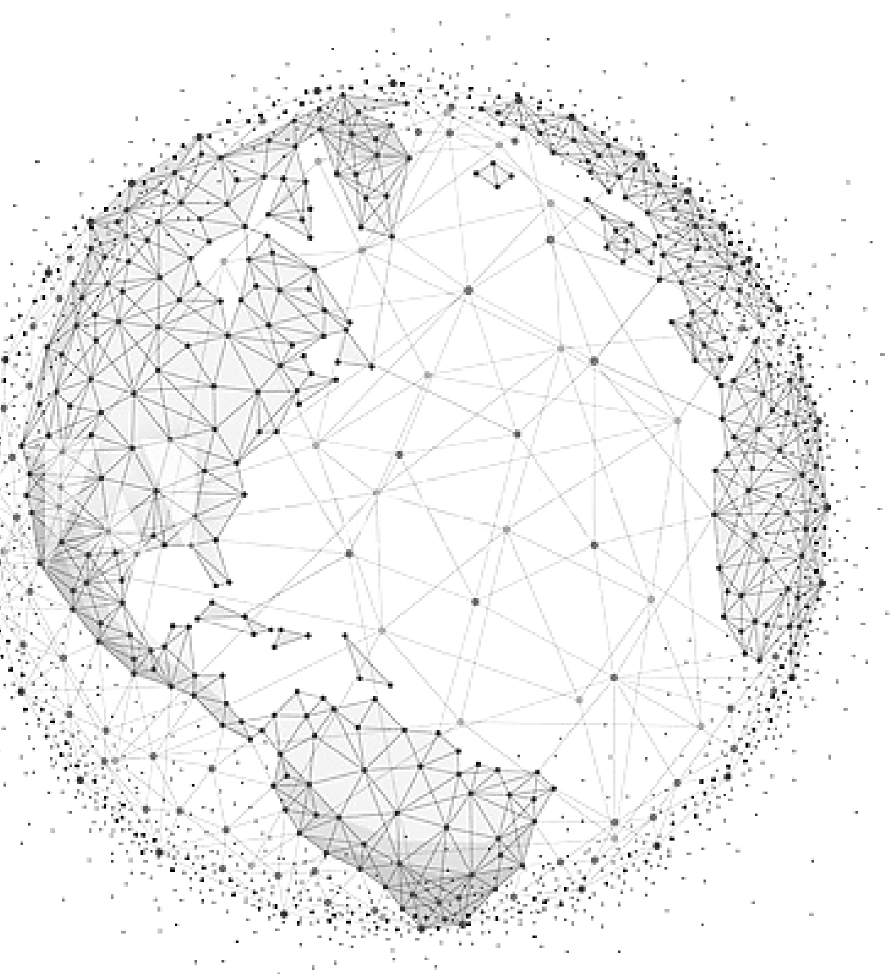
Framework for updating scenarios

A multi-layer framework for structurally incorporating new information and uncertainties into scenarios



MSc. Thesis

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Framework for updating scenarios

A multi-layer framework for structurally incorporating new information and uncertainties into scenarios

By

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Graduation committee

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Acknowledgement

“DEEP IN OUR HEARTS, WE WOULD ALL CHOOSE A SCENARIO WITH NO SURPRISES”

Pierre Wack, the father of scenarios

This research was conducted as a final assessment for the master program Complex Systems Engineering and Management at the Delft University of Technology. The quote of Pierre Wack is in all ways very applicable to my thesis. When writing this thesis there were many unexpected turns, and it was nothing but a linear process. We would like to know on forehand how the entire process is structured, at the same time we know this is not going to be the case, but deep in our hearts we still hope it does. I learned so much from executing this research, academically and personal. How to tackle such a big and complex assignment, how to keep focus and ensure everyone is on the same page. This made it a very challenging assignment but at the same time one of the biggest and most satisfying accomplishments.

I could not have executed this research without the help of a number of people. First, I would like to thank Daniel Scholten for being my first supervisor on behalf of TU Delft, the continuous believe in the relevance of my topic and the many discussions on my subject, and other topics, which I always really enjoyed; Kornelis Blok for being Chairman & Second Supervisor on behalf of the TU Delft and providing a critical view on my research which made my entire thesis much stronger.

Second, I would like to express my special gratitude to Jonathan Schachter for supervising me on behalf of Shell, coaching on a weekly basis, having many fruitful discussions, being amazing and always supporting me. Additionally, of course the entire Power Fundamentals team for giving me this opportunity, helping me throughout the entire process and providing me with many new insights related to energy and beyond.

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Paulien van den Berg

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Executive summary

The dynamic and fast-changing environment brings challenges for generating long-term visions of the future; scenarios. Outdated scenarios will result in future pathways that are no longer achievable and therefore reduces their relevance and usefulness for making decisions. As some uncertainty is resolved over time, while others arise, it is important to take these changes into account. It is very inefficient and time-consuming to make new scenarios every time something changes, therefore, finding an efficient and time-effective way to incorporate new information into scenarios, is a research theme to be analyzed.

To understand how scenarios are currently kept up-to-date, extensive literature research was executed. The research identified two important factors influencing how an update should be performed. First, within a scenario a long-term macro perspective and a short-term micro perspective view are present. Due to this difference, these parts are differently influenced when incorporating changes. Nonetheless, within literature no explicit distinction is made between different parts of a scenario. Second, the nature of the change influences how scenarios are affected. However, no tool is found to assess which changes need to be considered in what way. Furthermore, although prior studies have noticed the importance of keeping scenarios up-to-date, a methodological approach for executing this process is non-existing. However, performing an update in an unstructured manner imposes multiple problems. First, the update becomes time-consuming as there is no standardized way of executing the process. Secondly, an unstructured way of working imposes difficulty in communicating how and which changes are made.

The objective of this research is to create a process to structurally incorporate new information and uncertainties into scenarios, reducing some of the complexity of the process, ensuring scenarios are properly updated. Thereby guaranteeing the scenarios remain plausible and relevant. From the research objective, the research question is formulated: *How to structurally incorporate new information and uncertainties into scenarios, keeping them up-to-date, guaranteeing that the scenarios remain realistic and useful?*

I propose that to configure a solution, two novel concepts, inspired by the literature review, need to be introduced: 1) Scenarios consist of a multi-layered structure, and 2) changes considered should be classified according to their impact and uncertainty. Based on this classification, changes are incorporated into the different layers distinguished (figure A).

