experiencing political and public expectations, leading to a pressure on reliable and affordable distribution. The regulator (in the Netherlands Energiekamer) limits the DSO's revenues through a fixed tariff structure and conditions (codes), and regulates the level of reliability by penalties for excessive disruptions [17]. Consequently, it becomes important to justify any expenditure by showing that it either prevents a larger expenditure in the future, or that it is an efficient way of serving the goals of the DSO. At some point in time, if reliability is seriously threatened, investments in grid reinforcement are inevitable. It is worthwhile to postpone such investments as long as possible by optimally utilizing the capacity of the existing grid for two reasons. First, this leads to NPV (NPV) savings, as an investment in the future is less valuable than an investment today. Second, additional knowledge arises over time, which could lead to more economic efficient grid design [18].

The previous sections mentioned that smart grids can improve the cost-effectiveness of future distribution grids. This section describes how the DSO can benefit from smart grids based on concepts in literature.

An important benefit for the DSO mentioned are reduced investments costs in terms of deferred or mitigated capital investments [6]. Avoided capital spending is also the main benefits for the DSO mentioned by McKinsey [19].

Currently, the distribution grids are dimensioned using historic data about customer peak demand and assuming an autonomous increase on of that over the years. Grids experience typically prominent peaks on a daily and on a seasonal basis [20]. For the Netherlands, this peak is expected in winter due to an increased use of electric applications. The US grid on the other hand experiences most peak during summer due to air conditioning. Future energy technologies are expected to influence this demand significantly. Distributed generation (such as solar panels or combined heat power systems) will decrease demand, while electric vehicles and heat pumps will significantly increase demand [20]. The intermittent and often unpredictable nature of this influence, complicates demand forecasting and grid planning.

The DSO currently uses a method for grid planning that is based on peak demand. This means that the distribution grids are dimensioned to facilitate peak demand. This results in the fact that the ratio between the used and available grid capacity has been relatively low. This means that there is an opportunity to

transport more electricity with the same grid capacity, if it is transported outside peak times. Research shows that there is indeed a great potential for transporting extra energy with the existing Dutch power distribution grids [4]. One basic application of smart grids is that they are used to enable more electricity transport with the same grid capacity. ICT technology thus enables a higher utilization of the existing grids by active network management [21], making use of real-time information, decision, and controls of load flexibility, smart storage, and online switchable grid components.

The ICT technology is applied to enable load flexibility, this concept is often called Demand Side Management (DSM) or Demand Control (DC). There are different suggestions how ICT architectures can support DSM (by e.g. [22]. An essential element of these architectures is the smart meter [3]. This meter can digitalize the information on the generators and loads connected to the distribution grid. This digital information can be used for all kinds of applications. One of them is that the DSO can get insight in the utilization of the distribution grids. Based on this insight, in can control of the connected generators and loads, to optimise the power flow across the distribution grid and better utilize their assets [23]. Control is in this respect interpreted as the voluntary response of consumers, by changing their energy consumption behaviour according to the electricity price, transport price or other incentives [24]. This does not necessarily mean that the consumer has to give up on its comfort of using electrical appliances. Innovative energy management systems (connected to the smart meter) support DSM on a voluntary basis, without negative effect on the comfort experiences of the customer. However, the increased information provision potentially lowers the overall power consumption, since consumers are more aware of their behaviour. Broadly defined, these systems could use technology (such as in-home displays), education (raising customer awareness), and dynamic tariffs to manage demand [19]. Research shows which consumer electronics products will be an integral part of smart grids, and the features required order to manage them [8].

The DSO can benefit from DSM by shifting demand from capacity utilization peak time to off-peak times. The demand that can be shifted is sometimes referred to as 'non time critical load' [4]. The DSO is thus able to get contact with consumers, and persuades them to shift some peak-time consumption by waiting to run power-intensive appliances. Interesting power-intensive appliances are washing machines (sometimes referred to as smart washing) and, years to come, electric vehicle charging (smart charging). This mechanisms lowers the peak demand, and is therefore often referred to as peak shaving.

Peak shaving is expected to lower the need of capacity during peak time, and thus to a lower grid capacity need. This means that the DSO's investments of grid reinforcement can be deferred or even eliminated. Another benefit for the DSO is that energy losses due to power transport are expected to be reduced. However, Söder mentions that a higher utilization of the existing grid does not necessarily to coincides with lower losses [25]. He reasons that a high utilization of the existing grid leads to more energy losses compared to a grid that is heavily upgraded. However, from a system-wide perspective, it is arguable that smart grids do lower energy losses since they enable distributed generation (closer to its consumption) and thereby reduce the need for transport from central generation to consumption.

The concept of smart grids means that reliability gets another dimension. Ensuring the reliability as today may no longer be required. Instead the system may be maintained within technical acceptable limits though flexibility of all resources connected to the grid. This means that different reliability contracts can exist with different customer segments, and that reliability retains market value. Some researches introduce a new role of future load serving entities, such as energy companies [9]. The entities can offer a new type of energy product including a reliability level of supply. This principle of customer segmentation in coherence with the preferred reliability level enables effective incentives for peak shaving.

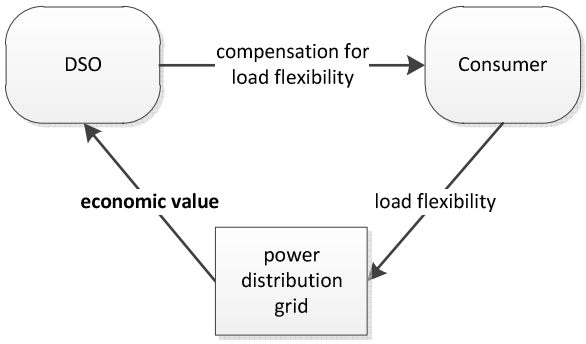


FIGURE 3 THE ECONOMIC VALUE OF SMART GRIDS IN RELATION TO THE CONSUMER

An important condition for the functioning of DSM is the establishment of a good tariff structure. Smart pricing is the principle of offering different energy tariffs to the consumer based on the day and the moment on the day that energy is offered. Literature distinguished multiple pricing options, including real time pricing (RTP), critical peak pricing (CPP), and flexibility reward [23, 26-28]. Within the grid oriented approach, smart pricing should reflect the availability of distribution grid capacity (not to be confused with the electricity market price). The value of load flexibility can thus be passed to the consumer by lowering the distribution tariff (which is currently a fixed rate in the Netherlands). However, the smart pricing options can only be evaluated if there is insight in the economic value of smart grids resulting from load flexibility. One difficulty of determining the economic value is the earlier described local character of distribution grid capacity. This means that in some regional areas there is more available capacity then in other, leading to price discrimination according to the location of the consumer. The question is if this is acceptable. If it is chosen to socialize the benefits over all grid users, the participation incentive is lowered [29].

In relation to the described context, this research evaluates the economic value of smart grids, more in specific load management, for the DSO. This can contribute to the determination of an appropriate tariff structure, since it gives insight in what the size of the expenditure savings is and thus what the compensation for load flexibility should be (Figure 3). The feasibility of load management itself is beyond the scope of this research.

2.4 PREVIOUSLY PERFORMED BENEFIT ANALYSES

Though the previous described economic benefit for the DSO is promising, smart grids only make sense if the cost of such a system are modest compared to the cost of the traditional approach: grid reinforcement [8]. Economists question the economic feasibility of smart grid and are seeking for further assessment of the value of smart grids [30]. Söder emphasizes that smart grids are in principle not needed. They will not change the physical principle of power transport over copper and iron. He mentions that we should only invest in smart grids if it creates a net benefit, otherwise not [25]. To this regard, the European Technology Platform Smart Grids also states that the implementation of smart grids should not overall lead to increased cost for consumers. Therefore, mechanisms need to be put in place to ensure that financial benefits are ensured, and passed on to consumers [2]. The previous section shortly introduced the concept of passing the benefits through a dynamic capacity tariff. A significant challenge however exists to assess the value of smart grids in comparison to traditional approaches [21].

The infrastructural character of smart grids complicates the estimation of costs and benefits. To this respect, the Dutch Taskforce Intelligent Grids talks about 'asymmetric distribution of costs and benefits'. This means that the stakeholder that makes the investments, cannot capture all value created. They mention that even if a societal business case exists, its realization is not guaranteed by the uneven

distribution of incentives [16]. The principle of asymmetric distribution of costs and benefits is also explained by Figure 4 [15]. A crucial question is how much value will be captured, and by whom [19].

Central question are how real, and how big the value of smart grids is, by who it is captured, and how the value can be passed to the consumer. This research has the ambition to give more insight in how big the value of smart grids its, purely from the perspective if the DSO. Smart grids is interpreted as an enabler of demand control, with the objective to maximize utilization of the existing power distribution grid. The value is defined as cost savings as result of deferred or eliminated grid reinforcements. The question how this value can be passed to the consumer is beyond the scope of this research, though the results of this research can be used as a starting point for this question.

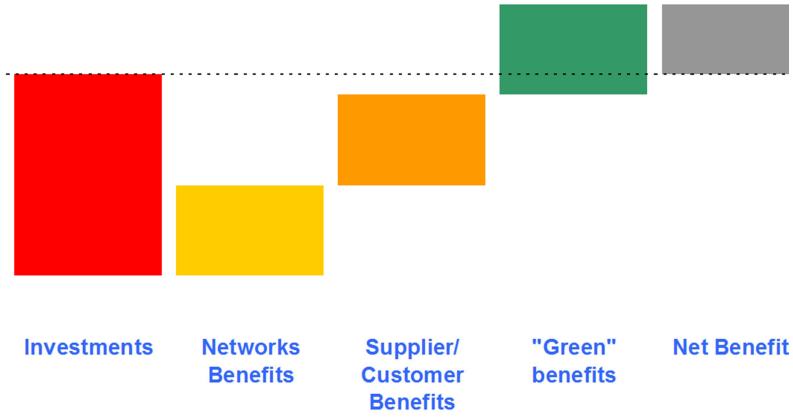


FIGURE 4 DISTRIBUTED COST AND BENEFIT OF SMART GRIDS [15]

CHAPTER 3 THE MEDIUM VOLTAGE POWER DISTRIBUTION SYSTEM

In this chapter a conceptualisation of the problem situation of the DSO concerning smart grids is presented. The conceptualisation functions as the foundation for model development and simulation. The objective is to identify the aspects that are taken into account, to give clear definitions of these aspects, and to understand what the positioning of the aspect is in the total problem situation. The conceptualisation is based on a systems diagram, which identifies subsystems, goals, policies, external influences and requirements. The system is referred to as the *Medium Voltage Power Distribution System*.

Paragraph 3.1 starts with an overview of the system. Paragraph 3.2 continues with the a description of the subsystems. Paragraph 3.3 defines the goals of the DSO. Paragraph 3.4 defines the external influences that affect the system. Finally, paragraph 3.5 presents the policies that the DSO can implement to control the system.

3.1 SYSTEM DIAGRAM

This paragraph introduces the Medium Voltage Power Distribution System, by giving an overview in Figure 5. The figure distinguishes the system and its boundary. Inside the system the subsystems can be found. Outside the system boundary the external influences, policies, goals, and requirements are positioned.

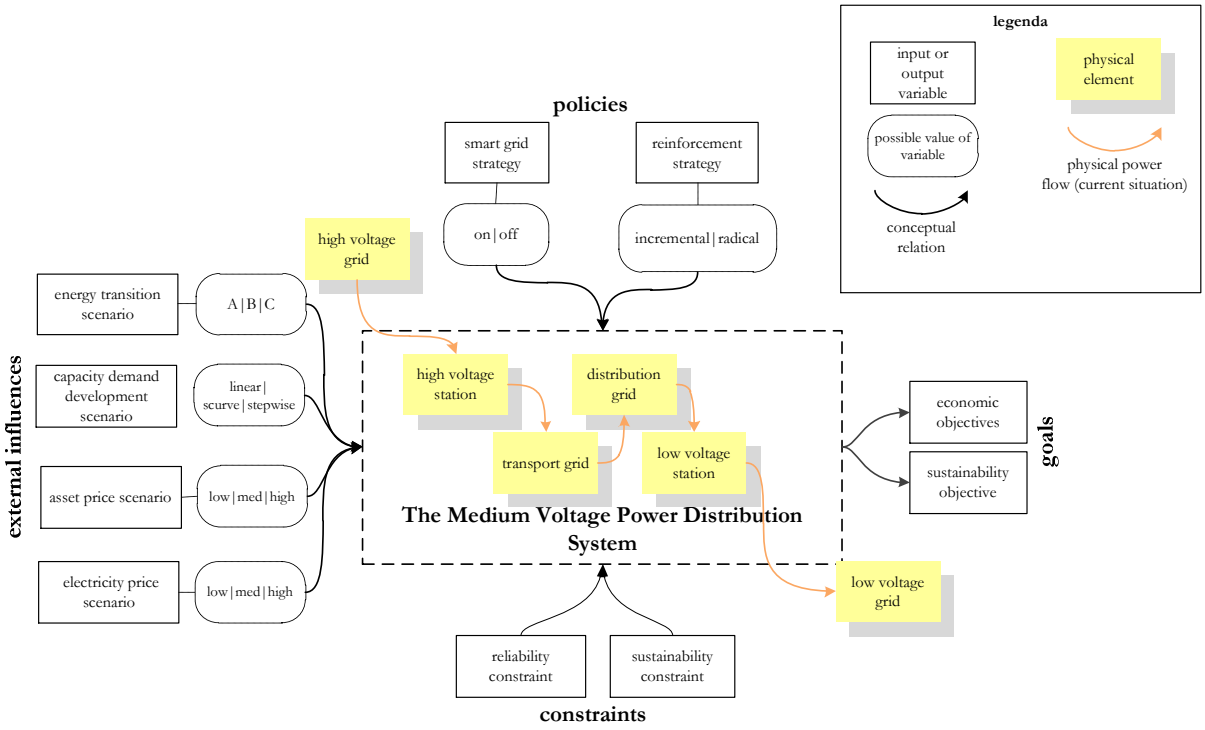


FIGURE 5 SYSTEM DIAGRAM OF THE MEDIUM VOLTAGE POWER DISTRIBUTION SYSTEM

The subsystems are the types of physical elements of the medium voltage distribution grid: high voltage stations, transport grids, distribution grids, and low voltage stations. These elements are sometime referred to as grid components. The elements are distinguished since they have different physical characteristics and should therefore be treated differently. The diagram shows that the physical elements are connected to the high voltage grid and the low voltage grid, which are not taken into account in this research. The

high voltage grid is controlled by the TSO, and is thus not part of the responsibility of the DSO. The low voltage grid is part of the responsibility of the DSO, though its physical configuration (grid topology) differs significantly from the medium voltage grid. Analysis of this grid part requires a different approach, which is considered beyond the scope of this research due to time limitations. Because of the complexity of the system being studied and the wide range of scenarios to be considered, a system model is a useful and often indispensable tool in this process. A system model is an abstraction of the system of interest – either the system as it currently exists, or as it is envisioned to exist for purposes of evaluating policies in a different (e.g., future) context. Here it is important to note that we employ a broad interpretation of the term "model," including both a conceptual formulation and=or a mathematical model (algorithm), frequently found in the form of a computer programme. The system model represents the cause-effect relationships characteristic of the system. In a mathematical model, the relationships among the various components of the system are expressed as functions. Although formulated in mathematical terms, these models usually contain inherent components of subjectivity. Subjectivity manifests itself already in the conceptual phase when decisions are made concerning which elements will be included in the analysis and which will be left out. Subjectivity affects the manner in which modellers translate the conceptual model into mathematical equations.

The goals are the outcomes of interest for DSO. The system goals are related to ambitions of the DSO, captured by its company values: sustainability, economy, reliability (i.e. quality of supply), legality, safety, and customer satisfaction. From these company values, sustainability, economy, and reliability are considered relevant for this research. The other objectives are considered beyond the scope of this research. Economy is translated into the economic objective. The DSO interprets sustainability in two ways. One interpretation is the facilitation of a sustainable energy system, the other interpretation is sustainable operation of the grids by the DSO itself. Sustainability can therefore be translated into a goal, the sustainability objective, and into a requirement, the sustainability requirements. Reliability is a translated into a system requirement.

The requirement requirements the operational degrees of freedom of the DSO. As explained above, the requirements are based on the goals of the DSO itself. The identified requirements are the reliability requirement and the sustainability requirement. The reliability requirement is enforced by the national energy regulator (in the Netherlands: de Energiekamer), which imposes a certain degree of quality of supply. The sustainability requirement refers to the responsibility of the DSO to facilitate the a sustainable energy market.

External influences are developments in surrounding the system that the DSO cannot control. They induce uncertainty that the DSO often needs to respond to. During the introduction it was mentioned that one major source of uncertainty is how the future energy system will develop. This aspect is reflected by two external influences: the energy-transition scenario And the capacity demand development scenario. The first defines what the energy system will look like 30 years from now, and the latter defines how the energy system will develop over the years. Another source of uncertainty is how the costs of reinforcement will develop over the years, reflected by the asset price scenario. The last source of uncertainty that is taken into account in this research, is how the electricity price will develop the next 30 years, reflected by the electricity price scenario.

Policies are the instruments the DSO has in order to reach its goals. This research identified two policies, referred to as a strategy. The smart grid strategy reflects the extent to which the DSO makes use of smart grids. This is an important aspect of the system diagram because the objective of this research is mainly to understand the impact of this strategy. The grid reinforcement strategy reflects the way the DSO

reinforces the grid. It is related to grid design directives that the asset manager of the DSO uses to prescribe how local asset engineers should reinforce the grid.

Paragraph 3.2 gives a more thorough explanation of the types of physical elements. Paragraph 3.3 gives definitions of the goals. Paragraph 3.4 continues with definitions of the external influences. Finally, the definitions of the policies were presented in paragraph 3.5

3.2 PHYSICAL ELEMENTS

This paragraph gives a description of the subsystems. Four subsystems are distinguished because of their different technical functions and characteristics. The identified subsystems within the scope of this research are the physical elements of the system, or the distribution grid components:

- the high voltage stations (section 3.2.1)
- the transport grids (section 3.2.2)
- the distribution grids (section 3.2.3)
- the low voltage stations (section 3.2.4

Figure 6 gives an overview of where the different types of physical elements are positioned in the power distribution grid. High voltage stations are connected to the high voltage grid. From here, electricity flows through the transport grid to the distribution grid. Low voltage stations are connected to the distribution grids, and feed the low voltage grids that run all the way to the consumers. Residential loads are always connected to the low voltage grid. However, industrial loads (often referred to as customers) can be connected to the distribution grid at other levels, depending on their location and electricity demand.

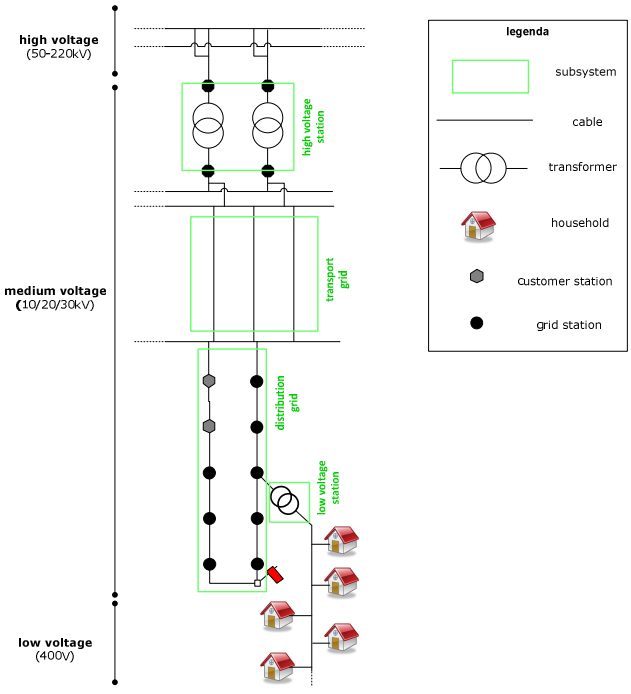


FIGURE 6 THE POSITION OF THE PHYSICAL ELEMENTS IN THE POWER DISTRIBUTION GRID

In general, stations consist of at least one transformer as their basic function is to transform the voltage level of the electricity flow from a higher voltage level to a lower voltage level. Grids consist of cables, their function is to transport the medium voltage electricity flow from one place to another. Other

functional parts of the physical elements (such as technical installations) are not considered in this research.

This research is based on the distribution grid of a Dutch DSO (Enexis). The type of grid components and grid topology is thus based on the power grid situation in the Netherlands. The DSO is one of the three DSO that are responsible of a large area. The DSO manages about 300 high voltage stations, 8.3 million kilometres of transport grid, 36.0 million kilometres of distribution grid, and 50.000 low voltage stations.

Note that within the four types of physical elements also different types of assets exist. These differences are predominantly different nominal capacities (e.g. a 250 kVA low voltage transformer versus a 630 kVA low voltage transformer).

3.2.1 HIGH VOLTAGE STATIONS

The basic function of high voltage stations is to transform high voltage power (110/150 kV) to medium voltage power (50 kV). The stations are located between the high voltage grid and the medium voltage transport grid.

A high voltage station feeds a large geographical area, one station feeds multiple municipalities. The station consists of transformers and other technical installations. At least two transformers are installed at every station, because of the N-1 principle. This principle requires no degradation of power quality during disruption of grid component. If one transformer fails, a backup transformer is switched on with at least the same capacity.

A high voltage station consists of a configuration of two to six transformers. Most stations (90%) consist of two or three transformers. The nominal capacity is the capacity of the transformer as indicated by the manufacturer. The capacity is expressed in MVA (mega volt-ampere), the unit for apparent power in electric circuits, and ranges from 20 to 80 MVA. Historically, transformers were tailor made based on the capacity demand. This leads to a wide range of transformer types in the power distribution system. Today, the DSO works towards more standardization of its grid components and installs only standardized transformation types (i.e. 40, 60, 80 MVA). The different configurations and transformer types lead to a high degree of diversity in high voltage stations. The research categorizes the high voltage stations as explained in Appendix II.

3.2.2 TRANSPORT GRID

The basic function of the transport grid is to transport medium voltage power from the high voltage station to the distribution grid. It has thus solely a transport function, and does not feed any stations (with the exception of customer stations that may be connected to this grid). For the transport grid, the N-1 principle accounts as well. This means that a defect cable does not influence the grid functioning. If one cable is defect, the other cable(s) are dimensioned to maintain regular operations (see Figure 7).

Transport cables can be characterized by its conducting material, conducting surface, and length. Separate transport cables are mostly shorter than 3 km. The conducting material (copper or aluminium) and conducting surface (in mm^2) define the cable type (i.e. type 630AL stands for a conducting surface size $630mm^2$ made of aluminium). Every cable type has an accompanying transport capacity, expressed in Ampere (A), the unit of electric current. Just like high voltage transformers, a wide range of type of cable types is installed due to historical grid design choices. Today, the DSO uses standard types (i.e. with a conducting surface of either 240AL, 400AL, or 630AL). The research categorizes the high cables as explained in Appendix II.

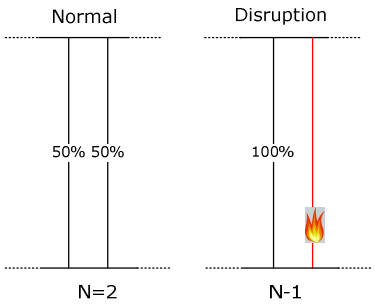


FIGURE 7 THE N-1 PRINCIPLE FOR TRANSPORT GRID

3.2.3 DISTRIBUTION GRID

The basic function of the distribution grid is to feed medium voltage power to the low voltage stations (and sometimes feeding customer stations that may be connected to this grid). Multiple low voltage stations are connected to one distribution cable. The distribution grid has mostly a ring configuration, and sometimes a radial configuration (Figure 8).

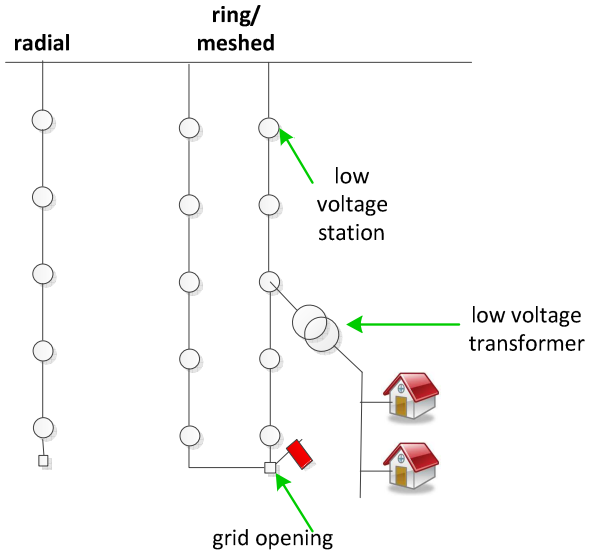


FIGURE 8 RING AND RADIAL DISTRIBUTION GRID CONFIGURATIONS

A meshed configuration means that multiple distribution grids are connected to each other in different configurations. The configuration occurs locally, though it is not preferred by the DSO because of its reduced predictability.

A ring configuration is preferred because this enables the grid to feed low voltage stations from two sides. In the situation that a distribution cable fails, the low voltage station can be fed via another route. In normal conditions, the meshed grid becomes radial by a grid opening (or split point). The grid opening is located at the 'confidence middle', the point where the difference between the product of the lengths and the amount of connections fed by the grids are minimal. During disruptions, the grid opening can be closed so that the low voltage station can be reached via another route. In the meantime, the defected cable can be repaired (Figure 9).

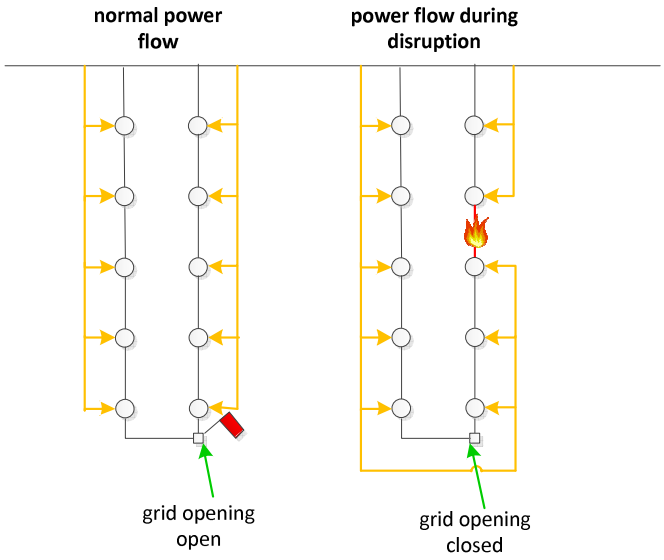


FIGURE 9 SWITCHABILITY DURING DISRUPTION

Similar to transport cables, distribution cables can be characterized by its conducting material, conducting surface, and length. The nominal capacity of the cables is expressed in ampere (A). Distributions cables are mostly shorter than 1 km. The Dutch power grid also consists of a wide range of installed distribution cables due to historical grid design choices. Today, the DSO uses standard types (i.e. with a conducting surface of either 150AL, 240AL, or 400AL). The research categorizes cables as explained in Appendix II.

3.2.4 Low voltage stations

The basic function of low voltage stations is to transform medium voltage power (50 kV) delivered by the distribution grid to low voltage power (400 V). The stations are located between distribution grid and low voltage grid. From the low voltage station, the power will flow via the low voltage grid to residential connections.

A low voltage station includes mostly only one low voltage transformer. The nominal capacity of LV transformers is expressed in kVA (kilo volt-ampere) and ranges from 100 to 630 kVA. The DSO chooses not to install transformers with a higher capacity than 630 kVA for safety reasons. Just like for the other physical elements, accounts for low voltage stations that historically led to a wide range of tailor made transformers different nominal capacities. Today the DSO uses standard types (i.e. 100, 250, 400, 630 kVA transformers). The research categorizes the low voltage stations as explained in Appendix II.

3.3 Goals

This paragraph gives definition of the goals that are included in this research. Goals are the outcomes of interest of the system for the DSO. The goals of the system are based on the DSOs company values economy, sustainability, and reliability. The goals are defined as:

- *Economy - minimization of the expenditures associated with operation, maintenance, and development of the power distribution system*
- *Sustainability - facilitation of a national, sustainable energy system and maximization of energy efficient operations*
- *Reliability - minimization of the yearly outage duration*

These goals are specified into objectives and requirements of the system. The objectives are defined as a minimization or maximization function (system output), while requirements are defined as preconditions

for the system (system input). The economy goal is translated into economic objectives (section 3.3.1 . The sustainability goal is translated into a sustainability objective and requirement (section 3.3.2 The reliability goal is translated into a reliability requirement (section 3.3.3

3.3.1 ECONOMIC OBJECTIVE

The economy goal of the DSO is translated into the following economic objective:

- *the total costs, which is the sum of capital expenditures and operational expenditures, must be minimized*

Capital expenditures are expressed as *capex*, operational expenditures as *opex*. It does not make sense to take all capex and opex of the DSO into account. Therefore, a selection of the capex and opex drivers must be made, that are considered relevant for this research. A cost and revenue breakdown of the DSO was made, which shows all drivers that related to the economy goal of the DSO (Figure 10). Based on this, it is determined which economic aspects are taken into account.

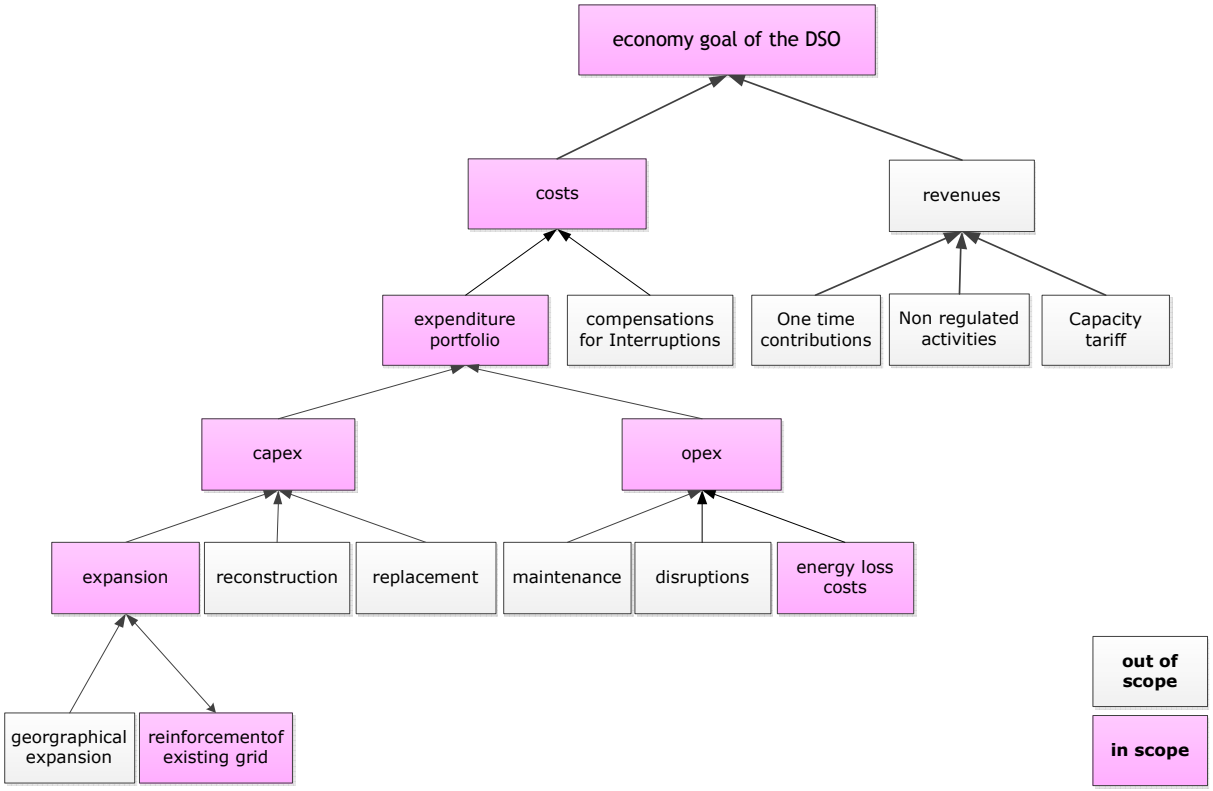


FIGURE 10 THE DSO'S COST AND REVENUE BREAKDOWN

First, it can be stated that this research does not take the revenues of the DSO into account. Though revenues may be important in relation to smart grids when evaluating price incentives, this is not the focus of this research.

The focus of this research is thus only on the economic aspects related to costs. Since reliability is put as a requirement, and not as an objective, the compensations for interruptions are not taken into account. This means that this research only observes the costs related to the DSO expenditure portfolio, consisting of capex and opex.

Capex are the expenditures that potentially create future benefits. Considering the DSOs situation this means that the expenditures upgrade the value of the physical power distribution assets. Capex is thus the

expenditure that increases the nominal capacity of the distribution grid. The money is spent to a fixed asset or adds value to an existing fixed asset with a useful lifetime that extends beyond that taxable year. Capex can therefore be depreciated over the years. The amount of years over which is depreciated depends on the physical element (i.e. low voltage transformer 50 years, high voltage transformer 40 years)[2]. This research looks at capex as a result of grid expansion, and is limited to the expenditures related to expansion of the *existing* medium voltage power distribution grid, or to its current geographical coverage. This category of grid expansion is called 'grid reinforcement'. This means that it does not involve the construction of new medium voltage power distribution grid as a results of the development of residential or industrial areas in new geographical areas. Also, reconstruction (translocation) and replacement of the medium voltage power distribution grid are out of scope. This means that for instance replacement of grid component by new grid components with the same capability (i.e. same nominal capacity) – due to aging or failure - is not observed.

In general, opex are the expenditures for operations and maintenance. From the perspective of the DSO, these costs consist of maintenance of the existing grid, costs of disruptions, and costs of energy loss. Maintenance costs are related to the activities of the DSO to maintain the quality its current distribution grid, and includes periodic maintenance of the assets. Costs of disruptions are the costs of reparations of failed assets. Energy loss is the difference between generated electricity and administered electricity that is delivered to consumers. Energy loss is typically divided into technical losses and non-technical losses. Technical losses are caused by power transportation (mainly due to the resistance of the grid components). Non-technical losses include to metering errors, electricity theft, and billing errors. The DSO must purchase the energy loss. This research takes only technical energy loss into account, the non-technical losses are beyond its scope.

The economy objective in this research takes only expenditure for energy loss into account. Maintenance is not taken into account because determining the impact of smart grids on the DSOs maintenance efforts and accompanying costs would be a research in itself. Cost of disruptions are not taken into account because this research put reliability as a requirement, not as an objective.

To sum up, economic objective in this research includes capex and opex. Capex involve only the expenditures related to grid reinforcement that upgrades the capacity of the existing grid. Expenditures related to replacement and reconstruction (due to aging, failure, or translocation) are not taken into account. Opex involve only the expenditures related to energy losses. Expenditure of maintenance and disruptions are beyond the scope of this research.

3.3.2 SUSTAINABILITY REQUIREMENT AND OBJECTIVE

As introduced previously, sustainability can be approached in two ways: facilitation of a sustainable energy system and maximizing sustainable operations. The first interpretation is translated into a requirement, the latter into an objective.

The sustainability requirement is defined as:

- *all local developments that contribute to a more sustainable energy system must be facilitated by the medium voltage power distribution grid*

This means that a whole range of new technologies that improve the energy-efficiency system must have access to the power distribution grid in the way that is appropriate. An example of these developments is that distributed generation systems (i.e. solar/wind power systems and combined heat-power systems)

[2] Based on desk research at Enexis

must have access to the distribution grid. Another example is that customers must be able to charge their electric vehicles in a comfortable way. The relation of this requirement to the medium voltage power distribution system is that the system must supply sufficient capacity to make these energy efficient technologies operational. A different approach would be for instance to limit the connection of electric vehicles to the distribution grid. The reason that this aspect is approached as a requirement, is that the DSO is currently responsible for giving any consumer unrestricted access to the existing grid [1]. Though it is possible that this requirement is adapted in the future because of a changed energy system, there are no direct arguments to assume that this will be adapted.

The sustainability objective is defined as:

- *the energy loss as a result of power transportation is minimized*

The DSO can contribute to its sustainability goals by minimizing one's own energy consumption. The most energy consuming activity of the DSO is the earlier introduced technical energy loss caused by transport of electricity. The energy loss in the Dutch grid (transmission and distribution) is about 5% of the total electricity production. These losses are mostly the result of resistance of the physical elements. This objective is an output of the medium voltage power distribution system, and functions therefore as the sustainability indicator of the system performance from the perspective of the DSO. This research expresses the energy loss in kilowatt-hours. The energy loss can also be expressed in CO_2emission costs, by multiplying the amount of CO_2 (about 0.5 kg per kWh) with the price of CO_2 (about €15 per ton CO_2) [31].

3.3.3 RELIABILITY REQUIREMENT

The reliability goal of the DSO is translated into a reliability requirement. The requirement is defined as:

- *the reliability level of the current grid is either maintained or increased*

This requirement safeguards that the reliability level of the system is either maintained or improved. This requirement can be safeguarded by reinforcement of all assets that threaten the reliability of supply. It is currently not needed to improve the Dutch level of reliability since the level is already very high relative to European countries. The relation of this requirement to the medium voltage power distribution system is that the physical elements must be reinforced if its environment demands a higher capacity, which impacts the system output. Note that the choice to define reliability as a requirement is arguable, as reliability can be improved by smart grids because they enable real information on the status of grid. However, this research approaches smart grids as an enabler of active load management, not of active network management related to grid operations.

3.4 EXTERNAL INFLUENCES

This paragraph describes the external influences surrounding the system. External influences create uncertainty and cannot be controlled by the DSO. These influences act on the system, which leads to changes in the system and, ultimately, changes the goals.

Four external influences are identified: the energy-transition scenario, the capacity demand development scenario, the asset price scenario, and the electricity price scenario. In the following sections, the external influences and their relation to the medium voltage power distribution system are explained.

3.4.1 ENERGY-TRANSITION SCENARIO

The energy-transition scenario describes what the future energy supply system will look like, 30 years from now, and what its impact is on the medium-voltage power distribution grid. This includes the integration of distributed generation facilities, such as renewable energy systems (e.g. solar panels) and CHP's. It also includes the normal electricity demand, and the electricity demand of new technologies such as electric vehicles and heat pumps.

The energy-transition scenarios are based on other research [20, 32]. The research focused on the translation of future energy scenarios into electricity profiles for the Dutch power distribution grid. The main drivers that lead to variations in the future energy supply and demand are assumed to be a more national or international focused policy, a more economic or environmental oriented society, and the economic growth. Differentiations in these drivers enabled the generation of three different, but all realistic, scenarios. It evaluated which technologies will be most successful and how fast they will develop in each scenario. Also, it predicted the amount of energy generated and consumed, based on assumptions on the economic growth. Moreover, it included assumptions on the flexibility of load. Electric vehicles were considered to be the main contributors to load flexibility. Customer demand was assumed to be non-flexible. The three energy-transition scenarios in this research are taken over on a one-on-one basis from the other research [20, 32]. Figure 11 positions the energy-transition scenarios on axes of demand and the share of decentralized generation.