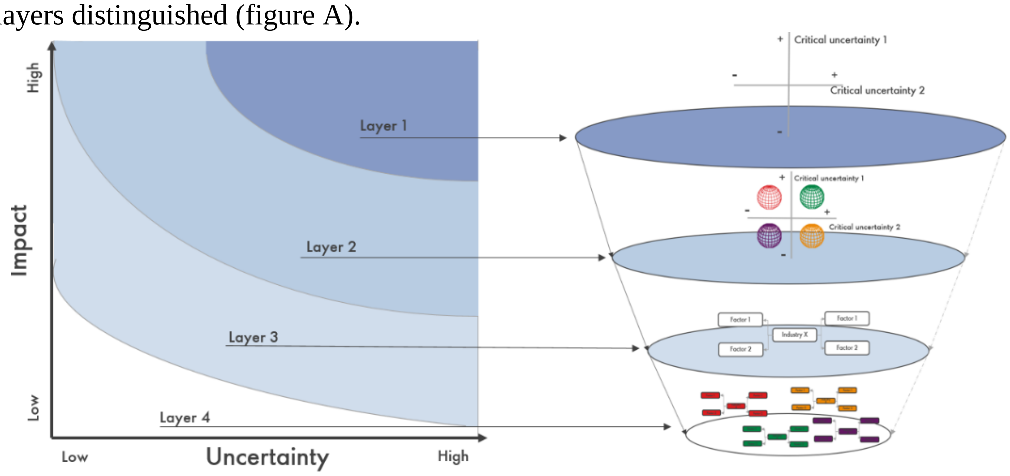

Figure A: Linking the impact-uncertainty matrix to the layers indicated within scenarios

To apply the concepts introduced during an update, several steps need to be performed. Figure B presents the dynamic scenario framework consisting of 7 steps to structurally incorporate new information and uncertainties into scenarios.

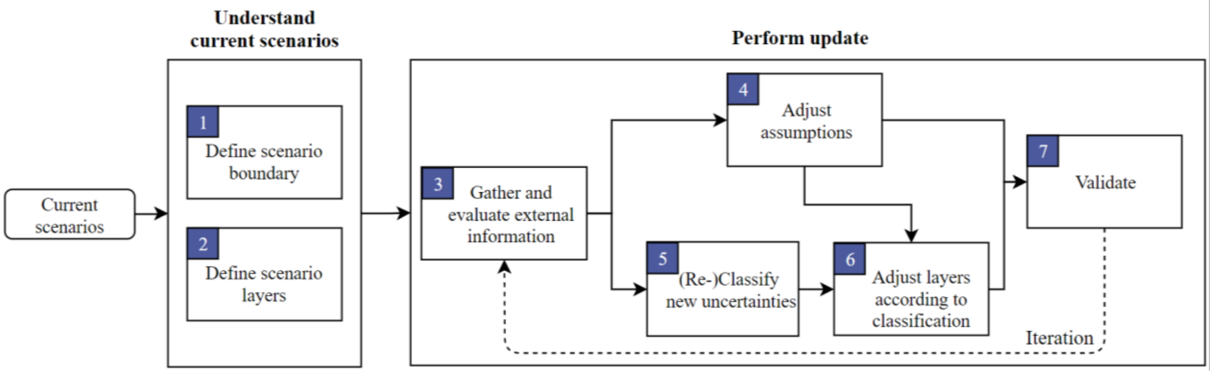

Figure B: Dynamic scenario framework

The first two steps are performed to understand the current scenarios and their buildup before performing any alterations. Step 3 is executed to understand the changing external environment and provides the required input for performing an update by retrieving information. This information is analyzed to understand how the different changes should be considered within the scenarios. After step 3, two routes could be taken (4-7 or 5-6-7). For each change is should be determined which route suffices. Step 4 is referred to as a regular update. New information will be added to the existing assumptions within the scenarios. Steps relating to this route are explained but not expanded upon as this is not the focus of this thesis. Within step 5 and 6, new trends and uncertainties not yet considered within the scenarios are dealt with by determining *if* and *how* these should be considered within the scenarios using the concepts introduced in figure A. This second route is primary the focus of this thesis as research on this topic is limited and there is currently no methodology in the literature that provides a structured process for incorporating new trends and uncertainties into scenarios. Lastly, the changes are validated in step 7.

To illustrate how the framework performs in a practical context a test case was executed, highlighting the benefits of using such a framework, while at the same time uncovering any of its limitations. After defining the boundary and the different layers (step 1 and 2), external information was gathered and analyzed (step 3). One example is provided to indicate the process of adjusting the assumptions, denoted as a regular update (step 4). This example refers to the assumptions made on installed capacity for solar PV. Additionally, three new uncertainties are considered, i.e. nuclear fusion, hydrogen and a coal phase-out in Germany. These are currently not yet considered and should be incorporated differently within the scenarios, based on its classification on the impact-uncertainty matrix (step 5 and 6). After validating the executed update, results show that using the framework allows the complexity of the update to be simplified into a step-by-step process. Additionally, it increases transparency by creating a common language for understanding *if* and *how* the changing external environment should be incorporated within scenarios.

Concluding, to structurally incorporate new information and uncertainties into scenarios, keeping them up-to-date, guaranteeing that the scenarios remain realistic and useful, a framework consisting of 7 steps is developed. The aim of the framework is to offer the user a tool that helps you to think about *if* and *how* changes should be incorporated within scenarios and what the impact of these changes are for the rest of your scenario. Using the framework allows the complexity of the update to be simplified in a step-by-step process. By separating the update in smaller concrete steps and understanding how these steps influence the rest of the scenario, complexity is reduced. Additionally, when using the framework, the process becomes increasingly transparent. Increasing the transparency of the process increases understanding of the scenarios itself and changes made. It makes the updating process explainable and justifiable, why and how choices are made. The framework proposed also creates a language for communicating it to a broader audience. This could help more people to better understand the scenarios itself and their outcome. The dynamic scenario framework, therefore, provides a better understanding of the consequences of our actions today for our future tomorrow.

Further research needs to be carried out to validate the choice of the impact-uncertainty matrix. Other tools might also be suitable for classifying changes and linking them to the different layers within the scenario. Additionally, it is recommended to execute an entire update with the framework, as an update is now partly performed. This could highlight additional benefits or uncover limitations. Lastly, a natural progression of this work is to apply the framework to scenarios discussing other sections of the energy industry. The test case was applied to scenarios representing the European power market. However, to confirm the generalizability of the framework, it should be applied to scenarios discussing other parts of the energy industry.

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Terminology

Within the subject of scenarios, the terminology is not inclusive. During this research, it became apparent that, in order to have a fruitful discussion, it is important to first established a common understanding of the terminology used. As there are many ambiguities about the definition of a scenario and what a scenario constitutes, special attention is provided within this thesis to this subject. As this thesis is about keeping scenarios up-to-date, it is of high importance to understand what a scenario is and what it is not. A short list of the most important terminology used is provided below.

Scenario

"*A scenario is a story that describes a possible future while it identifies some significant events, the main actors and their motivations, and it conveys how the world functions.*" (Shell International BV, 2008, p.8). This definition highlights the fact that a scenario is qualitative in nature as the scenario is first defined using a narrative before any numbers are added.

Keeping scenario's up-to-date:

Incorporating new information and new uncertainties (changes in the external environment) into scenarios to keep these plausible and relevant.

Trend

"*A general development or change in a situation or in the way that people are behaving*" (Cambridge Dictionary, n.d.-a).

Critical uncertainties

Matters that have a high uncertainty with a high impact on the business environment.