In energy-transition scenario A, the energy market and energy policies are very similar as the situation today. The economic growth is limited, which lead to a low electricity demand growth (0.5% annual growth). The focus of national policy is on the economics of the energy system as opposed to a more environmental focus. This leads to a predominantly centralized energy supply (on the high voltage level). Compared to the other scenarios, not many new energy technologies are introduced. There is very little distributed generation (solar panels and micro-CHPs), and the penetration of electric vehicles and heat pumps is minimal.

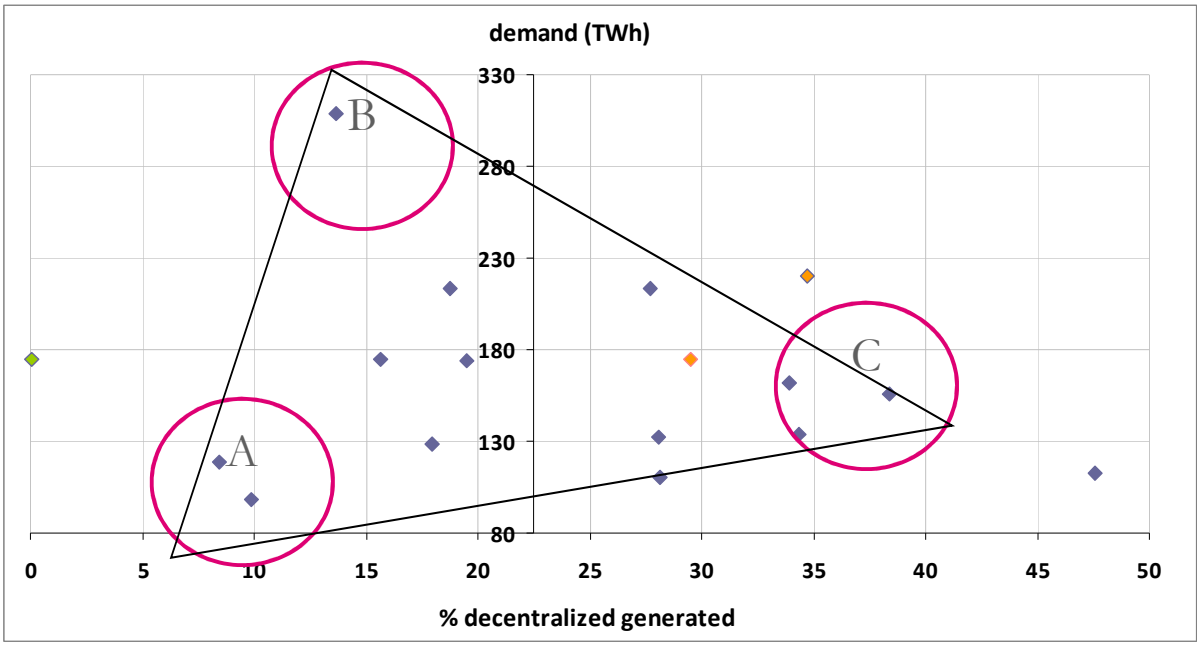


FIGURE 11 THE THREE ENERGY TRANSITION SCENARIOS A,B AND C (SCHEPERS 2011)

In energy-transition scenario B, a global economy dominates. The economic growth is high, which leads to a high energy demand growth (2% annual growth). This scenario also includes a large growth of customer demand (as opposed to residential demand), which is assumed to be non-flexible. Energy savings are considered very important, which leads to the introduction of electric vehicles and heat pumps. Generation facilities grow at all grid levels, though centralized production remains most important. The penetration of distributed generation is limited in this scenario.

In energy-transition scenario C, national energy policy focuses on sustainability and local energy systems. The high degree of investments lead to a high penetration of new energy technologies, such as distributed generation systems (solar panels and micro-CHPs), electric vehicles, and heat pumps. Economic growth is high (1% annual growth), but the effect on the energy demand is average, because of the focus on energy savings and efficient technologies.

Note that the energy-transition scenario will determine the flexibility of loads, or to which extend demand can be shifted. It is assumed that different types of demand have different flexibility characteristics. 'Normal' demand is considered not very flexible, it is assumed that about 10% of peak demand is non-time critical. Demand as a result of new technologies such as electric vehicles, are assumed to be much more flexible.

Table 1 shows how the different energy transition scenarios impact the medium voltage power distribution grid, by showing the average peak loads of the different physical elements 30 years from now. The peak load is the quotient of the capacity demand and the nominal capacity of the grid component. It can be concluded that energy-transition scenario B leads to the most increased average peak load, followed by scenario C (73%) and scenario A (53%).

energy transition scenario	high voltage transformers t_0: 74%	transport grid t_0: 37%	distribution grid t_0: 16%	low voltage transformers t_0: 61%	**average per scenario** t_0: 47%
A	95%	54%	23%	84%	53%
B	256%	11%	48%	151%	103%
C	164%	76%	33%	110%	73%

TABLE 1 AVERAGE PEAK LOAD, 30 YEARS FROM NOW, IN THE DIFFERENT ENERGY-TRANSITION SCENARIOS

3.4.2 CAPACITY DEMAND DEVELOPMENT SCENARIO

The energy-transition scenario determines what the energy supply system looks like, 30 years from now. The electricity profiles of the parallel research are used to predict what the distribution grid capacity demand looks like under the three energy-transition scenarios. However, this does not describe how the capacity demand will develop over the next three decades. Therefore, the capacity demand development scenario is introduced.

The capacity demand development scenario determines how the capacity demand will develop over the next three decades, knowing the capacity demand today and the capacity demand 30 years from today. The scenario interpolates the capacity demand over the time horizon. Three possible capacity demand development scenarios are identified: a linear scenario, a s-curve scenario, and a stepwise scenario (Figure 12). In a linear scenario, the capacity demand will develop linear, meaning that every year the capacity demand will develop incrementally. The s-curve scenario is associated with a slow start and slow end, and an exponential growth at the midst of the observed period (the year 2025). This curve is often used to describe the introduction of new technologies. It is assumed that after slow acceptation by the early adaptors, a fast mass introduction will follow. The stepwise curve assumes that capacity demand will develop in steps. This means that the capacity demand will increase dramatically in one year, and will than

remain the same over a period of 5 years. This would mean that for instance the introduction of new technologies will develop in steps, for instance due to policy periods.

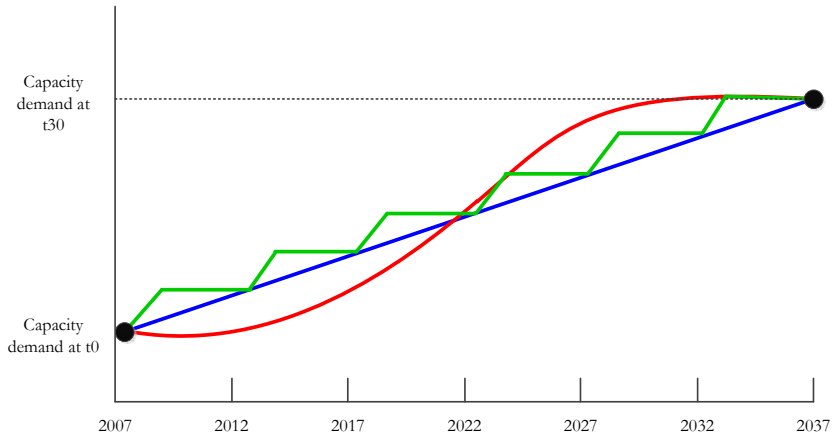


FIGURE 12 CAPACITY DEMAND DEVELOPMENT SCENARIOS

3.4.3 ASSET PRICE SCENARIO

The asset price scenario describes how the price of new physical elements of the medium voltage power distribution system develops over the next decades. The price includes both price of hardware (material) and installation service. The price of new assets is considered important because it directly influence the capex as a results of grid reinforcement, which involves the purchase of new hardware and installation services. Over the next decades, the asset price scenario is expected to have an annual price increase that is either low, medium, or high.

The asset price is a source of uncertainty because of recent price trends in the asset supply industry. According to the DSO, there is an increasing risk of affordable availability of hardware and installation services. Over the last decade, the scarcity of hardware increased rapidly because the amount of European grid component manufacturers declined. Many production facilities moved to the Far East. At the same time, emerging countries such as China and India are rapidly developing power infrastructures, which puts heavy pressure on the global markets of commodities and manufacturing capacities. Scarcity on the market leads to heavily fluctuating and mostly increasing prices and delivery times, making expenditure forecasts of the DSO complicated. The scarcity of installation services increases as a results of a declining amount of electro-technical personnel in the Netherlands. This development leads to increasing prices for technical services, such as the installations of grid components.

3.4.4 ELECTRICITY PRICE SCENARIO

The electricity price scenario describes how the price of electricity develops over the next decades. The electricity price is considered important because it directly influences the opex, or the energy loss cost. As explained before, power transport coincides with energy losses, or electricity losses. The DSO must purchase this lost electricity. The electricity price associated with energy loss is not similar to the electricity price paid by consumers, because this price includes energy taxes. The DSO pays only the power generation cost, without the energy taxes (currently about €0,08 per kWh). Over the next decades, the electricity price scenario is expected to have an annual price increase that is either low, medium, or high.

The electricity price is a source of uncertainty because of developments in the energy market. As fossil fuels become more scarce, the cost associated with power generation is expected to increase.

3.5 POLICIES

This paragraph describes policies that the DSO controls. A policy is a set of measures taken to control the system, to help solve problems within it or caused by it, or to obtain benefits from it. The measures affect the structure and performance of the system. Policies are intended to help achieve the goals. In this research, policy is perceived as a combination of strategies. Two strategies are identified: smart grid strategy and grid reinforcement strategy. This first refers to the choice the DSO has to make use of smart grid technologies. It is an important input of the medium voltage power distribution system, because this research has the ambition to get more insight in smart grids on the goals of the DSO. The grid reinforcement strategy refers to the way the DSO chooses to reinforce its power distribution grid: either incremental or radical. Both strategies are explained in the next sections.

3.5.1 SMART GRID STRATEGY

In this research, the 'smart grid on' strategy is defined as:

- *to take advantage of load flexibility by pro-active demand control with the objective to maximize utilization of the medium voltage power distribution grid capacity*

The DSO has the choice to take advantage of smart grids, or to do nothing and continue operating the grid as usual. There is a whole range of other approaches in between that the DSO can take concerning smart grids. However, in order to make research comprehensible, a black and white approach to smart grids is taken. The DSO has the option to either take advantage of smart grids, or not. Although it is acknowledged that it is more realistic that smart grids will develop gradually, and that the activities of the DSO will develop accordingly, this considered beyond the scope of this research.

The two options of the smart grid strategy are thus defined as:

- smart grid on
- smart grid off

The 'smart grid off' strategy means that the DSO does not change its operations from the way today. The 'smart grid on' strategy does change the way the DSO operates. This research makes assumptions on the effects of smart grids on the system, and then treats them as given. This means that the complications related to the implementation of smart grids, are not taken into account. An important aspect of this approach is that this research does involve the costs of the smart grids ICT infrastructure. It purely looks at the economic costs and benefits of the effect of smart grids, once implemented. Although it is acknowledged that there would be costs associated with the deployment of the ICT infrastructure required for smart grids, this aspect is considered beyond the scope of this research.

But how do smart grid change the operations of the DSO? This research approaches smart grids as an enabler of load management, or demand control, with the objective to maximize utilization of the capacity of the existing grid. The existing grid is capable of distributing more electricity, by shifting non-time critical demand to off peak hours. This mechanism changes the demand profile, and thereby the load profiles of the distribution grid assets. It is assumed that the incentive for load flexibility is based on the available distribution capacity. This assumption is arguable, since future incentive structures for energy demand and supply are still widely debated. Though it is acknowledged that incentive structures based on other than available grid capacity would have different implications on the asset load profiles, this is considered beyond the scope of this research.

3.5.2 GRID REINFORCEMENT STRATEGY

Next to the smart grid strategy, the DSO controls a grid reinforcement strategy. This strategy refers to the power grid design choices of the DSO's grid designers when a physical element is indicated as a bottleneck (threat to normal operations). The grid reinforcement strategy is defined as:

- *the technical strategy the DSO implements to safeguard sufficient power distribution grid capacity*

In reality, asset engineers of the DSO have the task to guarantee the required transport capacity by signalling (potential) capacity bottlenecks in-time (risks), and provide *investment plans* to adequately solve these bottlenecks. The investment plans include a technical analysis of the grid, and a suggestion for solving the bottleneck. The suggestions are based on grid design directives, formulated by the DSO's asset managers.

Two options of the grid reinforcement strategy are identified:

- incremental
- radical

The options refer to the degree to which the DSO reinforces an overloaded asset. Under the incremental strategy, the bottleneck is reinforced by a grid components with a one-step higher nominal capacity. This means that over the next three decades, the distribution grid capacity is increased by small steps. A potential advantages of this approach is costs related to reinforcements are minimized. However, the disadvantage is that added nominal capacity is lower, potentially leading to an early need for follow-up reinforcements. Under the radical reinforcement strategy, a more rigorous reinforcement approach is taken. Bottlenecks are reinforced by grid components with significant higher nominal capacities. The potential advantage of this approach is that it takes longer before follow-up reinforcements are needed. However, a radical approach does result in higher costs in the year of reinforcement, since grid components with higher nominal capacity have a higher price.

INTERMEZZO I

Part I of this thesis gave background information on smart grids in order to understand how this research approaches the concept, and to have insight in the state of knowledge on this matter. It introduced the Medium Voltage Power Distribution System as a conceptualisation of the system of interest for the DSO. The conceptualisation included a description of the subsystems, defined as the different physical elements that are part of the medium voltage distribution grid. It also presented the system goals: the economic objectives and the sustainability objective. It furthermore identified the policies the DSO controls to influence the system, a combination of a smart grid strategy and a grid reinforcement strategy. The system conceptualisation acknowledged that the future environment of power distribution grid is uncertain. It identified the most important external influences that will affect the system over the next three decades: the energy-transition scenario, the capacity demand development scenario, the asset price scenario, and the electricity price scenario. The system conceptualisation defines the scope of this thesis, and functions as the foundation of the model conceptualisation in Part II.

Part II introduces the Economic Impact Model for Smart Grids. This model that is able to translate how the external influences and policies affect the goals of the Medium Voltage Power Distribution System. Part II includes a conceptualisation of the model, which identifies how the system inputs lead to system outputs through a chain of causally related factors. It then describes the model that is developed in MS Excel by definition of its structure. The model is verified and validates, so it can be used Part III.

PART II THE ECONOMIC IMPACT MODEL FOR SMART GRIDS

CHAPTER 4 MODEL CONCEPTUALISATION

The previous chapter introduced the Medium Voltage Power Distribution System, the conceptualisation of the situation of the DSO. The conceptualisation identifies sub systems, goals, external influences, and policies.

In order to get a further understanding of the system and its behaviour, we replace the system by the Economic Impact Model for Smart Grids. This means, that the external influences, policies, and requirements function as inputs, and goals as outputs. The model is able to replicate how the inputs lead to the outputs, and gives us insight in system behaviour. In the previous chapter, the system was presented as a black box, which means that we could not see how the systems input leads to its output. This chapter attempts to reveal how the system inputs lead to its output, through a chain of causally related factors. A causal relation diagram is used to identify the key factors and their relations. The causal relation diagram is a simplification of the medium voltage power distribution system, based on the way the DSO operates the grid in real life. Furthermore, the diagram includes assumptions on how the inputs relate to the system. The relation of smart grids to the system is of great importance, while it is at the same time unknown how smart grids exactly affect the grid. Therefore, the research assumptions on the way smart grids affect the system is explained in more detail.

Paragraph 4.1 starts with a definition of the model objective. Paragraph 4.2 presents the causal relations diagram, and gives further explanations of the factors and their causal relations. Finally, paragraph 4.3 presents the assumed impacts of smart grids on the causal relation diagram.

4.1 MODEL OBJECTIVE

Based on the system conceptualisation, the objective of the Economic Impact Model for Smart Grids is to get insight in the impacts of alternative policies on the goals in different environmental scenarios under predefined requirements. In order to get this insight, first, an understanding is needed of how the alternative policies and environmental scenario have impact on the goals. Then, it is possible to get this insight by varying the settings of policies and environmental scenarios.

The modelling questions thus become:

- How do the identified external influences and alternative policies lead to the economic and sustainability goals?
- What are the impacts of alternative policies on the economy and sustainability goals in different environmental scenarios?

It is briefly discussed what the model should be capable of in order to reach its objective. First, the model must safeguard the predefined requirements. The requirements were defined as maintenance or improving the current level of reliability, and facilitation of all energy systems that contribute to the system-side energy efficiency. Secondly, the model must be able to estimate the economic impact as well as the sustainability impact of alternative policies in different environmental scenarios. The economic impact can be expressed in monetary values, and the sustainability impact in kilowatt-hours (energy loss). Fourthly, the model must be able to compose different environmental scenarios by interpretation of the identified external influences. One environmental scenario consists of interpretations of the energy transition scenario, the capacity demand development scenario, the asset price scenario, and the electricity price scenario. Finally, the model is able to determine how the DSO should give substance to its policies, including a smart grid strategy and a grid reinforcement strategy.

The first modelling question is answered using a causal relation diagram, which is described in the next section. The second modelling question is answered in Part III Simulation.

4.2 CAUSAL RELATION DIAGRAM

Figure 13 presents the causal relation diagram of the Economic Impact Model for Smart Grids. This is a conceptualisation that reveals how inputs relate to outputs, through a chain of causally related factors. The factors are indicated as circles, the arrows as relations, and the inputs and outputs as blocks. The external influences are represented by pink blocks, the strategies by green blocks, and the goals by white blocks. A positive relation means that an increase of a factor leads to an increase of the following factor. A negative relation means that an increase of a factor leads to a decrease of the following factors. Some relations are indicated by a question mark, which means that it is not clear what type of relation a factor has to the following factor.

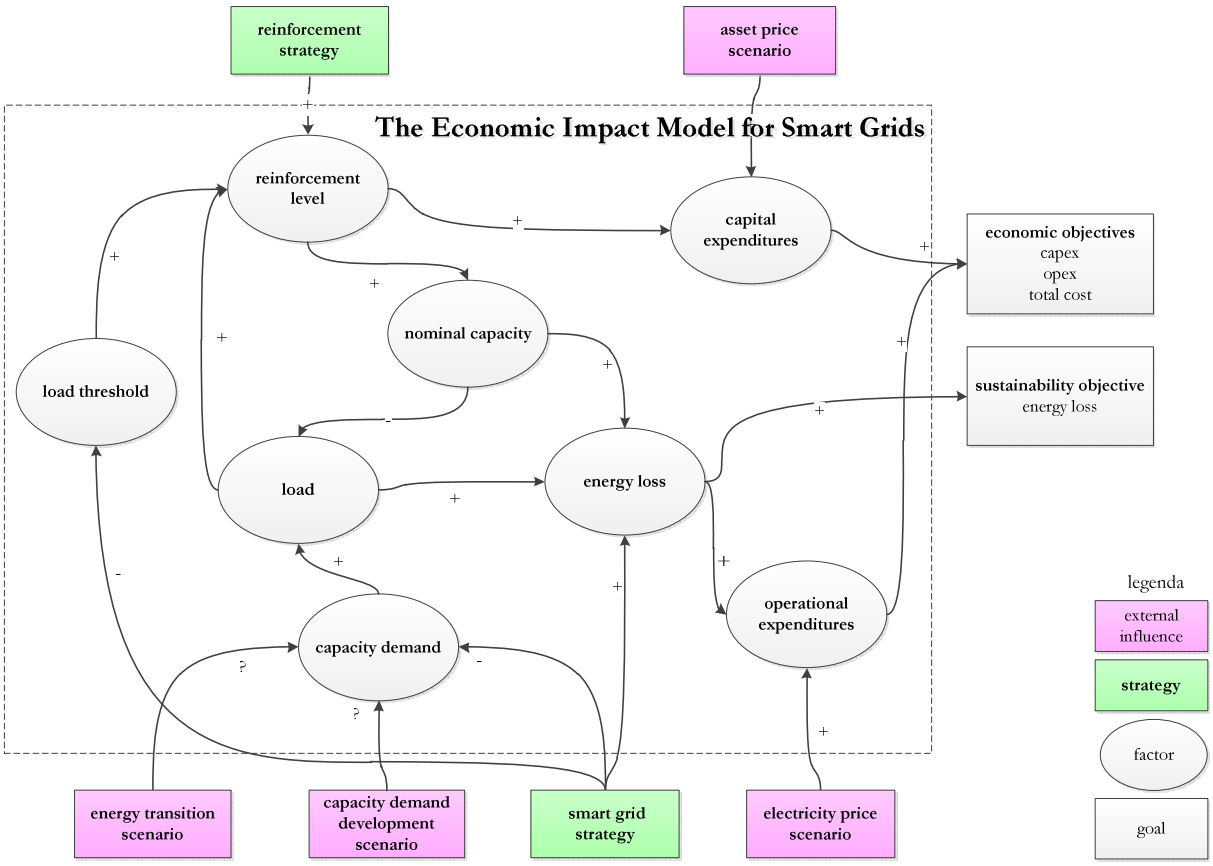


FIGURE 13 CAUSAL RELATION DIAGRAM

The causal relation diagram is configured for one asset of the medium voltage power distribution grid. Though different assets differ physically, the conceptualisation allows a general approach as to how inputs related to outputs for each asset. The factors can be interpreted as the properties of the asset, and the relations as how the properties influence each other. The input settings are the same for all assets, and the outputs are aggregated over all assets.

The model is able to simulate multiple assets at the same time, in coherence with the medium voltage power distribution grid which obviously consists of multiple assets. Each asset is of one type of physical elements, each with different technical characteristics (i.e. high voltage station, distribution grid, transport grid, or low voltage station). Within the types of physical elements, assets also differ based on their

nominal capacity. The model is able to include this asset-specific information by lookup tables. The lookup tables, often use categorization of the asset. This means, that the model uses general assumptions for each asset. Although these assumptions might not always be accurate looking at one specific asset, this is considered irrelevant because of our interest in the distribution grid in total.

The model takes is furthermore time dependent, which means that it observes the status of the factors for each year over the observed time horizon of 30 years[3].

In order to clarify how the causal relation diagram should be interpreted, its factors and relations are briefly described.

As mentioned before, the model outputs are aggregations of all assets. The economic objective of the DSO is expressed as total cost, which is the sum of capex and opex. Capex is determined by the aggregated capital expenditures, and opex is determined by aggregated operational expenditures. The sustainability objective of the DSO is aggregated energy losses of each asset. The outputs are aggregated, but the further conceptualisation is described for one asset.

The asset-specific capital expenditures exist only if the asset is reinforced. If this occurs, the capital expenditures are calculated for that year, based on the reinforcement type and the accompanying costs, which are both asset specific. The cost of reinforcement is influenced by the asset price scenario and the associated price increase in that year of reinforcement.

The asset is reinforced if it is overloaded. An asset is considered overloaded of its peak load exceeds the load threshold. The load threshold is the maximal load of the asset without excessive reduction in lifetime and increasing risk of failure. The peak load is the quotient of the assets capacity demand during peak hours and its nominal capacity. The capacity demand is related to the electricity demand during peak hours. The capacity demand of the asset is influenced by the energy-transition scenario And the capacity development scenario. The energy-transition scenario determines the capacity demand associated with the energy system 30 years from now. The capacity demand development scenario determines what the exact capacity demand is each year. The nominal capacity is the capacity of the asset as indicated by the manufacturer. If the asset is reinforced, its nominal capacity increases because it is replaced by an asset with a higher nominal capacity, or an asset is added to the configuration. The type of reinforcement and accompanying additional nominal capacity is determined by the grid reinforcement strategy, either incremental or radical, which includes the realistic reinforcement options the asset engineer has.

The capacity demand is determined by the energy-transition scenario, the capacity demand development scenario, and the smart grid scenario. The energy-transition scenario's determines what the capacity demand is 30 years from now, and the capacity demand development scenario determines what the capacity demand in each year. Under the smart grid on strategy the capacity demand is lowered by demand control.

The asset-related operational expenditures are caused by the assets annual energy loss and the electricity price in that year, determined by the electricity price scenario. The energy loss is influenced by the asset specific energy loss character (which can be determined based on its nominal capacity) and its peak load.

The next sections will describe the identified factors in more detail:

- outputs of the model: section 4.2.1
- the inputs of the model: section 4.2.2

[3] Because the model uses data with information on the assets of 2007, the time horizon becomes 2007 to 2037 (respectively t_0 and t_{30})

- capital expenditures: section 4.2.3
- operational expenditures: section 4.2.4
- energy loss: section 4.2.5
- reinforcement: section 0
- load threshold: section 4.2.7
- load: section 4.2.8
- nominal capacity: section 4.2.9
- capacity demand: section 4.2.10

4.2.1 OUTPUTS

Six outputs are identified, based on the economic and sustainability objectives, which were stated in the system conceptualisation. One output is related to the sustainability objective, and five outputs are related to the economic objectives.

Identified outputs:

1. Total Costs [€]
2. NPV [€]
3. Total Energy Loss [kWh]
4. Annual Total Costs (t) [€/year]
5. Annual Capex (t) [€/year]
6. Annual Opex (t) [€/year]

Economic outputs

All economic outputs are expressed in monetary terms (euro). Of the five economic outputs, three outputs are time dependent, and two time independent. The time dependent outputs are expressed in euro per year, and the time independent outputs are expressed in euro. The time independent outputs are based on the total over the observed time horizon of 30 years.

The time dependent outputs are annual total costs, annual capex, and annual opex. Annual total costs is the sum of annual capex and annual opex. Annual capex are the aggregated expenditures of reinforcement of assets. Opex are the aggregated expenditures of energy loss of assets. The time independent outputs are total costs and net present value (NPV). Total costs is the sum of all annual total costs over the observed time horizon. NPV is the sum of the present values of the yearly total costs, and takes the time value of money into account.

The formulas for the economic outputs are:

$$annual\ total\ cost\ (t) = annual\ capex\ (t) + annual\ opex\ (t)$$

$$total\ cost = \int_{t_0}^{t_{30}} annual\ total\ cost\ (t) dt$$

$$net\ present\ value = \int_{t_0}^{t_{30}} \frac{annual\ total\ cost\ (t)}{(1+i)^t} dt$$

in which:

- t is the time in year
- i is the discount rate of 4%

If we are interested in the total costs, capex, and opex, we can also just present the total costs and the capex-opex ratio, because the total costs is the sum of capex and opex. The capex-opex ratio describes how the capex and opex are distributed, defined by the formula:

$$capex - opex\ ratio = \frac{capex\ (t)}{opex\ (t)}$$

A ratio value reaching 1 means that the capex and opex are the same, a ratio value >1 means that the capex dominates, while a ratio value <1 means that the opex dominates.

Energy loss

The sustainability output is time-independent, and is observed over the time horizon of 30 years. objective is the energy loss associated with power distribution. The energy loss can be observed per year, and over the total time horizon of 30 years. The observed output is the total energy loss over the time horizon. Its formula thus becomes:

$$total\ energy\ loss = \int_{t_0}^{t_{30}} anual\ energy\ loss\ (t)dt$$

4.2.2 INPUTS

This paragraph specifies the six inputs of model (Table 2). These inputs are based on the external influences and policies. The four identified external influences are the energy-transition scenario, the capacity demand development scenario, the asset price scenario, and the electricity price scenario. A policy consists of two strategies, the smart grid strategy and the grid reinforcement strategy.

Starting with the external influences, the three different settings of the energy-transition scenarios are A, B, and C. Each setting represents the energy system that the medium voltage power distribution grid must facilitate 30 years from now by supplying sufficient capacity.

The three different settings of the capacity demand development scenario are linear, s-curve and stepwise (formulas are explained Appendix VI). Each setting represents another way of how the capacity demand will develop over the next three decades.

The three different levels asset price scenario and the electricity price scenario are low, medium, and high. The scenarios describe how the market prices of assets (both hardware and construction) and electricity will develop over the next three decades. The price increase is assumed to be exponential. In the low price scenario, the price increases 1,0% annually. In the medium and high scenario's the annual price increase is respectively 2,5% and 4,0%. These price increases are based on the price increases that the DSO has experienced over the past decade.

Considering the strategies, the two settings of the smart grid strategy are smart grid on and smart grid off. Smart grid on means that the DSO takes advantage of smart grids by load management.

The two settings of the grid reinforcement strategy are incremental and radical. This strategy influences the reinforcement level, and determines the additional nominal capacity that is associated with reinforcement and the accompanying cost of reinforcement.

We will now take a closer look at how these inputs lead to the previously identified outputs, through the chain of causally related factors, starting from the outputs.

	Level 1	*Level 2*	*Level 3*
energy-transition scenario	A	B	C
capacity demand development scenario	linear	s-curve	stepwise
asset price scenario	low	medium	high
electricity price scenario	low	medium	high
smart grid strategy	on	off	-
grid reinforcement strategy	incremental	radical	-

TABLE 2 IDENTIFIED INPUTS AND THEIR LEVELS

4.2.3 CAPITAL EXPENDITURES

Capital expenditures exist if an asset is reinforced. It is based on the costs associated with reinforcement projects. In general the costs of reinforcement is determined by four cost drivers:

1) Work - the costs engineering work done by the asset engineers of the DSO, typically 25% of the total cost of a reinforcement project
2) Material - the costs of hardware (new assets), typically 35% of the total cost of a reinforcement project
3) Outsourcing - the costs of work done by third parties such as construction contractors or legal advisors, typically 40% of the total cost of a reinforcement project
4) Taxes - typically 10% on top of the sum of the earlier described cost drivers

It is important to note that the values of the four cost drivers differ per type of reinforcement. They differ per type physical element, as reinforcement of a high voltage transformer coincides for instance with a different expenditure than reinforcement of a low voltage transformer. The cost drivers also differ per asset type, as the reinforcement of a low voltage transformer with a nominal capacity of 250 kVA is different than reinforcement of a 630 kVA transformer. Therefore, the model uses lookup tables to determine the expenditure associated with the specific reinforcement[4].

The asset price scenario influences only the cost drivers that depend on the market price, which are material and outsourcing. Based on the identified cost drivers, and the influence of the asset price scenario, the annual capex can be calculated using the following formula:

$$annual\ capex\ (t) = (x\ (t) * ((1+\alpha)^{t_{30}-t} * (M_x + O_x)) + W_x) * (1 + T_x)$$

in which:

- x(t) is the reinforcement of type x at *t* in [-]
- α is the annual asset price increase in [%]
- M_x is the material cost of reinforcement type x in [€]
- O_x is the outsourcing cost of reinforcement type x in [€]

[4] The capital expenditures lookup tables that the model uses are not presented in the thesis because this information is confidential

- W_x is the work cost of reinforcement type x in [€]

- T_x is the tax rate of reinforcement type x in [€]

Now we know how the capital expenditures are determined, we will take a closer look at how the operational expenditures are determined.

4.2.4 OPERATIONAL EXPENDITURES

The operational expenditures are the costs of energy losses. The DSO must purchase the electricity that is lost due to power distribution for the market electricity price (only generation costs, no taxes). The electricity price is currently €0.08 per kilowatt-hour, however the electricity price scenario influences this price over the years.

The operational expenditures can be calculated by multiplying the energy loss in year t by the electricity price in year t, or:

$$annual\ opex(t) = E_{loss}(t) * (1 + \beta)^{t_{30}-t}$$

in which:

- β is the annual electricity price increase in [%]

Here also accounts that the energy losses differ per physical element and per type of physical element.

4.2.5 ENERGY LOSS

Energy losses are the loss that coincide with power distribution due to the resistance of asset. Energy losses dependent on the grid configuration, the type of assets, and the assets peak load. The model is able to estimate the energy loss coinciding with the medium voltage power distribution grid of the DSO, based on some assumptions on these three aspects. This section presents the formulas that are used to calculate the energy loss. In order to determine asset specific energy loss, the model uses look up tables that can be found in Appendix V.

Energy loss is typically divided into copper loss and iron loss. Transformers cause both types of loss. However, cables coincide only with copper loss. Copper losses are a function of current and resistance, and iron losses are a function of voltage and frequency. Since the grids run nearly at constant voltage and a fixed frequency of nearly 50Hz, the iron losses of transformers are nearly constant. In contrast, the copper losses in both transformers and cables are not constant, and are related to the asset peak load.

Energy losses of transport and distribution grids

Energy losses in cables are influenced by the following factors:

1. the copper loss related to the cable type (conducting material and surface size)
2. the cables peak load - the quotient of the capacity demand during peak hours and the nominal capacity of the cable
3. the length of the cable
4. the duration of peak loss – dependent on load profile

The first two factors are combined into one lookup value (P_{copper}), which means that the model looks up what the copper loss is related to the cable type and the cable peak load. The length of the cable is given by the data base. The duration of peak loss (d_p) can be determined by observations on the load profile.

Because in different energy-transition scenarios and under the smart grids on strategy on the load profile differs, the duration of peak loss differs. The lookup table of the durations of peak loss can also be found in Appendix V.

The total energy loss formula for the transport and distribution cables (only copper loss) is:

$$E_{loss}(t) = P_{copper} * length * d_p$$

in which:

- P_{copper} is the asset-specific copper loss depending on the type of cable and cables peak load in [W/m]
- $length$ is the cable length in [m]
- d_p is the duration of peak loss in [hours/year]

Energy losses of high voltage and low voltage stations

Energy losses in transformers are influenced by the following factors:

1. the copper loss related to the transformer type (related to its nominal capacity)
2. the transformers peak load - the quotient of the capacity demand during peak hours and the nominal capacity of the cable
3. the duration of peak loss – dependent on load profile
4. the iron loss related to the transformer type (related to its nominal capacity)
5. the duration of operation time of the transformer (continuously, thus 8760 hours a year)

The copper loss and iron loss of the transformer type can be found in a lookup table. The model is able to lookup the transformer peak load, since this value is also used to determine if reinforcement is needed (see next section). The duration of peak loss is, similar as with cables, different in different energy-transition scenarios and under the smart grid on strategy, and can be found in the lookup table. The duration of operation time of the transformer is standard 8760 hours a year, which means that the transformer is continuously operated.

The total energy loss formula for a transformer (iron and copper losses) is:

$$E_{loss}(t) = P_{iron} * d_0 + P_{copper} * l(t)^2 * d_p$$

in which:

- P_{iron} are the asset-specific iron losses in [kW]
- d_o is the duration of the operation time of the transformer, 8760 [hours/year]
- P_{copper} is the asset-specific copper loss at nominal power [kW]
- $l(t)$ is the transformers peak load in year t in [%]
- d_p is the duration of peak loss in [hours/year]

So far we have seen how the model calculates capital expenditures, the operational expenditures, and energy losses. It was shown that the capital expenditures depend on reinforcements. The next section describes the process of reinforcement, and how the model treats this factor.

4.2.6 REINFORCEMENT

Reinforcement is done if the nominal capacity of the asset is not sufficient to facilitate demand. In this situation, the asset is either replaced by another asset with a higher nominal capacity or another asset is added to the existing configuration, increasing the overall nominal capacity of the configuration.

The grid reinforcement strategy of the DSO determines to what extent the asset is reinforced or how much extra nominal capacity is created after reinforcement. Incremental reinforcement means that an asset is reinforced by a solution with a nominal capacity one step higher than the bottleneck. Radical reinforcement means that an asset is reinforced by a more rigorous solution: a significant higher nominal capacity. Radical reinforcement leads to higher capital expenditures on the short term. However, more extra nominal capacity possibly leads the elimination or postponement of second series reinforcements on the longer term.

The strategies for reinforcement differ per physical element, are described in the next sections. The specific incremental and radical grid reinforcement strategies for the different type of assets can be found in Appendix III.

4.2.6.1 HIGH VOLTAGE STATION REINFORCEMENT

Reinforcement of a high voltage stations involves either replacing a high voltage transformer by one with a higher nominal capacity or adding a high voltage transformer (including a new connection to the high voltage grid). Another option is to build a whole new high voltage station at another location, which is a reasonable option if the capacity demand is very dramatically increased or the capacity demand develops at a new location (for instance in the situation of a new residential neighbourhood, business park or industrial area). These options are illustrated in Figure 14. The latter option is outside the scope of this research.

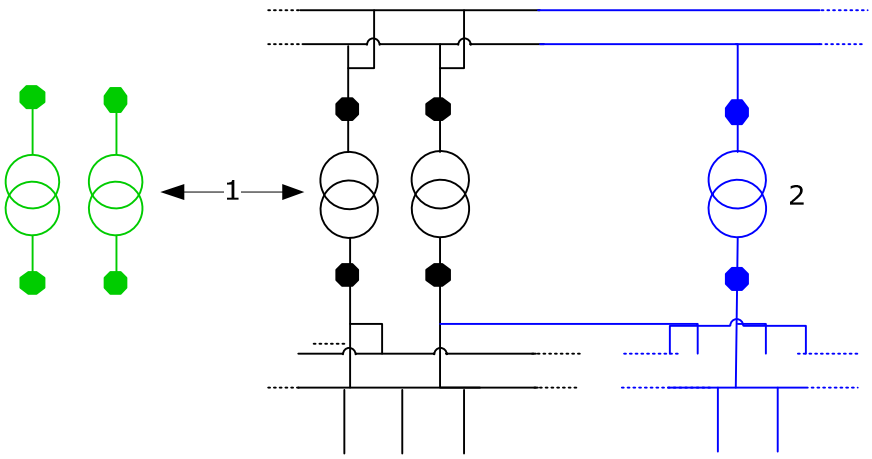


FIGURE 14 TWO REINFORCEMENT OPTIONS TO THE HIGH VOLTAGE STATION

At the station two, three, four, five or six transformers are installed. A high voltage station with one transformer does not exist because of the N-1 criterion, meaning that at the HV station always one reserve (back-up) transformer is installed. This reserve transformer must be able to take over the capacity demand if another transformer fails. In the situation of two transformers, this means that both transformers must be able to carry the capacity demand individually. If in this situation the transformer is overloaded, both transformers must be replaced. In the situation of three or more transformers, the grid designer has more degrees of freedom as to how the station is reinforced: all transformers are replaced, one transformer is added, or one transformer is replaced and one transformer added.

Transformers with a nominal capacity of 20 MVA are very old (these types are not produced anymore), and always directly replaced by another transformer. Only standard types of high voltage stations are installed: either 40, 60, or 80 MVA.

4.2.6.2 TRANSPORT GRID REINFORCEMENT

The transport grid consists of parallel cables with not very complex configurations. The grid designer must take the N-1 criterion into account.

Reinforcement is mostly done by laying a parallel cable next to the overloaded cable (1, Figure 15). If there are not enough connection possibilities at ends of the cables (at the installation), the grid designer can choose to bundle two cables and connect them together to one connection. An alternative is to unburden the overloaded cable by laying a cable to another transport grid (2, Figure 15). This alternative will only be chosen of the distance to another transport grid is shorter than the length of the transport cable.

Only standard types of transport cables are installed: either 240AL, 400AL, 630AL, or 800AL.

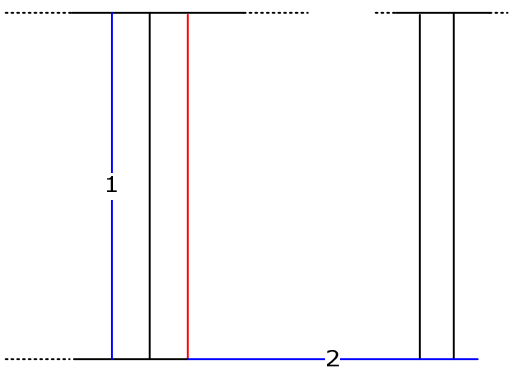


FIGURE 15 TWO REINFORCEMENT OPTIONS OF THE TRANSPORT GRID

4.2.6.3 DISTRIBUTION GRID REINFORCEMENT

The configuration of the distribution grid was explained in section 3.2.3 The configuration of the distribution grid depends on the historical developments, the local situation and the creativity of the grid designer. In the case of a bottleneck, the grid can be reinforced in the following ways (see also Figure 16):

1. replace the cable one-on-one by a cable with a higher nominal capacity
2. add a long diagonal to the distribution ring
3. add a short diagonal (spoke) to the distribution ring
4. add a cable to another distribution ring, if there is another distribution ring nearby, thereby redirecting the electricity flow
5. add two long diagonals, if the distribution ring is heavy overloaded
6. add a new distribution ring, if the distribution ring is very heavy overloaded, or a new groups of customers must be connected (in the case of a new residential neighbourhood or business park)

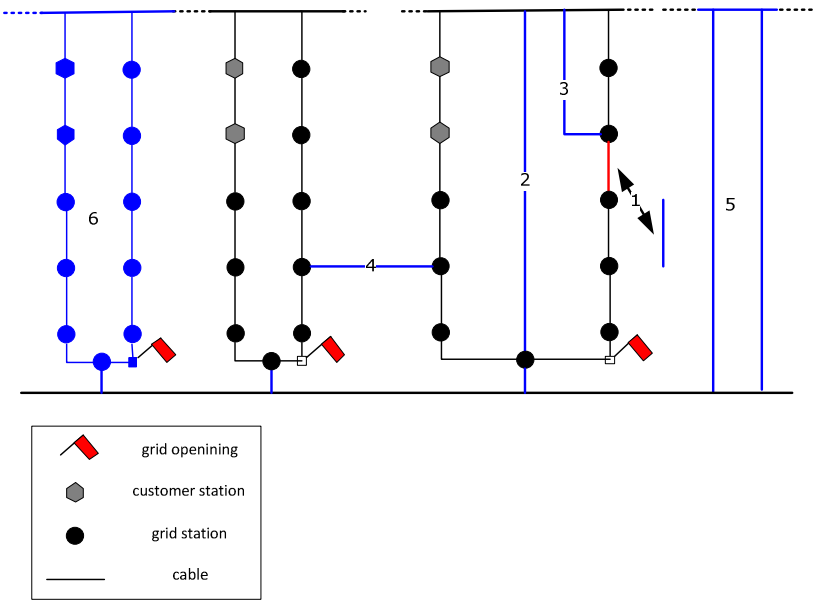


FIGURE 16 SIX REINFORCEMENT OPTIONS OF THE DISTRIBUTION GRID

In the situation that the bottleneck is a copper cable with a conducting surface of 35mm² or smaller, or an aluminium cable of 50mm² or smaller, it is assumable that the bottleneck is caused by the relatively old cable (these small types of cables are not used anymore). In this situation, the cable is directly reinforced by a cable with a larger nominal capacity, meaning that a cable is laid parallel to the bottleneck (1, Figure 16 Six reinforcement options of the distribution grid

), the existing cable stays active. The model distributes the other reinforcement options randomly amongst the distribution grid bottlenecks. The distribution of reinforcement options and the assumed accompanying cable length is presented in Appendix III.

Only standard types of transport cables are installed: either 150AL, 240AL, 400AL, or 630AL.

4.2.6.4 LOW VOLTAGE STATION REINFORCEMENT

Reinforcement of an overloaded LV transformer is straightforward. In the situation that a transformer has a nominal capacity lower than 630 kVA, it is replaced by a transformer with a higher nominal capacity (1, Figure 17). The old transformer is thrown away if its nominal capacity is lower than 250 kVA, or used again with a resale value 40% of its purchase price.

Transformers with a higher nominal capacity than 630 kVA are not installed because of safety reasons. In this situation an additional transformer and building is placed next to the existing transformer (2, Figure 17), which that stays operational.

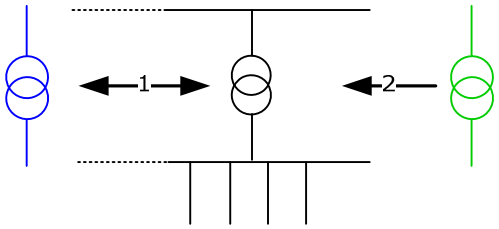


FIGURE 17 REINFORCEMENT OPTIONS OF THE LOW VOLTAGE STATION

4.2.7 LOAD THRESHOLD

The previous section described the principle of reinforcement. Reinforcement is done when the nominal capacity of the asset is not sufficient to facilitate demand. This situation occurs when the asset load (influenced by the capacity demand and the nominal capacity of the asset) exceeds the load threshold of the asset, or:

$$l(t) \geq l_t$$

in which:

- l_t is the load threshold

The load threshold thus determines when the asset must be reinforced. The physical reason for the load threshold is that asset heats up as a result of electricity transport. It is able to deal with a certain degree of heating, but overheating leads to an excessive reduction of lifetime and an increased risk of failure. The load threshold, or l_t, is the maximal permissible overload, which differs per asset type. The thermal nature of load explains why the load threshold also depends on environmental factors, such as the ambient temperature surrounding a transformer, or the temperature and heat resistance of the ground in which a cable lays.

The model bases the load thresholds on international standards. The load threshold differs per physical element. It is based on the grid configuration, the assets load profile, the ambient temperature surrounding the asset, and the assets technical characteristics including its nominal capacity. For transport cables this means for instance that the N-1 criterion is incorporated in the load threshold. The load thresholds and the calculation process behind the values is specified in Appendix IV Appendix IV

It was explained that reinforcement is done if the assets peak load exceeds the load threshold. The next section describes how the assets peak load is determined.

4.2.8 PEAK LOAD

As explained before, the peak load determines when an asset must be reinforced. The peak load also influences the energy loss of the asset. The peak load of the asset is the degree to which the grid component is loaded during peak hours, or the quotient of the maximal capacity demand and the assets nominal capacity:

$$l(t) = \frac{I_{demand}(t)}{I_{nominal}(t)}$$

in which:

- $I_{demand}\,(t)$ is the capacity demand at *t* in [A] for cables and [VA] for transformer
- $I_{nominal}\,(t)$ is the installed nominal capacity of the asset at *t,* in [A] for cables and [VA] for transformer

Determination of the capacity demand and nominal capacity are explained in the next two sections.

4.2.9 NOMINAL CAPACITY

The nominal capacity is the installed capacity of the asset. The data base gives information on the nominal capacity of the physical element at t_0. The asset retains its existing nominal capacity, until it is reinforced. This means that if the asset is not reinforced the nominal capacity in year *t:*

$$I_{nominal}(t) = I_{nominal(t-1)}$$

In which:

- $I_{nominal}(t)$ is the nominal capacity at *t,* in [A] for cables and [VA] for transformer
- $I_{nominal,(t-1)}$ is the nominal capacity at *(t-1)*, in [A] for cables and [VA] for transformer

Reinforcement at *t* induces a higher nominal capacity of the asset.

$$I_{nominal}(t) = I_{nominal(t)}$$

In which:

- $I_{nominal,t}$ is the new installed nominal capacity at *t*, in [A] for cables and [VA] for transformer

The new nominal capacity is determined by the reinforcement level, which is determined by the grid reinforcement strategy (incremental or radical)**.** Because the reinforcement depends on the type of asset, the model uses a lookup table to determine how much nominal capacity is added. The lookup table can be found in Appendix III.

A higher nominal capacity causes a lower load, which means that the asset is now capable of facilitating a higher capacity demand. The higher nominal capacity changes the energy loss character of the asset, as was previously described.

We now know how the nominal capacity of the asset is determined. However, it was previously shown that in order to determine the load, we must also know the capacity demand. Determination of this factor is explained in the next section.

4.2.10 CAPACITY DEMAND

The capacity demand represents the capacity associated with energy system facilitation in year *t*. This factor is influenced by the energy-transition scenario, the capacity demand development scenario, and the smart grid strategy. These three external influences define what the energy system looks like in year *t*, and what the accompanying capacity demand is. The model bases the end state capacity demand (at t_{30}) on the energy-transition scenario. It uses the capacity demand scenario to interpolate how the capacity demand develops from t_0 to t_{30}.

The model uses the data base to provide information on the nominal capacity of the assets at t_0, the peak load at t_0, and the peak load at t_{30}. The peak load at t_{30} is different in different energy-transition scenarios, and under different smart grid strategies. Based on this information, the capacity demands at t_0 and t_{30} can be calculated using the following formulas:

$$I_{demand,t0} = l_{peak,t0} * I_{nominal,t0}$$

$$I_{demand,t30} = l_{peak,t30} * I_{nominal,t0}$$

in which:

- $I_{demand,t0}$ and $I_{demand,t30}$ are the capacity demands at respectively t_0 and t_{30}, in [A] for cables and [VA] for transformers

- $l_{peak,t0}$ and $l_{peak,t30}$ are the asset's peak loads at respectively t_0 and t_{30}, in [%]

- $I_{nominal,t0}$ is the nominal capacity of the asset at t_0 (as indicated by the fabricant), in [A] for cables and [VA] for transformers

The capacity demand is interpolated from t_0 and t_{30}. The interpolation curve is determined by the capacity demand development scenario: linear, a s-curve, or stepwise. In Appendix VI the formulas of the different capacity development curves can be found. The capacity demand at year t can now be estimated.

The previous sections have shown how the causally related factors can be determined. The effect of the smart grid on strategy was mentioned three times. It influences the energy, the load threshold, and the capacity demand. The next section explains in more detail why smart grids are assumed to have these effects.

4.3 EFFECTS OF SMART GRIDS

In this research, the impact of smart grids is studied. However, it is unknown how smart grids will affect the power distribution grid. Therefore, this research makes assumption on what the effects if smart grids are. This paragraphs presents these assumptions, and explains their background.

This research assumes that under the smart grid on strategy, a part of the load is flexible in time. Flexibility means that non-time critical load can be shifted in time. The utilization of the existing grid capacity can be maximized by shifting the non-time critical load from capacity demand peak hours to off capacity demand peak hours. This section explains what the effect of this is on the customers demand profile and the asset load profile. Based on these effects, it is explained why under the smart grid on strategy some of the factors of the model are adapted.

Currently, the power distribution grid is designed based on assumptions of a demand profile, referred to as a stylized demand profile. The stylized demand profile differs consumer. The demand profile of industry customers can for instance be characterized by a continuous demand. The demand profile of residential demand is associated with a typical daily curve. The grey line in Figure 18 shows such a stylized residential demand profile during one day. It can be observed that the demand increases in the morning, leading to a small peak when people wake up. The largest demand peak is in the evening, when people are at home. Experience over the years proved that grid design based on this residential demand profile works. However, smart grids have the potential to change this demand profile.

The pink line in Figure 18 shows how smart grids may change the shape of the residential demand profile. First, it lowers the peak height of the power demand, which is called 'peak shaving'. Secondly, it enlarges the peak width of the power demand. In general, the customer's power demand profile is smoother as the peak height is lowered and the peak width is increased.

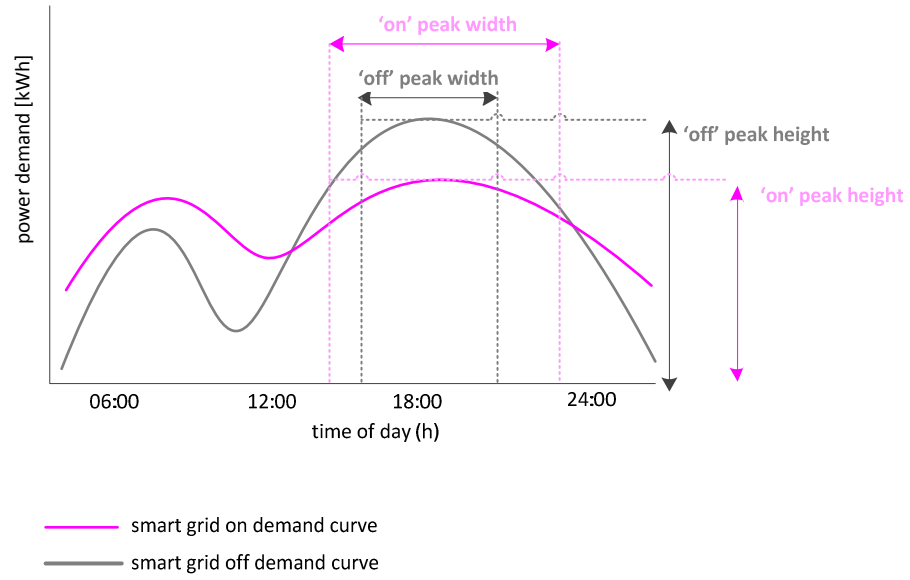


FIGURE 18 RESIDENTIAL POWER DEMAND PROFILE

It is important to understand these effects, because under a smart grid on strategy these resonate in the asset load profiles of the power distribution grid. Figure 19 shows the asset load profile. The grey line represents the asset load under the standard residential demand profile. It can be observed that the asset load profile is similar to the demand profile, which is logical because during peak demand the capacity demand will be higher leading to a higher asset load.

The green line in Figure 19 shows how smart grids change the shape of the asset load profile. The two changes of the residential demand profiles are assumed to have three effects:

1. **peak shaving**
2. **increased duration of peak loss**
3. **decreased load threshold**

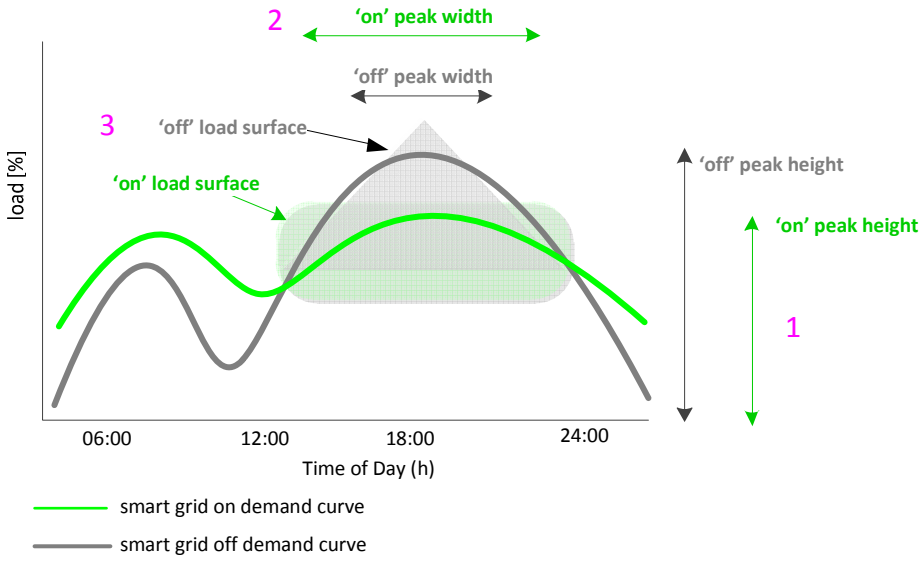


FIGURE 19 ASSET LOAD PROFILE

The effect of peak shaving on the asset load profile is comparable to its effect on the demand profile. If the peak height of the demand is decreased, the peak load of asset is decreased as well (see number 1 in Figure 19). In many cases, only this effect of smart grids is mentioned. This may lead to misinterpretations on the potential of smart grids from the perspective of the DSO. Table 3 shows the average peak shaving effects of the smart grid on strategy in the different energy transition scenarios. The model bases these effects on other research [32, 33]. It shows that the peak shavings effect on the assets peak load is on average 15%.

energy-transition scenario	high voltage transformers	transport grid	distribution grid	low voltage transformers	average per scenario
A	22%	16%	6%	20%	**16%**
B	15%	9%	4%	15%	**11%**
C	24%	15%	7%	23%	**17%**
average	**22%**	**14%**	**6%**	**20%**	**16%**

TABLE 3 AVERAGE PEAK SHAVING EFFECTS ON THE ASSET PEAK LOAD IN DIFFERENT ENERGY-TRANSITION SCENARIOS

The second effect of smart grids is the increased duration of peak loss, as a results of the increased duration of the peak. Though the peak height is decreased under the smart grid strategy, its duration is longer. The duration can be interpreted as the peak width in hours (see number 2 in Figure 19). In the smart grid situation, the peak duration is longer, the duration of peak loss is therefore also longer than in the current situation.

The third effect of smart grids is the decrease load threshold. The load threshold is the maximal degree to which grid components may be loaded during peak hours in relation to its nominal capacity. The threshold is, amongst other factors, influenced by the shape of the load profile. The physical reason is that grid components heat up as a results of load, and the degree to which they can be heated depends on the degree to which they are able to cool down (during off peak hours). If the peak has a short duration (small peak width), the load threshold can be relatively high, whereas a peak with a long duration (large peak width) leads to a relatively low load threshold. It can thus be stated that the load threshold depends on the load surface of peak hours (see number 3 in Figure 19). In the smart grid situation, surface of the peak is enlarged, which leads to the assumption that the load threshold must be lowered.

This section explained why under the smart grids in strategy some of the factors of the causal relation diagram are adapted under the smart grid on strategy. Note that although these three are justifiable, they are not technically proven.

CHAPTER 5 MODEL DESCRIPTION

The previous chapter described the conceptualisation of the Economic Impact Model for Smart Grids, using a causal relation diagram. This conceptualisation is the foundation for the development of a quantified model that simulates how the medium voltage power distribution system responds to different environmental scenarios under alternative policies. The quantified model is developed in MS Excel. MS Excel is suitable simulation environment because of its flexibility, it enabled modelling all factors and their relations identified during conceptualisation. It was furthermore compatible with the data used for simulation. Visual Basic was used as a support tool for simulation. The additional advantage of this simulation environment is that it can be easily adapted for further research.

This chapters elaborates on the quantified model starting with a description the model structure by identifying the input dashboard, output dashboard, and sub models and simulation activities. Hereafter, the developed model is verified and validated. The verified and validated model can be used for simulation.

5.1 MODEL STRUCTURE

Figure 20 shows the model, its inputs (factors 1 to 6), and its outputs (responses 1 to 6). The next two sections discuss the factors and responses. The model itself (in Figure 20 displayed as a black box) consists of a sequence of simulation activities, which are explained after.

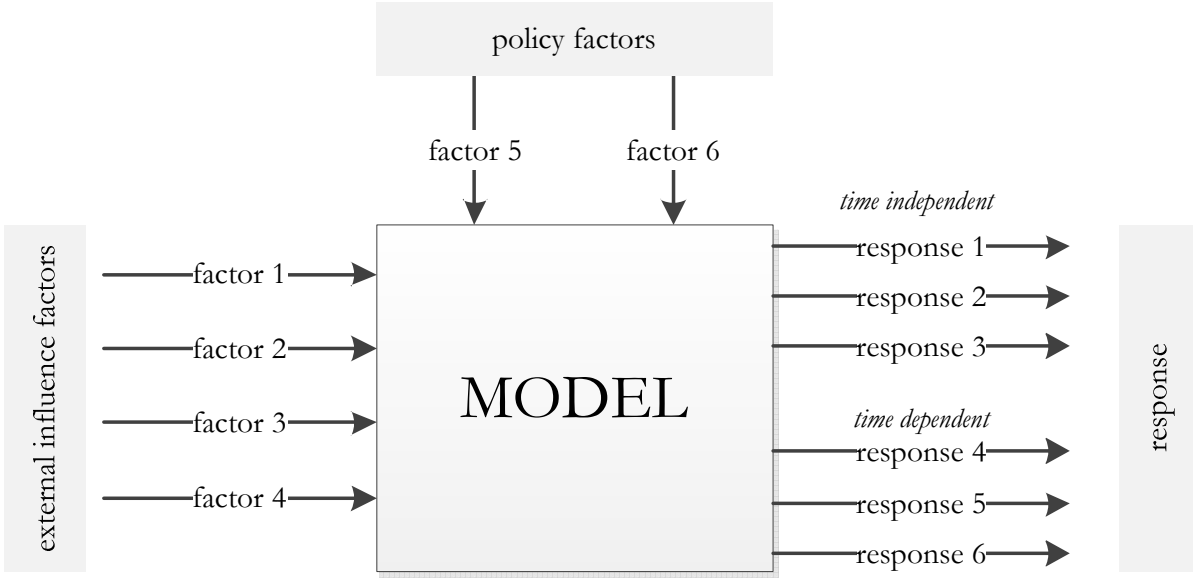


FIGURE 20 OVERVIEW OF FACTORS AND RESPONSES OF THE ECONOMIC IMPACT MODEL FOR SMART GRIDS

5.1.1 OUTPUT DASHBOARD

The output dashboard contains model responses. Responses are any measured output of the model. The studies 6 different responses, and distinguishes 3 time independent and 3 time dependent responses. The time independent responses are one-value outputs over the observed total time horizon (30 years). The time dependent responses are output values observed over the years (see Figure 21).

Time *independent* responses:

- R1: Total Costs [€]

- R2: NPV [€]
- R3: Total Energy Loss [kWh]

Time *dependent* responses:

- R4: Annual Total Cost (t) [€]
- R5: Annual Capex (t) [€]
- R6: Annual Opex (t) [€]

As explained previously, annual total cost is the sum of annual capex and opex, and opex includes only costs associated with energy loss.

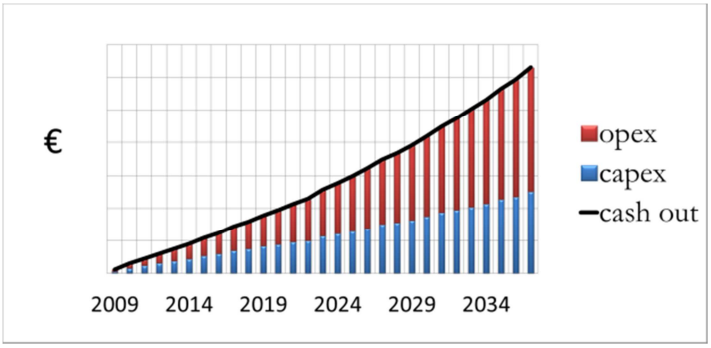


FIGURE 21 REPRESENTATION OF TIME DEPENDENT RESPONSES

5.1.2 INPUT DASHBOARD

The input dashboard contains the input factors, as described in the model conceptualisation. Factors are varied to make observations on how the system responses to this variation. The variation is requirement by levels. All selected factors have *discrete* levels (as opposed to continuous), some are ordinal and others categorical. Categorical levels have no implied order, while ordinal factors do have a position in relation to the.

In coherence with the model conceptualisation, the following factors and their levels are distinguished:

- F1: Energy transition scenario [a|b|c]
- F2: Capacity demand development scenario [linear|s-curve|stepwise]
- F3: Asset price scenario [low|medium|high]
- F4: Electricity price scenario [low|medium|high]
- F5: Smart grid strategy [on|off]
- F6: Grid reinforcement strategy [incremental|radical]

5.1.3 SUB MODELS AND SIMULATION ACTIVITIES

Figure 22 gives an overview of the Economic Impacts Model for Smart Grids. This model consists of four sub models, each sub model is able to simulate multiple assets of one type of physical element: high voltage stations, transport grids, distribution grids, and low voltage stations. Each sub model uses the input of the same input dash board. This enable the model to simulated the total medium-voltage distribution system in the same environmental scenario under the same alternative policy. The model user can use the input dashboard to enter the desired levels of the six factors, and thus determines the environmental scenario and the policy. The response of all sub models is aggregated in one output dashboard, displaying the six responses.

Each sub model consists of four simulation activities. The model conceptualisation of the previous chapter can be recognized in the simulation activities. The simulation activities use inputs of the input dashboard, of the data base, and of lookup tables. Lookup tables are used to collect asset specific information. Outputs of the simulation activities function either as input for a follow up simulation activity, or as information for the output dashboard.

The first simulation activity calculates for each asset the capacity demand each year over the next three decades. It starts with collecting the basic asset information from the data base, and categorization of the assets using a lookup table. It then determines the capacity demand in year 0 and year 30 based on the basic asset information, together with the chosen energy-transition scenario (Factor 1) and the chosen smart grid strategy (Factor 5) in the input dashboard. The capacity demand each year can then be determined using the capacity demand development scenario (Factor 2). The capacity demand each year functions as input for the second simulation activity.

The second simulation activity determines if the asset must be reinforced in order to facilitate the capacity demand. It starts with determination of the nominal capacity of the asset, based on the basic asset information of the previous simulation activity. Then, the assets peak load is calculated using the capacity demand of the previous simulation activity and the nominal capacity. Finally, it is determined if reinforcement is needed, based on a comparison of the assets peak load and the load threshold. The load threshold is selected from the lookup table, taking the smart grid strategy into account (Factor 5). If the assets peak load exceeds the load threshold, the asset is reinforcement according to the chosen grid reinforcement strategy (Factor 6). A lookup table is used to determine the type of reinforcement and the accompanying added nominal capacity. If the asset is reinforced, the nominal capacity is adapted and the reinforcement type functions as input for the third simulation activity.

The third simulation activities calculates the capital expenditures related to the asset as a result of asset reinforcement. It collects information on the type of reinforcement, the asset price scenario (Factor 3) and a lookup table of the costs of the different type of reinforcements. The calculated capital expenditure functions as information for the aggregated response in the output dashboard.

The fourth simulation activity calculates the energy loss and accompanying operational expenditures of the asset. The energy loss is based on the nominal capacity of the asset and its assets peak load (determined in simulation activity 2). The energy loss can be calculated using a lookup table in the energy loss associated with the type of asset. Another lookup table is used to determine the duration of peak loss, in coherence with the chosen smart grid strategy (Factor 5). The calculated energy loss of the asset is collected by the output dashboard. The operational expenditures are calculated multiplying the energy loss with the electricity price, which depends on the electricity price scenario (Factor 4). The operational expenditures functions as information for the output dashboard.

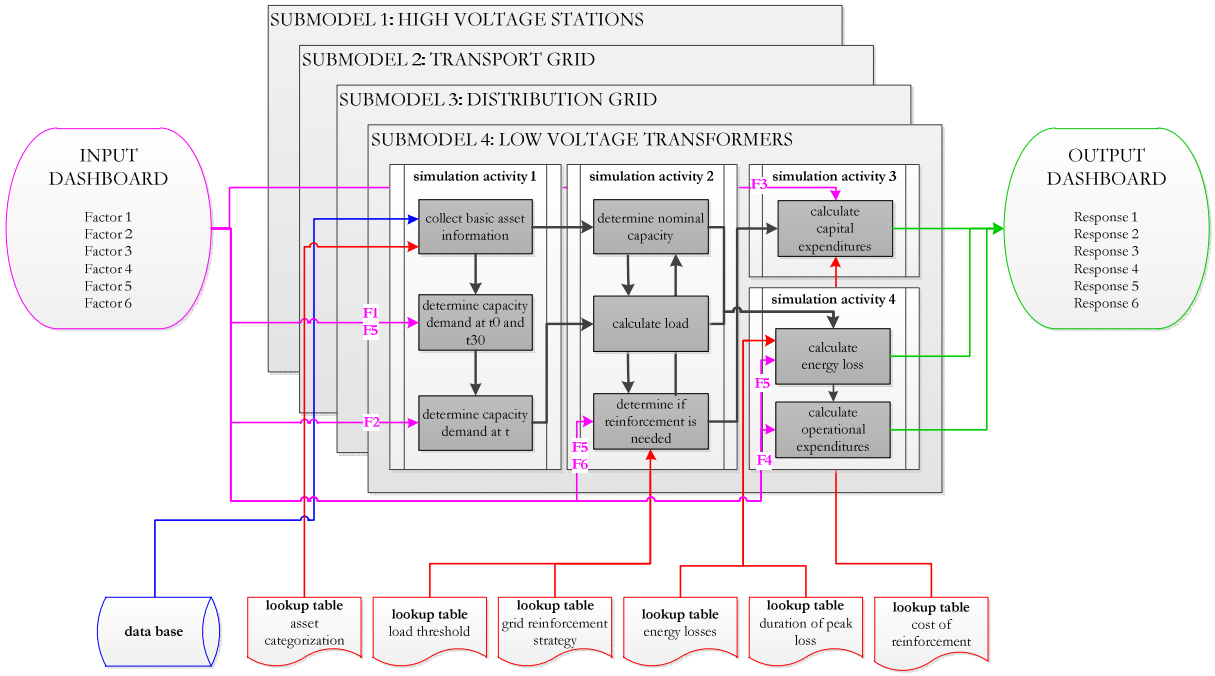


FIGURE 22 OVERVIEW OF THE ECONOMIC IMPACT MODEL FOR SMART GRIDS

The Economic Impact Model for Smart Grids is developed according to the model structure as described in this paragraph. Before it is ready for simulation, it is verified and validated in the next two paragraphs.

5.2 VERIFICATION



This paragraph evaluates if the model is programmed correctly and if the model works as expected. During model development, was continuously determined if the model specification was complete and if the model logic was correct. In the case that modelling objects or relations were missing, they were added to the model conceptualisation. Model development thus led to a constant feedback loop on both model conceptualisation and the model structure. The automated trace program on precedents and dependents supported the evaluation of relations between factors. Furthermore, all modelling objects were assigned a dimension. Dimension analysis was thus inherent to the modelling process. An example of a dimension analysis is presented in Appendix VII.

During model development, the model was continuously corrected for programming errors and bugs. The simulation software allowed automated error checking, such as trace errors and circular references. Formulas that resulted in errors were not accepted, as invalid data that was entered. The software also checked for consistency, and warned if formulas were inconsistent with other formulas in the region. Model verification proceeds as more simulations are done. Parallel to model development test simulations were done to see if the model responses as expected. The model has passed the verification tests.

5.3 VALIDATION

The purpose of the validation step is to determine if the model developed is useful to answer the questions it was designed to answer. There are basically two types of validation: replicative validation and structural validation. Replicative validation encompasses the comparison of model output with the output of the real life system the model represents. Structural validation is aimed at confirming the validity of the model structure. There are several forms of structural validation. Direct structure tests validate the model logic without the model running. Examples are structure and parameter checks and face validation by

experts. Structure oriented behaviour tests require experimentation with the model. Examples are extreme conditions tests, sensitivity analysis, and comparison with accepted theory.

This research does both replicative validation and structural validation. During the replicative validation model output is compared to the real life system of the DSO. Structural validation is done by face validation by experts and extreme conditions tests.

5.3.1 REPLICATIVE VALIDATION

First, the annual amount of reinforcement projects calculated by the Economic Impact Model for Smart Grids are compared to the actual number of a Dutch DSO. The DSO reinforces on average 10.0 high voltage transformers a year, the model 10.0, so this number is very similar. The amount of kilometres medium voltage grid (both transport and distribution) that the DSO annually reinforces 570 km compared to a 720 km grid in real life. This means that the model slightly underestimates the amount of grid reinforcements. DSO reinforces about 1000 low voltage transformers a year, compared to 606 in the model. In this case the model also underestimated the amount of reinforcements. However, it can be stated that the model has similar amount of reinforcement projects in terms of magnitude. If we take a look at the distribution of reinforcement project, the model seems to be very realistic. The amount of high voltage station reinforcement is only 2%, which makes sense because there is a relatively small amount of these stations (Figure 23). The share of the low voltage station reinforcement is by far the largest, which also makes sense because there are a lot of these type of stations. Therefore the model is considered valid with respect to the amount of reinforcement projects.

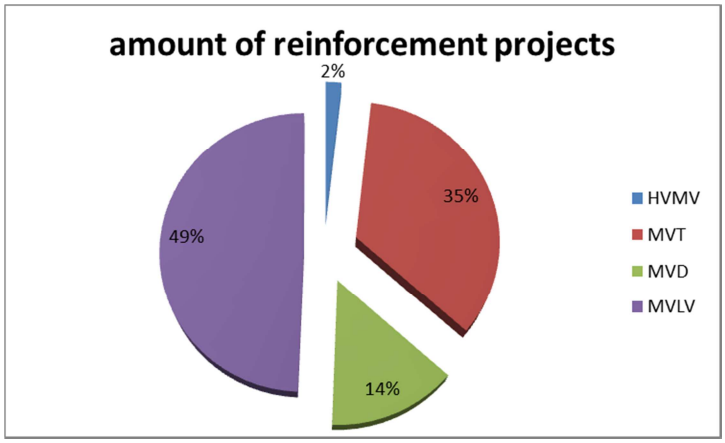


FIGURE 23 DISTRIBUTION OF REINFORCEMENT OF PROJECTS AMONGST GRID PARTS

Secondly, the annual capex of the model is compared to the actual annual capex of the DSO. The model has an average annual capex of €130 million (Figure 24). In real, the DSO spends about €162 million a year on grid reinforcement. Since the magnitude of these figures is thus the same. If we take a look on the distribution of costs amongst the different grid parts, it can be concluded that most capital expenditures are spent on the distribution grid, and least on the low voltage transformers. This is in line with the capital expenditure portfolio of the DSO. The model is considered valid for the annual capex.

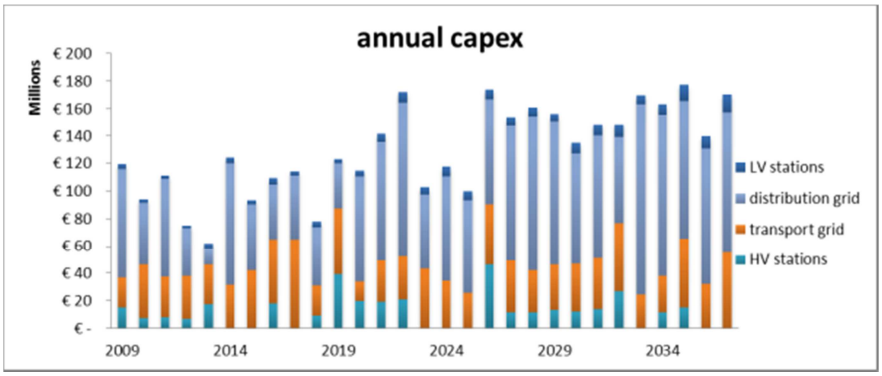


FIGURE 24 ANNUAL CAPEX ESTIMATION BY MODEL

Thirdly, the annual opex is compared. According to the model, the average annual opex is €130 million (Figure 25). The DSO spends on average €110-120 million on energy loss. The difference is less than 15%, and the modelled values are considered valid. The distribution of opex is even amongst the different grid parts, though the expenditure is slightly lower for high voltage stations. The energy loss costs of the DSO are in real distributed in a similar way. The figures are thus very similar and the model is considered valid for the annual opex.

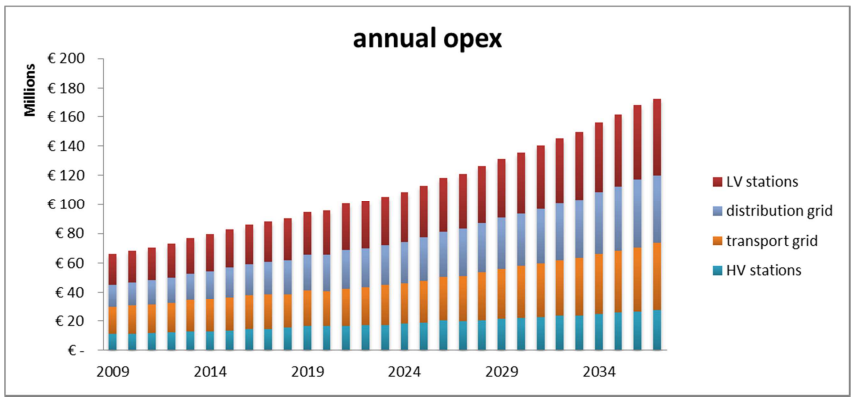


FIGURE 25 ANNUAL OPEX

The model is considered valid based on replicative validation.

5.3.2 STRUCTURAL VALIDATION

The model is evaluated using an expert panel throughout model development. The expert panel includes specialists of the DSO (strategy developers, business analysts, and innovators). The model structure was tested by explain the model logic, and with an open attitude for improvements. The questions and criticism of the experts was carefully processed during the research. The model was also face validated by allowing the experts to do some experiments. They could observe how the system responded to different inputs. The observations involved not only the responses as described in the model structure, they were also able to look at other responses, such as the average load of different assets, the amount of reinforcement per grid part, or the capital expenditures associated with one asset. Because the feedback of the expert is processed during the model development, the model is considered valid by face validation.

The model is furthermore structurally validated doing an extreme value analysis. Three tests are done and compared to the actual model output, visualised in Figure 26. The first test involved an extreme value of the discount rate used to calculate NPV. During this test the discount rate was set on 200%. This means that the NPV must decrease dramatically, because future expenditures are discounted extremely over the

years. Figure 27 shows that such an extreme value coincides with a strong decrease of present values (green line). The NPV is €2.7 billion under a discount rate of 4%, compared to a NPV of €18.5 million under a discount rate of 200% (Figure 27).

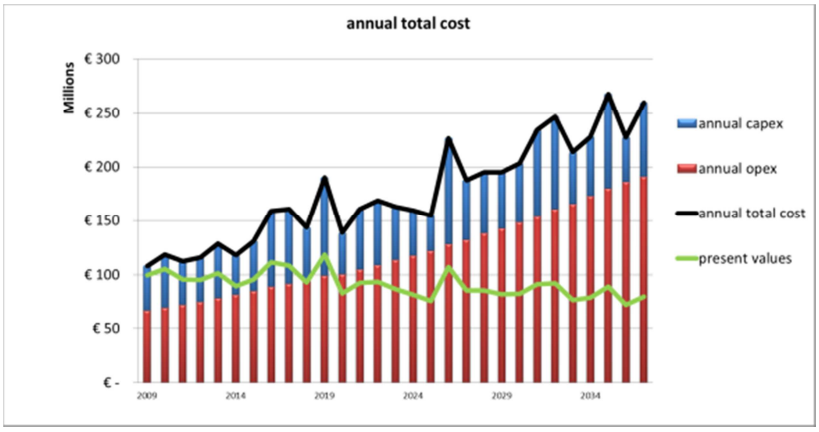


FIGURE 26 MODEL OUTPUT

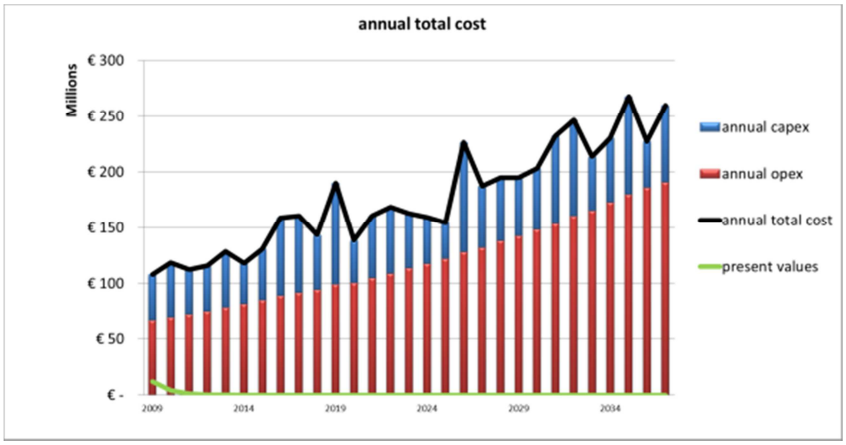


FIGURE 27 EXTREME VALUE ANALYSIS DISCOUNT RATE NPV

The second test involved the an extreme value of the load threshold. During this test the load threshold was set on 30%. This means that all assets must be reinforced, which should lead to a dramatic increase of total costs. The graph in Figure 28 shows that in these extreme situation, the annual total are increased extremely: from €200 million to €12 billion. As expected, this is due to an extreme increase of capex.