Assumptions within scenarios

The meaning of an assumption according to the Cambridge dictionary is as follow (n.d.-b): *"Something that you accept as true without question or proof".* The assumptions made within scenarios should, however, be validated as much as one can but you accept that it may be wrong. Within this thesis the assumptions are underlying the scenarios and are needed to create a coherent storyline on how the future might develop.

Relevance of research for Royal Dutch Shell

This master thesis was conducted at Royal Dutch Shell within the Strategy and Portfolio group, supporting New Energies. Shell is an international energy company with expertise in the exploration, production, refining and marketing of oil and natural gas and the manufacturing and marketing of chemicals. Working to thrive in the energy transition, Shell created in 2016 a New Energies unit focusing on commercial opportunities linked to the energy transition. Royal Dutch Shell was formed in 1907 and expanded to one of the biggest energy companies in the world with its headquarters located in The Hague (Royal Dutch Shell, n.d.-a). Although the core business of Shell lies within oil and gas, they recognize fundamental changes are required in the way energy is produced and used around the world. Shell announced an ambition, pegged to society's progress, to reduce the net carbon footprint of their operations and of their customers' emissions from using their products. It aims to reduce the overall footprint of their energy products by 20% by 2035 and by around half by 2050 (Royal Dutch Shell, 2018). Shell is motivated by innovation and acknowledges that long-term success depends on the ability to anticipate to the changes in the environment in which they operate.

The political and technological environment surrounding the energy industry is rapidly changing. As these changes are external to the company, Shell uses scenarios to investigate possible future pathways. Scenarios do not try to predict the future nor are they a business plan. They allow to investigate and assess the impact of a wide range of uncertainties on long-term decisions. By mapping the multiple possible futures, Shell can analyze how to navigate through uncertainty.

Shell has been using scenario generation for over nearly 50 years to help deepen its strategic thinking and is known to have popularized scenario usage on a corporate level. Shell started using scenarios to investigate uncertain events and help cope with the oil shocks of the 70s. After that, it was observed that the usage of scenarios had doubled among US companies (Amer, Daim, & Jetter, 2013). Developing and applying energy-focused scenarios is part of an ongoing process in Shell that encourages decision-makers to explore the features, uncertainties, and boundaries of the future landscape, and engage with alternative points of view (Bentham, 2014). Its scenarios have been helping generations of Shell leaders, academics, governments and businesses to explore ways forward and make better decisions.

The International Energy Agency (IEA) expects power to have the fastest growth among all energy carriers (IEA, 2018) and predicts demand for power to increase by 60% by 2040 compared to 2018, reaching a share of one-quarter of final global energy consumption. Scenario generation within Shell has so far focused on oil and gas markets, however as a result of the energy transition, Shell is keen to understand how power could be incorporated into its scenarios. The purpose of this thesis is hence to create an applicable framework to structurally incorporate new uncertainties into their scenarios guaranteeing that these remain relevant and useful for their organization.

1
Introduction

This chapter provides the context and motivation for the particular research question at hand that this thesis is attempting to resolve. After first providing the problem context, the motivations for such research and the methodology applied for answering the proposed research question will be described.

1.1 Problem context - A changing energy system

Climate change is increasingly gaining attention in almost all sections of society. The increasing concentration of greenhouse gases produced by human activities is negatively impacting the environment. The global average temperature from pre-industrial levels to the decade 2006-2015 was assed to have risen by 0.87ºC and is likely to rise even more with our current emissions rate (IPCC, 2018). Over the last decade, society has become increasingly aware of the problems related to the increase in emissions, which has led to different reactions around the world. One of these reactions is the Paris agreement in which countries have joined forces to combat climate change. The central aim is to limit global warming to well below 2 degrees compared to 1990 levels, with pursuing efforts to limit it to 1.5°C (UNFCCC, n.d.). To reach the goals set in the Paris agreement, the Dutch government, for example, has proposed a climate act in which calls for a 49% reduction in greenhouse gas emission by 2030 compared to 1990 levels and a 95% reduction by 2050 (Ministerie van Economische Zaken, Landbouw en Innovatie, 2019).

As a consequence of these initiatives, it is necessary for the world to explore other energy sources and fundamental changes to our energy system are likely to occur in the coming decades. Certain trends can already be seen, such as an increased share of solar and wind generation, a strong shift towards the adoption of electric vehicles, and new research into the applications for hydrogen. These trends are driven by changes in policy, technological improvements and societal push. However, the speed and trajectory of this transition are highly uncertain. Different parts of the world will develop in their own way at their own speed.

Energy is essential for an economy to function. The energy system in Europe is built on three pillars: reliability, sustainability and affordability (Donker, Huygen, Westerga, & Weterings, 2015). These three ambitions should be considered when incorporating change in the energy system. However, these pillars are highly interlinked but might not be mutually supportive. For example, proposing a phase-out of coal is very attractive in terms of sustainability but might reduce the reliability of our energy system. This problem is referred to as the “Energy Trilemma”; how to create an energy system while meeting all three ambitions (World energy council, 2019)? A successful transition towards a low carbon future is therefore challenging and not a clear path. This results in an environment characterized by uncertainty and complexity.

1.1.1 Central issue – outdated scenarios

Due to this uncertainty and complexity, well-grounded projections about the future are an essential foundation for today's policy and investment choices. Scenarios are considered to be a valuable tool for dealing with uncertainties and complexity in the future (Amer et al., 2013; Chermack, Lynham, & Ruona, 2001). Malaska, Malmivirta, Meristö & Hansén (1984), found a positive correlation between the amount of uncertainty and instability in the business environment and the use of scenarios. Scenarios do not try to predict the future nor are they a business plan: they help us think about how the world might develop and investigate what the result of a particular decision might be within each of these possible worlds (figure 1.1). By mapping multiple possible futures, companies can analyze how robust investment decisions are to uncertainty.

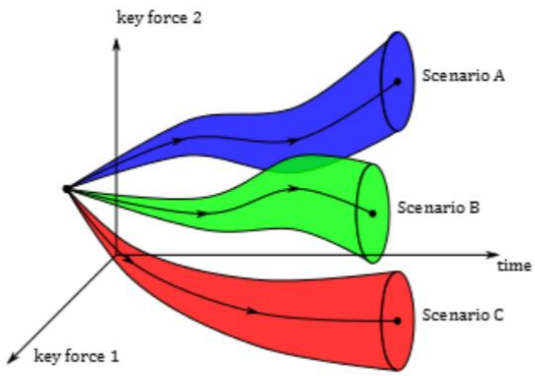


Figure 1.1: Visualization of scenarios (Cardoso & Emes, 2014)

Using these scenarios helps considering the potential implications of different events and imagine possible responses to these events. Shell is currently using scenarios for strategic insight in the energy transition. However, the fast-changing environment influences the plausibility and relevance of the generated scenarios. Because these scenarios help strategic planning involving multi-million-dollar investments, there is a need to incorporate new information as it becomes available. As it is very inefficient and time-consuming to make new scenarios every time something changes, finding an efficient and time-effective way to incorporate changes and new uncertainties into scenarios, is an important research theme to be analyzed.