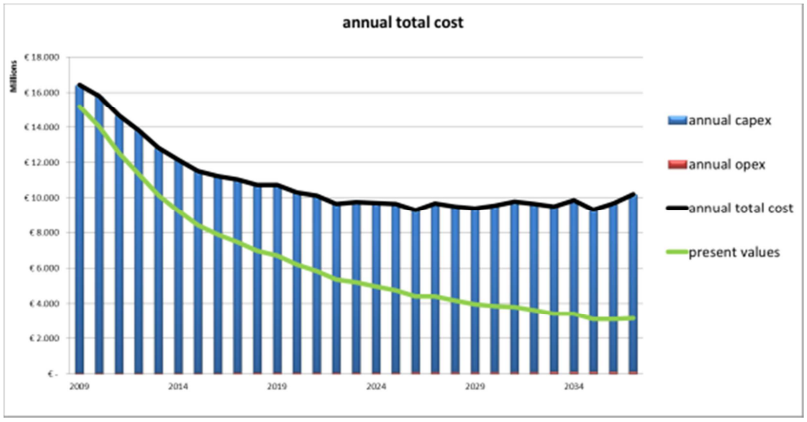


FIGURE 28 EXTREME VALUE ANALYSIS LOAD THRESHOLD

The third test involved an extreme value of the asset price scenario. The annual asset price increase was set on 50%. This means that the asset price increases by 50% each year. The expected result is that capex increases dramatically. The graph in Figure 29 shows that the annual total cost increases dramatically (from €200 million to €6.2 billion), due to an extreme capex increase. The total cost curve is not visible until 2025, because the previous annual total cost were too low compared to the extreme total cost after 2025. This can be explained by the exponential character of the asset price increase.

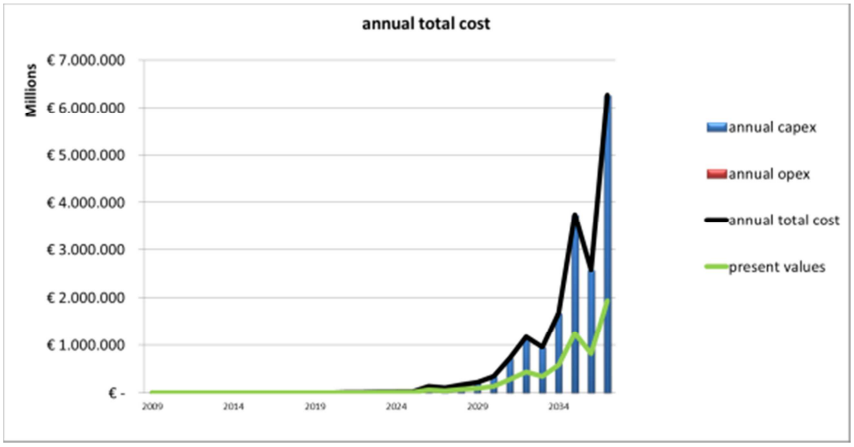


FIGURE 29 EXTREME VALUE ANALYSIS ASSET PRICE SCENARIO

The extreme value analysis showed results in coherence with the expectations. The model is therefore considered valid based on an extreme value analysis.

INTERMEZZO II

Part II introduced the Economic Impact Model for Smart Grids. This model that is able to simulated how different environmental scenarios and alternative policies have impact on the system goals. The verified and validated model can now be used for simulation.

Part III describes the results of simulation using the Economic Impact Model for Smart Grids. It starts with describing the design of experiments that are performed in order to get insight in system behaviour. It then presents the simulation results and analyses, and gives explanations for the observations. Hereafter, a further exploration is done to get further insight in the impact of smart grids only. The insights of this part are used to define conclusions and recommendations.

PART III SIMULATION

CHAPTER 6 RESULTS

The previous part introduced the Economic Impact Model for Smart Grids. This model is used for simulation. The focus of the simulation exercise is on the response of the system to environmental changes and policy changes. This chapter presents and analyses the results of simulation.

The design of experiments can be found in Appendix VIII. The model includes 81 different environmental scenario settings and four alternative policy settings. This means that the model is able to simulate 324 situations. In order to define relevant conclusions, a systematic simulation approach is needed. The design of experiments includes a detailed description of the experiments and analyses that are done, and the accompanying model settings. The different analyses are therefore only briefly described.

First, it is analysed how the system responses in different environmental scenarios. Therefore, an environmental analysis is done under the base policy. This analysis changes the model settings of the external influences, and keeps the policy settings constant. Based on this analysis, conclusions can be made on what the estimated consequences of the different environmental scenarios is on economic and sustainability objectives of the DSO. Furthermore the base environmental scenario is defined based on this analysis.

Secondly, it is analysed how the system responses to alternative policies, in the base environmental scenario. An alternative policy analysis is done, exploring the estimated impacts of the four alternative policies. This analysis changes the model settings of the alternative policies, and keeps the environmental scenario settings constant. Based on this analysis, conclusions can be made on what the impact of the alternative policies is on the economic and sustainability objectives of the DSO.

Thirdly, the interactions between the different environmental scenario and the alternative policies are analysed. This is done by a full factorial analysis, which means that all combinations of environmental scenarios and alternative policies are analysed. This analysis includes all possible model settings of the environmental scenarios and policies. Based on this analysis, it is determined which interactions effects are interesting for further exploration. The further exploration changes a fraction of the model settings. Based on this analysis, insight is given in overall system behaviour.

In coherence with this design of experiments, this chapter consists of three paragraphs. Paragraph 6.1 presents the environmental analysis. Paragraph 6.2 continues with the alternative policy analysis. Paragraph Appendix XI presents the analyses of interactions.

6.1 ENVIRONMENTAL SCENARIO ANALYSIS

The objective of this paragraph is to understand what the consequences of different environmental scenarios are on the economic and sustainability objectives of the DSO. An environmental scenario consists of an interpretation of each of the four identified external influences.

The environmental analysis identifies the impact of each external influence on the system response. An experiment changes the settings of one external influence, while keeping the settings of the other external influences constant. All experienced are done under the base policy, defined as the smart grid off strategy and the incremental grid reinforcement strategy. Appendix VIII presents a more detailed the design of experiment of this analysis.

Each of the next four sections presents the impact of one external influence (e.g. energy-transition scenario, capacity demand development scenario, asset price scenario is analysed, electricity price scenario). Finally, some concluding remarks are given based on insights on the environmental scenarios.

6.1.1 THE IMPACT OF THE ENERGY-TRANSITION SCENARIO

In this analysis the impact of the different energy-transition scenarios is analysed. Table 4 shows the responses related to the different energy-transition scenarios.

energy-transition scenario	total costs [billion €]	total cost ratio	NPV [billion €]	NPV ratio	capex:opex [-]	energy loss [billion kWh]
A	7.0	1	3.7	1	1.0	26.2
B	24.0	3.4	12.2	3.3	3.1	34.3
C	13.0	1.9	6.7	1.8	2.0	27.1

TABLE 4 IMPACT ENERGY-TRANSITION SCENARIOS

The total costs of the power distribution grid over the observed time horizon of three decades is €7.0 billion in energy-transition scenario A, compared to €24.0 billion in scenario B, and €13.0 billion in scenario C. The capex-opex ratio can be used to estimate the magnitudes of capex and opex. The first conclusion is that facilitation of the future energy supply systems is associated with significant costs. In the most conservative energy-transition scenario (i.e. scenario A), the estimated capex is €3.5 billion. Compare this to the annual capex of a DSO in 2010 of €131.3 million, which includes geographical expansion and grid reinforcement[5]. Assuming that 50% of this capex is grid reinforcements, the capex of this DSO over the observed time horizon would be €2.0 billion. This means that even the most conservative energy-transition scenario is associated with a 75% capex increase compared to the current capex of the DSO.

The different energy-transition scenarios can be compared by the total cost ratio (i.e. the total costs value in relation to the total costs value of energy-transition scenario A). The total costs associated with energy-transition scenario B is 3.4 times the total cost in scenario A, a very significant difference. The difference between energy-transition scenarios A and C is smaller, but still significant, as scenario C leads to a total costs of 1.9 times the total costs if scenario A. These observations can be explained by the assumptions behind the energy-transition scenarios, determined by other research (Grond, 2011; Schepers, 2011). Energy-transition scenario A was associated with a low economic growth and little integration of new energy technologies. This leads to the smallest economic consequences for the DSO. Energy-transition scenario B on the other hand, was associated with a high economic growth and a high penetration of new technologies. This energy-transition scenario leads to the highest economic consequences. Scenario C was associated with a medium economic growth and a high penetration of technologies, which results in economic consequences that lay in between the economic consequences of scenarios A and B. Since energy-transition scenario B and C were both associated with a high penetration of new technologies, and scenario B leads significant higher total costs, it can be concluded that the total costs of the distribution grid are mainly caused by the excessive economic growth and the high share of customer demand.

The NPV is significantly smaller, ranging between €3.7 and €12.2 billion. The lower magnitude of the NPVs can be explained by the fact that future investments are discounted over the years. The relative impact of the different energy-transition scenarios in terms of NPV is the same as the impact in terms of total costs. This means that the time value of money does not change the relative impact of the three energy-transition scenarios.

The capex-opex ratio shows furthermore that in energy-transition scenario B capex is more than three times the size of opex, and in scenario C the capex is two times the size of opex. Capex and opex are

[5] Financial statements of the Dutch DSO Enexis

evenly distributed in energy-transition scenario A. The high total cost are apparently caused by a higher capex and thus by a larger amount of grid reinforcements.

The total energy losses over the observed time horizon are on average 29.2 billion kWh, which corresponds with 146.000 ton CO_2 or €2.2 million on CO_2 certificates. Different energy-transition scenarios have a different impact on the energy loss, though the differences between energy-transition scenarios A and C is minimal. Energy-transition scenario B causes the highest energy loss, the energy loss in this scenario B is 30% higher. This can be logically explained by the fact that a higher energy demand leads to a higher electricity transport demand and more energy losses.

The chosen base energy-transition scenario is A. The reason is that this scenario is most comparable with the current energy system. The other environmental scenario analyses will thus be performed in energy-transition scenario A.

The energy-transition scenario has a major economic consequence on the medium voltage distribution system. In a conservative energy-transition scenario (A), the total cost over the next three decades are €7.0 billion, though a more extreme energy demand scenario (B) can multiply these costs with a factor 3.4. The total amount of energy losses over this period is about 29.2 billion kWh.

6.1.2 THE IMPACT OF THE CAPACITY DEMAND DEVELOPMENT SCENARIO

In this analysis the impact of the different capacity demand development scenario is analysed. Table 5 shows the system responses of the different scenarios in energy-transition scenario A (which was chosen as the base scenario in the previous section).

Comparing the responses of in different capacity demand development scenarios shows that this external influence does have economic consequences. The linear scenario leads to the highest total cost, followed by the stepwise and s-curve scenarios. The maximum difference between the scenarios is 20% in terms for both total costs and NPV. The NPV does not lead to different conclusions on the relative impact of different scenarios. The explanation for the high costs associated with the linear scenario is that there are more late stage reinforcements in this scenario. These reinforcement are more costly because of the exponential asset price increase over the years.

capacity demand development scenario	total cost [billion €]	total cost ratio	NPV value [billion €]	NPV ratio	energy loss [billion kWh]
linear	7.0	1.0	3.7	1.0	26.2
s-curve	5.8	0.8	3.0	0.8	26.3
stepwise	6.6	0.9	3.4	0.9	26.7

TABLE 5 IMPACT CAPACITY DEMAND DEVELOPMENT SCENARIOS

To understand the impact of the capacity demand development scenarios, Appendix X shows the cost curves in different scenarios. The scenarios can be clearly recognised in these curves (i.e. having either a linear, an s-curve, or a stepwise pattern). This can be explained by the fact that the capacity demand curve determines how the capacity demand develops over time, reflected by the number of reinforcements over time, which is reflected in capex. The linear scenario leads to high capex in a late stage.

The figures also show that the opex is similar for all three curves, the capacity demand curve does thus not influence the opex. The capacity demand development scenario has no impact on the energy loss. This means that the timing of reinforcements does not impact the total energy loss over the observed time horizon.

The selected base capacity demand development scenario is the s-curve.

> The capacity demand development scenario has an economic impact of maximal 20%. The linear scenario leads to the highest costs, followed by respectively the s-curve and the stepwise scenarios.

6.1.3 THE IMPACT OF THE ASSET PRICE SCENARIO

In this analysis the impact of the different asset price scenarios is analysed. Table 6 shows the responses to the different asset price scenarios in energy-transition scenario A.

asset price scenario	total costs [billion €]	total cost ratio [-]	NPV [billion €]	NPV ratio [-]
low	6.1	1.0	3.3	1.0
medium	7.0	1.1	3.7	1.1
high	8.2	1.3	4.1	1.2

TABLE 6 IMPACT ASSET PRICE SCENARIOS

Comparing the responses of in different asset price scenarios shows that this external influence also has economic consequences. This impact can be explained by the fact that the model calculates capex based on the amount of reinforcements and their price, which includes the asset price scenario.

Figure 30 shows the annual total costs curves for the various asset price scenarios. The difference between the curves becomes larger over the years, which can be explained by the exponential price increase. Within 30 years, the medium asset price scenario will lead to 14% higher total costs, and the high scenario to 32% higher total costs. The NPV will be increased by respectively 12% and 27%.

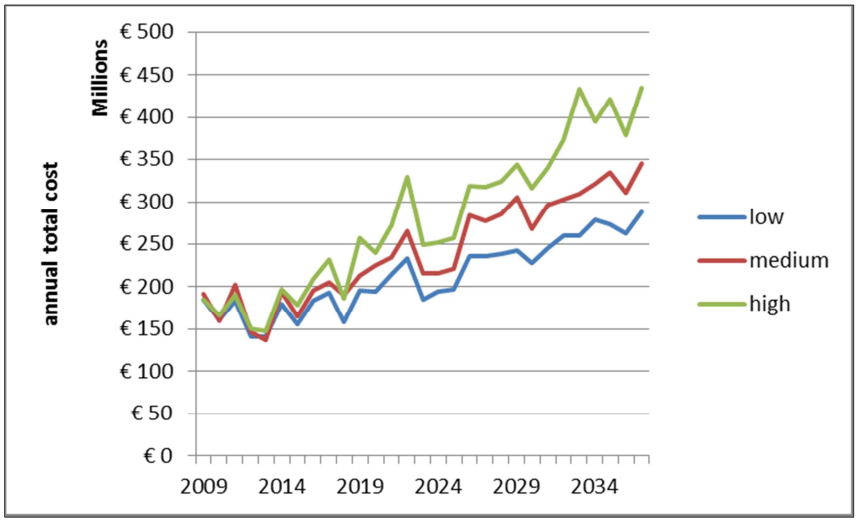


FIGURE 30 ANNUAL TOTAL COST CURVES FOR ASSET PRIE SCENARIOS

The asset price scenario has no impact on the energy loss. This can be logically declared by the fact that there is no causal relation between the asset price and energy loss.

The selected base asset price scenario is medium.

> The asset price scenario has economic consequences; the high asset price scenario increases the total costs of the medium voltage distribution system by 32% compared to a low scenario.

6.1.4 THE IMPACT OF THE ELECTRICITY PRICE SCENARIO

In this analysis the impact of the different electricity price scenarios is analysed. Table 7 presents the system responses for the different scenarios.

electricity price scenario	total costs [billion €]	total cost ratio [-]	NPV [billion €]	NPV ratio [-]
low	6.2	1.0	3.3	1.0
medium	7.0	1.1	3.7	1.1
high	8.0	1.3	4.0	1.2

TABLE 7 IMPACT OF THE ELECTRICITY PRICE SCENARIO

Comparing the responses of in different electricity price scenarios shows that this external influence also has economic consequences. The impact is the result of an increase in opex, because opex is based on the energy loss and the electricity price, including its price increase.

Figure 31 presents the annual total costs for the various electricity price scenario levels. It shows a similar effect as the effect of the asset price scenario: the difference between the curves becomes larger over the year, which can be explained by its exponential character. Within 30 years, the medium electricity price scenario will lead to 13% higher costs, and the high scenario to 28% higher costs. The NPV will be increased by respectively 12% and 27%.

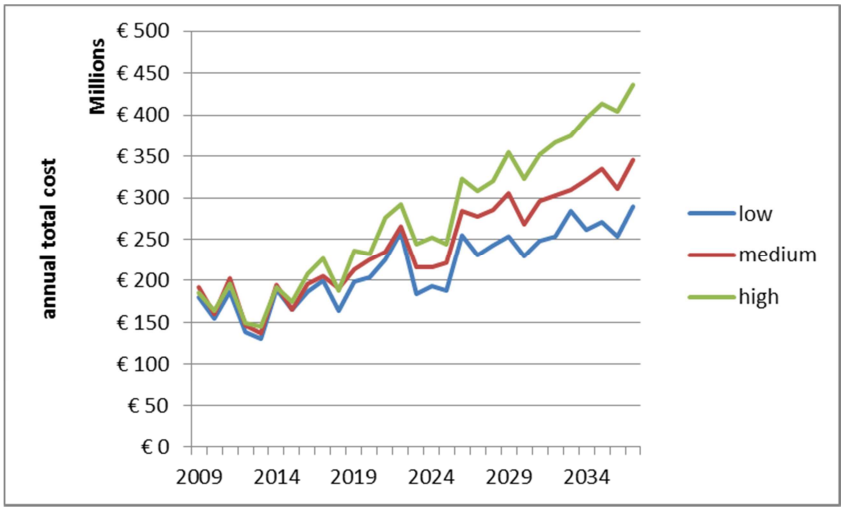


FIGURE 31 ANNUAL TOTAL COSTS FOR ELECTRICITY PRICE SCENARIOS

The electricity price scenario has no impact on the energy loss. This can be logically declared by the fact that there is no causal relation between the electricity price and energy loss.

The selected base electricity price scenario is medium.

> The electricity price scenario has economic consequences; a high electricity price scenario increases the total costs of the medium voltage distribution system by 30% compared to a low scenario.

6.2 ALTERNATIVE POLICY ANALYSIS

The objective of this paragraph is to understand what the impact of the alternative policies on the system responses is. A policy consists of the interpretations of two strategies: the smart grid strategy and the grid reinforcement strategy. Because each strategy has two possible settings (i.e. on/off and incremental/radical), four alternative policies exist:

1. Smart grid *off* strategy in combination with an *incremental* grid reinforcement: *off, incremental*
2. Smart grid *off* strategy in combination with a *radical* grid reinforcement: *off, radical*
3. Smart grid *on* strategy in combination with an *incremental* grid reinforcement: *on, incremental*
4. Smart grid *on* strategy in combination with a *radical* grid reinforcement: *on, radical*

In order to estimate the impact of the alternative policies, the policy settings in the model are changed, while the environmental scenario is kept constant. All experiments are done in the base environmental scenario, which was defined in the previous paragraph. Appendix VIII presents a more detailed the design of experiment of this analysis.

Each of the next three sections presents different responses of the alternative policies (i.e. total costs and NPV, capex, and opex). Finally, some concluding remarks are given based on insights on the alternative policies.

6.2.1 TOTAL COSTS AND NPV

In this analysis the impact of the alternative policies on the total costs and NPV is analysed. Table 8 shows the responses under the four alternative policies.

alternative policy	total costs [billion €]	total cost ratio [-]	NPV [billion €]	NPV ratio [-]
off, incremental	5.8	1.00	3.1	1.00
off, radical	5.6	0.96	3.0	0.97
on, incremental	5.8	0.99	3.1	1.01
on, radical	5.3	0.91	2.8	0.93

TABLE 8 IMPACT ALTERNATIVE POLICIES

Based on the total cost and NPV, the sequence from most to least favourable is:

- on, radical
- off, radical
- on, incremental
- off, incremental

The difference between the alternative policies is very minimal: a maximum difference of 9%. The same conclusion can be made observing the annual total cost curves (Figure 32). Based on this it can be

concluded that the impact of the alternative policies is not visible in the total cost or NPV in the base environmental scenario.

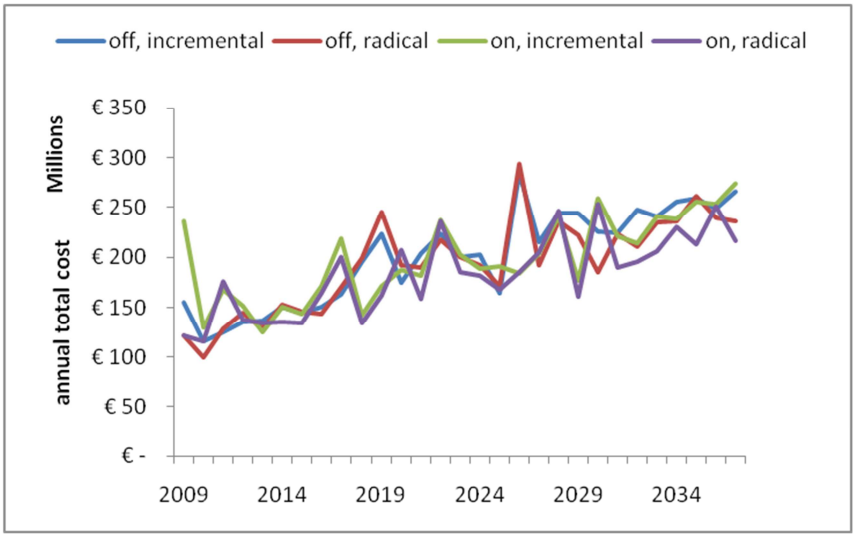


FIGURE 32 TOTAL ANNUAL COST FOR ALTERNATIVE POLICIES

In order to get more understanding of why the impact of the alternative policies is not clearly visible, capex and opex are analysed in the next sections.

The alternative policies have a minimal impact (maximal 9%) on the total costs and NPV in the base environmental scenario.

6.2.2 CAPEX

In this analysis the impact of the alternative policies on capex is analysed.

Figure 33 shows the annual capex curves under the four alternative policies. The difference between a radical and an incremental grid reinforcement strategy is minimal. Based on this it can be concluded that the grid reinforcement strategy does not have a big impact on the capex. This can be caused by a leverage effect of both strategies: a more expensive radical strategy coincides with more additional capacity and thus lower need for future reinforcement costs; a less expensive incremental strategy coincides with less additional capacity and thus a higher need for future investments. Another possible reason is that in the base environmental scenario, too little reinforcements are performed in order to see the effect of the grid reinforcement strategy. It is therefore important to take a look at the impact of this strategy in a different environmental scenario.

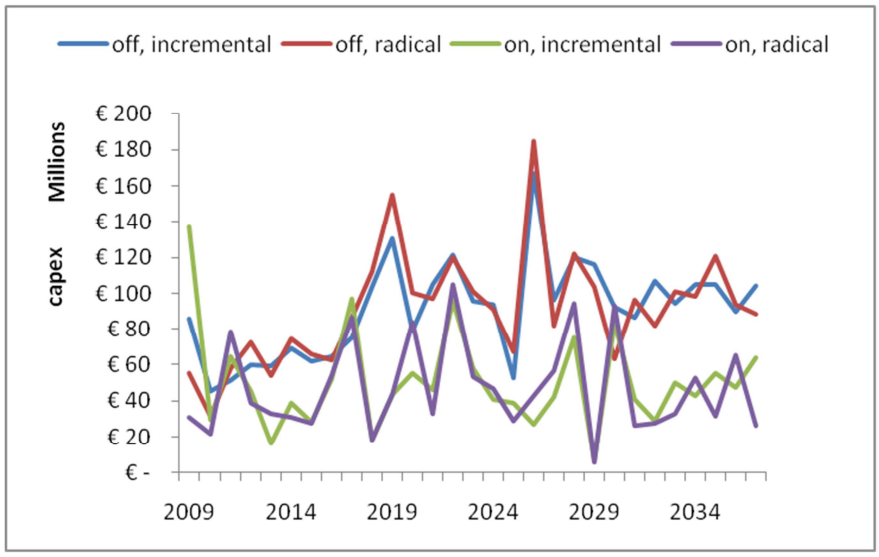


FIGURE 33 ANNUAL CAPEX FOR ALTERNATIVE POLICIES

However, the difference between the smart grid strategies is clearly visible. The smart grid on strategy lowers capex. This can be explained by the fact that load management lowers the peak demand and thus the need for asset reinforcement. Figure 34 shows the accumulated capex over the years. Based on this figure the same conclusions can be made: the grid reinforcement strategy does not have a significant impact on capex, and the smart grid strategy does, with the smart grid on strategy as the most favourable strategy.

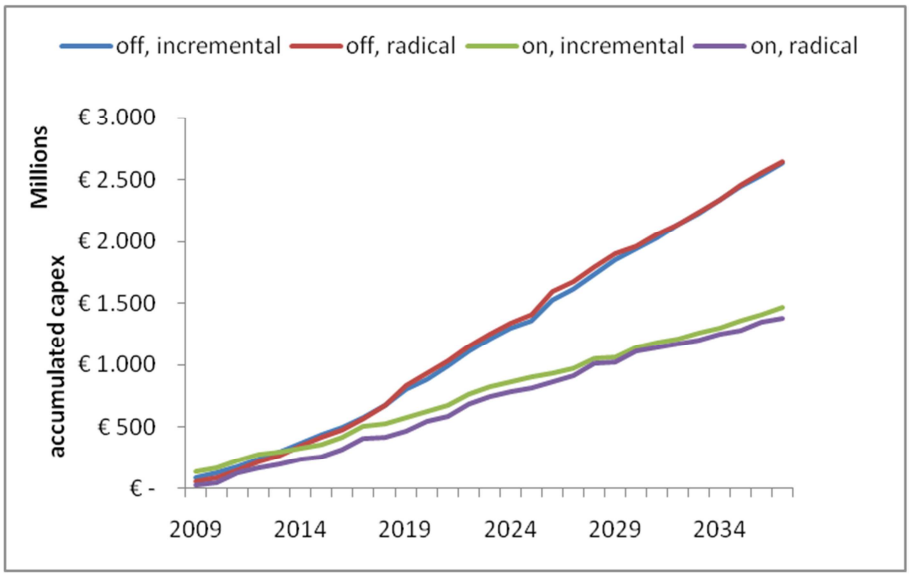


FIGURE 34 ACCUMULATED CAPEX FOR ALTERNATIVE POLICIES

The alternative policies do have an impact on capex. The smart grid on strategy lowers capex, while the grid reinforcement strategy does not seem to have an impact on capex.

6.2.3 OPEX

In this analysis the impact of the alternative policies on opex is analysed.

Figure 35 shows the annual opex curves under the four alternative policies. It can be concluded that a radical grid reinforcement strategy leads lower opex. The explanation for this impact is that a radical grid reinforcement strategy to relatively higher nominal capacities, and thus lower asset peak loads, leading to lower energy losses.

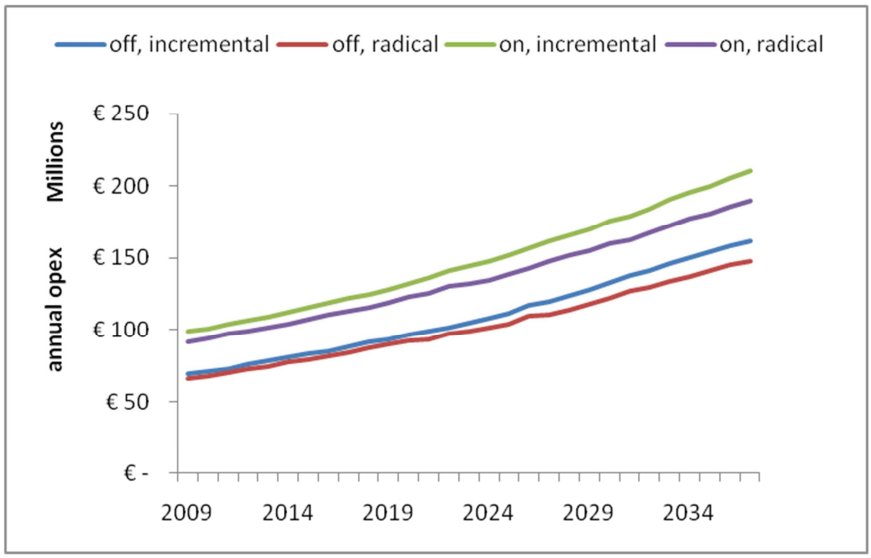


FIGURE 35 ANNUAL OPEX FOR ALTERNATIVE POLICIES

The smart grid on strategy leads to a higher opex. Under the smart grid on strategy, the energy losses increased. The higher energy losses can be explained by the fact that a higher utilization of the existing assets, coincide with more continuous high asset loads, and therefore higher energy losses.

The alternative policies do have an impact opex. The smart grid on strategy and the radical grid reinforcement strategy both lower opex.

6.2.4 CONCLUDING REMARKS ALTERNATIVE POLICY ANALYSIS

In the base environmental scenario, the effect of the alternative policies could not be clearly identified in the total cost and NPV. However, analyses on capex and opex showed that the alternative policies do impact the system. The smart grid on strategy decreases capex and increases opex in comparison to the smart grid off strategy. The grid reinforcement strategy does not have an impact on capex, but the radical grid reinforcement strategy decreases opex.

It can be concluded that in the base scenario, no clear advice can be given as to which policy the DSO should pursue. However, in order to properly evaluate alternative policies, it is important to understand their impact on capex and opex.

The base environmental scenario is associated with energy-transition scenario A. In this scenario, the capex and opex are evenly distributed amongst the total cost (i.e. capex-opex ratio of 1.0). This can be the reason that the positive and negative impacts of the policies were leveraged. It is presumable that the effect of the policies is different in other energy-transition scenarios, since their capex-opex ratios differ.

6.3 INTERACTION EFFECTS

During the environmental scenario analysis and the alternative policy analyses it became clear how the system responses to different environmental scenarios under the base policy, and to alternative policies in the base environmental scenario. However, it did not evaluate system responses to different environmental scenarios and alternative policies at the same time. Therefore, the interaction effects are analysed in this paragraph.

First, the conclusions based on analysis of the full factorial experiment are discussed. The detailed analysis of the experiment can be found in Appendix XI. This analysis gives suggestions for further exploration of the most interesting interaction effects. Then, the results of the further explorations are presented in the following four sections. Finally, the concluding remarks based on analysis of the interaction effects are defined.

6.3.1 RESULTS OF FULL FACTORIAL ANALYSIS

The full factorial analysis observes the system responses to all combinations of inputs (i.e. both environmental scenario and alternative policies), which are 324 observations. Two responses are observed: the total cost and the NPV. The objective of the analysis was to identify which further analyses should be performed to get more insight in the system. The result of this analysis is thus a set of suggestions for further analyses. The analysis of the full factorial experiment can be found in Appendix XI. This paragraph only presents the main results of the analysis: the suggestions for further analyses.

The main conclusion of the full factorial analysis is that the energy-transition scenario has a major impact. Further analyses should therefore take the different energy-transition scenarios into account.

The first suggestion is to get further insight in the impact of the asset price scenario and the electricity price scenario. In the base environment, the impacts of both scenarios were similar. Analysis must show if this is true in varying energy-transition scenarios. In order to get more insight on the impacts of the asset price scenario and the electricity price scenario, it can also be analysed if the impacts differ under different smart grid strategies.

Furthermore, the impacts of the alternative policies seem to differ for each energy-transition scenario, so more insight in the impact of the different strategies in different energy-transition scenarios is needed. Suggestions include analyses of the smart grid strategies in the different energy-transition scenarios, and analyses of grid reinforcement strategies in different energy-transition scenarios. Finally, the impact of the four alternative policies in different energy-transition scenarios should lead to more insight in which policy the DSO should implement.

Based on the full factorial analysis, four analyses are presented in the next four sections:

- the impact of the asset price scenario and the electricity price scenario in different energy-transition scenarios and under different smart grid strategies
- the impact of the smart grid strategy in different energy-transition scenarios
- the impact of the grid reinforcement strategy in different energy-transition scenarios
- the impact of alternative policies in different energy-transition scenarios

Appendix VIII presents a more detailed the design of experiment of these analyses.

6.3.2 ASSET PRICE AND ELECTRICITY PRICE SCENARIOS

The objective of this analysis is to get a further understanding of the impacts of the asset price scenario and the electricity price scenario. It is analysed if the asset price scenario and electricity price scenario have a different impact in different energy-transition scenarios, and under different smart grid strategies.

Asset price scenario

The impact of the asset price scenario on the total costs is largest in energy-transition scenario B, followed by respectively C and A. The impact was similar on capex associated to the three energy-transition scenarios. The opex is not influences by the asset price scenario. The impact of the asset price scenario in different energy-transition scenarios can therefore be explained by the different capex-opex ratios in the different energy-transition scenarios. The higher the capex-opex ratio, the higher the contribution of capex to the total cost, and thus the higher the impact of the asset price scenario on the total cost.

The asset price has a larger impact on total costs under the smart grid off strategy than under the smart grid on strategy. A smart grid on strategy decreases capex, while increasing opex. This means that under the smart grid on strategy, the capex-opex ratio is decreased. This effect lowers the impact of the asset price scenario on total cost.

Electricity price scenario

The impact of the electricity price scenario is largest in energy-transition scenario A, followed by respectively C and B. The electricity price scenario has no impact on capex. Again, the different impacts of the electricity price scenarios in the different energy-transition scenarios can therefore be explained by the capex-opex ratio. The higher the capex-opex ratio, the lower the contribution of opex to the total cost, and thus the lower the impact of the electricity price scenario on total cost.

With regard to the smart grid strategy, the electricity price has a larger effect under the smart grid on strategy than in the smart grid off strategy. A smart grid on strategy increases opex, while decreasing capex. This means that under the smart grid on strategy, the capex-opex ratio is increased. This increases the impact of the electricity price scenario on total cost.

Concluding remarks

The impacts of the asset price scenario and the electricity price scenario on the total cost depend on capex-opex ratio. A high ratio increases the impact of the asset price, and a low ratio increases the impact of the electricity price. The impacts of the asset price scenarios and the electricity price scenarios differ in different energy-transition scenarios because their capex-opex ratios differ. Because a smart grid on strategy increases opex, and therefore decreases the capex-opex ratio, the electricity price becomes more impactful under this strategy while the asset price becomes less impactful under this strategy.

6.3.3 SMART GRID STRATEGY AND ENERGY-TRANSITION SCENARIO

The objective of this analysis is to determine if the smart grid strategy has a different impact in different energy-transition scenarios. This allows us to understand which smart grids strategy is best in which energy-transition scenario.

Total costs

Based on the total cost, it can be concluded that the smart grid on strategy is beneficial in energy-transition scenarios A and C (Table 9). In energy-transition scenario A the savings are €690 million, a 10%

decrease. In energy-transition scenario C the savings are €2.268 million, a 17% decrease. However, the smart grid on strategy is not beneficial in energy-transition scenario B. The strategy leads to a €593 million total cost increase, a 2.5% increase. This means that the smart grid on strategy is not beneficial in all energy-transition scenarios.

energy-transition scenario	smart grid off strategy	smart grid on strategy	absolute difference	marginal difference
A	€7.0 billion	€6.3 billion	- €690 million	**- 10%**
B	€24.0 billion	€24.7 billion	+ €593 million	**+ 3%**
C	€13.2 billion	€11.0 billion	- €2.268 million	**-17%**

TABLE 9 TOTAL COST IN DIFFERENT ENERGY-TRANSITION SCENARIOS AND UNDER DIFFERENT SMART GRID STRATEGIES

Figure 36 shows the annual total cost curves in the three energy-transition scenarios. The graphs show that in energy-transition scenario A and C the smart grid on strategy is more beneficial (as the red line lays under the blue line). In energy-transition scenario B, the lines are very near to each other.

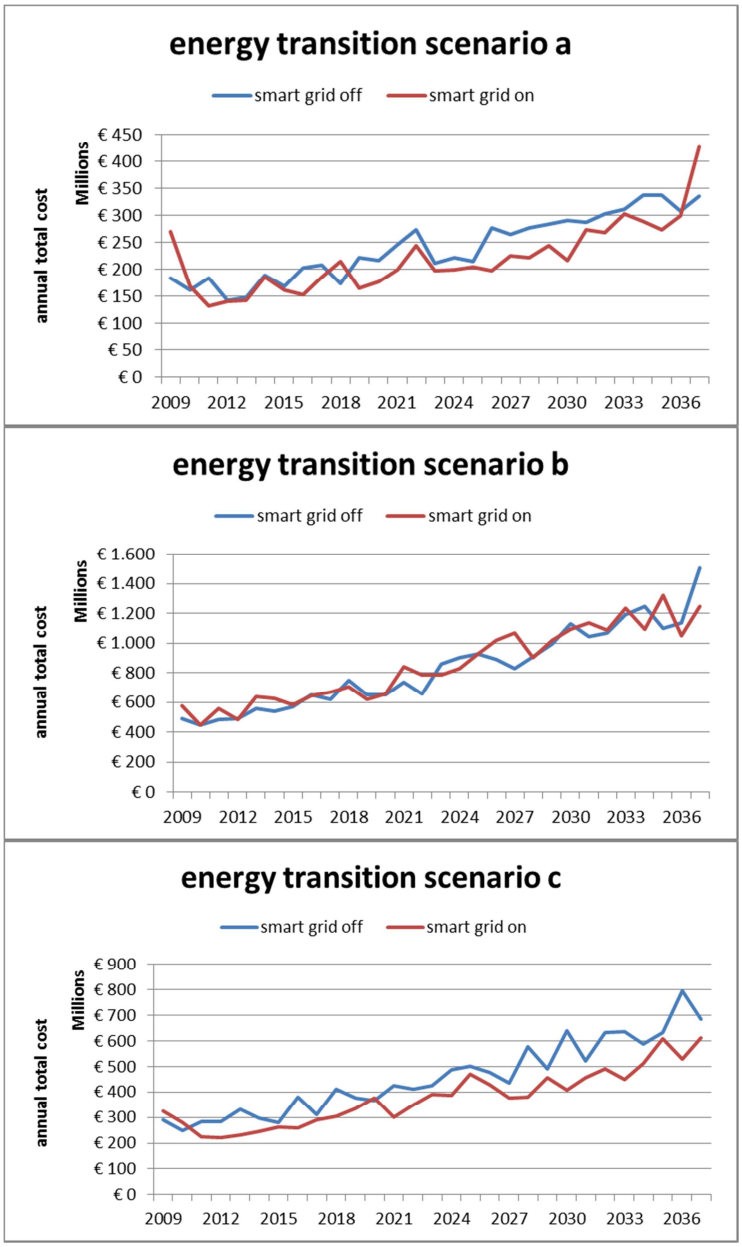


FIGURE 36 ANNUAL COSTS CURVES FOR SCENARIO A, B AND C

NPV

The NPV shows similar results as the total costs: the smart grid on strategy is beneficial in energy-transition scenarios A and C, and not beneficial in scenario B (Table 10). The absolute difference of NPV in energy-transition scenarios A and C can be interpreted as the value of smart grids over the next three decades, if we take the time value of money into account.

energy transition scenario	smart grid off strategy	smart grid on strategy	absolute difference	marginal difference
A	€3.7 billion	€ 3.4 billion	€ -268 million	-7%
B	€12.2 billion	€ 12.5 billion	€ 345 million	+3%
C	€ 6.7 billion	€ 5.7 billion	€ -977 million	-15%

TABLE 10 NPV IN DIFFERENT ENERGY-TRANSITION SCENARIOS AND UNDER DIFFERENT SMART GRID STRATEGIES

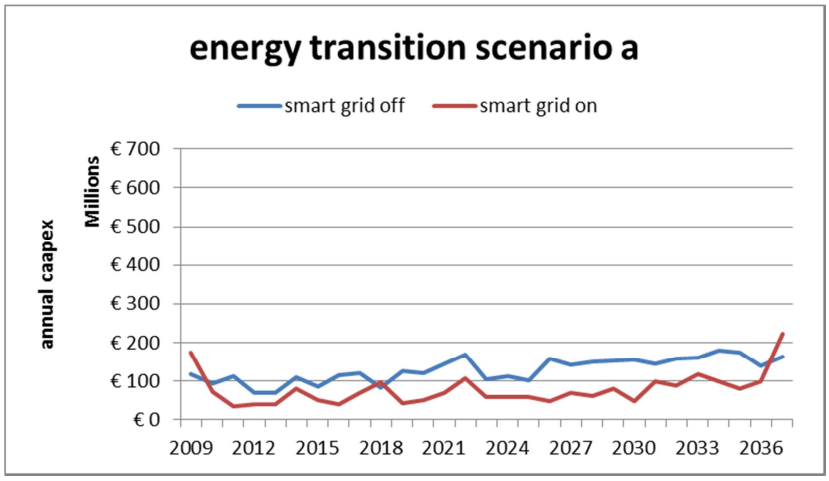
Annual capex

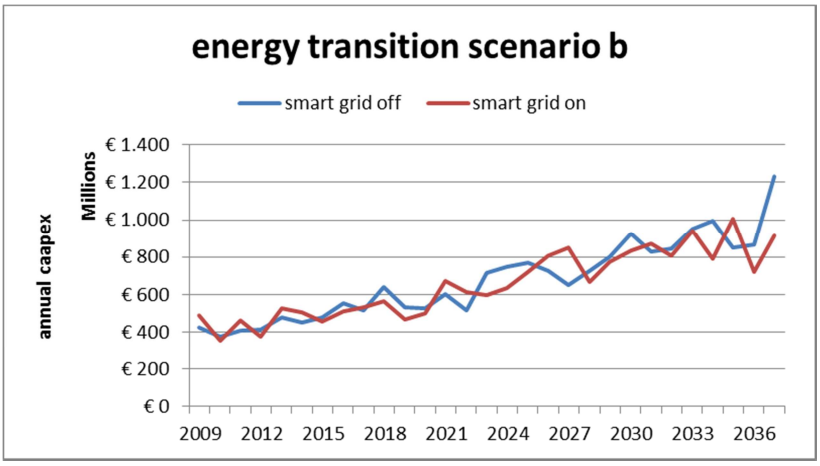
The smart grid on strategy leads to capex savings in all three energy-transition scenarios (Table 11). The impact is largest in energy-transition scenario A, in which 40% capex is saved, corresponding with an annual amount of €51.2 million. In energy-transition scenario C, annual capex is decreased by 30%, corresponding with an annual amount of €102.0 million. The impact of the smart grid strategy in energy-transition scenario B is very small: only 3% annual capex is saved in this scenario (€51.2 million)

energy transition scenario	smart grid off strategy	smart grid on strategy	absolute difference	marginal difference
A	€ 129 million	€ 78 million	- €51 million	**-40%**
B	€ 674 million	€ 654 million	- €20 million	**-3%**
C	€ 336 million	€ 234 million	- €102 million	**-30%**

TABLE 11 ANNUAL CAPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS AND UNDER DIFFERENT SMART GRID STRATEGIES

Figure 37 shows the annual capex curves in the three different energy-transition scenarios, under the smart grid on and smart grid off strategy. The annual capex under the smart grid on strategy is clearly lower than smart grid off strategy in energy-transition scenarios A and C, as the smart grid on curve lays on or under the smart grid off curve. For energy-transition scenario B it is less distinct which strategy is more beneficial, as both curves lay very close to each other.





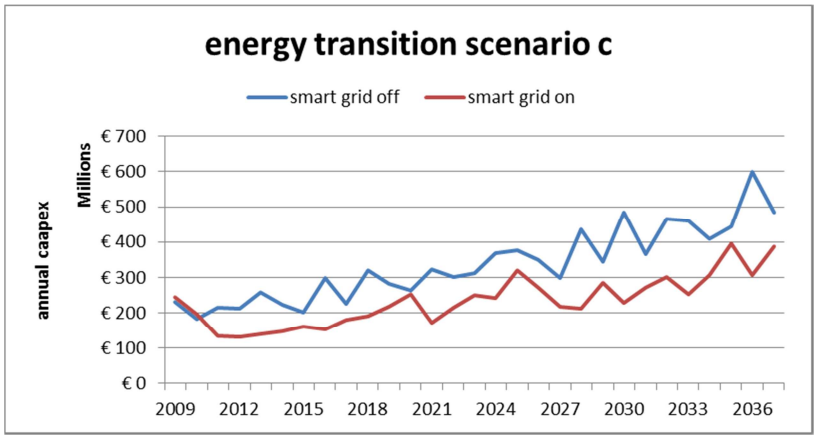


FIGURE 37 CAPEX CURVES FOR ENERGY TRANSITION SCENARIOS A,B AND C

The decrease in annual capex can be explained by the peak shaving effect of the smart grids on strategy. Peak shaving lowers the capacity demand during peak hours, by shifting non-time critical demand to off-peak hours. A lower capacity demand means a lower asset load, and thereby a lower reinforcement need. Reinforcements are postponed, or even eliminated.

The question is why the effect of the smart grid on strategy is not significant in energy-transition scenario B. The expected cause is the fact that this energy-transition scenario was associated with a high increase of customer demand, which was assumed to be non-flexible. In combination with the high demand increase, this leads to a high need for reinforcements, while its flexibility is limited. Therefore, the impact of load management on capex is limited.

Annual opex

In all three energy-transition scenario's, the annual opex is increased under the smart grid on strategy (Table 12). In energy-transition scenario A, the annual opex is increased by 27% (€30.4 million), in energy-transition scenario B by 26% (€40.1 million), and in energy-transition scenario C by 20% (€23.9 million). The high capacity demand in energy-transition scenario B corresponds with more grid capacity, and thus more energy losses.

energy transition scenario	smart grid off strategy	smart grid on strategy	absolute difference	marginal difference
A	€ 111 million	€ 142 million	+ € 30 million	**+ 27%**
B	€ 156 million	€ 196 million	+ € 40 million	**+ 26%**
C	€ 120 million	€ 144 million	+ € 24 million	**+ 20%**

TABLE 12 ANNUAL OPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS AND UNDER DIFFERENT SMART GRID STRATEGIES

Figure 38 shows the annual opex curve, over the observed time horizon, in energy-transition scenario C. The annual opex curve looks similar in the two energy-transition scenarios. The curves have a similar smooth, exponential shape (referring to the percentage annual electricity price increase), without any peaks. The exponential shape can be logically explained by the annual increasing electricity price.

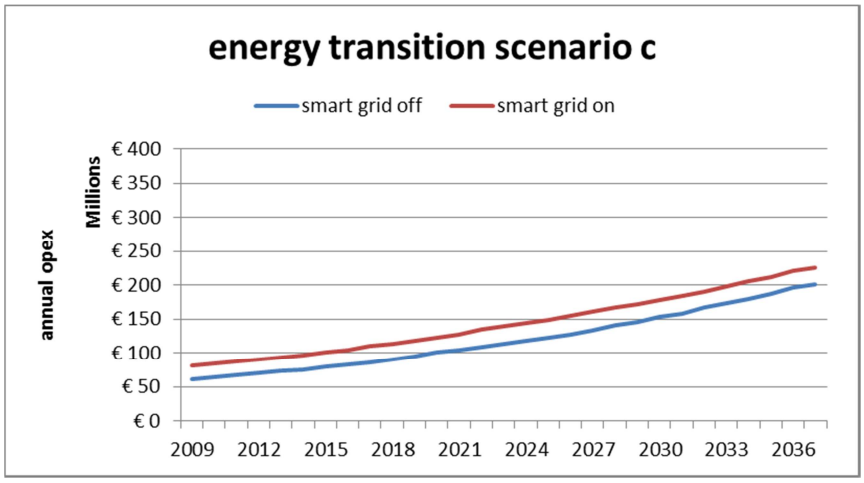


FIGURE 38 ANNUAL OPEX CURVE FOR ENERGY TRANSITION SCENARIO C

The increase in opex under the smart grid on strategy can be explained the fact that a smart grid on strategy increases the utilization of the existing assets. This means, that the asset load becomes higher and more continuous. This increases the duration of the (lowered) peak, or increases the duration of peak loss. This leads to higher energy losses, and thus to higher opex.

Concluding remarks

The objective of this analysis was to determine if the smart grid strategy has a different impact in different energy-transition scenarios. Analysis shows that the mart grid on strategy is beneficial in energy-transition scenario A and C, and not beneficial in energy-transition scenario B. The smart grid on strategy is thus not always more advantageous than the smart grid off strategy.

However, looking at capex, the smart grid on strategy is beneficial in all three energy-transition scenarios. This is the result of peak shaving, lowering the need for costly reinforcements. The smart grid on strategy increases opex in all three energy-transition scenarios, which explains why the smart grid strategy is not only economically beneficial.

6.3.4 GRID REINFORCEMENT STRATEGY AND ENERGY-TRANSITION SCENARIO

The objective of this analysis is to determine if the grid reinforcement strategy has a different impact in different energy-transition scenarios. This allows us to understand which grid reinforcement strategy is best in which energy-transition scenario.

Total costs

The radical grid reinforcement strategy decreases the total cost in all three energy-transition scenarios (Table 13). It has the largest impact on energy-transition scenario B in which the total cost were decreased by 19%, corresponding with €4.7 billion. In energy-transition scenario C, it decreases the total cost by 13%, corresponding with €1.8 billion. In energy-transition scenario A, it decreases the total cost by 4%, corresponding with €286 million.

energy transition scenario	incremental strategy	radical strategy	absolute difference	marginal difference
A	€ 7.0 billion	€ 6.8 billion	- €286 million	**-4%**
B	€ 24.0 billion	€ 19.4 billion	- €4.679 million	**-19%**
C	€ 13.3 billion	€ 11.5 billion	- €1.766 million	**-13%**

TABLE 13 TOTAL COST IN DIFFERENT ENERGY TRANSITION SCENARIO UNDER DIFFERENT GRID REINFORCEMENT STRATEGY

This means that based on evaluation of the total cost, the radical grid reinforcement strategy is more beneficial than the incremental strategy in all three energy-transition scenarios. This can be explained by the fact that although a radical reinforcement is more expensive, it also coincides with a heavier upgrade. This leads to the postponement or elimination of a following upgrade. Apparently, the additional nominal capacity is worth its additional costs.

NPV

The NPV results are comparable to the total costs results. The radical grid reinforcement strategy is most beneficial in all three energy-transition scenarios (Table 14). This means, that even if the time value of money is taken into account, the radical strategy is more beneficial.

energy transition scenario	incremental strategy	radical strategy	absolute difference	marginal difference
A	€ 3.7 billion	€ 3.6 billion	-€ 75.0 million	-2%
B	€ 12.2 billion	€ 10.3 billion	-€ 1.865 million	-15%
C	€ 6.7 billion	€ 6.2 billion	-€ 519 million	-8%

TABLE 14 NPV IN DIFFERENT ENERGY TRANSITION SCENARIO UNDER DIFFERENT GRID REINFORCEMENT STRATEGY

Annual capex

Table 15 shows that a radical grid reinforcement strategy decreases the annual capex in all three energy-transition scenarios. The impact is the biggest in energy-transition scenario B (22%), followed by energy-transition scenario C (15%) and energy-transition scenario A (2%). The explanation for a decreased capex is the fact that a radical grid reinforcement strategy coincides with a heavier upgrade, creating more additional capacity. Although this strategy is more costly, its price is recovered by the fact that following reinforcements are postponed or eliminated.

energy transition scenario	incremental strategy	radical rategy	absolute difference	marginal difference
A	€ 131,7 million	€ 129,1 million	€ -2,6 million	**-2%**
B	€ 678,5 million	€ 528,9 million	€ -149,6 million	**-22%**
C	€ 341,7 million	€ 289,5 million	€ -52,2 million	**-15%**

TABLE 15 ANNUAL CAPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS UNDER DIFFERENT GRID REINFORCEMENT STRATEGIES

Annual opex

Table 16 shows that a radical grid reinforcement strategy also decreases the annual opex in all three energy-transition scenarios. The impact is similar in all three energy-transition scenarios, the annual opex is 7% decreased under the radical strategy. The explanation for a decreased opex is the fact that a radical grid reinforcement strategy coincides with a heavier upgrade, creating more additional nominal capacity. At the same level of capacity demand, a higher nominal capacity lowers the asset load (as the load is the quotient of the capacity demand and the nominal capacity). A lower asset load leads to less energy losses, and thus a decreased opex.

energy transition scenario	incremental strategy	radical strategy	absolute difference	marginal difference
A	€ 111,3 million	€ 104,0 million	€ -7,3 million	**-7%**
B	€ 150,5 million	€ 138,8 million	€ -11,8 million	**-8%**
C	€ 116,8 million	€ 108,1 million	€ -8,7 million	**-7%**

TABLE 16 ANNUAL OPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS UNDER DIFFERENT GRID REINFORCEMENT STRATEGIES

Concluding remarks

The objective of this analysis was to determine if the grid reinforcement strategy has a different impact in different energy-transition scenarios. The answer is that a radical strategy is more beneficial than an incremental one in all three energy-transition scenarios. The magnitude of its impact ranges from a 4% to 22% decrease of total cost, depending on the energy-transition scenario.

6.3.5 ALTERNATIVE POLICIES AND ENERGY-TRANSITION SCENARIO

In paragraph 6.2 the impact of alternative policies in the base environmental scenario was analysed. The base environmental scenario included energy-transition scenario A. It was concluded that the alternative policies have a minimal impact on total costs and NPV in this environmental scenario. However, it also showed that the alternative policies do have impact on the capex and opex. In order to get a better understanding of the impacts of the alternative policies, this paragraph evaluates the impacts of alternative policies in energy-transition scenarios B and C.

It can be concluded, that the impacts of the alternative policies is visible in the total costs and NPVs of in in energy-transition scenarios B and C.

In energy-transition scenario B, the radical grid reinforcement strategy is more beneficial, both with respect to total costs and NPV, than the incremental strategy (Table 17, Figure 39). Furthermore, the smart grid off strategy is more beneficial than the smart grid on strategy. The most beneficial policy is the *off, radical* policy. The least beneficial policy is the *on, incremental* strategy.

Alternative policy	total cost ratio	NPV
off, incremental	1,00	1,00
off, radical	0,80	0,81
on, incremental	1,07	1,08
on, radical	0,83	0,84

TABLE 17 TOTAL COST AND NPV IN ALTERNATIVE POLICIES UNDER ENERGY-TRANSITION SCENARIO B

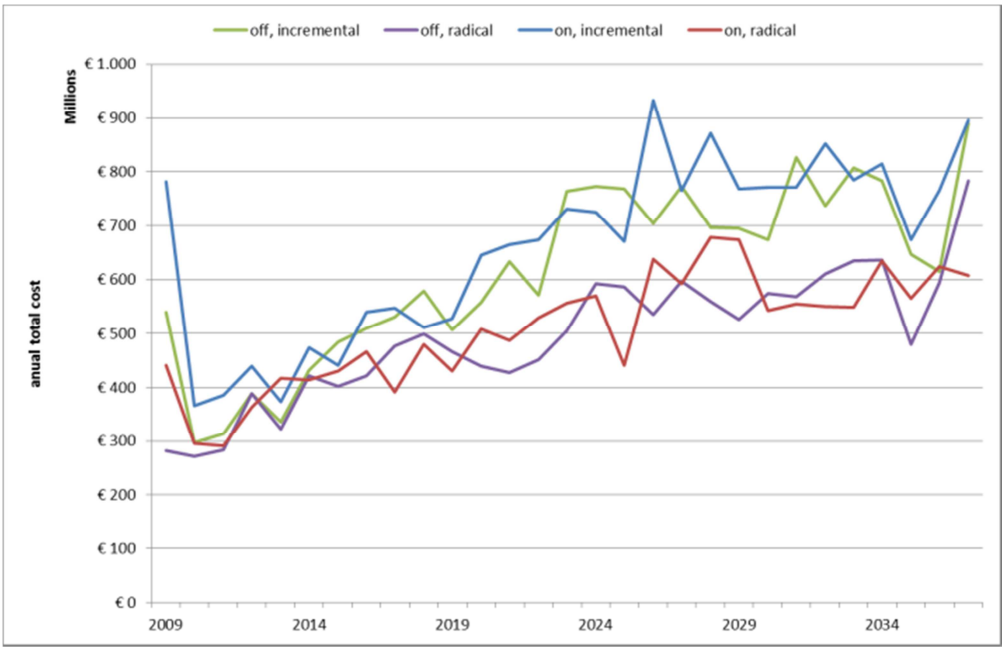


FIGURE 39 ANNUAL TOTAL COST IN ALTERNATIVES POLICIES UNDER ENERGY-TRANSITION SCENARIO B

In energy-transition scenario C, the radical grid reinforcement strategy is more beneficial than the incremental strategy, with respect to total costs and NPV (Table 18, Figure 40). Furthermore, the smart grid on strategy is more beneficial than the smart grid off strategy. The most beneficial policy is the *on, radical* policy. The least beneficial is the o*ff, incremental* policy. The *off, radical* and *on, incremental* policies have a similar impact.

Alternative policy	total cost ratio	NPV
off, incremental	1,00	1,00
off, radical	0,89	0,90
on, incremental	0,89	0,91
on, radical	0,78	0,79

TABLE 18 TOTAL COST AND NPV FOR ALTERNATIVE POLICIES UNDER ENERGY-TRANSITION SCENARIO C

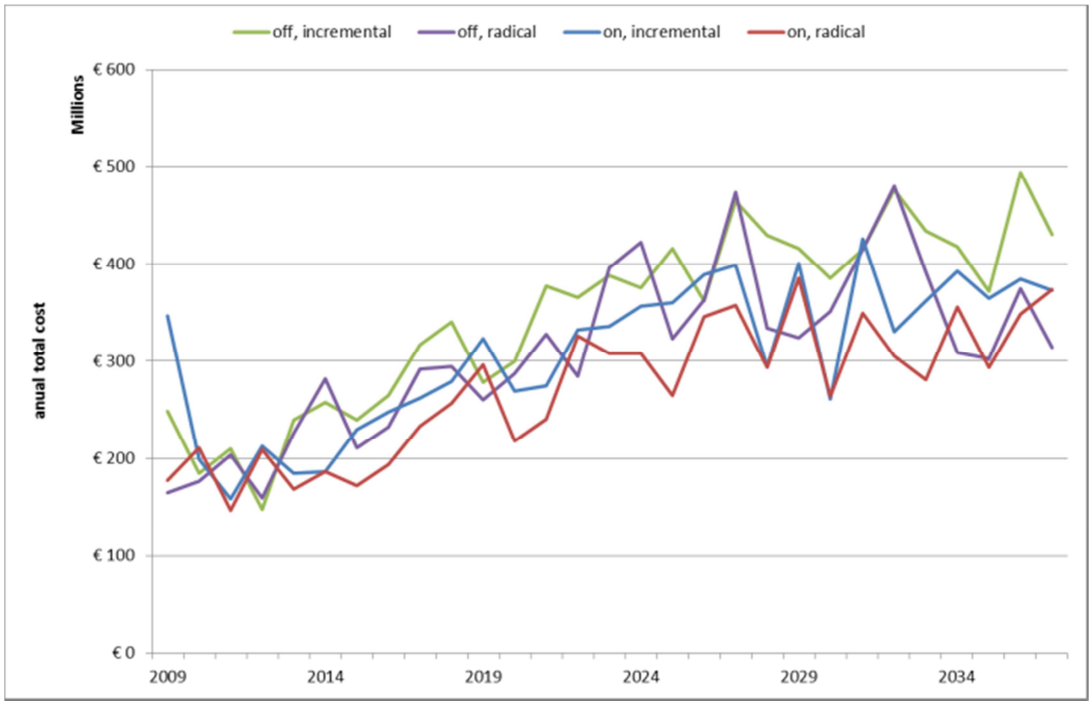


FIGURE 40 ANNUAL TOTAL COSTS IN ALTERNATIVES POLICIES UNDER ENERGY TRANSITION SCENARIO C

6.3.6 CONCLUDING REMARKS INTERACTION EFFECTS

The objective of this paragraph was to understand how the system responds to different environmental scenarios under alternative policies. The insight is given by analysis of the results of two full factorial experiments and by further exploration of the most interesting relationships by a fractional factorial analysis. Based on these analyses, the following conclusions can be made.

It can be concluded that the impact of the asset price scenario and the electricity price scenarios on the total cost depend on the capex-opex ratio. A high ration increases the impact of the asset price, and low ration increase the impact of the electricity price. Because a smart grid on strategy decreases capex and increases opex, the electricity price becomes more impactful under this strategy while the asset price becomes less impactful under this strategy in comparison to a smart grid off strategy.

Furthermore, it can be concluded that the impact of the smart grid strategy on the total cost differs in different energy-transition scenarios. The impact of the smart grid on strategy on capex is positive in all three energy-transition scenarios. This is the result of peak shaving, lowering the need for costly reinforcements. However, the smart grid on strategy has always a negative impact on opex is.

Finally, it is concluded that a radical strategy is more beneficial than an incremental one, in all three energy-transition scenarios.

This chapter has shown how the system responds to different environmental scenarios, to alternative policies, and to combinations of these two. One important insight with regard to the smart grids strategy, is that its impact is not very straightforward. What we have seen is that a smart grid on strategy has different impacts on capex and opex, and thereby on the total cost. Because the main objective of this research is to get more insight in the economic impact of smart grids, the smart grid on strategy is further explored in the next chapter. The objective of this chapter is to get further understanding of how the economic impact of smart grids can be declared. This allows us to get more insight in system behaviour, purely related to smart grids. The impact of the electricity price scenario is largest in energy-transition

scenario A, followed by respectively C and B. Again, the different impacts of the electricity price scenarios in the different energy-transition scenarios can be explained by the described capex-opex ratio. The higher the capex-opex ratio, the lower the contribution of opex to the total cost, and thus the lower the impact of the electricity price scenario on total cost.

CHAPTER 7 FURTHER EXPLORATION OF SMART GRIDS

The previous chapter identified how the system responses to different environmental scenarios and alternative policies. It was shown, that the effect of smart grids is not straightforward, having different effects on capex and opex. This chapter uses the Economic Impact Model for Smart Grids to explore what exactly happens under the smart grid on strategy to get more understanding of the economic and sustainability impact of smart grids.

During this research (0, the technical impact of smart grids was explained by introducing three smart grids factors, namely:

1. peak shaving
2. increased duration of peak loss
3. decreased load threshold

In the experiments described in the previous chapter, all three effect were active under the smart grid on strategy. However, in order to get more detailed insight in the effect of smart grids, this chapter investigates the isolated effects of the smart grid factors. The experiments of this chapter focus on how the system response to these three effects specifically. This is done by varying the three smart grids one by one or in an isolated way, keeping the other effects constant.

The chapter starts with the design of experiments, shortly introducing the experiments that are done (7.1 Hereafter, the effect of peak shaving is analysed (7.2), followed by the effect of the increased duration of peak loss (7.3), and the effect of the decreased load threshold (7.3). Based on these three analysis the integral smart grid effect can be estimated (7.5).

7.1 DESIGN OF EXPERIMENTS

The Economic Impact Model for Smart Grid is used to do experiments related to the further exploration of smart grid on strategy. Therefore we must define the six input variables.

Factors 2, 3, 4, and 6 have a fixed values in order to be able to make observations on how the system responses to factors 1 and 5. The fixed level values of these factors are:

- Factor 2: s-curve capacity demand scenario
- Factor 3: medium asset price scenario
- Factor 4: medium electricity price scenario
- Factor 6: incremental grid reinforcement strategy

Factor 1 is not fixed, because of the earlier conclusion that the energy-transition scenario has such a big impact that they should be observed separately. The level values of this factor are therefore:

- Factor 1: s-curve capacity demand scenario
  - energy-transition scenario A
  - energy-transition scenario B
  - energy-transition scenario C

Factor 5, the smart grid strategy, is set fixed on the smart grid on strategy. However, the effect of this level is split into the three different smart grid factors. In order to determine the impact of the isolated smart grid factors, these can either be put on or off. If it is put on, it means that under the smart grid on

strategy, that smart grid factor is activated. If it is put off, it means that under the smart grid on strategy, the smart grid factor is inactive.

- Factor 5: smart grid on strategy
  - 5a: peak shaving
    - on/off
  - 5b: increased duration of peak loss
    - on/off
  - 5c: decreased load threshold
    - on/off

To summarize, the experiments were done based on the settings of factors is visualised in Figure 41.

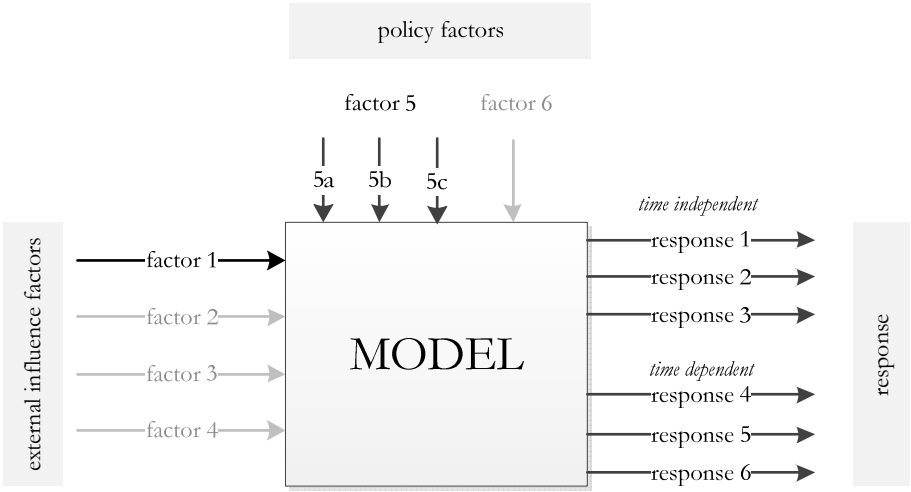


FIGURE 41 ADAPTED OVERVIEW OF FACTORS AND RESPONSES OF THE ECONOMIC IMPACT MODEL FOR SMART GRIDS

This chapter distinguishes three experiments, which are shown in Figure 42. Note that all experiments are done in the three energy-transition scenarios a, b and c.

1. The first experiment identifies the isolated impact of peak shaving by setting 5a at 'on', while keeping 5b and 5c at 'off'.
2. The second experiment identifies the isolated impact of the increased duration of peak loss by setting 5b at 'on', while keeping 5a and 5c at 'off'.
3. The third experiment identifies the isolated impact of the decreased load threshold by setting 5c at 'on' and 5a and 5b at 'off'.

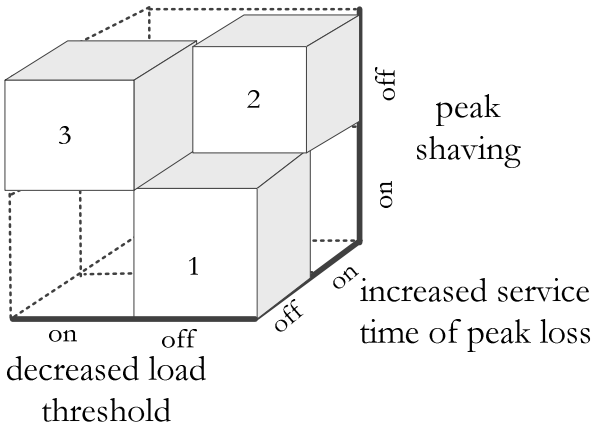


FIGURE 42 THE THREE SMART GRID FACTOR EXPERIMENTS

Based on these experiments the isolated impacts of the smart grids factors are determined. These impacts are used to estimate the integral smart grid effect.

7.2 THE EFFECT OF PEAK SHAVING

This paragraph present the results of the first experiment introduced in the previous paragraph. The objective of this experiment is to determine if peak shaving has impact on the system response, and if so, what the magnitude of its impact is and if this differs in different energy-transition scenarios. First, the impact of peak shaving on the total costs is presented, followed by the impact on annual capex, annual opex and total energy loss. The paragraph ends with some concluding remarks based on this analysis.

Total cost

Peak shaving is often seen as the main effect of smart grids, and is therefore expected to lower total cost. Table 19 and Figure 43 show that peak shaving indeed leads to lower total costs, in all three energy-transition scenarios. The magnitude of its impact however differs in the varying energy-transition scenarios. Peak shaving has the largest impact on the total costs in energy-transition scenario C. In this scenario, the total cost is decreased by 38% in relation to no peak shaving, which corresponds with €5.0 billion over the observed time horizon. In energy-transition scenario A, peak shaving causes a 33% decrease, or €2.3 billion. In energy-transition scenario B the total cost decreases by 22% decrease, or €5.3 billion. The assumed explanation behind the total cost decrease, is that peak shaving leads to decreased capex and opex. Decreased capex due to the postponement or elimination of grid reinforcements. Decreased opex due to lower energy losses during peak hours. In order to confirm these assumptions, the capex and opex are further analysed.

energy transition scenario	peak shaving off	peak shaving on	absolute difference	marginal difference
A	€7.0 billion	€4.7 billion	- €2.3 billion	**- 33%**
B	€24.1 billion	€18.8 billion	- €5.3 billion	**- 22%**
C	€13.1 billion	€8.0 billion	- €5.0 billion	**- 38%**

TABLE 19 THE EFFECT OF PEAK SHAVING ON TOTAL COST IN DIFFERENT ENERGY-TRANSITION SCENARIOS

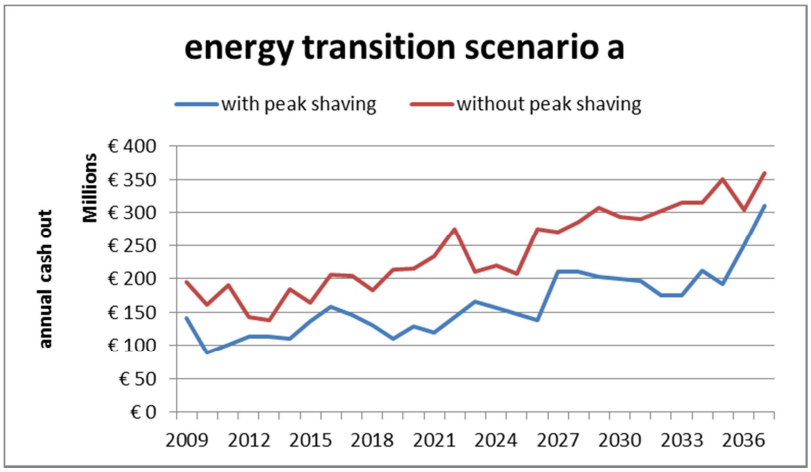


FIGURE 43 THE EFFECT OF PEAK SHAVING ON TOTAL COST IN ENERGY-TRANSITION SCENARIO A

Annual capex

Table 20 shows that peak shaving leads to lower annual capex in all three energy-transition scenarios. The assumption on the impact of peak shaving on annual capex is thus correct. The decrease can be explained by the fact that a lower peak capacity demand leads to a lower need for costly grid reinforcements. This need is either postponed or eliminated. The magnitude of the impact differs per energy-transition scenario. Peak shaving has the largest impact on annual capex in scenario energy-transitions a (53%), followed by energy-transition scenario C (47%) and energy-transition scenario B (23%).

energy transition scenario	peak shaving off	peak shaving on	absolute difference	marginal difference
A	€ 131 million	€ 62 million	- €69 million	**- 53%**
B	€ 671 million	€ 514 million	- €157 million	**- 23%**
C	€ 335 million	€ 179 million	- €156 million	**- 47%**

TABLE 20 THE EFFECT OF PEAK SHAVING ON ANNUAL CAPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Annual opex

The other assumption was that peak shaving also lowers the annual opex, as it lowers the energy loss during peak hours. Table 21 confirms this assumption, and shows that peak shaving leads to lower annual opex in all three energy-transition scenarios. This can be explained by the fact that the peak load of the grid components is decreased resulting in lower energy losses. The magnitude of the impact is very similar in the different energy-transition scenarios. Peak shaving has the largest impact on annual opex in energy-transition scenario C (15%), followed by b (11%), and a (10%). The effect is thus lower than the effect of peak shaving on the capex.

energy transition scenario	peak shaving off	peak shaving on	absolute difference	marginal difference
A	€111.3 million	€100.0 million	- €11.4 million	- 10%
B	€150.5 million	€134.2 million	- €16.3 million	- 11%
C	€116.8 million	€99.3 million	- €17.5 million	- 15%

TABLE 21 THE EFFECT OF PEAK SHAVING ON ANNUAL OPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Energy loss

Peak shaving is expected to be beneficial from the sustainability perspective, as it should lower the energy loss during peak hours. Table 22 confirms this assumption, and shows that the annual energy loss is decreased by on average 13%. This means that from a sustainability perspective this smart grid factor is beneficial.

energy transition scenario	peak shaving off	peak shaving on	absolute difference	marginal difference
A	903 million kWh	818 million kWh	-86 million kWh	- 10%
B	1.187 million kWh	1.064 million kWh	-123 million kWh	- 12%
C	933 million kWh	802 million kWh	-131 million kWh	- 16%

TABLE 22 THE EFFECT OF PEAK SHAVING ON TOTAL ENERGY LOSS IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Concluding remarks peak shaving

Based on this analysis it can be concluded that the impact of peak shaving is beneficial in all three energy-transition scenarios, both from an economic as from a sustainability perspective. The magnitude of its impact on total cost, annual capex, and annual opex, differs per energy-transition scenario. However, in all three energy-transition scenarios the impact of peak shaving is larger on capex (23-53%) than on opex (10-15%).

7.3 THE EFFECT OF INCREASED DURATION OF PEAK LOSS

This paragraph present the results of the second experiment introduced in the first paragraph of this chapter. The objective of this experiment is to determine if an increased duration of peak loss has impact on the system response, and if so, what the magnitude of its impact is and if this differs in different energy-transition scenarios. First, the impact on the total costs is presented, followed by the impact on annual capex, annual opex and total energy loss. The paragraph ends with some concluding remarks on the increase duration of peak loss.

Total cost

The effect of increased duration of peak loss is expected to increase total cost, because it increases energy losses and thus opex. Figure 23 shows that the increased duration of peak loss leads indeed to higher the total costs, in all three energy-transition scenarios. The magnitude of the effect differs for the different energy-transition scenario's. In energy-transition scenario A, the impact of this smart grid factor is the largest, increasing the total cost by 46%, or € 2.1 billion. In energy-transition scenario C, the smart grid factor lowers total cost with 24%, or € 2.0 billion. In energy-transition scenario C, the smart grid factor lowers total cost with 16%, or €3.1 billion.

energy transition scenario	increased service time of peak loss off	increased service time of peak loss on	absolute difference	marginal difference
A	€ 4.6 billion	€ 6.7 billion	€ 2.1 billion	**+ 46%**
B	€ 18.9 billion	€ 22.0 billion	€ 3.1 billion	**+ 16%**
C	€ 8.2 billion	€ 10.1 billion	€ 2.0 billion	**+ 24%**

TABLE 23 THE EFFECT OF INCREASED DURATION OF PEAK LOSS ON TOTAL COSTS IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Annual capex

As expected, this smart grid factor has no effect on annual capex. The reason is that the duration of peak loss only affects the energy losses and thus annual opex. Note that in real the annual capex can be affected by this smart grid factor. It is possible that due to an increased duration of peak loss, the durability of the asset is affected. In this case, the asset would need earlier replacement. However, replacement is not taken into account in this research (only reinforcement or asset upgrade).

Annual opex

If the increased duration of peak loss increases the total costs, and does not impact capex, its impact must be caused by an impact on annual opex. Table 24 shows that an increased duration of peak loss causes indeed an opex increase. The effect is very significant, its magnitude is on average 72%. The difference between the different energy-transition scenario's is negligible (<3%). The effect can be explained by the fact that a higher duration of peak loss means the copper losses of transformers and cables are increased during peak hours.

energy transition scenario	increased service time of peak loss off	increased service time of peak loss on	absolute difference	marginal difference
A	€ 100.0 million	€ 172.5 million	€ 72.6 million	**+ 73%**
B	€ 134.2 million	€ 233.7 million	€ 99.5 million	**+ 74%**
C	€ 99.3 million	€ 169.6 million	€ 70.3 million	**+ 71%**

TABLE 24 THE EFFECT OF INCREASED DURATION OF PEAK LOSS ON ANNUAL OPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Energy loss

In coherence with the effect on annual opex, the energy loss is expected to increase significantly by an increased duration of peak loss. The magnitude is of the impact is similar to its impact on annual opex. on average 72% (Table 25). The difference between the different energy-transition scenario's is negligible. This means that from a sustainability perspective this smart grid factor is not beneficial.

energy transition scenario	increased service time of peak loss on	increased service time of peak loss off	absolute difference	marginal difference
A	817 million kWh	1.411 million kWh	594 million kWh	**+ 73%**
B	1.064 million kWh	1.850 million kWh	786 million kWh	**+ 74%**
C	802 million kWh	1.368 million kWh	566 million kWh	**+ 71%**

TABLE 25 THE EFFECT OF INCREASED DURATION OF PEAK LOSS ON TOTAL ENERGY LOSS IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Concluding remarks increased duration of peak loss

Based on this analysis it can be concluded that the impact of increased duration of peak loss is not beneficial. This smart grid factor causes more energy losses, resulting in higher annual opex and thus higher total cost. The magnitude of its impact is similar in all three energy-transition scenarios.