1.1.2 Scenario generation – A qualitative step in developing scenarios

Scenarios are used to stretch thinking and navigate critical uncertainties (Royal Dutch Shell, n.d.-b). Scenario generation is a creative process that seeks to include many different perspectives rather than to pursue consensus (Shell International BV, 2008). One popular way to generate scenarios is to first provide a narrative about the future in which certain themes are highlighted. These themes are often highly uncertain trends with a high impact on society (e.g. degree of decarbonization or political instability). These trends can be identified conducting interviews with experts and extensive literature research. It is important to gain knowledge about the driving factors. These trends are used to generate storylines of possible futures, which can be defined as qualitative scenarios. This process is time-consuming and iterative since the scenarios must form a coherent and relevant set of stories (Cardoso & Emes, 2014; Shell International BV, 2008). Once the storylines have been generated, it is important to test their plausibility and relevance. This is about clarifying rather than adding new ideas and it is often done by interactive workshops where the scenarios are discussed (Dechesne, 2015). It is important to note that the scenarios should not give a detailed description of events but rather a context description. Scenarios are built upon an improvisational nature involving many different views.

1.1.3 Scenarios as a tool for making decisions

Scenarios are built using storylines to discuss possible futures while incorporating uncertainties, thereby helping to create a framework for decision-making (Bentham, 2014). Before scenarios are used for evaluating political or investment decisions, several steps are taken to quantify these storylines and generate meaningful insights (Chermack et al., 2001; IPCC, 2005). Understanding these steps is essential as this thesis proposes a solution that combines these multiple steps. A short outline of these steps is given to gain insight into how this process is structured. These steps have not yet been explicitly stated within the literature, but many authors implicitly use and refer to these steps in one way or another (Bishop, Hines, & Collins, 2007; IPCC, 2005; Shell International BV, 2008). This therefore not only provides a basis for the proposed solution but also creates a common language for the rest of this thesis.

1. The first step is to create qualitative scenarios given critical uncertainties and are built using certain trends and themes. Some scenarios will highlight certain trends in a more extensive way than others, thereby creating different scenarios. This step is called “qualitative scenarios” in which the storylines about the future are created. This step provides a long-term macro perspective view of how possible future societies could develop.
2. These qualitative scenarios can be transformed into quantitative scenarios to provide insight and create a language for executives (Bentham, 2014). Transforming qualitative scenarios into quantitative scenarios is done using external information (data) about the indicated uncertainties. In more simpler words, this conversion step puts numbers to the storyline of each scenario. Within this step, critical choices need to be made on which factors to focus, else the level of complexity simply becomes too large.
3. These quantitative scenarios can be used as an input for a model to see how the different scenarios might play out in society. A model can have many forms but within this thesis a model is defined as a simplified representation of a physical system that aims to capture the behavior of such a system (Wellstead, 1979). The model itself is out of the scope in this thesis. The scenarios are different depicted worlds that then translate how you perceive the input parameters to the model.
4. The outcome of the model can, finally, be used as insights for strategic decisions by analyzing the robustness of these decisions to uncertainty.

Figure 1.2 shows the process of transforming scenarios into insights for strategic thinking.

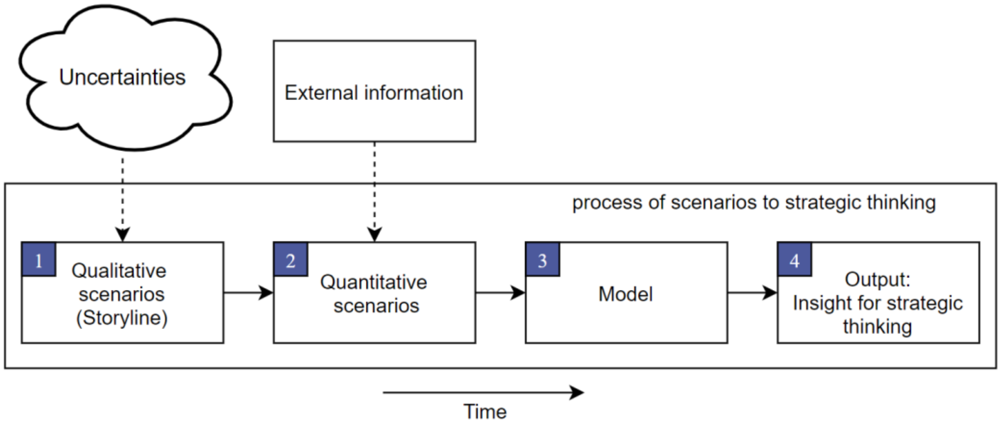


Figure 1.2: Visual representation of translating scenarios into insight for strategic thinking

1.2 Problem description

The dynamic and fast-changing environment brings challenges for generating long-term visions of the future as these rapid changes influence the plausibility of the generated scenarios. Outdated scenarios will result in future pathways that are no longer achievable and therefore reduces their relevance and usefulness for making decisions. This will be referred to as "*outdated scenarios*" and are not desired. As some uncertainty is resolved over time, while other uncertainties arise, it is important to take these changes into account. Incorporating new information and uncertainties into scenarios will be referred to as performing "*an update*".

The need to update scenarios to create meaningful insight for making decisions is clearly recognized. However, while several studies discuss how an update is performed, a clear and structured method for executing this process remains unclear (Creutzig et al., 2017; IEA, 2014; Leggett, Pepper, & Swart, 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010).

Executing an update is a complex process due to the increasing complexity of scenarios. Performing an update in an unstructured manner, therefore, imposes multiple problems. First, the update becomes time-consuming as there is no standardized way of executing the process, leading to inefficiencies. Secondly, as the process is often completed by multiple people, an unstructured way of working imposes difficulty in communicating how and which changes are made. Each individual will have their own way of executing the process and as there is no single way of performing an update, this might result in miscommunication. Lastly, as the process currently may lack transparency, it is difficult to track changes made.

Additionally, how an update should be performed is partly determined by the nature of the change. Changes with a high impact on the business environment and high uncertainty should hence be considered in all scenarios while changes with a small impact on society and small uncertainty might be incorporated at a more granular level or even be disregarded. Although literature clearly shows a distinction in how different changes are incorporated into the scenario, a tool to assess which changes should be incorporated in what way is currently undecided (IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010).

Moreover, when considering new information and uncertainties in one part of the scenario it might change other aspects as well as the different components within the scenarios are highly interlinked. One of the main obstacles of performing an update is to understand how the rest of the scenarios is influenced when incorporating changes. However, it is currently unclear how to assess which other parts are influenced by incorporating changes.

In summary, due to the complexity and high uncertainty surrounding energy markets it is a challenge to keep these scenarios up-to-date. As there is currently no method for incorporating new information and uncertainties into scenarios in a consistent way, the process can be time-consuming, difficult to communicate and is lacking transparency. Moreover, it is unclear how to distinguish between the different changes and how these changes, when incorporating them into scenarios, influence the rest of the scenario.

1.3 Research objective & Research questions

1.3.1 Research objective

As described in the problem description, Section 1.2, it is a challenge to keep scenarios up-to-date with the rapidly changing environment. The need to keep scenarios up-to-date requires scenarios to dynamically evolve over time as uncertainty is resolved, more information becomes available and new uncertainty emerges. As a basis of this research it is therefore important to provide a literature review on how scenarios are generated, currently kept up-to-date and why this is not satisfactory. As there is no tool within literature to structurally incorporate new information into scenarios, it is important to gain insight how this ability could be provided.

The objective of this research is to create a process that helps to structurally incorporate new information and uncertainties into scenarios, such as policy and technological changes, thereby reduce some of the complexity within this process and ensuring scenarios are properly updated, thus guaranteeing that the scenarios remain plausible and relevant. The structured process proposed provides the ability to make scenarios dynamic. To demonstrate how this process can be used in practice, a test case is provided.

When executing an update in a structured manner the process cannot only become increasingly time-efficient but also transparent. Transparency increase the ability to communicate changes and to track previous alterations made.

1.3.2 Research question & sub-questions

From the research objective, Section 3.1, the research question is formulated:

How to structurally incorporate new information and uncertainties into scenarios, keeping them up-to-date, guaranteeing that the scenarios remain realistic and useful?

To be able to answer the research question, the research will be divided into 4 sub-questions. The sub-questions are formulated in such a way that answering these questions will allow the author to give a well-founded answer to the main research question. Each question will be answered using different research methods and will be discussed in a separate chapter.

The following sub-questions are formulated and will be discussed in more detail in Section 1.4.1:

1. How are scenarios currently kept up-to-date?
    a. What are scenarios and what are they used for?
    b. Why is the updating process currently unsatisfactory?
2. What are important factors that need to be considered if you want to structurally incorporate new information and uncertainties?
3. Which steps need to be executed for scenarios to be kept up-to-date in a structured manner?
4. Test case
    a. How does the framework perform in practice?

1.3.3 Scope

The practical context of this research attentions on how to incorporate the rapidly changing environment into scenarios. The focus within this practical context is not about making the scenario itself, it is merely about adjusting the already existing scenario to keep them up-to-date. Although there will be some situations in which an entirely new set of scenarios have to be generated, this will not be demonstrated. This mainly due to time and resource constraints, as generating new scenarios is often a process including many stakeholders, financial resources and is very time-consuming.

To limit the scope of the research, during the creation of the framework, this thesis will focus on energy scenarios as this is the industry in which Shell is active. Moreover, as there are many different types of scenarios the focus will be on deductive scenarios. This type of scenario is qualitative in nature and no mathematical models are used to generate these. Chapter 2 provides more detailed information on this type of scenario. The framework is formulated to be generally applicable to deductive energy scenarios after which the framework is tested on power scenarios.

In total four scenarios are used as an input for the test case. These scenarios are taken as they are and the choices made when generating these scenarios are not questioned. The test case will focus on the day-ahead wholesale market within the power industry of Europe as this is the focus within the scenarios. An introduction to this market will be provided in chapter 5. This market was chosen since the day-ahead wholesale market is one of the most well-established markets for power generating assets and can be modelled using fundamental theories of energy economics. The focus of these scenarios is on the day ahead market since this market is the most important revenue stream for power generation assets. Europe is chosen as these markets have significant power interconnectivity which makes it a well-integrated power market.

Lastly, the model within Shell used to create insights for decision making is out of scope of this research. The model is constructed within an energy simulation software, however, highly confidential. Scenarios within this thesis, are seen as the input for this model.

1.4 Research design

In this section, a detailed description of the research design is provided. First, the research approach will be elaborated on, after which the research framework is discussed. This will highlight the different phases of the research and which methods are used to retrieve the required information.

The research approach helps to add structure to the report and is seen as a roadmap throughout this research. The approach used in this research is a design-oriented approach. A design-oriented approach is used as a problem-solving approach in which a structure is developed and implemented within an organization to increase effectiveness and efficiency (Hevner, March, Park, & Ram, 2004). A framework is such a structure and will be constructed for scenarios to be kept up-to-date, thereby increasing the efficiency of the current updating process. The structure within this design-oriented approach will be as follow: (1) preliminary analysis, (2) conceptualization, (3) operationalization, (4) illustration and (5) conclusions. The research framework will elaborate on the different phases indicated and discusses what methods will be used to execute the research.

1.4.1 Research framework and methods

The research framework is a visual representation of the structure of this thesis. The overall structure of the study takes the form of five phases and is presented in figure 1.3. Each phase will briefly be discussed, after which the different methodologies for data collection will be elaborated on.

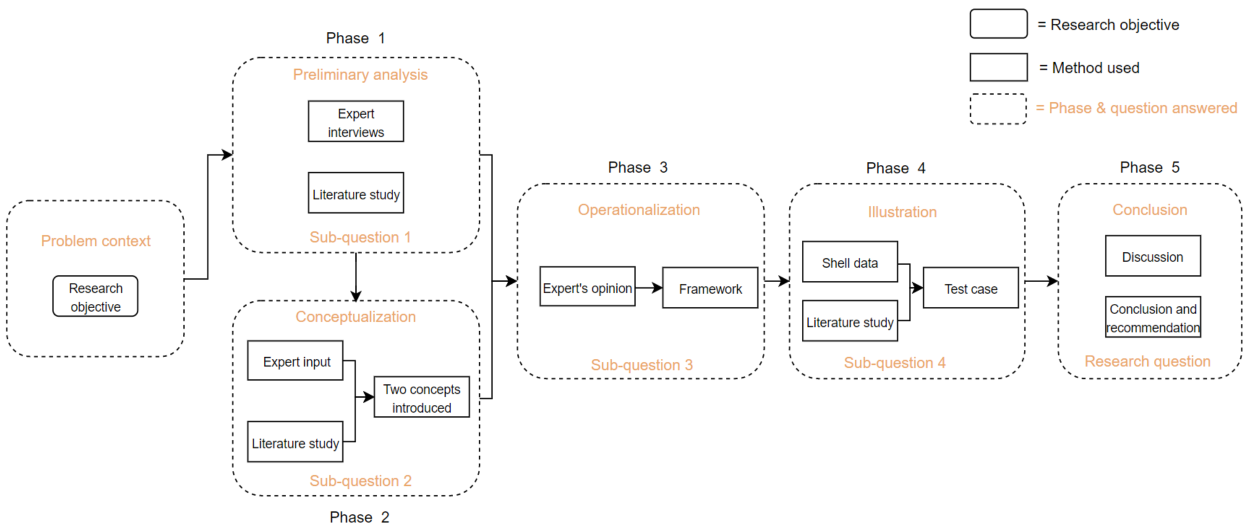


Figure 1.3: Research framework - indicating the different phases of the research

Phase 1: Preliminary analysis (sub-question 1)

The first section of this research will examine the indicated research problem from a theoretical perspective and provides a preliminary analysis of the subject, thereby indicating the research gaps. Additionally, executing this research helps to generate ideas on how to solve the gaps indicated. In this phase, it is specifically interesting to gain a high level understanding of the subject. Looking into this specific area will not only lay a foundation and give a better understanding of how to solve the other sub-questions, it will also highlight the scientific contribution of this thesis. Additionally, as there is no article found discussing how to structurally incorporate the fast-changing environment, this preliminary analysis is also used to think about possible solutions. To execute this phase, extensive literature study and expert interview are conducted and are discussed in table 1.1.