7.4 THE EFFECT OF DECREASED LOAD THRESHOLD

This paragraph present the results of the third experiment introduced in the first paragraph of this chapter. The objective of this experiment is to determine if the decrease load threshold has impact on the system response, and if so, what the magnitude of its impact is and if this differs in different energy-transition scenarios. First, the impact on the total costs is presented, followed by the impact on annual capex, annual opex and total energy loss. The paragraph ends with some concluding remarks on the decreased load threshold.

Total cost

The decreased load threshold is expected to increase total cost because it causes an earlier need for reinforcement. Table 26 shows that the total cost are indeed increased by the decreased load threshold. The magnitude of the effect is similar in energy-transition scenarios b and c: about 14%. However, in energy-transition scenario A the effect is negligible, only 3%. Based on this it can thus be stated that the magnitude of the effect of this smart grid factor on the total cost is clearly smaller than the effects of the other two smart grid factors. Also, the direction of this factor is less distinct as the effect in energy-transition scenario A is very small. In order to get more insight in the cause of this, the annual capex and opex are further explored.

energy transition scenario	decreased load threshold off	decreased load threshold on	absolute difference	marginal difference
A	€4.7 billion	€4.8 billion	€152 million	**+ 3%**
B	€19.0 billion	€22.2 billion	€3184 million	**+ 14%**
C	€8.0 billion	€ 9.4 billion	€1384 million	**+ 15%**

TABLE 26 THE EFFECT OF DECREASED LOAD THRESHOLD ON TOTAL COST IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Annual capex

The decreased load threshold is expected to increase capex, as it causes an earlier need for reinforcement. Table 27 confirms this assumption, and shows that the annual capex is increased in all three energy-transitions scenarios. The magnitude of the effect of this smart grid factor is similar in all three energy-transition scenarios, a 22% increase of annual capex in relation to the annual capex under the regular (smart grid off) load threshold.

energy transition scenario	decreased load threshold off	decreased load threshold on	absolute difference	marginal difference
A	€61.0 million	€77.5 million	€16.5 million	**+ 21%**
B	€522.3 million	€645.7 million	€123.4 million	**+ 19%**
C	€177.4 million	€ 234.8 million	€57.4 million	**+ 24%**

TABLE 27 THE EFFECT OF DECREASED LOAD THRESHOLD ON ANNUAL CAPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Annual opex

The effect of the decreased load threshold on the annual opex is presented in Table 28. It shows that the annual opex is decreased in all three energy-transitions scenario's. This can be explained by the fact that assets are reinforced earlier, leading to lower asset loads, and thus lower opex. The magnitude of the effect is similar in all three energy-transition scenario, a 12% decrease of annual opex in relation to the annual opex under the regular (smart grid off) load threshold.

energy transition scenario	decreased load threshold off	decreased load threshold on	absolute difference	marginal difference
A	€99.9 million	€88.7 million	€11.2 million	**- 13%**
B	€120.5 million	€134.2 million	€13.6 million	**- 11%**
C	€89.7 million	€ 99.4 million	€9.6 million	**- 11%**

TABLE 28 THE EFFECT OF DECREASED LOAD THRESHOLD ON ANNUAL OPEX IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Energy loss

The decreased load threshold is beneficial from the sustainability perspective, as it lowers the total energy loss by on average 12% in relation to its energy loss under the regular (smart grid off) load threshold, see Table 29. The explanation of this effect is similar to the explanation of the effect on annual opex.

energy transition scenario	decreased load threshold off	decreased load threshold on	absolute difference	marginal difference
A	817.5 million kWh	726.5 million kWh	91.1 million kWh	**- 13%**
B	1064.0 million kWh	956.6 million kWh	107.4 million kWh	**- 11%**
C	802.4 million kWh	724.9 million kWh	77.5 million kWh	**- 11%**

TABLE 29 THE EFFECT OF DECREASED LOAD THRESHOLD ON TOTAL ENERGY LOSS IN DIFFERENT ENERGY-TRANSITION SCENARIOS

Concluding remarks decreased load threshold

Based on this analysis it can be concluded that the impact of decreased load threshold is not beneficial in terms of total cost. However, the impact is smaller than the impact of the other two smart grid factors, and in one scenarios negligible. Analysis of annual capex and annual opex show that the decreased load threshold increases capex, while lowering opex. This explains why the impact on total costs is relatively small, it is leveraged by its effect on capex and opex. The magnitude of its impact is similar in all three energy-transition scenarios.

7.5 ESTIMATION OF THE INTEGRAL SMART GRID EFFECTS

The previous sections presented the effects of the isolated smart grid factors on the economic (total cost, annual capex, annual opex) and sustainability objectives (energy loss). This paragraph aggregates the results, giving an overview of the isolated effects of the smart grid factors. Based on this, an estimation can be made on the integral effect of the smart grid.

Peak shaving has a only positive impacts on the system responses as it decreases annual capex, annual opex, total costs and the energy loss (Table 30). The effect of this smart grid factors depends on the energy-transition scenario, as it differs in the three energy-transition scenarios.

energy transition scenario	annual capex	annual opex	total costs	energy loss
A	-112%	-11%	- 50%	-10%
B	-32%	-12%	- 28%	-12%
C	-87%	-18%	- 62%	-16%

TABLE 30 OVERVIEW OF THE EFFECTS OF PEAK SHAVING

The increased duration of peak loss has only negative impacts on the system response, as it increases annual opex, total costs and total energy loss (Table 31). It has no effect on annual capex. The effect of this smart grid factors also differs in different energy-transition scenarios.

energy transition scenario	annual capex	annual opex	total costs	energy loss
A	0%	+ 42%	+ 31%	+ 42%
B	0%	+ 43%	+ 14%	+ 42%
C	0%	+ 41%	+ 19%	+ 41%

TABLE 31 OVERVIEW OF THE EFFECTS OF INCREASED DURATION OF PEAK LOSS

The decreased load threshold has both positive and negative impacts on the system response. The positive impact is the decrease of annual opex and total energy loss (Table 32). The negative effect is the higher capex, which is larger in magnitude than the positive effect on opex. This leads to a net effect of increased total costs.

energy transition scenario	annual capex	annual opex	total costs	energy loss
A	+ 21%	-13%	+ 3%	-13%
B	+ 19%	-11%	+ 14%	-11%
C	+ 24%	-11%	+ 15%	-11%

TABLE 32 OVERVIEW OF THE EFFECTS OF DECREASED LOAD THRESHOLD

Table 33 shows an overview of the effects of the three smart grid factors, averaged for all three energy-transitions scenarios. The integral effect of smart grids can be estimated by the sum of the effects of the isolated smart grid factors. It shows that on average, the annual capex is expected to decrease by 56%, the annual opex is expected to increase by 14%, and the total costs is expected to decrease by 15%. This means that on average, the net effect of the integral smart grid factors is positive from an economic perspective. From a sustainability perspective, the smart grid is not positive, as it is expected to increase the energy loss with 17%.

smart grid factor	annual capex	annual opex	total costs	energy loss
peak shaving	-77%	-14%	-47%	-13%
higher duration of peak loss	0%	+ 42%	+ 21%	+42%
lower load threshold	+21%	-12%	+ 11%	-12%
expected integral smart grid effect	**-56%**	**+16%**	**-15%**	**+17%**

TABLE 33 OVERVIEW EFFECTS OF THREE SMART GRID EFFECTS

PART IV SYNTHESIS

CHAPTER 8 CONCLUSIONS

This research evaluated the economic impact of smart power distribution grids with the objective to structurally maximize the utilization of the existing grid capacity. This was done by identifying external influences that will affect the power distribution system in the future, and identifying alternative policies – including smart grids - that the DSO can implement to minimize the costs. Experimental simulation was performed to analyse what the economic impact of alternative policies is in different environmental scenarios, and more importantly, what the reason behind this impact is. Based on these analyses the main and sub questions can be answered. This chapters starts with the answers to the sub questions. Then, the main question is answered.

8.1 ANSWERS TO SUB RESEARCH QUESTIONS

What are the economic consequences of future external influences on the power distribution system?

This research identified four external influences that will affect the power distribution system: the energy-transitions scenario, the capacity demand development scenario, the asset price scenario, and the electricity price scenario.

The energy-transition scenario describes what the future energy supply system looks like, and takes new technological developments such as distributed generation and electrification of heating and mobility into account. This research identified three energy-transition scenarios: A, B and C, based on other research performed at the DSO. The capacity demand development scenarios determines how the capacity demand that is associated with the energy-transition scenario will develop over the years. Three capacity demand development scenarios were identified: linear, s-curve and stepwise. The energy-transition scenario And the capacity demand development scenario together determine the capacity demand of the power distribution grid. This demand influences the asset load, and thereby the reinforcement need and accompanying capital expenditures. The asset price scenario is the price trend of acquiring and constructing new assets. Grid reinforcement requires new assets, the asset price thus influences the capital expenditures of the DSO. Three asset price scenarios were investigated: low, medium, and high. The electricity price scenario is the trend of how the electricity price will develop. This external influence affects the operational expenditure of the DSO associated with energy loss. The observed electricity price scenarios are: low, medium, and high.

The economic consequences were defined as impact on annual capex, annual opex, total cost, and NPV. Annual capex are the expenditures resulting from grid reinforcement. Annual opex are expenditures resulting from energy losses. Other capex and opex sources such as asset replacement due to aging or operational expenditures of operation and maintenance were not taken into account. Total cost is the sum of capex and opex over the observed time horizon, and NPV is the total cost discounted in time (discount rate 4%).

Analysis shows that the energy-transition scenario has the largest economic consequences in relation to the other external influences, as varying energy-transition scenarios lead to a large total cost difference. It was estimated that facilitation of energy-transition scenario A costs the DSO on average €6.6 billion over the observed time horizon of 30 years. This means, that in this energy-transition scenario the DSO will have to spend €6.6 billion over the next three decades (capex and opex) to supply sufficient grid capacity under the requirement of reliability. If we take the time value of money into account, the NPV of facilitation of this energy-transition scenario is €3.6 billion, which represents the value of the costs today.

In energy-transition scenario B, the total costs are significantly higher: €21.9 billion (NPV €12.2 billion), a 230% increase in relation to energy-transition scenario A. The total costs of facilitating energy-transition scenario C is €12.1 billion (and a NPV of €6.7 billion) a 80% increase in relation to energy-transition scenario A. We can thus conclude that energy-transition scenario B coincides with the highest total cost, followed by respectively energy-transition scenario C and A. This can be logically declared by the fact that energy-transition scenario A is most conservative, and assumes limited economic growth and new technologies, while energy-transition scenario B assumes a high demand growth and many electric vehicles and heat pumps.

Although their impact is smaller, the other three identified external influences also have economic consequences. The different capacity demand development scenarios influences the total cost up to 20%. A linear capacity demand scenario is associated with the highest cost and NPV, followed by a stepwise scenario and a s-curve scenario. The s-curve scenario decreases the total cost by 20% in relation to the linear scenario. This can be explained by the fact that earlier investments are cheaper, due to annual the asset price increase. A s-curve coincides with investments mostly around the year 2025, while a linear curve coincides with more costly investments after 2025. Furthermore, the asset price scenario influences the total costs up to 30%. This means that the total costs are increased by 30% in a high asset price scenario with relation to a low scenario. The electricity price scenario has a very similar impact, increasing the total costs up to 30%. Analysis showed that the relative impacts of the asset price and electricity scenarios are different in different energy-transition scenarios. This can be explained by the fact that different energy-transition scenario Coincide with different capex-opex ratios, the quotient of capex and opex. A higher capex-opex ratio increases the impact of the asset price, while a lower ratio increases the impact of the electricity price. Energy-transition scenario A has a capex-opex ratio of 1, meaning that capex and opex are of similar magnitude. Here, the asset price scenario and electricity price scenario both have an impact of 15%. Energy-transition scenario B has on the contrary a capex opex ratio of 3, and in this energy-transition scenario the asset price scenario has an impact of 20% and the electricity price scenario only 5%.

It can be concluded that the facilitation of the future environment will cost the DSO over the next three decades minimal €4.5 billion, maximal €31.9 billion, and on average €13.5 billion. These values correspond with a NPV of respectively €2.8, €15.4, and €7.5 billion. The main reason for this wide range is the energy-transition scenario, as the total costs in scenario B is 2.3 times the total costs in scenario A and in scenario C 1.8 times the total costs in scenario a. However, the capacity demand development scenario, asset price scenario, and electricity price scenario also have economic consequences, each potentially increasing the total costs up to 30%.

What is the impact of alternative policies –including smart grids - on the total costs of the power distribution grid?

This research identified four future alternative policies that the DSO can implement in order to minimize the costs of the power distribution grid. Each policy consists of two strategies: the smart grid strategy and the grid reinforcement strategy. The smart grid strategy determines if the DSO takes advantage of demand control or not. The two levels of this strategy are thus defined as the 'smart grid on' and 'smart grid off' strategy. The grid reinforcement strategy determines how the DSO chooses to reinforce its grid, either incremental meaning that each asset is upgraded by an asset with a one-step higher nominal capacity, or radical meaning that each asset is upgraded by an asset with at least two-steps higher nominal capacity. The two levels of this strategy are defined as the 'incremental' and 'radical' strategy. The four policies

become: *off, incremental* (which is the business as usual policy of the DSO), *off, radical*, *on, incremental*, and *on radical*.

Analysis shows that the impact of the four alternative policies is different in different energy-transition scenarios, and that they can lower the total costs by maximal 22%. In energy-transition scenarios a and c, the *off, incremental* policy is associated with the highest total cost and NPV, and is thus the least beneficial policy to implement. In these energy-transition scenarios, the *on, radical* policy is the most beneficial policy, decreasing total costs by 9% in A, and by 22% in B. In these energy-transition scenarios, the smart grid on strategy and the radical grid reinforcement strategy are always most beneficial than the smart grid off strategy and the incremental grid reinforcement strategy. However, in energy-transition scenario B, the *on, incremental* is the least beneficial policy and the *off, radical* the most beneficial, decreasing the total cost by 20%. This means that in this energy-transition scenario the radical grid reinforcement strategy is always more beneficial than the incremental strategy. However, the smart grid on strategy is in this energy-transition scenario not beneficial in relation to the smart grid off strategy. Apparently, smart grids don't have a positive impact on energy-transition scenario B, which is remarkable, because this energy-transition scenario also involves many new technologies (e.g. electric vehicles, heat pumps).

It can be concluded that a radical grid reinforcement strategy is more beneficial than an incremental one in all three energy-transition scenarios. Further analysis of the impact of the grid reinforcement strategy only, shows indeed that a radical strategy is in all three energy-transition scenarios more beneficial, though the magnitude of the impact differs per energy-transition scenario. In energy-transition scenario A, a radical grid reinforcement strategy lowers the total costs by 4% in relation to the incremental strategy, in B by 19% and in C by 13%. The reduction in costs can be explained by the fact that a radical strategy decreases capex, which means that the higher expenditures associated with a radical strategy are recovered by the fact that follow-up reinforcements are deferred. The capex savings differs per energy-transition scenario (respectively by 2%, 22%, and 15% in energy-transition scenario A, B, and C). The higher savings in energy-transition scenario B can be explained by the fact that this scenario assumes high demand growth, and thus a high grid capacity demand. A radical grid reinforcement strategy is apparently more beneficial is the capacity demand is high. The radical grid reinforcement strategy also decreases opex, which can be explained by the fact that a higher nominal capacity of the assets lowers the load, and thus the energy losses. The opex savings are very similar in different energy-transition scenario, and about 7%. The energy losses are also decreased under a radical grid reinforcement strategy, which means that from a sustainability perspective the radical strategy is advised.

An remarkable conclusion is that the smart grid strategy on strategy is not beneficial in all energy-transition scenarios. Further analysis on the smart grid strategy shows that a smart grid on strategy is indeed more beneficial than a smart grid off strategy in energy-transition scenarios A and C, each lowering the total cost by respectively 10% and 17% and the NPV by 7% and 15%. This means that smart grids have a positive impact in an energy-transition scenario with little demand growth and low penetration of new technologies. The positive impact of smart grids is apparently higher in an energy-transition scenario with medium demand growth and a high penetration of new technologies. The high penetration of new technologies is assumed to be the main reason why the impact of smart grids is high in this energy-transition scenario. However, in energy-transition scenario B the smart grid on strategy increases the total cost by 3%, though this scenario also coincides with a high penetration of new technologies. The explanation for this negative impact is the high 'normal' demand growth, which is not very flexible. The normal demand growth seems to lower the effect of smart grids. In order to understand why smart grids can have both a positive and a negative impact, and why the impact differs in different energy-transition scenarios, we need to look into more detail what causes the economic impact of smart grids.

This research shows, that the smart grid on strategy lowers capex in all three energy-transition scenarios. This can be explained by the fact that peak shaving lowers the capacity demand during peak hours and lowers the need for grid reinforcement, leading to capex savings. But, whereas the capex savings are very significant in energy-transition scenario A and C (capex reductions of respectively 40% and 30%), it is very small in scenario B (3%). So we now know that the capex cost reduction is very small in energy-transition scenario B. A possible explanation for this small impact is that the high normal demand growth causes heavy capex investments anyways, the economic effect of smart grids becomes minimal. Energy-transition scenario B was associated with a high increase of customer demand, which was assumed to be non-flexible. Therefore, the peak shaving possibilities within this energy-transition scenario were limited. At the same time, the smart grid on strategy leads in all three energy-transition scenarios to an increase of opex (about 24%). If the opex increase transcend the capex reductions, the smart grid on strategy becomes less beneficial than the smart grid off strategy (as is the case in energy-transition scenario B).

In order to get a better understanding of why the smart grid on strategy leads to these capex savings and opex increase, and why the magnitude of the capex savings differ in different energy-transition scenarios, a further exploration to the economic impact of smart grids is done. This research assumed three technical effects of smart grids, namely peak shaving, increased duration of peak loss, and decreased load threshold. Peak shaving is the assumption that the asset peak load is lowered, or shaved, by shifting non-time critical loads during peak hours to off peak hours. Increased duration of peak loss is the assumption that though the peak load is lowered, its duration is increased. This leads to higher peak hour energy losses. Decreased load threshold is the assumption that the degree to which the assets may be loaded in relation to their nominal capacity without an excessive reduction of lifetime and increased risk of failure is lowered. Reason is that the duration of peak load is increased. Under the smart grid on strategy, all three effects become active. However, in order to understand what system response is to different effects, the impact of the isolated effects was estimated.

Simulation showed that the peak shaving solely leads to significant total cost savings in all three energy-transition scenarios. However, the magnitude of the cost savings differ largely in different energy-transition scenarios. The total cost savings can be explained by the fact that both capex and opex are decreased. Capex savings are the results of postponement or elimination of grid reinforcement. Opex savings are the result of lower asset load leading to lower energy losses. The difference in magnitude of cost savings are due to the difference in capex savings, as the opex savings are similar in all three energy-transition scenarios. Based on this it can be concluded that if peak shaving was the sole effect of smart grids, smart grids would always lead total cost savings. However, the isolated effect of increased duration of peak loss leads to a total cost increase. This is the result of higher opex, since a longer duration of peak load leads to higher energy losses. The isolated effect of decreased load threshold leads also to a net cost increase, though it impact is smaller than the impact if increased duration of peak loss. The impact can be explained by an capex increase as a result of earlier and more reinforcements. At the same time, opex is decreased because reinforcement leads to higher nominal capacity, and thus lower energy losses. The magnitude of the effects of increased duration of peak loss and decreased load threshold is similar in all three energy-transition scenarios.

Based on insight in the impacts of the three isolated technical effects of smart grids, we can explain why a smart grid on strategy is not always beneficial from the perspective of the DSO, and why this differs per energy-transition scenario. A smart grids on strategy is not always economically beneficial because the positive impact of peak shaving is leveraged by the two other technical effects of smart grids. Under the smart grid on strategy, the power distribution grid is operated continuously close to its maximum capacity. Though this coincides with capex benefits, as less costly grid reinforcements are needed, it also coincides with higher opex due to higher energy losses. The higher energy losses are caused by a longer duration of

the peak and associated energy losses. In some situations, the positive economic impact of peak shaving was not sufficient to overcome the negative economic impact, as is true in energy-transition scenario B. In this energy-transition scenario peak shaving caused total cost savings of only 28%, as opposed to the 50% and 62% total cost savings in respectively energy-transition scenario A and c. Based on analyses we can estimate what the a total cost reduction of peak shaving should be in order to leverage the total cost increase. The estimated total cost reduction of peak shaving only, should be at least 32%. It can thus be concluded that the extent to which peak shaving is possible (or the flexibility of loads) is very important.

Which future policies should the DSO implement in which future environmental scenarios?

Based on the analyses relating to the economic impact of the alternative policies, it is advised to always implement a radical grid reinforcement strategy. This strategy is more beneficial than the incremental grid reinforcement strategy in all observed energy-transition scenarios. Apparently, the higher reinforcement costs associated with more radical reinforcement, is recovered by the additional nominal capacity under the radical grid reinforcement strategy. This postpones or eliminates follow-up reinforcements, and thus lowers capex. It has the potential to decrease total costs up to 20% and the NPV up to 15%.

This research shows that the impact of the smart grids strategy depends to a large extend on the energy-transition scenario. The smart grid on strategy was more beneficial than the smart grid off strategy in two out of three energy-transition scenarios. In a conservative energy-transition scenario with limited demand growth (energy-transition scenario A), the total cost savings are €690 million over the observed time horizon (a NPV is of €268 million). In a more sustainable energy transition scenario with a higher penetration of new energy technologies (energy-transition scenario C), the total cost savings are much more significant. In such a scenario, the total cost savings are estimated on €2.268 million (a NPV of €977 million). In scenarios with low to medium energy demand increases, the DSO can benefit from smart grids, and the higher the penetration of new technologies, the higher the benefit. Note that the DSO should only implement a smart grid on if there is a net benefit, thus if the costs of the smart grids system are lower than or equal to the economic benefits. Based on this research, the average economic benefit of smart grids with the objective to higher grid capacity utilization, is 300 million in terms of NPV. If the DSO should for example invest in a smart grids system today, it should thus cost no more than €300 million assuming that the higher grid capacity utilization is the only economic benefit. However, the DSO should not invest in a smart grids system in an energy transition scenario with very high, non-flexible demand growth (energy-transition scenario B), since there is no economic benefit for the DSO in this scenario. The reason why a smart grids on strategy is not beneficial in this energy-transition scenario is that the economic impact of peak shaving is smaller in this energy-transition scenario. In general this research showed that a smart grids on strategy is not always beneficial, and that its economic potential depends mainly on the degree to which peak shaving is possible. The DSO should therefore only implement a smart grid on strategy only if a certain degree of load flexibility is guaranteed.

Another conclusion that can be made, is that the smart grid on strategy becomes more beneficial in a high asset price scenario, and less beneficial in a high electricity price scenario. The reason is that the smart grid on strategy coincides with lower capex and higher opex than the smart grid off strategy. In the high asset price scenario, it is important to lower the amount of grid reinforcements and thus implement a smart grid on strategy. However, in the electricity price scenario, it becomes more important to lower the energy loss, which is increased under the smart grid on strategy.

Note that this research makes a trade-off between the smart grids on strategy and the smart grids off strategy and evaluates the total costs, defined as the sum of capex and opex. The smart grids on strategy can be seen as facilitating the distribution capacity demand by making use of demand control to increase capacity utilization of the existing grid, while the smart grid off strategy simply increases grid capacity. We now know that a smart grid on strategy decreases capex, but increases opex in relation to a smart grid off strategy. This means, that the smart grid off strategy increases capex is, but decreases opex in relation to the smart grid on strategy. The optimum between the two strategy lays somewhere in between, making use of demand control (thereby decreasing capex and increasing opex) and increasing grid capacity (thereby increasing capex and decreasing opex). If for instance one would assume that the same amount of capex is spend under either the smart grid on and smart grid off strategy, one would conclude that smart grids on strategy is always more beneficial, as it would then not coincide with the higher energy losses and accompanying opex.

What are the most important sources of uncertainty relating to the economic impact of smart grids from the perspective of the DSO?

This research has given us insight in the economic impact of different environmental scenarios and of alternative policies. Based on the results on the magnitude of the impacts the following aspects are considered to be the most important sources of uncertainty for the DSO.

First, the future energy-transition scenario has a major impact and is highly uncertain. This aspect is important because it determines the degree to which peak shaving is possible. Different energy-transition scenarios coincide with capacity demand increase due to electricity demand increase (often corresponding with economic growth) and capacity demand increase due to new energy technologies. This research showed that peak shaving determines the success of smart grids. Therefore, it is crucial that the DSO maximizes its knowledge on the future energy-transition scenario And the degree to which peak shaving is possible.

Another major source of uncertainty is the extent to which the duration of peak loss is influenced under the smart grid on strategy. This research assumed that the duration of peak loss was increased, based on assumptions on the 'smart' demand profile. However, it is unknown what the real effect is of a changed load profile on the duration of peak loss. This is important to know since this effect strongly impacts the energy losses and thereby the opex under the smart grid on strategy, and thereby lowers the predicted potential of smart grids.

Finally, a major source of uncertainty is the extent to which the load threshold is lowered under the smart grid on strategy. This research assumed that the load threshold had to be lowered in order to meet the reliability requirement. However, it is unknown what the actual effect a 'smart' load profile is on the assets, and if it changes its load threshold. The reason is that the assets and their load threshold are currently dimensioned based on a current standard load profile.

8.2 ANSWER TO MAIN RESEARCH QUESTION

'What is the economic impact of smart power distribution grids from the perspective of the DSO, taking uncertainty in its future environment into account'

The main conclusion is that the benefit of peak shaving effect of smart grids cannot be translated one-one-one into economic value for the DSO. This research shows that under the assumption that the future environment of the power distribution grid is uncertain, the economic benefit of smart power distribution

grids is not guaranteed. The reason is that the positive impact of peak shaving is leveraged by the increased energy loss, and accompanying opex. The higher opex are the result of assumptions on the technical effect of 'smart load profiles' on the power distribution grid. In the situation that the opex increase transcends capex savings, a the situation exists in which smart grids do not create a net economic benefit for the DSO. However, the in the situation that peak shaving is possible, the economic benefit of the DSO in terms of capex savings should not be underestimated. This research shows, that smart grids possibly lead to total cost savings of 17%, which is very significant since we are talking about billion euro investments.

In order to become certain about the economic impact of smart power distribution grids from the perspective of the DSO, it thus becomes important to get more insight in the opportunities and limitations of peak shaving and the technical effects of a smart load profiles on the power distribution grids. The first aspect determines the potential of the economic benefits, while the latter aspect determine the downsides of smart grids.

An essential consideration of the DSO is if it should fully deploy smart grids, thereby lowering its capex, but increasing its opex. Or if it should fully reinforce its grids, thereby increasing its capex, but lowering its opex. Since the optimal policy is expected to lay somewhere in between, a logical next step would be to investigate where this optimum lies, so that the DSO can make well-argued trade-offs when designing the distribution grid of the future.

CHAPTER 9 RECOMMENDATIONS

This chapter defines recommendation based on the conclusions in the previous chapters. First, policy recommendations for the DSO are made. Then, recommendations for further research are made.

9.1 POLICY RECOMMENDATIONS FOR THE DSO

Based on the conclusions, the first policy recommendation towards the DSO is to consider a more radical reinforcement strategy. This research showed that this leads total cost and NPV savings, up to 20%. From an sustainability perspective, the radical grid reinforcement strategy is also more beneficial, as it lowers the energy loss. An important remark to this advice is that this research assumes that this research observes a time horizon of 30 years, that the capacity demand will increase over the years, and that the end-state is known beforehand. In real, the asset engineers forecast over a period of only five years. Though a continuous capacity demand increase over time is a realistic assumption, the end state is not known beforehand, which could be an appropriate argument to implement a more incremental policy. Also, this research looks at the system wide impact of the increased capacity demand, while in real the DSO uses a more geographically focused approach. However, since analysis shows that a radical grid reinforcement can lead to significant cost reductions, it is advised to take a more radical grid reinforcement approach into consideration. In general it was observed that although a geographically focused approach is needed in some cases, it often limits the opportunities for system-wide improvement.

Considering smart grids, the DSO is advised to consider carefully why smart grids are important, and to a take a role accordingly. One approach would be to implement smart grids to take full advantage of economic benefits. This research gives insight in one category of the economic benefits of smart grids, the economic benefits associated with increased grid capacity utilization. The research shows how the benefit can be estimated, what the estimated economic benefit is in different energy-transition scenarios, and which uncertainties play a major role. However, it is important to understand that there are more economic benefits, that were beyond the scope of this research and therefore not identified. These are the economic benefits of operating the grid smarter, for instance by automatic monitoring and control. If the DSO chooses to implement smart grids to take advantage of its economic benefit, it should thus further investigate both categories of economic benefits: the higher grid capacity utilization and operational savings. This research is as the starting point for understanding the first aspect. However, this research has its limitations and has therefore defined suggestions for further research (see next paragraph). If the DSO takes this approach, it is advised to put further research effort according to the suggestions. In coherence with this approach, the DSO would be the initiator and leader in the implementation of smart distribution grids. Though the costs of smart distribution system (including the ICT system) should cost the DSO not more than the sum of both benefits, in order to take a net advantage.

Another approach by the DSO would be to take another approach towards benefits. Besides the purely economic benefits of smart grids, other benefits are facilitation of a more sustainable energy system and more effective energy markets. To this respect we will elaborate on the sustainability aspect of smart grids, in connection to this research. Smart grids will facilitate the facilitation of new energy technologies, such as distributed generation units, electric vehicles, and heat pumps. Moreover, they enable new energy services that we cannot even imagine today. If we move towards a society that uses more local energy sources, the dependency on central generation will be lower. This means that the role of the medium voltage distribution power will also become smaller, which means that the energy losses associated with power transport are decreased. This research however showed that smart grids increase energy losses, which seems contradictory. The reason is that in this research, smart grids enabled facilitation of the same increased energy demand with less nominal capacity, which coincides with more energy losses. If smart

grids are implemented in combination with less nominal capacity, more energy losses are created. However, if smart grids are implemented with the normal nominal capacity, less energy losses are created, and the energy losses are thus reduced by smart grids. From a sustainability perspective this is thus a trade-off of the DSO.

A total different approach by the DSO would be to totally ignore the benefits of smart grids on its own operations. This would shift smart grids leadership from the grid operators to market players, such as energy suppliers and new service providers. The DSO would manage the grid as usual, and not interact with the consumer, suppliers and those that do both. The incentive for demand control would then be purely based on electricity price as opposed to on grid capacity availability. The disadvantage of this approach is that the full potential of smart grids is not reached.

9.2 RECOMMENDATIONS FOR FURTHER RESEARCH

This research gives more insight in the economic impact of smart grids with the objective to maximize grid capacity utilization. It developed the Economic Impact Model for Smart Grids in order to estimate the economic impacts. The model was used for experimentation, which gave insight on what the economic impact of different environmental scenario and alternative policies is. Based on analysis of the results conclusions were made. However, this research is based on some assumptions that must be verified by further research, considering their economic consequence. Furthermore, the research leaded to suggestions for research that will advance our insight in the economic impact of smart grids. These two aspect are discussed in the following sections.

9.2.1 VALIDATION OF ASSUMPTIONS

The first recommendation for further research is to further investigate the potential of peak shaving, which is obvious considering its crucial role in the economic potential of smart grids. Research should be done from multiple perspectives. With regard to the future energy supply system, it is important to understand which new technologies are technically able to facilitate peak shaving, and what their expected penetration degree in future will be. From a user oriented perspective, it must be clear to which degree the user is willing to adapt its behaviour, and what the corresponding load flexibility is. If further research shows, that the load is more flexible than assumed in this research, the economic benefit of smart grids may be much higher. If further research on the other hand shows that load is less flexible than assumed, the smart grids benefits are expected to decrease significantly.

The second recommendation is to do more research on what the technical effect of a 'smart' demand profile is on the load profile of the power distribution grid assets. The DSO has currently no experience with the effect of a smart, more continuous demand profile. The grid design directives that the DSO uses are based on stylized demand profiles that were similar over the past decades. This research assumed that the smart demand profile increased the duration of peak loss. This factor was needed to calculated the energy loss and associated opex. Though this assumption is defensible by logical reasoning, it is not technically proven. Moreover, the magnitude of the increase is uncertain. If research shows that the smart demand profile does not increase the duration of peak loss, or that the increase is significantly smaller than assumed in this research, the economic impact of smart grids would be more beneficial than estimated in this research. Another assumption that was made based on the smart demand profile, is that it decreases the capacity threshold. This assumption is also based on logical reasoning, but not technically proven. The load threshold that the DSO uses is based on tests with the physical assets and the current demand profile. However, tests with the physical assets and the smart demand profile might result in the conclusion that a smart demand profile does not affect the degree to which the asset can be loaded

without excessive reduction of lifetime or risk of failure. In this case, the economic impact of smart grids would be more beneficial than estimated in this research.

The third recommendation is to improve the knowledge on energy losses. During model development is appeared that the knowledge on the determination of energy loss is limited. This research showed that the energy losses are of major importance in determining the economic potential of smart grids. This research made assumptions on how to calculate the energy losses. Although these assumptions were well argued, and conducted in collaboration with technical experts at the DSO, they may be inaccurate.

The fourth recommendation for further research is to investigate the impact of smart grids on the maintenance of the power distribution grids. This research only investigated grid reinforcement, which means that assets are upgraded as a result of an increased capacity demand. This means that asset replacement, because of asset failure (for instance due to aging) is not taken into account. Similar to the assumption that the load threshold is decreased in a smart grid situation, it can be assumed that the life expectation of an asset is decreased in a smart grid situation. The reason is that a more continuous utilization of the asset close to its nominal capacity increases asset heating and lowers its life expectation. If further research shows that this aspect leads to a significant increase of replacements, the economic impact of smart grids may be less beneficial than estimated in this research.

The final recommendation for further research is related to the trade-off between implementing a policy that uses demand control to facilitate the future grid capacity demand and implementing a policy that uses grid reinforcement to facilitate the future capacity demand. This research shows, that there are situations in which the first policy is more beneficial, and that there are situations in which the latter policy is more beneficial. This is explained by the fact that demand control decreases capex while increasing. If reinforcement is used, capex is increased while opex is increased. An economic optimum will thus be somewhere between making use of demand control and reinforcement. In this optimal situation, the DSO makes use of demand control to pull down capex, while it implements grid reinforcement to pull down opex. Further research should give more insight in where this optimum is positioned.

9.2.2 SUGGESTIONS FOR NEW INSIGHTS

The first suggestion is to develop an economic impact model to estimate the operational benefits of smart grids from the perspective of the DSO. This research has treated smart grids as an enabler of higher grid capacity utilization, and investigated if this corresponds with cost saving for the DSO. However, as was mentioned before, smart grids have more benefits for the DSO. These are related to day-to-day operation of the power distribution grid. It concerns automated monitoring, decision-making, and control of the power distribution grid. This can support the DSO during maintenance and disruptions. Whereas this research treated the reliability goal a requirement, in this suggested research it is likely to function as an objective.

The second suggestion is to investigate the economic impact of smart grids on the low voltage level of the power distribution grids. Today there are not many problems at this level, since they are high dimensioned and the demand side is predictable. However, energy-transitions scenarios will heavily impact the grid on the low level, which might lead to low voltage grid reinforcements. Note that although these assets are often less expensive each, because of their lower nominal capacity. However the amount of these types of asset is significantly higher, and construction of these assets (in residential areas) is often more expensive.

The third suggestion for further research continuous on the discussion of the distribution of the costs and benefits, and the role of the stakeholders in the power market. This research estimated the economic value of smart grids for the DSO only. However, a further understanding is needed what the economic value of

smart grids is for other market parties. What is the benefit for other stakeholders, such as market parties? If we assume that smart grids create economic value for the DSO (as shown by this research), the next question becomes what we should do with this benefit. Should the DSO pass it directly to its consumers? And if so, how? This goes along with price incentives that are given to consumers in order to realise peak shaving. Should the economic benefit for instance be used for implementation of the smart grids system? In order to reach the full potential of smart grids, and design the power market accordingly, estimations are needed of the costs and benefits that affect other stakeholders. A high level approach, that integrate the costs and benefits of smart grids from multiple dimensions, should support decision makers on the road towards a more sustainable energy system.

CHAPTER 10 DISCUSSION

This chapter discusses the research efforts and results. This is done by giving a reflection on the research method, and describes what the added value of this research is from an academic perspective.

This research used modelling to compare different policies. It started with conceptual modelling of the system, its inputs and outputs. It the quantified the input and output factors, and the relations between the different factors. The quantified model was used to estimate how the system responded (in terms of outputs) to different inputs. The method is considered to be very valuable in this research. The main reason is that it allowed to incorporate aspects from different disciplines, it allowed the research to embrace complexity. The method is compatible with any aspect the researcher wants to take into account. Through this method, we were for instance able to translate technical aspects into economic consequences. A purely technical method, or a purely economic method would not be able to adequately take these different aspects into account. To give an example, this research is based on many rules from the electro-technical field of knowledge. At the same time, it was able to take market aspects such as the influence of a high asset price scenario into account. The method was especially well applicable since smart grids is by nature a complex concept, combining technological opportunities with market and policy concepts. The downside of this method is that it has no restrictions to add complexity. This was experienced as a big challenge, especially during the analysis phase in which an overwhelming amount of responses could be observed. In retrospect, the simulation environment (MS Excel and VisualBasics) might have been chosen more carefully. Though this simulation environment did support all experiments that were planned, it did not support a systematic experimental approach. One advantage of the chosen simulation environment is that the software is installed at most computers, which means that the Economic Impact Model for Smart Grids is user-friendly for further research.

This research was performed parallel to two other master thesis research projects, done by student from other universities and faculties. The three research projects were closely interrelated. The first research project focused on the translation of future energy system scenarios into electricity profiles for network calculations. The second research calculated the impact of future residential loads on the medium voltage networks by doing network calculations. This research was the third research, which translated the future energy system scenarios and network calculations into economic consequences. The collaborative character of these research projects is predominantly experienced as very positive. It enabled a good focus on the research objective of this research while taking advantage of the insights of others. The downside of this collaborative approach was the mutual interdependency, which sometimes leaded to waiting for research results or adaptation of the previously received research results. However, this research is by all means enriched by the collaborative approach. Mainly, because it eliminated the need to make even more assumptions on the system. The results of this research therefore considered much more substantial. It is based on solid research efforts on the future energy-transition scenarios, on their impact on the power distribution grid, and on the economic consequences of these aspects. The collaborative approach also improved a better understanding of the system during research, especially since the research projects were performed from the perspective of different disciplines (i.e. MSc Electrical Engineering, MSc Sustainable Energy Technology and MSc Systems Engineering, Policy Analysis and Management). And above all, it created a very pleasant research environment in which quick brainstorms and discussions were not exceptional.