Phase 2: Conceptualization (sub-question 2)

The literature research provided some ideas that give guidance in configuring a solution. In the conceptualization phase, two concepts are introduced that are found important to formulate a solution and are further applied to the subject. The first idea is dividing scenarios into different layers. The characteristics of these different layers are defined by using the theory of Geels (2002), multi-level-perspective (MLP). The second idea introduced provides a tool for classifying changes according to their uncertainty and impact on the business environment. Lastly, the two concepts are linked together. Understanding the link between the two concepts provides the basis of the framework proposed. The methods used to retrieve the required information for phase 2 are expert interviews and literature study. Literature study is executed to retrieve the required information to formulate the two concepts, additionally, expert interviews will be used for validating the concepts proposed (table 1.1).

Phase 3: Operationalization (sub-question 3)

Drawing upon the extensive literature review, the operationalization is about outlining the steps for an update to be structurally executed. In total 7 steps will be introduced to structurally consider new information and uncertainties into scenarios (figure 1.4). The concepts introduced in phase 2 are used to provide the basis of the framework. Each step is individually introduced and explained to provide the reader with a practical tool to execute an update. To validate the framework proposed, experts within Shell are asked to provide input on the different steps outlined.

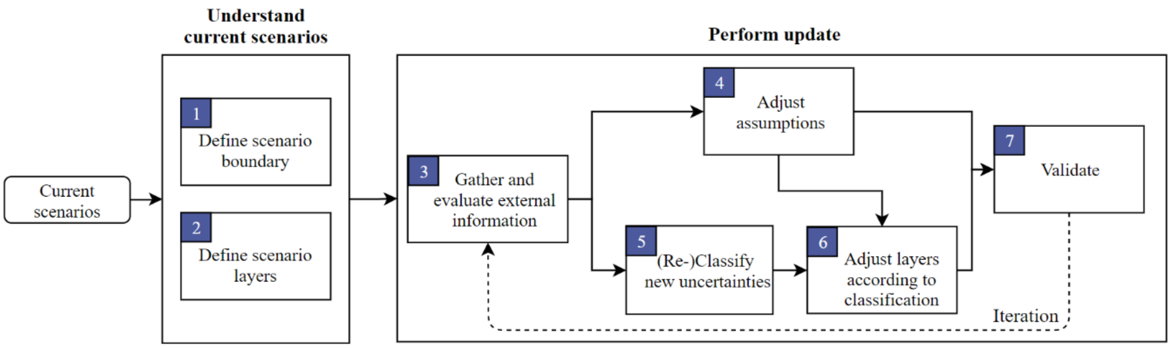


Figure 1.4: Dynamic scenario framework

Phase 4: Illustration - (sub-question 4)

The first three phases of the research build-up to a framework that is capable of determining *if* and *how* changes need to be incorporated into the scenario. Hence, phase 4 of the research illustrates how this process can be executed in practice by using the framework to execute an update on four distinct power market scenarios. Every step within the framework will be discussed using examples. Examples are provided due to limited time and resources. An update requires information on the changing external environment, therefore, extensive literature research was conducted.

Phase 5: Discussion, Conclusion & Recommendation (main research question)

The fifth and final phase of this research presents the findings of the research and is divided into two parts. First, a discussion is provided on the main result of this research. Additionally, the societal and scientific contributions will be discussed as well as the limitation of the research executed. The second part consists of the conclusion and recommendation. In this part, the main research question is answered, followed by recommendations for future research.

Data collection & methods used

Table 1.1 gives an overview of the methods used to retrieve the information needed, the data requirements and the limitation to the chosen methodology per research phase.

Table 1.1: Overview research methods

Research Phase	Method used	Data required	Limitation to approach
1. **Preliminary analysis:** Provide general information about scenario generation and gain insight in how scenarios are currently kept up-to-date.	Literature study, expert interviews Why: lays theoretical basis for rest of research; efficient way to quickly gain information and validate findings.	Theory on scenario history, methodologies, validation criteria. Theory how industry and academia update their scenarios. *Sources:* TU Delft library, Data bases (WorldCat, Scopus), Google Scholar, Experts on energy scenario's	As there is many literature about scenarios and how to generate these, it is difficult to guarantee a complete overview.
2. **Conceptualization**: Define different layers within scenarios Classify changes according to impact and uncertainty Linking the two concepts to provide a part of the solution	Literature study, desktop research, expert input (e.g. Shell) Why: time efficient; creative input for layers; bring in experts' knowledge to find missing inputs.	Theory on possible layers within scenarios and theory on classifying changes. *Sources:* TU Delft library, Data bases, Reports, Google Scholar	Necessary data might be unavailable; abundance of theories on classifying changes; due to many different approaches might not incorporate best method.
3. **Operationalization:** Create a framework to structurally execute the process of keeping scenarios up-to-date	Expert's opinion (Shell) Why: generate ideas for steps required for keeping scenario up-to-date; validate framework by experts.	Concepts defined in last phase. Literature on how updates are currently performed (from phase 1).	Here only a theoretical point of view is taken while a practical point of view can be different. Experts can be biased as they are focused on the energy market.
4. **Illustration:** Show how the framework can be used within practice	Executing framework in test case using power market scenarios Why: evaluate the framework proposed	Framework generated within last phase; theory on electricity market	As this test case is done for a specific market (the power market), the framework and its application are not tested for other markets.
5. Discussion	Evaluation main results, societal and scientific contribution	Findings and evaluation of previous phases	
6. **Conclusion & recommendations**	Evaluate sub-questions 1, 2, 3 and 4 and answer research question	Findings and evaluation of sub-questions	

Within the table several limitations are addressed. It is important to be aware of these limitation in order to overcome them. Within each chapter attention is paid on how to address these limitations and will be discussed in chapter 7.

2
Literature research

This chapter presents a critical review of the literature on how scenarios are currently kept up-to-date within academia and industry. It highlights the research gaps on how emerging events and new information should be incorporated within existing scenarios. While, the need to update scenarios to create meaningful insight for making decision is clearly recognized, a well-established approach to execute this process appears to be missing (Creutzig et al., 2017; IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010). Using a framework to define, categorize and incorporate information and uncertainties into the scenarios does not only improve the reporting process, increase the transparency and the ability to track changes over time, it also creates a structured process for decision makers to understand the types of uncertainties involved and how these affect their scenarios. This literature research will not only indicate the current state-of-the-art for keeping scenarios up-to-date but will also help to generate ideas on how to solve the indicated research gaps.

To provide some background information, this chapter will first explore the broader theme of the thesis: scenarios, from a theoretical perspective. A definition of a scenario will be proposed, after which the methods available for generating scenarios will be discussed. The background information is finalized by elaborating on how scenarios are validated. Secondly, the literature review will highlight how scenarios are used for evaluating strategies, as multiple steps need to be executed before a qualitative scenario can be used within strategic planning (Chermack et al., 2001). Thirdly, this literature research will describe how scenarios are currently kept up-to-date within academia and industry. It thereby indicates the research gaps on how this process is executed as no information is found regarding a method. Fourth, to validate the claim that currently no method exists to structurally incorporate new information and uncertainties into scenarios, highly valued experts were asked for their knowledge of a method to structurally execute an update. Finally, conclusions are drawn, and recommendations are made for driving this research to a more practical tool.

Methodology for literature research

This literature review will create a frame of reference and a basis on which this research is built. It takes a theoretical view on *how* to answer the main research question. To guide the literature study the approach in figure 2.1 is followed.

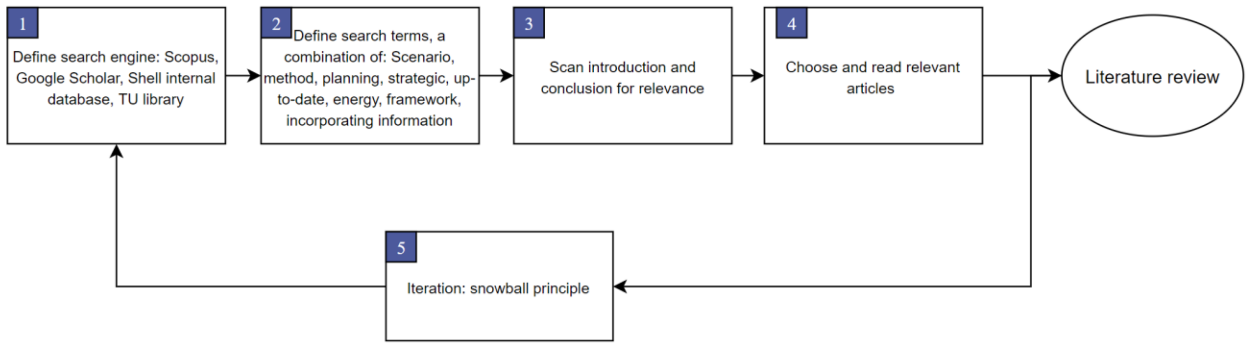


Figure 2.1: Literature study approach

As the scenario generation literature is very abundant, a selection of relevant articles must be made. To overcome the limitation indicated in Section 1.4.1, many literature reviews were searched as these articles provide an excellent overview of the available literature on the topic. However, many literature reviews were written before 2015, therefore, additional literature research was needed to consider more recent articles.

Aside from the abovementioned keywords (figure 2.1), the snowball principle is used. This is a method in which the bibliography of an interesting paper is checked to search for other interesting and relevant articles referenced. The bibliography may not only point into the direction of other interesting scientific papers but also give ideas for new keywords (Verschuren & Doorewaard, 2010).

The relevance of the articles was assessed by first scanning the abstract, introduction and conclusion to indicate the fit with the research. A requirement for a relevant article was to find the search term(s) within the indicated section. Additionally, articles that were cited many times (more than 10 citations) were found more valuable than publications with a low number of citations. The amount of citations is seen as a positive indicator of the influence of a researcher's work.

For the validation of the information found, other papers were used to cross-check the retrieved information. When a method or statement was discussed in multiple papers the information was found more valuable. Moreover, multiple Shell employees were asked to confirm the findings with the condition they had knowledge on the subject.

An important outcome of this literature review is that there does not seem to be a method for incorporating new information and evens into scenarios. This statement was formulated after no literature was found discussing this topic in detail. However, to reinforce the validity of this statement, multiple highly-regarded energy scenario experts were asked about their knowledge on this topic, Prof Dr. Detlef van Vuuren, Prof Dr. Gert Jan Kramer and Dr. Oreane Yasmin Edelenbosch. Their knowledge was used to validate the statement, to gain extra information on the topic and to ask feedback on the proposed idea.

2.1 Introduction to scenarios

Definition

The reviewed literature describes scenarios as the portrayal of a possible future situation and the story of the path that leads to that specific future (Bishop et al., 2007; Chermack et al., 2001; Cornelius, Van de Putte, & Romani, 2005). For almost 50 years, scenario practice has been extensively used. Despite this, no single clear definition of a scenario exists (Chermack et al., 2001). Herman Kahn, seen as one of the founders of scenario generation, describes a scenario as "*a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points*" (Kahn & Wiener, 1967, p. 6). Whereas, Schoemaker (1991, p. 549–550) defines a scenario as "*a script like characterization of a possible future represented in considerable detail, with special emphasis on causal connection, internal consistency and concreteness*." Within the report "An Explorer's Guide" written by Shell International BV (2008, p. 8) the following definition is used: "*A scenario is a story that describes a possible future while it identifies some significant events, the main actors and their motivations, and it conveys how the world functions*." Although a precise definition of a scenario is lacking, all agree on the fact that a scenario is a future vision highlighting causal events.

While a variety of definitions have been suggested, this paper will use the definition defined in "An Explorer's Guide" throughout the remainder of this thesis. This definition highlights the fact that a scenario is qualitative in nature as the scenario is first defined using a narrative before any numbers are added.

Origin

Scenarios originate from the Second World War, where it was used to make strategic plans against possible enemy actions (Cardoso & Emes, 2014). After the war ended, scenarios and their use did not become less important. With the Cold War entering, creating an uncertain and unstable political environment, there was an urgency for strategic defense planning. Scenarios were used within the military as an effective tool to provide guidance in generating these strategies (Cardoso & Emes, 2014). As others also saw the value of using scenarios, from 1960 they were increasingly being used within public policy analysis and social forecasting (Amer et al., 2013). The first time scenarios were used in a business environment was not until the 1970s, when Shell used scenarios to look at possible future outcomes given critical uncertainties which helped them to overcome the oil shock in 1973 (Cardoso & Emes, 2014). It was Pierre Wack, seen within Shell as the father of scenarios, that highlighted the possibilities of other future pathways for the oil market (Chermack, 2018). When the oil shock happened, Shell had already considered this as a possible pathway. They were able to quickly respond when the oil price radically changed, while other companies may have been slower to respond, causing them significant losses as a result (Chermack, 2011). Afterwards, many other companies followed by recognizing the value of using scenarios. Already in the early 1980s, almost fifty percent of the US fortune 1000 companies had made scenario generation a part of their activities (Amer et al., 2013).

Scenarios are currently being developed within different layers of our society (e.g. international, national, industry and corporate) (Amer et al., 2013; Van Notten, Rotmans, Van Asselt, & Rothman, 2003). As the pace of technological change increases, globalization and polarization happening at the same time and climate change is acknowledged, it creates a highly uncertain environment. Emphasis is therefore being placed on the use of scenarios within all industries, as a scenario has the ability to stimulate strategic thinking by indicating future problems and develop a macroscopic view of the environment you function in. Additionally, as the level of uncertainties increases when looking further into the future, scenarios are often used for long-term planning (more than 10 years) (Rigby & Bilodeau, 2007; Varum & Melo, 2010).