Another major contributor to the realization of this research project was that it was performed in close collaboration with a Dutch DSO (Enexis). Its openness towards this research project enabled face-to-face interviews with experts such as grid designers and business analysts, desk research of internally used documents, and rich discussion about assumptions and results with both managers and employees. This

did not only give a lot of inspiration on how to perform this research, it also created a sound foundation for a realistic approach. The Economic Impact Model for Smart Grids is for instance based on how this DSO implements grid reinforcement in real life. Although this can be considered important for all fields of knowledge, it is believed is that this is especially true for issues related to smart grids. This is presumed, because experience at the DSO showed that the operations of the DSO a to a large extend based on tacit knowledge, or the craftsmanship of the employees at the DSO. Many intellectual property within the organization is located in the heads of experienced workers, which is (in general) transferred to younger workers. This research has attempted to capture part of this valuable knowledge and translate it to a more abstract level.

Evaluating the practical relevance of this research, the following can be stated. Since this research observed a time horizon of 30 years, its results are not directly applicable by the DSO. This research shows that complexity that is inherent to smart grids, makes it difficult to make ambiguous recommendations. However, it is believed that this research can function as a good starting point as to how policy decisions of the DSO can be evaluated from an economic perspective. The Economic Impact Model for Smart Grids can be adapted if better information is available (for instance by the suggestions for further research on the research assumptions). Moreover, the main conclusions of this research give any stakeholder more insight in the potential economic impact of smart grids on the DSO. This can make the discussions on who experiences the benefits and who bares the costs more substantial.

Finally, a review on the scientific contribution is given. This research has shown that a modelling approach is suitable for estimating the economic consequences of asset related investment decisions. The power distribution grid is take as a case example, though the method used in this research can be applied to any other system with an infrastructural character. One could for instance translate the system conceptualisation to the rail system, a system with an infrastructural character, though in the transportation sector as opposed to the energy sector. It would then define the external influences as the future transportation system (including new technologies such as electric buses), the asset price scenario (the price of trains, rails and stations), the maintenance price scenario (wear of the rails and trains). The policies of the rail operator are smart ticketing strategy (demand control by dynamic train ticket prices in coherence with peak hours) and the reinforcement strategy (the degree to which the rail system is expanded). Based on this system conceptualisation, a model can be developed that estimated the economic consequences of the different environmental scenarios and alternative policies. This example might be considered irrelevant, though it shows that this research has a more abstract contribution parallel to insights on the power distribution system in specific. It shows the research approach of this research can be used to support the decision making process of infrastructure operators, which future environment is highly uncertain.

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Appendix I DATA

This appendix describes the data used by the Economic Impact Model for Smart Grids.

The data base includes information on the assets of 5 regions from Dutch DSO (Enexis). The database includes:

- 54 high voltage stations
- 15.989 low voltage transformers
- 2086 transport cables
- 29.338 distribution cables

First, it is described how samples of the database are selected. Hereafter it is described how the research deals with the high loads at t0.

Taking samples: distribution cables and low voltage transformers

Samples from the data are taken for the distribution cables and low voltage transformers. The data of high voltage transformers and transport cables is directly used as model input, since this is relatively small and therefore comprehensible for simulation (118 high voltage transformers as opposed to 15.989 low voltage transformers).

Low voltage transformers

- $n_{database}$= 15.989
- n_{sample}= 5.000 (10% of DSO area)

Distribution cables

- $n_{database}$= 29.338
- n_{sample}= 3.000

T-Test

The Student's t test is used to investigate if the a selected sample is representative for the data base. It tests if there is a significant difference between the average of the data base and the sample. The control variable is the capacity of the grid component (in volt-ampere for transformers and ampere for cables).

A One sample t test can be used to determine if the sample average is equal to the data base average. In this case, the zero-hypothesis is $H_0: \mu = \mu_0$ (no statistic difference between the two sets of data) and the alternative hypothesis $H_a: \mu \neq \mu_0$, in which μ_0 is the average of the data base. The zero-hypothesis is accepted if the P value (probability that zero-hypothesis is true) is larger than 0.05 (P critical value).

- Low voltage transformer sample: P value 0.57
- Distribution cables sample: P value 0.88

Low voltage stations	Database	Sample
Mean	250	251
Variance	36.950	37.739
Observations	15.989	5.000
Hypothesized Mean Difference	0	
df	8286	
t Stat	-0,56	
P(T<=t) one tail	0,29	
t Critical one tail	1,65	
P(T<=t) two tail	**0,57**	
t Critical two tail	1,96	

Distribution cables	Data base	Sample 2
Mean	187	187
Variance	4.966	4.776
Observations	29.338	3.031
Hypothesized Mean Difference	0	
df	3712	
t Stat	0,15	
P(T<=t) one tail	0,44	
t Critical one tail	1,65	
P(T<=t) two tail	**0,88**	
t Critical two tail	1,96	

Appendix II LOOKUP TABLE: CATEGORIZATION

This appendix shows the categorization that was used by the Economic Impact Model for Smart Grids.

High voltage station

Nominal capacity of installed trafo's	Trafo category	Nominal capacity, categorized
[MVA]	*[cat]*	*[MVA]*
15	**a**	**20**
18	**a**	**20**
20	**a**	**20**
24	**a**	**20**
25	**a**	**20**
26	**b**	**30**
30	**b**	**30**
34	**b**	**30**
40	**c**	**40**
44	**c**	**40**
48	**c**	**40**
60	**d**	**60**
65	**d**	**60**
80	**e**	**80**

Transport and distribution cables

Category	Nominal capacity, categorized	Viewed as	Nominal Capacity
[cat]	*[range]*	*[type]*	*[A]*
1	≤35 mm² CU ≤50 mm² AL	50 mm² AL	130
2	≤120 mm² CU ≤150 mm² AL	150 mm² AL	285
3	≤185 mm² CU ≤240 mm² AL	240 mm² AL	370
4	≤240 mm² CU ≤400 mm² AL	400 mm² AL	475
5	≤630 mm² CU ≤630 mm² AL	630 mm² AL	605

Low voltage transformers

Trafo category	Nominal capacity, categorized	Based on possible replacement transformers
[x]	*[kVA]*	*[kVA]*
1	0-50 kVA	100
2	51-125 kVA	160
3	126-160 kVA	250
4	161-350 kVA	400
5	351-500 kVA	630
6	501-1000 kVA	1260
7	1001-1600 kVA	1890
8	1601-2400 kVA	2520
9	2401-3000 kVA	3150
10	3001-3500 kVA	3780
11	3501-4200 kVA	4410
12	4201-5000 kVA	5040
13	5001-5500 kVA	5670

Appendix III LOOKUP TABLE: GRID REINFORCEMENT STRATEGIES

This appendix shows the grid reinforcement strategies that are used by the Economic Impact Model for Smart Grids.

High voltage stations

Incremental reinforcement

category	Action	Total capacity	Save capacity (n-1)	Reinforcement ratio	New station type	Extra capacity
[cat]	[-]	*[MVA]*	*[MVA]*	[-]	*[cat]*	*[MVA]*
1	replace both by trafo type b	60	30	1,5	2	10
2	add trafo type b	90	60	2,0	7	30
3	add trafo type c	120	80	2,0	8	40
4	add trafo type d	180	120	2,0	9	60
5	add trafo type e	240	160	2,0	10	80
6	replace all three by trafo type b	90	60	1,5	7	20
7	add trafo type b	120	90	1,5	7	30
8	add trafo type c	160	100	1,7	8	40
9	add trafo type d	240	180	1,5	9	60
10	add trafo type e	320	240	1,5	10	80

Radical reinforcement

Station category	Action	Total capacity	Save capacity (n-1)	reinforcement ratio	New station type	Extra capacity
[cat]	[-]	*[MVA]*	*[MVA]*	[-]	*[cat]*	*[MVA]*
1	replace both by trafo e	160	80	4,0	5	60
2	replace both by trafo e	160	80	2,7	5	50
3	replace both by trafo e + add trafo e	240	160	4,0	10	120
4	replace both by trafo e + add trafo e	240	160	2,7	10	100
5	add trafo type e	240	160	2,0	10	80
6	replace all three by trafo type e	240	160	4,0	10	120
7	replace all three by trafo type e	240	160	2,7	10	100
8	replace all three by trafo type e	240	160	2,7	10	100
9	add trafo type e	260	200	1,7	10	80
10	add trafo type e	320	240	1,5	10	80

Transport grid

Incremental reinforcement

Category	Solution category	Action	Extra capacity
[cat]	*[cat]*	[-]	*[A]*
1	1	Add cable 50 mm² AL	125
2	2	Add cable 150 mm² AL	285
3	3	Add cable 240 mm² AL	370
4	4	Add cable 400 mm² AL	475
5	5	Add cable 630 mm² AL	605

Radical reinforcement

Category	Solution category	Action	Total capacity
[x]	*[cat]*	[-]	*[kVA]*
1	1	Add cable 240 mm² AL	370
2	2	Add cable 400 mm² AL	475
3	3	Add cable 630 mm² AL	605
4	4	Add cable 800 mm² AL	675
5	5	Add 2 cables 630 mm² AL	1210

Distribution grid

Reinforcement options and their distribution

reinforcement options	cable length	distribution of reinforcement options	extra capacity
Add cable 1:1	same as cable part	specified cable types	capacity new cable
Add long diagonal	1000 m	50%	0.5*capacity new cable
Add short diagonal	400 m	25%	0.5*capacity new cable
Add cable to other ring	400 m	15%	0.5*capacity new cable
Add two long diagonals	2000 m	5%	0.5*capacity new cable
Add new ring	4000 m	5%	0.5*capacity new cable

Incremental reinforcement

Category	Action	Capacity new cable
[cat]	*[-]*	*[A]*
1	Add cable 50 mm² AL	125
2	Add cable 150 mm² AL	285
3	Add cable 240 mm² AL	370
4	Add cable 400 mm² AL	475
5	Add cable 630 mm² AL	605

Radical reinforcement

Category	Action	Capacity new cable
[cat]	*[-]*	*[A]*
1	Add cable 240 mm² AL	370
2	Add cable 400 mm² AL	475
3	Add cable 630 mm² AL	605
4	Add cable 800 mm² AL	675
5	Add 2 cables 630 mm² AL	1210

Low voltage stations

Incremental reinforcement

Station category	Solution category	Action	New capacity	Reinforcement ratio
[cat]	*[cat]*	[-]	*[kVA]*	[-]
1	1	replace by trafo 100	100	2,0
2	2	replace by trafo 160	160	1,6
3	3	replace by trafo 250	250	1,6
4	4	replace by trafo 400	400	1,6
5	5	replace by trafo 630	630	1,6
6	6	add 630	1260	2,0
7	7	add 630	1890	1,5
8	8	add 630	2520	1,3
9	9	add 630	3150	1,3
10	10	add 630	3780	1,2
11	11	add 630	4410	1,2
12	12	add 630	5040	1,1

Radical reinforcement

Capacity category of station	Solution category	Action	Total capacity	Reinforcement ratio
[x]	*[cat]*	[-]	*[kVA]*	[-]
1	1	replace by trafo 630	630	12,6
2	2	replace by trafo 630	630	6,3
3	3	replace by trafo 630	630	3,9
4	4	replace by trafo 630	630	2,5
5	5	replace by trafo 630	630	1,6
6	6	add 630	1260	2,0
7	7	add 630	1890	1,5
8	8	add 630	2520	1,3
9	9	add 630	3150	1,3
10	10	add 630	3780	1,2
11	11	add 630	4410	1,2
12	12	add 630	5040	1,1

Appendix IV LOOK UP TABLE: LOAD THRESHOLDS

This appendix presents the load thresholds that are used by the Economic Impact Model for Smart Grids. It is furthermore explained how the load thresholds were calculated.

physical element	smart grid off strategy	smart grid on strategy
high voltage transformer	120%	100%
transport cable	59%	50%
distribution cable	57%	47%
low voltage transformer	116%	100%

Calculating process of load thresholds related to transformers

This section explains how the load threshold of transformers is determined. The sections starts with the explanation of how the thresholds for low voltage transformers are determined. Hereafter, the load thresholds for high voltage transformers are presented since its determination is comparable.

The load threshold of a low voltage transformer is based on assumptions on the customer's power demand profile (as shown in **Error! Reference source not found.**). Stylized profile are assigned to a customer group: households, industry, or mixed. The profiles determine a load factor K_1, an overload factor K_2 and the duration of the peak load in hours per day, as shown in **Error! Reference source not found.**.

The following formula describes K_1:

$$K_1 = \frac{I_1}{I_{nominal}}$$

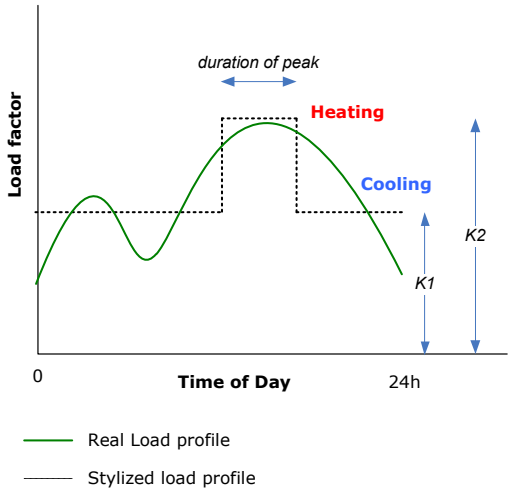
In which

- $K_1$is the load factor in [%]
- $I_1$is the normal capacity demand in [VA]
- $I_{nominal}$ is the nominal capacity of the transformer in [VA]
- The following formula describes K_2:

$$K_2 = \frac{I_2}{I_{nominal}} =$$

In which

- l_t is the load threshold in [%]
- $K_2$is the overload factor in [%]
- I_2 is the maximal capacity demand that the transformer can serve without an excessive reduction of lifetime of the grid component and a strong increased risk of failure in [VA]



Representative values of K_1, the ratio $\frac{K_2}{K_1}$, and t are made based on real load profiles and ambient temperatures, as shown in the table.

The table shows that a LV transformer connected to a household LV grid may be overloaded 116% to 135%, depending on the ambient temperature (30˚C - 10˚C). The ambient temperature is the temperature in the direct surrounding of the transformer.

Based on this theory and in alignment with the grid engineers of the DSO, the standard load threshold of low voltage transformer is set on **116%** under the *smart grid off* strategy, and on **100%** under the *smart grid on* strategy.

Customer Group	$\frac{K_2}{K_1}$	t [h]	K_2 $T_{ambient}$=10˚C	K_2 $T_{ambient}$= 20˚C	K_2 $T_{ambient}$= 30˚C
Households	1,6	4	135%	126%	116%
Mixed	2,3	8	126%	118%	**108%**
Industry	2,7	8	109%	118%	**95%**

The load threshold of a HV transformer is calculated in a comparable way. The thresholds for high voltage transformer is set on **120%** under the *smart grid off* strategy, and on **100%** under the *smart grid on* strategy.

Calculating process of load thresholds of cables

The load threshold of cables is also based on international standards[6]. According to the grid design directives of the DSO, the load threshold is based on the following factors:

- the material type – GPLK or XLPE, aluminium or copper – and the diameter of the conducting surface (together determining the nominal capacity of the cable)
- the mutual thermal influence of cables that lay parallel next to each other
- the temperature of the soil where the cable is located (because Dutch power distribution grids lay underground)

[6] NPR3107 for GPLK cables and NPR3626 for XLPE cables at continuous load, and IEC60853 at cyclical load

- the heat resistance of the soil where the cable is located
- the pattern and nature of the demand load profile of the connected loads
- a time dependent permissible higher load in case of disruptions (other defect cables that lay in the same grid)

The influence of these factors is represented by the following formula:

$$I_t = I_{nominal} * P * T * D$$

In which:

- I_t is the maximal capacity demand that the cable can serve in [A]
- $I_{nominal}$ is the nominal capacity of the cable in [A]
- P is the correction factor for the mutual thermal influence of parallel cables in [%], based on the temperature resistance of the soil, depending on the type of Dutch ground (peat: 70% and non-peat: 100%)
- T is the correction factor in [%] for the seasonal ground temperature, which is 92% in summer and 107% in winter
- D is the correction factor in [%] for the demand load profile (specified for households, industry, individual customers, and mixed)

This means that the load threshold of cables can be determined by:

$$l_t = P * T * D$$

Transport cables

Based on the presented formula the load threshold, the load threshold of transport cables is determined, in which

$$l_t = P * T * D$$

- P is assumed 70% (average of peat and non-peat)
- T is 92% (summer is worst case scenario because the soil is warmer than in winter)
- D depends on the shape of the demand load profile:
    - without demand control (standard): 130%
    - with demand control (assumed): 110%

The load threshold of a transport cable without demand control is thus:

$$l_t = 70\% * 92\% * 130\% = 84\%$$

And the load threshold of a distribution cable with demand control is:

$$l_t = 70\% * 92\% * 110\% = 71\%$$

However, the N-1 criterion must be taken into account for transport cables. The N-1 criterion means that every MV-T cable is able to transport the amount of electricity in the situation that another cable fails. The load threshold must therefore be multiplied with another correction factor:

$$correction\ factor_{N-1\ criterion} = \frac{n-1}{n}$$

Meaning that the correction factor becomes 50% for two parallel distribution cables and 67% for three parallel distribution cables.

In accordance with grid design engineers, an average correction factor of 70% is chose (under the assumption that in most transport grids three cables are installed, and in some cases more than three cables).

This leads to a load threshold of a transport cable without demand control of:

$$l_t = 84\% * 70\% = \mathbf{59}\%$$

And a load threshold of a transport cable with demand control of:

$$l_t = 71\% * 70\% = \mathbf{50}\%$$

Distribution cables

Based on the presented formula the load threshold of distribution cables is determined, in which:

- P is assumed 85% (average of peat and non-peat)
- T is 92% (summer is worst case scenario because the soil is warmer than in winter)
- D depends on the shape of the demand load profile:
    - without demand control (standard): 145%
    - with demand control (assumed): 120%

The load threshold of a distribution cable without demand control is thus:

$$l_t = 85\% * 92\% * 145\% = \mathbf{113}\%$$

And the load threshold of a distribution cable with demand control is:

$$l_t = 85\% * 92\% * 120\% = \mathbf{94}\%$$

However, failure of a distribution cable leads to redirecting the power over another distribution cable. This means that every distribution cable is able to transport the amount of electricity in the situation that another cable fails (as explained in). The load threshold must therefore be multiplied with another correction factor:

$$correction\ factor_{N-1\ criterion} = \frac{n-1}{n}$$

In which

- n=2 (two cables)

So the correction factor becomes $\frac{1}{2}$ and the final load threshold of a distribution cable without demand control:

$$l_t = \mathbf{113}\% * \mathbf{50}\% = \mathbf{57}\%$$

And the load threshold of a distribution cable with demand control is:

$$l_t = \mathbf{94}\% * \mathbf{50}\% = \mathbf{47}\%$$

Appendix V LOOKUP TABLE: ENERGY LOSS

This appendix presents the lookup tables associated with the calculation of energy losses.

Energy loss characteristics high voltage station

Energy loss per type of trafo [W]		
Capacity	**Iron Loss**	**Copper Loss**
	P0	Pk
[kVA]	*[W]*	*[W]*
15	15.000,0	75.000,0
18	17.034,3	87.284,3
20	19.068,6	99.568,6
24	21.102,9	111.852,9
25	23.137,1	124.137,1
26	25.171,4	136.421,4
30	27.205,7	148.705,7
34	29.240,0	160.990,0
40	31.274,3	173.274,3
44	33.308,6	185.558,6
48	35.342,9	197.842,9
56	37.377,1	210.127,1
60	39.411,4	222.411,4
65	41.445,7	234.695,7
80	43.480,0	246.980,0
120	74.754,3	420.254,3

Energy loss characteristics transport and distribution cables

Copper loss lookup table

Cat 1		*Cat 2*		*Cat 3*		*Cat 4*		*Cat 5*	
Load	**Copper loss**	**Load**	**Copper loss**	**Load**	**Copper loss**	**Load**	**Copper loss**	**Load**	**Copper loss**
[%]	*[W/m]*	[%]	*[W/m]*	[%]	*[W/m]*	[%]	*[W/m]*	[%]	*[W/m]*
0%	0	0%	0	0%	0	0%	0	0%	0
10%	1	10%	1	10%	1	10%	1	10%	1
20%	2	20%	2	20%	4	20%	4	20%	3
30%	3	30%	5	30%	5	30%	5	30%	7
40%	4	40%	6	40%	10	40%	10	40%	12
50%	5	50%	10	50%	14	50%	14	50%	20
60%	6	60%	14	60%	20	60%	23	60%	25
70%	7	70%	23	70%	25	70%	30	70%	40
80%	8	80%	24	80%	30	80%	40	80%	50
90%	9	90%	25	90%	40	90%	50	90%	60
100%	10	100%	50	100%	55	100%	60	100%	70
110%	11	110%	60	110%	65	110%	70	110%	80
120%	12	120%	70	120%	75	120%	80	120%	90
130%	13	130%	80	130%	85	130%	90	130%	100
140%	14	140%	90	140%	95	140%	100	140%	110
150%	15	150%	100	150%	105	150%	110	150%	120

Low voltage station

energy loss per type of trafo [W]		
Capacity	**Iron Loss**	**Copper Loss**
Snom	P0	Pk
[kVA]	*[W]*	*[W]*
50	115	840
100	190	1350
160	260	1905
250	365	2640
400	515	3750
630	745	5200
1260	1490	10400
1890	2235	15600
2520	2980	20800
3150	3725	26000
3780	4470	31200
4410	5215	36400

Duration of peak loss in hours per year

[hrs/year]	transport cables	distribution cables	high voltage transformers	low voltage transformers
Energy scenario A Smart grid on	6218	5202	3566	6106
Energy scenario A Smart grid off	3109	2601	1783	3053
Energy scenario B Smart grid on	4768	4208	2976	4266
Energy scenario B Smart grid off	2384	2104	1488	2133
Energy scenario C Smart grid on	4926	4190	2874	4522
Energy scenario C Smart grid off	2463	2095	1437	2261

Appendix VI CAPACITY DEMAND DEVELOPMENT

This appendix explains the capacity demand development scenario, by giving the formula that is associated with each scenario. The model uses these formula to calculate the capacity demand each year.

Linear

A linear curve is has the following general form:

$$y = mx + b$$

The formula is translated to the model:

$$I_{demand}(t) = \frac{I_{demand,t30} - I_{demand,t0}}{n} + I_{demand,(t-1)}$$

in which:

- $I_{demand}(t)$ is the capacity demand at *t,* in [A] for cables and [VA] for transformer
- $I_{demand,(t-1)}$ is the capacity demand at *t-1,* in [A] for cables and [VA] for transformer
- $I_{demand,t0}$ and $I_{demand,t30}$ are the capacity demands at respectively t0 and t30, in [A] for cables and [VA] for transformers
- n is the amount of years

or:

$$I_{demand}(t) = \frac{I_{demand,t30} - I_{demand,t0}}{30} + I_{demand,(t-1)}$$

S curve

The common formula for the s-curve is:

$$P(t) = \frac{1}{1 + e^{-t}}$$

or:

$$P(t) = \frac{S}{1 + e^{-k(t-t_m)}}$$

$$t_m = t_g + \frac{(t_s - t_g)}{2}$$

in which:

- S is the saturation value [x]
- t is the point in time in [years]
- t_m is the midpoint in time in [years]
- t_g is the point in time that 10% of the saturation value is reached in [years]
- t_s is the point in time when 90% of the saturation value is reached in [years]

or:

$$P(t_s) = 0.9S$$

$$P(t_g) = 0.1S$$

Assuming that the curve s symmetrical around t_m, factor k can be determined by the formula:

$$k = \frac{\ln(9)}{t_s - t_m}$$

The formulas are translated to the model:

$$I_{demand}(t) = I_{demand,t0} + \frac{I_{demand,t30} - I_{demand,t0}}{1 + e^{-k*(t-(t_m)}}$$

in which:

- $I_{demand}(t)$ is the capacity demand at *t*, in [A] for cables and [VA] for transformer
- $I_{demand,t0}$ is the capacity demand at t0, in [A] for cables and [VA] for transformer
- $I_{demand,t0}$ and $I_{demand,t30}$ are the capacity demands at respectively t0 and t30, in [A] for cables and [VA] for transformers
- assumed t_g = 2002 (2007 minus 5 years)
- assumed t_s = 2042 (2007 plus 5 years)
- leading to t_m = 2022
- leading to a k-value of 0,11

or:

$$I_{demand}(t) = I_{demand,t0} + \frac{\partial I}{1 + e^{-0,11*(t-2022)}}$$

Stepwise

A stepwise function with an interval of 5 years is chosen. Over a time horizon of 30 years, this leads to 6 steps.

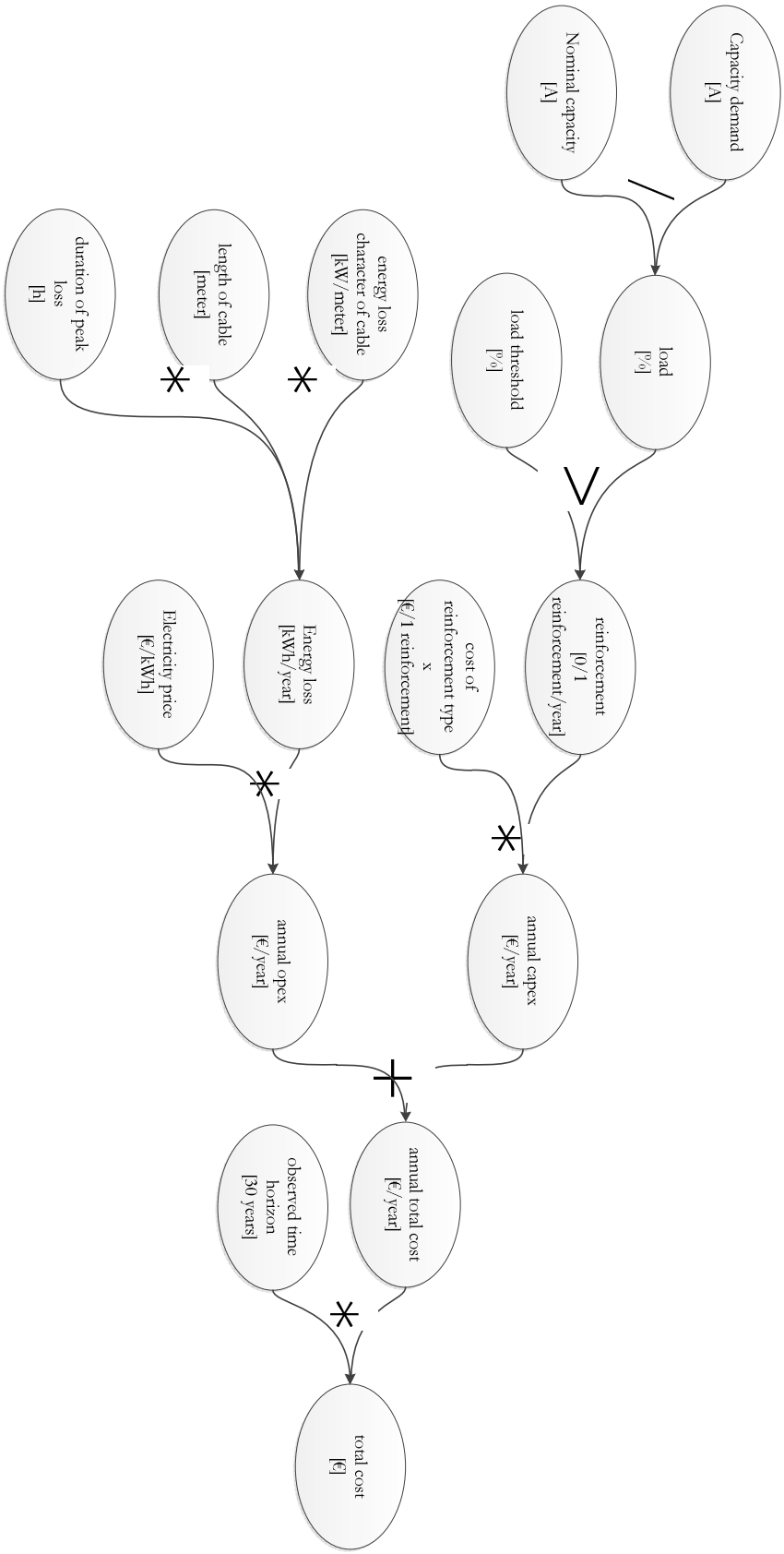
$$I_{demand}(t) = I_{demand,to} + (I_{demand,t30-}I_{demand,t0} * \begin{Bmatrix} \frac{1}{6}\ if\ t < 6 & \frac{4}{6} if\ 16 \leq\ t < 21 \\ \frac{2}{6} if\ 6 \leq t < 11 & \frac{5}{6} if\ 21 \leq t < 26 \\ \frac{3}{6} if\ 11 \leq t < 16 & \frac{6}{6} if\ 26 \leq t < 31 \end{Bmatrix})$$

in which:

- $I_{demand}(t)$ is the capacity demand at *t,* in [A] for cables and [VA] for transformer
- $I_{demand,t0}$ and $I_{demand,t30}$ are the capacity demands at respectively t0 and t30, in [A] for cables and [VA] for transformers

Appendix VII DIMENSION ANALYSIS

This appendix shows an example of the dimension analyses performed during model development.



Appendix VIII DESIGN OF EXPERIMENTS

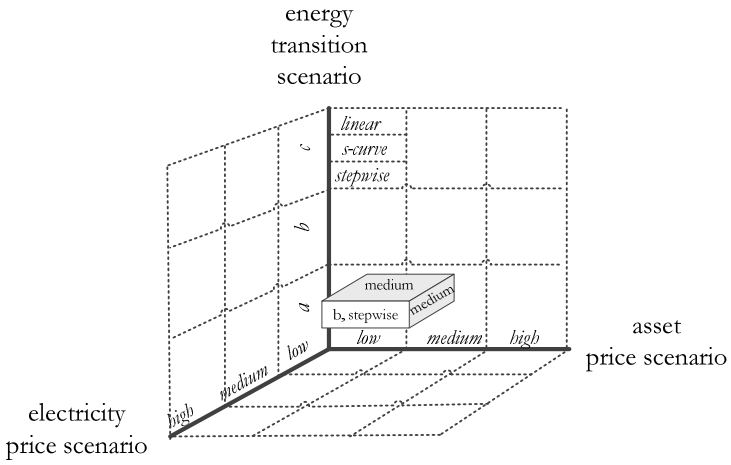
This appendix describes the experiments that are done using the Economic Impact Model for Smart Grids. It starts with a definition of the different environmental scenarios and alternative policies. It then describes three series of experiments: environmental scenario experiments, alternative policy experiments, and interaction effects experiments.

Introduction to environmental scenarios and alternative policies

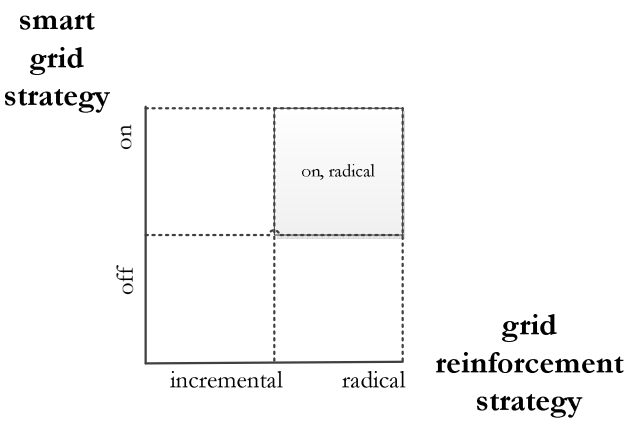
The objective of experimentation is to understand how the system responses to different environmental scenarios under alternative policies. Therefore, these two aspects need to be defined by the model user.

The Economic Impact Model for Smart Grids allows the model user to choose the levels of 4 external influence factors with each 3 levels, and 2 policy factors with each 2 levels. This leads to a total of 6 factors and a total of 324 different factor combinations ($2^2 * 3^4$). This means that there are 81 environmental scenario's (3^4) and 4 alternative policies (2^2).

The different environmental scenarios are shown below, with the example of one environmental scenario indicated by the cube: energy-transition scenario B that is developing stepwise, with a medium asset and electricity price scenario.



The alternative policies are shown below, with the example of one alternative policy: smart grid on and radical grid reinforcement.



Experiment design task

This paragraph explains which experiments are performed and analysed. The table below presents an overview of the design task. First, the tentatively accepted model is used to do experiments that explore how the system responses to the environmental scenarios, under a base policy. This helps us to define a proper base environmental scenario. Second, experiments are described that explore how the system responses to alternative policies, under the base environmental scenario. Third, the interaction effects are explored using a full factorial experiment and fractional factorial experiments.

analysis	experiments	objectives
environmental scenarios experiments	E1, E2, E3	insight in system response to different environmental scenario's to define base environment scenario
alternative policies experiments	P	insight in system response to alternative policies in base environment scenario
full factorial experiments	F	insight in system behaviour in all environmental scenarios under all alternative policies
fractional factorial experiments	FF1	insight in the different impacts of asset price scenario and electricity price scenario in different energy-transition scenarios
	FF2	insight in the different impacts of the smart grid strategies in different energy-transition scenarios
	FF3	insight in the different impacts of the grid reinforcement strategies in different energy-transition scenarios
	FF4	insight in the impact of the alternative policies in different energy-transition scenarios

Environmental scenario experiments

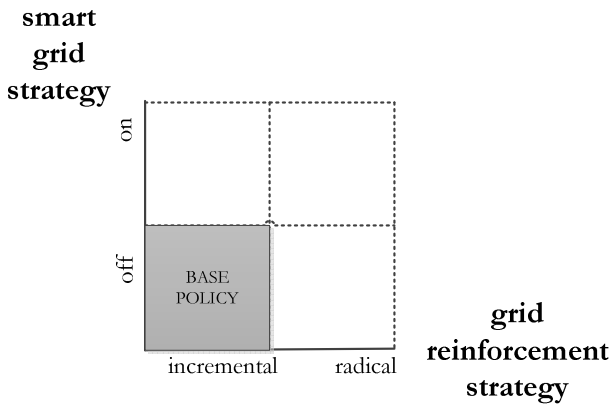
The experiments described in this section show how the system responses to different environments. All experienced are done under a base policy. The experiments are *one-factor-at-a-time* (OFAT) type of analyses, involving the testing of factors one at a time instead of all simultaneously. This means that interaction effects cannot be observed.

Experiment E1 varies the energy-transition scenario's (factor 1) and the capacity demand development scenarios (factor 2). Though two factors are varied in this experiment, the nature of the experiment is still OFAT since the factors do not interact (factor 1 is the capacity demand end-stated and factor 2 the curve towards the end-state). Experiment E2 varies the asset price scenario's (factor 3), and experiment E3 varies the electricity price scenario's (factor 4). Based on these analyses, a rationale for choosing a base environment is made.

Definition of the base policy

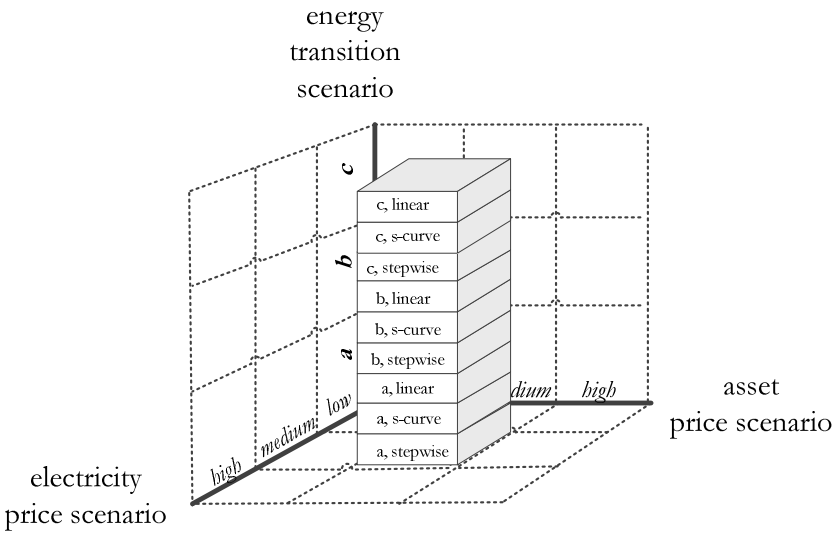
The base policy is the policy that looks most at the Dutch DSO's current policy, or its 'business as usual'. Currently, there is no smart grid present in the Netherlands, so a smart grid *off* strategy is part of the base

policy. Furthermore, the DSO currently reinforces its assets incrementally, so an *incremental* grid reinforcement strategy is the part of the base policy. The base policy is presented in the figure below.



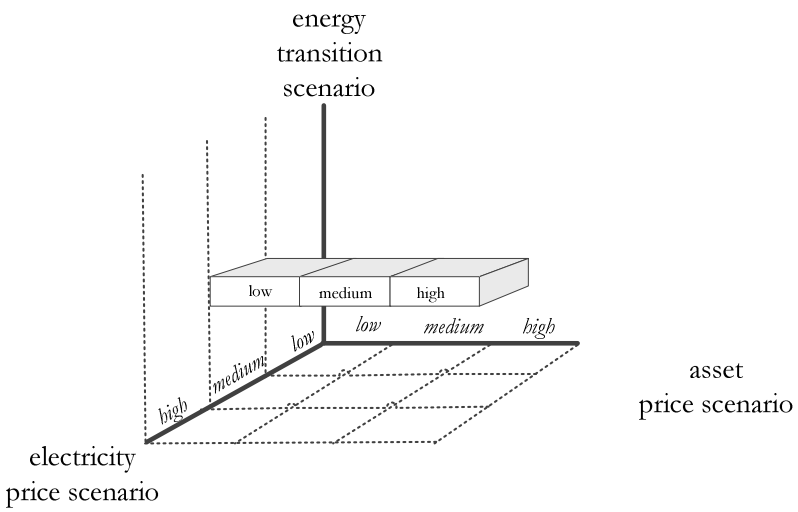
Analysis E1

This analysis shows how the system response to the energy-transition scenario (factor 1) and to the different capacity demand development scenarios (factor 2). This analysis helps us understand two things. First, it allows us to compare the different energy-transition scenarios responses. Second, it shows how the capacity development curve influences the system behaviour, and allows us to compare different curves. **Error! Reference source not found.** shows the 9 experiments (or 9 model runs) that are done, each cube representing one experiment. It shows that the energy-transition scenarios and capacity demand curves are observed in medium asset price and electricity price scenario's. Based on these experiments the base energy-transition scenario And base capacity demand curve can be determined.



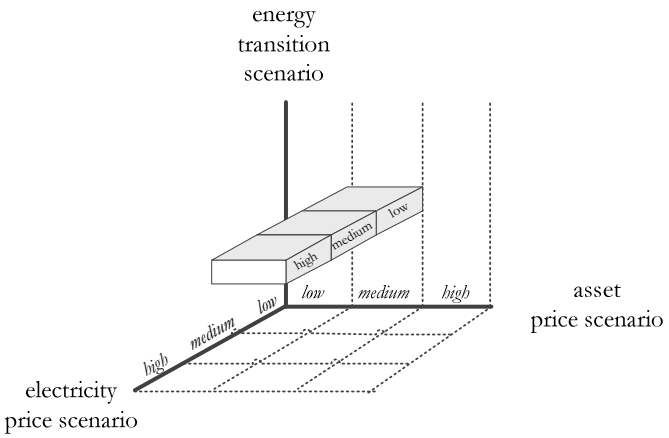
Analysis E2

This analysis shows how the system response to the asset price scenario (factor 3). **Error! Reference source not found.** shows the 3 experiments (or 3 model runs) that are done, each cube representing one experiment. Note that the experiments are 'floating', since the base energy-transition scenario And the base capacity demand curve is not yet determined (these will be determined based on Analysis E1). Also, it shows that the base electricity price scenario is assumed to be *medium*.



Analysis E3

This analysis shows how the system response to the electricity price scenario (factor 4). This allows us to understand what the impact of the electricity price scenario on the system response is. **Error! Reference source not found.** shows the 3 (or 3 model runs) experiments that are done, each cube representing one experiment. Similar to the previous analysis, the experiments are 'floating', since the base energy-transition scenario And the base capacity demand curve is not yet determined (these will be determined based on Analysis E1). Also, it shows that the base asset price scenario is assumed to be *medium*.

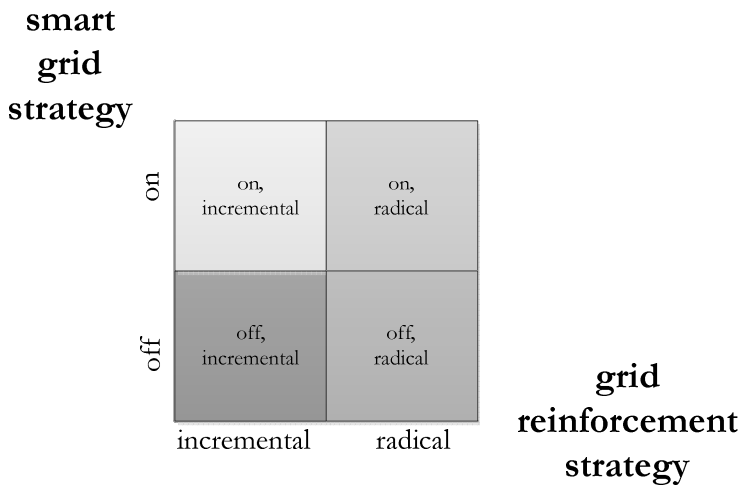


Definition of the base environmental scenario

The base environmental scenario is defined to do first policy explorations. The base environmental scenario is chosen based on the rationale that it is the most obvious or closest to the expected scenario. This choice for the base environmental scenario will be debatable, since the exact future situation is highly uncertain. However, full exploration of the system response in all environmental scenario's under all alternative policies (full factorial analysis) gives more insight in the effects of alternative policies in different environments.

Alternative policy experiments

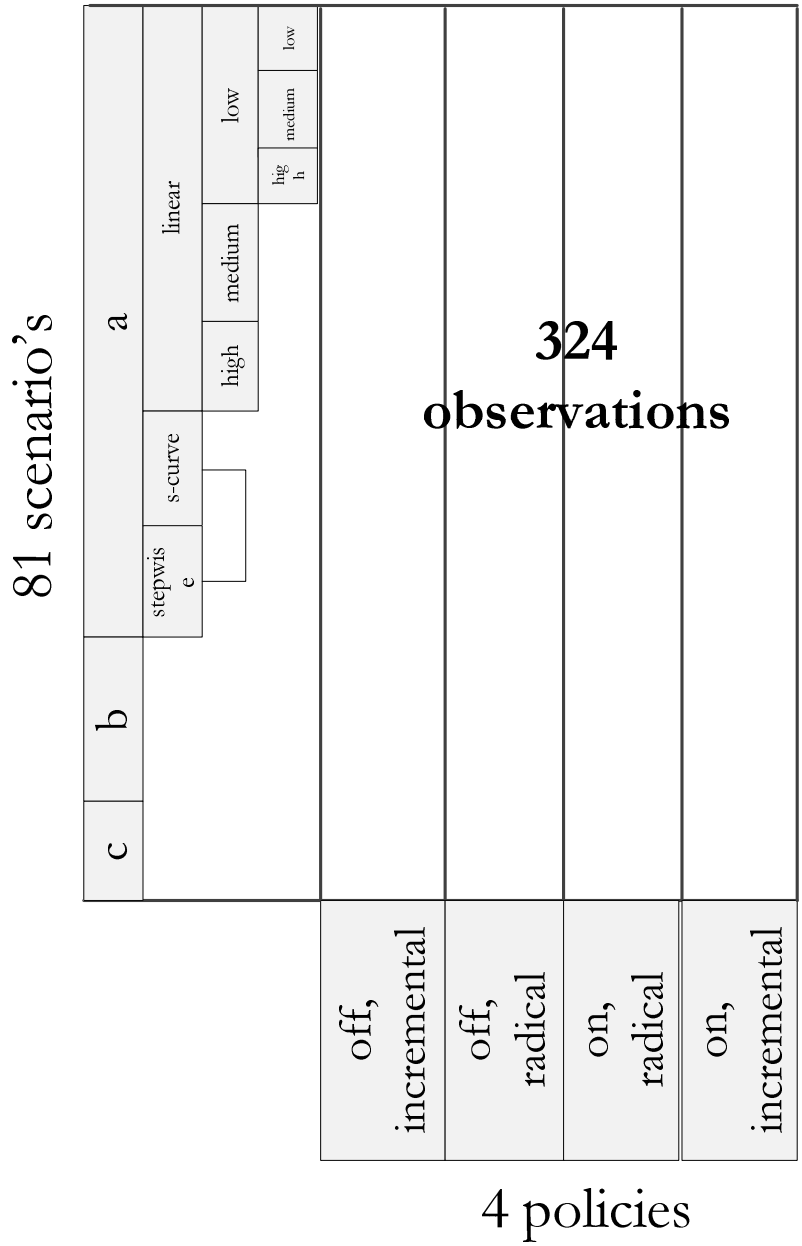
This section describes the experiments that show the systems response to the four alternative policies in the base environmental scenario. The goals of the analyses is to understand how the system responses to alternative policies, and to determine which policy is most advantageous. This analysis uses the base environmental scenario to do first experiments with. Conclusions should thus carefully be made, since alternative policies might have a different impact in other environmental scenarios. **Error! Reference source not found.** shows the 4 experiments (or 4 model runs) that are done, each square representing one experiment.



Interaction experiments

Full factorial analysis

A full factorial design contains all possible combinations of the factors. It observes one response, the NPV. The figure below shows how the 324 model runs are observed. Per row, one possible environmental scenario is observed. The classification of the different external influence factors is done as shown in **Error! Reference source not found.**: from energy-transition scenario, to capacity demand curve, to asset price, to electricity price. Per column, the 4 alternative policies are categorized: from *off, incremental*, to *off, radical*, to *on, incremental* to *on, radical.*



The full factorial analysis allows us to observe all 324 situation for one response parameter at the same time. Colouring certain value ranges, results in a colour plot that shows certain landscapes of values. Exploration of these landscapes of values allows us to understand how the system responses to combinations of factors.

The full factorial analysis is performed for two responses: the total cost and the NPV, both in billion euro's over the total observed period of three decades.

Fractional factorial analysis

Based on the full factorial analysis the most interesting relations can be distilled. The most interesting relations are further explored in a fractional factorial experiment, meaning that the interaction effects are determined by observations on varying a part of the factors.

Analysis FF1: asset price, electricity price and energy-transition scenario

This analysis first observes how the system responses to the varying asset price scenarios in different energy-transition scenarios and under different smart grids strategies. This is done by comparing the total cost, annual capex, and annual opex in the low and high asset price scenario in relation to the medium asset price scenario. All experiments are done in a s-curve capacity demand development scenario and a medium electricity price scenario, under an incremental grid reinforcement strategy. A similar analysis is performed to analyse system response to the varying electricity price scenarios. These experiments are done in a medium asset price scenario.

Analysis FF2: smart grid strategy and energy-transition scenario

This analysis observes how the system responses to the varying smart grid strategies in different energy-transition scenarios. This is done by comparing the total cost, annual capex, and annual opex under the smart grid on and the smart grid off strategies. All experiments are done in a s-curve capacity demand development scenario, a medium asset price scenario, a medium electricity price scenario and under an incremental grid reinforcement strategy.

Analysis FF3: grid reinforcement strategy and energy-transition scenario

This analysis observes how the system responses to the varying grid reinforcement strategies in different energy-transition scenarios. This is done by comparing the total cost, annual capex, and annual opex under the smart grid on and the smart grid off strategies. All experiments are done in a s-curve capacity demand development scenario, a medium asset price scenario, a medium electricity price scenario and under a smart grid off strategy.

Analysis FF4: alternative policies and energy-transition scenario

This analysis observes how the system responses to the alternative policies in different energy-transition scenarios. This is done by comparing the total cost, annual capex, and annual opex under the smart grid on and the smart grid off strategies. All experiments are done in a s-curve capacity demand development scenario, a medium asset price scenario, and a medium electricity price scenario.

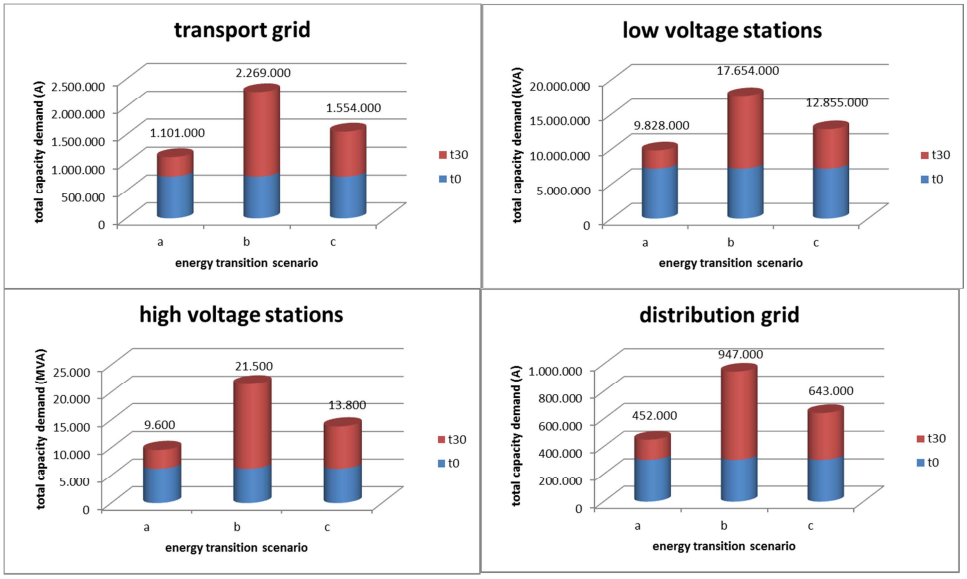
Appendix IX DESCRIPTION OF INPUTS

This appendix gives descriptions of different inputs used in the Economic Impact Model for Smart Grids.

The inputs of factor 1

Different energy-transition scenario's lead to a different grid capacity demand. The model observes the capacity demand per asset, and reinforces the asset when its nominal capacity cannot cope with the demand. In order to get an understanding of the varying energy-transition scenario levels, the total capacity demands of all assets at t_0 and t_{30} is presented.

The figures below show these for the different physical elements. The total capacity demand is the sum of the capacity demands of all assets (expressed in volt-ampere for transformers, and in ampere for cables). The blue part of the cylinders show the capacity demand at t_0, which is the same in all scenario (starting point). The red parts show the additional capacity demand at t_{30}. In general, it can be stated that energy-transition scenario A demands the lowest amount of additional capacity, while scenario B demands the highest amount of additional capacity.

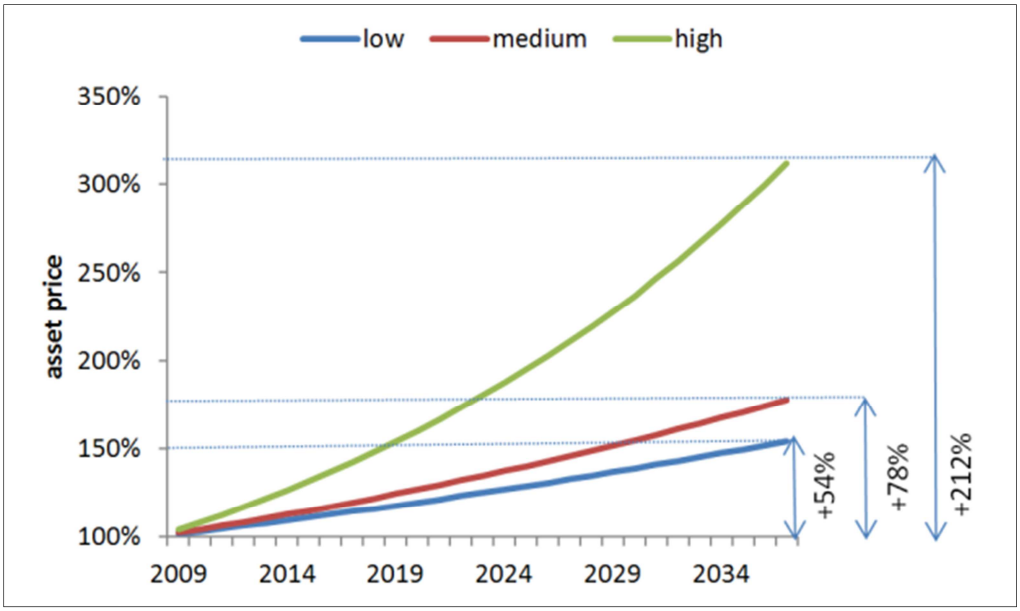


The table below shows that scenario A leads to a capacity demand in t_{30} of 1.5 times the capacity demand in t_0, in scenario B this value is 3.0 and in scenario C 2.0.

energy transition scenario	high voltage transformers	low voltage transformers	transport grid	distribution grid	average
A	1,5	1,4	1,5	1,5	**1,5**
B	3,5	2,4	3,0	3,1	**3,0**
C	2,2	1,8	2,1	2,1	**2,0**

The inputs of factor 3 and 4

The three levels of the asset price scenario are low, medium and high, representing an annual increase of respectively 1.0%, 2.5%, and 4%. This means that for instance in the low scenario, the price of each new asset increases with 1.0% a year. The year after, this price is increased with another 1.0%, and further. This means that the asset price increases exponentially. **Error! Reference source not found.** shows how the asset price develops over the years. As indicated in the same figure, in the low asset price scenario, the asset price is 54% more expensive at t_{30} than at t_0. In the medium scenario, the price is 78% higher and in the high scenario 212% higher at t_{30} than at t_0, see the picture below.



Just like the asset price scenario, the three levels of the electricity price scenario are low, medium and high, representing an annual increase of respectively 1.0%, 2.5%, and 4%. This means that the same figure can be used to show how the electricity price develops over the years.

The inputs of factor 5

Under the smart grid strategy, the effect of peak shaving is activated. The effect used in this research is based on other research performed by a DSO . A summary of the result of this research is presented in the table below, in which average peak load shaving is defined as:

$$l_{peakshaving}(t_{30}) = l_{peak,off}(t_{30}) - l_{peak,on}(t_{30})$$

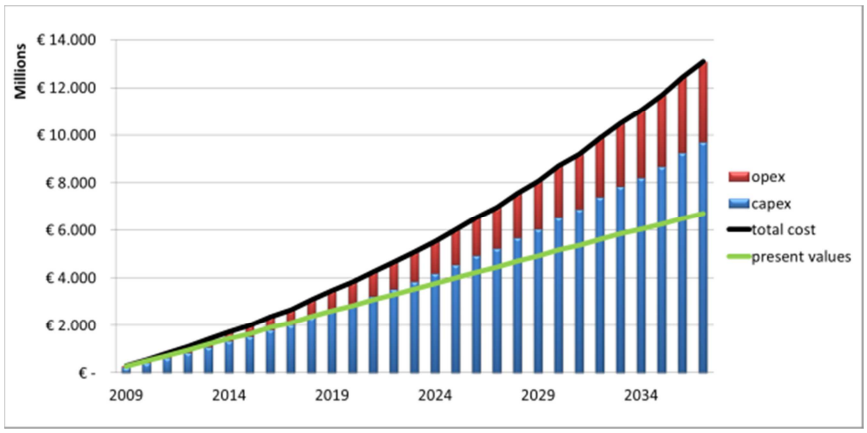
energy-transition scenario	high voltage transformers	transport grid	distribution grid	low voltage transformers	average per scenario
A	22%	16%	6%	20%	**16%**

B	15%	9%	4%	15%	**11%**
C	24%	15%	7%	23%	**17%**
average	**22%**	**14%**	**6%**	**20%**	**16%**

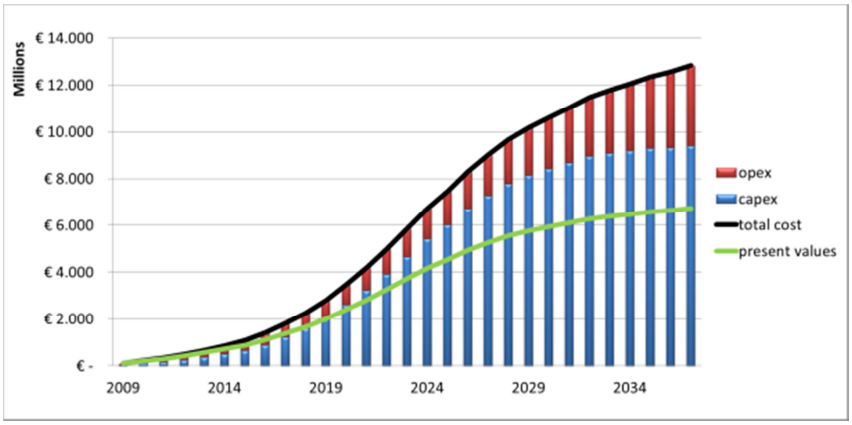
Appendix X RESULTS: ENVIRONMENTAL SCENARIO ANALYSIS

This Appendix presents the results of the environmental scenario, in different capacity demand development scenarios.

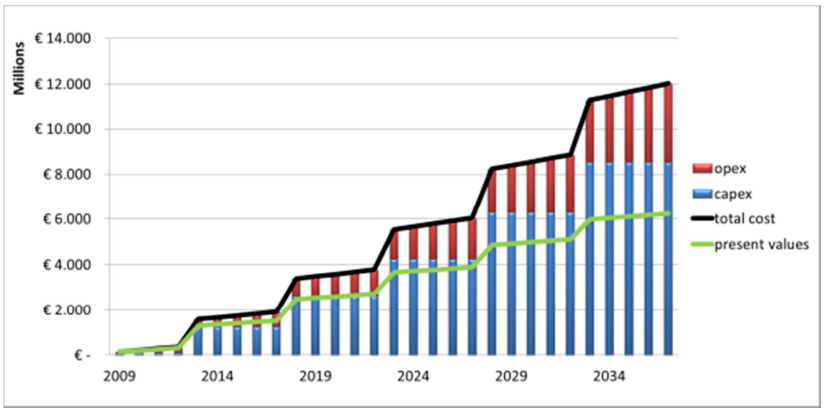
The graph below shows the accumulated total costs in the linear capacity demand development scenario.



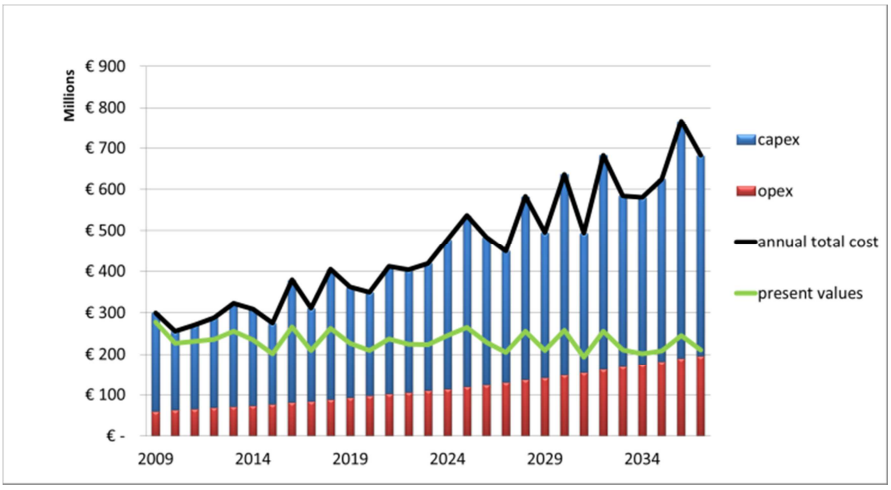
The graph below shows the accumulated total costs in the s-curve capacity demand development scenario.



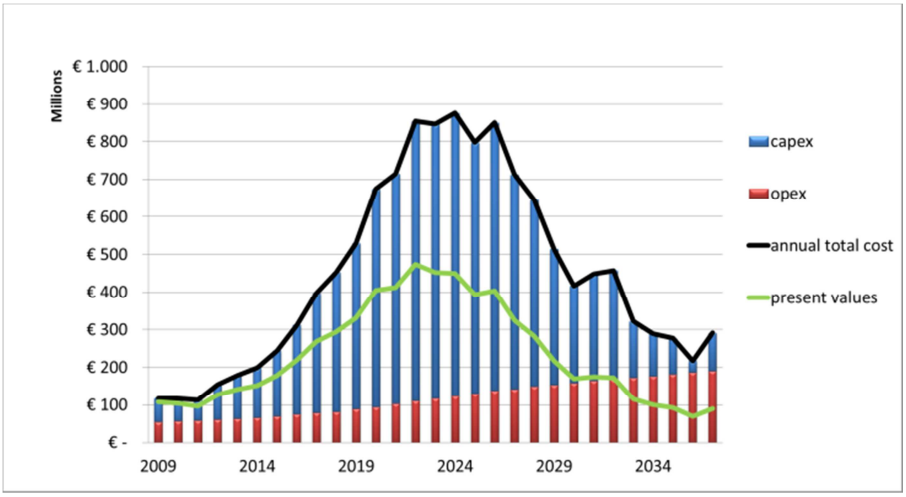
The graph below shows the accumulated total costs in the stepwise capacity demand development scenario.



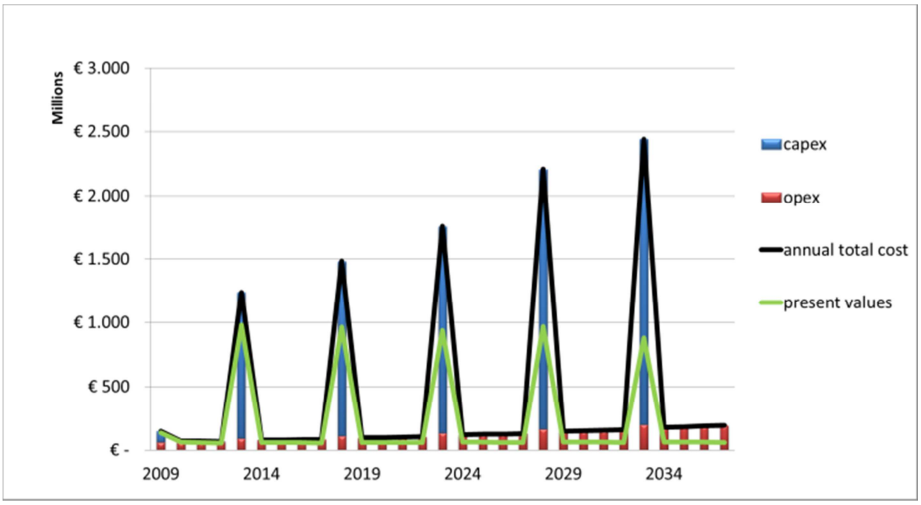
The graph below shows the annual total costs in the linear capacity demand development scenario.



The graph below shows the annual total costs in the s-curve capacity demand development scenario.



The graph below shows the annual total costs in the stepwise capacity demand development scenario.



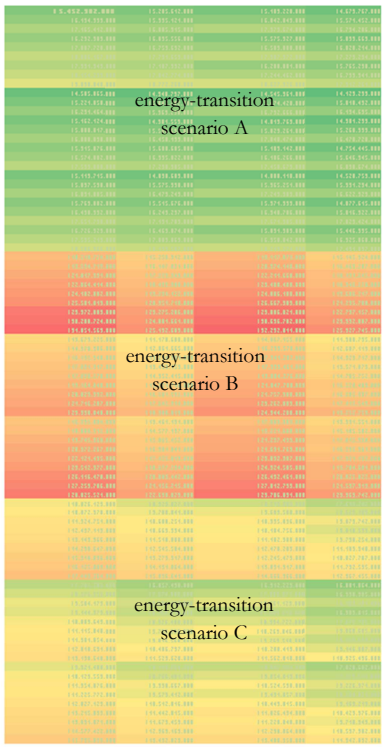
Appendix XI FULL FACTORIAL ANALYSIS

This objective of this appendix is to understand how the system responds to different environmental scenario's under alternative policies. The objective of this paragraph is therefore to get an overall insight in the interaction effects between all factors, and to highlight some of the most interesting interaction effects that help us understanding system behaviour.

A full factorial analysis observes the system response to all combinations of factors. As introduced in the design of experiments, this coincides with 324 observations. Two full factorial analyses are performed. First, a full factorial analysis of the system response total cost is done. Secondly, a full factorial analysis of the NPV is done, taking the time value of money into account. Both results are analysed in the next sections.

Total cost

The figure below shows a colour plot of the full factorial analysis: the system responses (NPVs) for all factor combinations. The responses are coloured, from low to high, from green to yellow to red. The minimum value is €4.1billion, the maximum value is €32.3 billion, and the average value is €12.3 billion. The plot can be observed as explained in the design of experiments (Appendix VIII). The figure shows that the energy-transition scenario is a very dominant factor, showing three vertical response areas. Scenario A is indicated by the green area, scenario B by the red area, and scenario C by the yellow area.



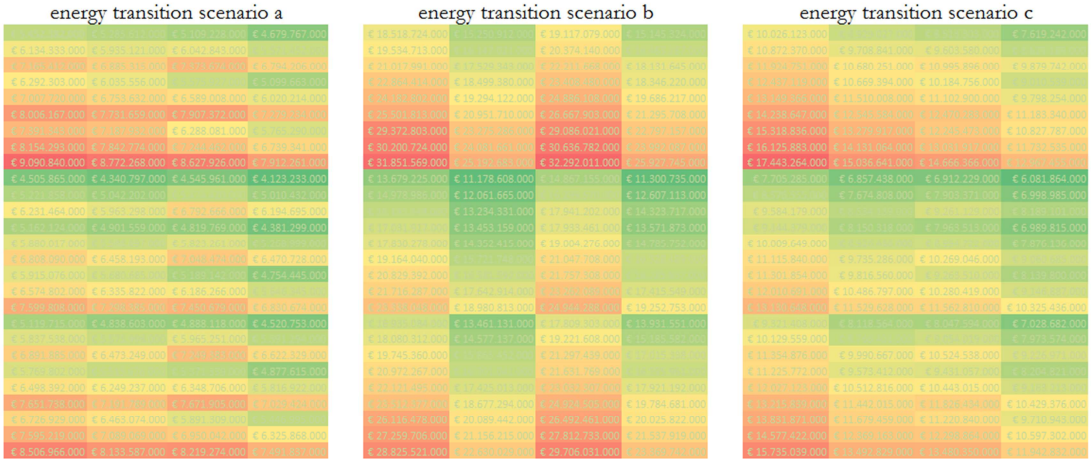
The table below shows the minimal, maximal, and average values of the different energy-transition scenario's, which cause the different response areas. The values are in line with the previous conclusion that the system response differs significantly in different energy-transition scenarios, with scenario B leading to the highest total cost (average €20,1 billion) followed by respectively scenario C (average €10,6

billion) and a (average €6,3 billion). The range of the different energy-transition scenario values is similar, with a minimum value of 0.33 times the mean and a maximum value of 2.33 time the mean.

value	all energy transition scenarios	**energy transition scenario a**	**energy transition scenario b**	**energy transition scenario c**
minimum	€ 4,1 billion	€ 4,1 billion	€ 11,2 billion	€ 6,1 billion
maximum	€ 32,3 billion	€ 9,1 billion	€ 32,3 billion	€ 17,4 billion
average	€ 12,3 billion	€ 6,3 billion	€ 20,1 billion	€ 10,6 billion

The dominant role of the energy-transition scenario makes analysis of the interaction effects of the other factors difficult. It can thus be concluded that the further exploration of the impact of different factors in the different energy-transition scenarios is needed.

In order to do more observations on the impact of the other factors using the full factorial results the figure below shows colour plots for the different energy-transition scenarios, thereby filtering the effect of this dominant factor.



The figure shows that in all three energy-transition scenarios, the linear capacity demand development, in combination with a high asset price and a high electricity price leads to the highest total cost. Also, it shows that the s-curve in combination with a low asset price and low electricity leads to the lowest cost. This is in line with previous environmental analyses.

A first observations is that we can see three vertical response areas with a similar pattern. This means that the different capacity development curves, interact in the same way with the other factors (the effects are slightly stronger in the linear capacity demand development scenario since the upper block shows strongest colour gradient). Therefore, it is assumed that this factor does not interact with the other factor, and the colour plots can be observed for one capacity development curve. Further exploration of interactions of this factor with the other factors is not interesting.

Also, it can observed that there is not a clear pattern in energy-transition scenario A caused by the asset price and electricity price scenarios, which means that the impact of both factors is comparable. However, in scenarios b and c the pattern of the asset price and electricity price scenario becomes clear (by the gradient colours at the levels of these external influences). The pattern also shows that the asset price is

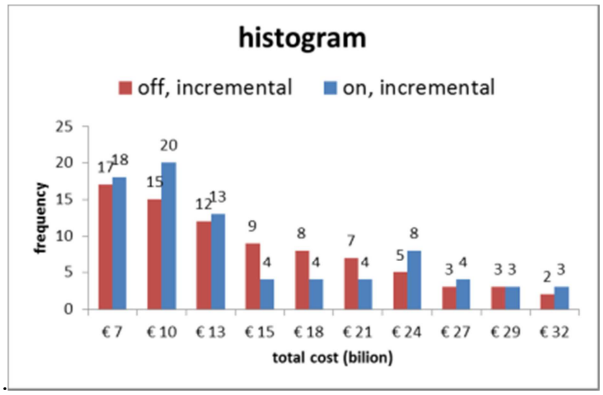
most dominant in energy-transition scenario B and C, as the gradient follows the asset price scenario. Further exploration is needed to determine what the impact of the asset price scenario and electricity price scenario is, in different energy-transition scenarios.

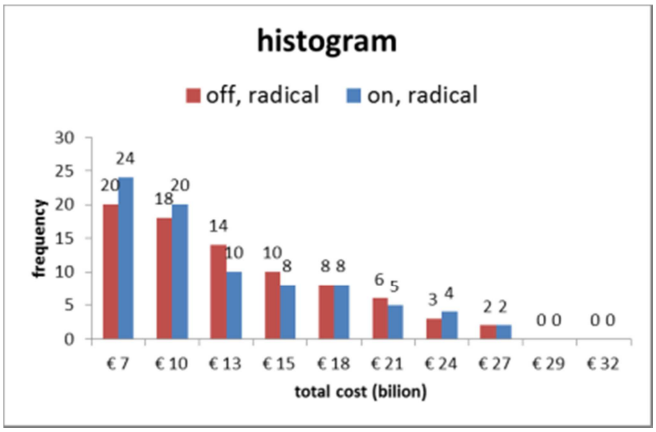
The alternative policies can be distinguished in the colour plots by the four horizontal response areas. In all three energy-transition scenarios, the *on, radical* policy is leads to the lowest cost, and the *off, incremental* to the highest cost. So it can be concluded that these are in all scenarios the respectively most advantageous and least advantageous policies. The difference between the *on, incremental* and *off, radical* policies is not the same in all energy-transition scenarios. In scenario b, the incremental grid reinforcement policies have a similar impact, and the radical policies have a similar impact. This leads to the assumption that the smart grid strategy does not have impact in energy-transition scenario B, in terms of total cost. In scenario c, the difference between the *off, radical* policy and the *on, incremental* policy is not clearly present. In scenario a, the *on, incremental* is more advantageous than the *off, radical* policy.

The table below shows that based on the mean total costs in all environmental scenarios, the *on, radical* policy is indeed most advantageous. It also shows that the *off, radical* policy is the second best policy, followed by the *on, incremental* and the *off, incremental* policies. Based on this one could conclude that the grid reinforcement strategy has more impact than the smart grids strategy, as the *off, radical* is more advantageous than *on, incremental*. With respect to the standard deviation, it can be concluded that the standard deviation is high, indicating that the values are spread over a wide range, which is logical since multiple energy-transition scenarios are observed, which cause large ranges. If we take a look at the mean total cost in the different energy-transition scenarios under the alternative policies, it can also be concluded that the *on, radical* policy is most advantageous and the *off, incremental* is the least advantageous policy. Though there is no difference between the off, radical policy and the on, incremental policies in scenario c, the off, radical policy is most advantageous in scenarios a and b.

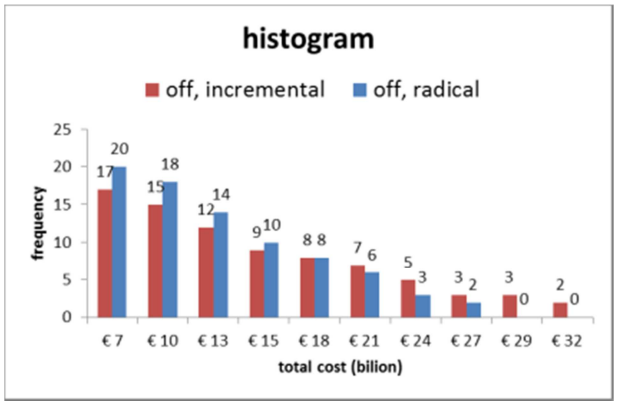
total cost	**off, incremental**	**off, radical**	**on, incremental**	**on, radical**
mean	€ 13,5 billion	€ 11,5 billion	€ 13,2 billion	€ 11,0 billion
minimum	€ 4,5 billion	€ 4,3 billion	€ 4,5 billion	€ 4,1 billion
maximum	€ 31,9 billion	€ 25,2 billion	€ 32,3 billion	€ 25,9 billion

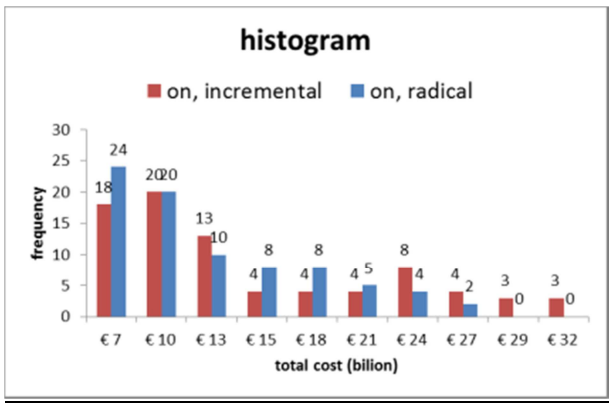
The figures below shows two histograms that present the frequency of the total cost responses over all different environmental scenario's. Each histogram compares the two smart grid strategies, one under the incremental grid reinforcement strategy and the other under the radical strategy. Based on this, it can be concluded that the smart grid on strategy is in both situations more advantageous than an *off* strategy, though its difference is minimal





The figures below show two similar histograms, now comparing all responses for the two grid reinforcement strategies. The figure confirms that a radical strategy is always more advantageous than an incremental one, both in combination with a smart grids on strategy and a smart grids off strategy.

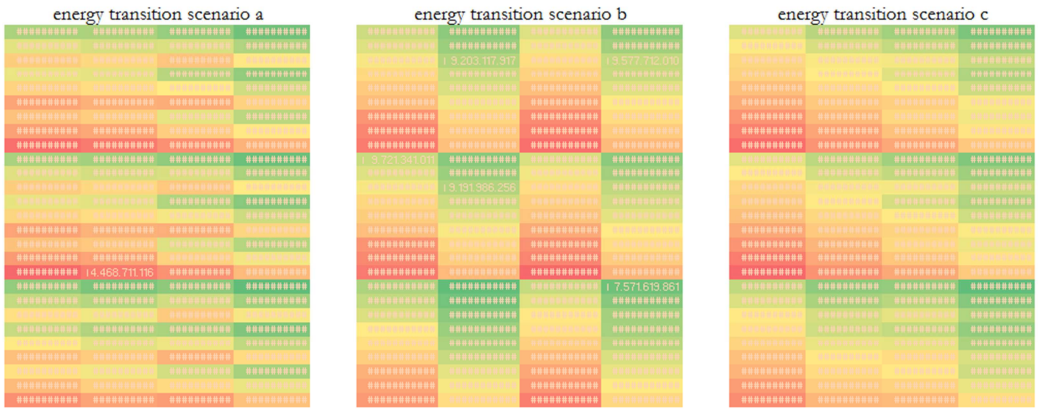




If one had to choose between an *off, radical* and the *on, incremental* policy, the *off, radical* policy is more advantageous in most of the energy-transition scenarios. This leads to the assumption that the grid reinforcement strategy has more impact on the total cost than the smart grids strategy. However in order to get more insight in the combination of two strategies, and which one is dominant, further analysis on the separate impacts of the smart grid strategy and the grid reinforcement strategy on the total cost in different energy-transition scenarios is suggested.

NPV

A full factorial analysis of the NPV shows that its minimal value is €2.5 billion, its maximum value €17.1 billion, and its average value €6.9 billion. The colour plot of the full factorial NPV values also shows three main landscapes of energy-transition scenarios. Therefore, the colour plots of the different energy-transition scenarios is presented in the figures below. The plots show many similarities with the total cost colour plots. It can therefore be concluded that the time value of money does change the system response in terms magnitude, but it does not change the system response in terms of direction. Further analysis is therefore based on the total cost.



Identification of further analyses

The energy-transition scenario has such a big impact, that the impact of the other external influence factors should be evaluated for each energy-transition scenario. Therefore, further analysis is needed that shows if the effect of the asset price scenario and the electricity price scenario on total cost is different in varying energy-transition scenarios, and how this difference can be explained. Furthermore, the impact of the alternative policies seem to differ for each energy-transition scenario, so more insight in the relation between the different strategies and the energy-transition scenario is needed. Therefore, an analysis that shows if the effect of different smart grid strategy on total cost in varying energy-transition scenarios is needed. Also, analysis that shows if the effect of the different grid reinforcement strategies in varying energy-transition scenarios is needed. In coherence with assumptions earlier made, explanations for the impact on the total cost are found by observations on the underlying capex and opex.