A study by Varum & Melo (2010) reveals that the main benefit of using scenarios is the increased insight in decision making. Scenarios help to increase this insight in two different ways:

1) They let managers think about possible other futures, then they currently imagine, to widen their perspective. Chermack et al. (2001) argue that managers who adapt their thinking to see a wider range of possible futures would have a big advantage to deal with unexpected changes and take advantage of opportunities that may appear.
2) Scenarios can help to evaluate strategies given different future perspectives. As the timescale of strategic planning is often greater than 10 years (within the energy industry), there is an amount of uncertainty associated with the end state of the business environment (Cardoso & Emes, 2014). Scenarios are a tool that helps to imagine how this uncertainty might develop. Strategies can then be tested based on the different proposed futures to check their robustness.

Scenario vs. forecast

It is important to notice that scenarios differ from forecasts and should not be used as such. As these definitions are often used in the same context, a short description is given to highlight their differences. The purpose of a forecast is to identify the most likely future and is usually constructed on the assumption that tomorrow's world will be much like todays. Multiple scenarios are constructed not to look a single possible future but explore multiple possible future pathways based on driving forces and cause-and-effect relationships (Amer et al., 2013). There are multiple historical examples in which forecasts have failed to give accurate predictions (figure 2.2).

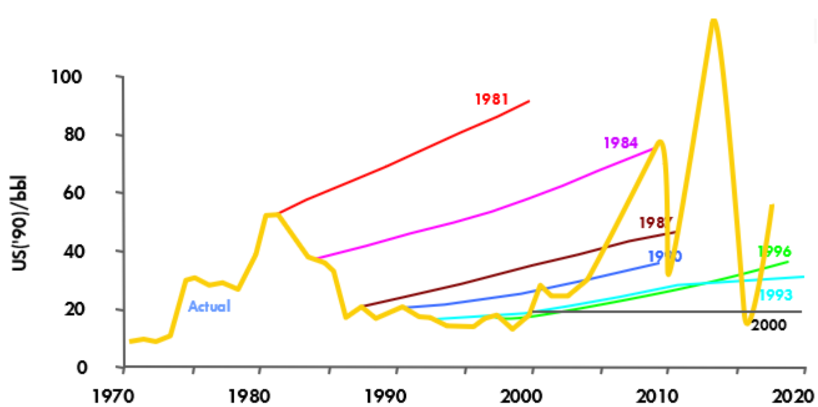


Figure 2.2 Forecast oil price & actual price (Source: Shell)

When looking at the actual oil price over time and the forecast of the oil price, none of the forecasts are close. If looking at the slope of the forecasts, they are often influenced by what has occurred in the past. One of the more recent examples is the case of Venezuela, which holds one of the largest petroleum reserves. As their income heavily relies on oil, the price they receive has a large impact on their budget. Many forecasts of oil prices to 2050 ranged from $95 to $150. However, the oil price today is only $63.50 (www.oil-price.net, 2019). They heavily invested in oil of which was forecasted to have a high price. If Venezuela had used scenarios to develop multiple possible futures, they may have more accurately considered the possibility of low oil prices and hence taken different steps to mitigate this risk (Benedict, 2017). Scenarios accept the notion of uncertainty and try to understand the consequences. They are built upon a sequence of different events. If we believe in a single future it can lock us into a small set of possible options, a risk that scenarios can help to overcome by evaluating different ranges of pathways (Cornelius et al., 2005).

2.1.1 Scenario generation methodologies

The scenario generation literature discusses many different methodologies which is often referred to as "methodological chaos" (Amer et al., 2013). These methodologies all have their own strengths and weaknesses or specific application. Despite the many methodologies, scenario generation is increasingly becoming a complex set of techniques difficult to implement and often require software or applications. In the face of tremendous uncertainty for making business decisions, it is important to have a better understanding of which scenario making methodologies are currently available and used within a specific application. From this review, a choice is made on which type to focus to limit the scope within this research.

In general, scenario generation techniques focus on identifying focal issues, driving forces and critical uncertainties and rank them according to their impact and uncertainty (Mietzner & Reger, 2005). The issues with the highest uncertainty and impact on the business environment will be used to generate the scenarios (Pillkahn, 2008). Although some scenario generation techniques use complex computations, this process is seen as highly subjective and remains qualitative in nature (Amer et al., 2013). Purely quantitative methods are considered more valuable for projects with a short time frame and narrowly focused research, while qualitative research is more appropriate for projects that have a long-term view and wider scope (Bentham, 2014). Taking this into account, this research takes a more qualitative view of how scenarios are generated.

In general, there are three different types of scenarios: (1) deductive, (2) inductive, and (3) normative (Cardoso & Emes, 2014).

1. *Deductive:* Within this type of method, two critical uncertainties are selected of which a 2x2 matrix is formed. The storyline of the scenarios is based on the extent to which these uncertainties are taken into account, which is described by the four different quadrants. This type is the most often used within practice and currently also favored within Shell (Cardoso & Emes, 2014).

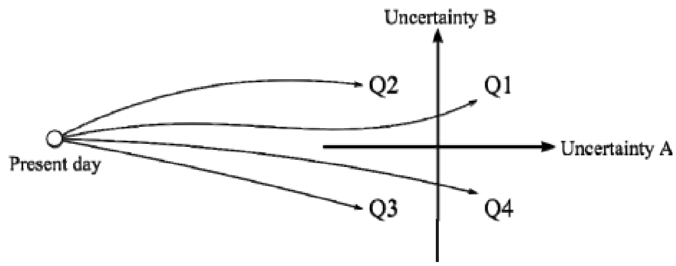


Figure 2.3: Deductive scenarios (Source: Cardoso & Emes, 2014)

2. *Inductive:* The storyline within these types of scenarios are created based on chains of events. Several chains of events will be discussed to create multiple paths. Based on different chains the present day will evolve in a different way, thereby creating different scenarios (Cardoso & Emes, 2014).

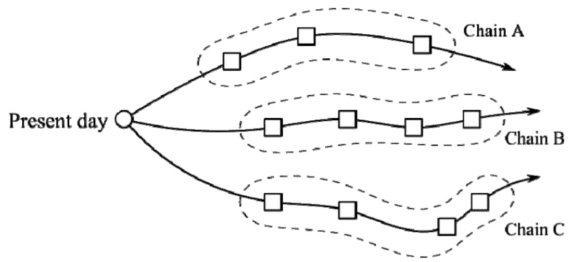


Figure 2.4: Inductive scenario (Source: Cardoso & Emes, 2014)

3. *Normative:* This approach is different than the previous two approaches since this approach does not begin from the present day but describes how a certain target in the future can be reached. There is a certain point set in the future, but how to get there is the question (Cardoso & Emes, 2014). An example of such a scenario is the *'Sky scenario'* provided by Shell (Royal Dutch Shell, n.d.-c).

Figure 2.5: Normative scenario (Source: Cardoso & Emes, 2014)

Over the last decade, the number of scenario generation methodologies have largely increased (Cardoso & Emes, 2014; Amer et al., 2013). Various typologies have been discussed within the literature to create an overview of the different methodologies (Cardoso & Emes, 2014; Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006; Pillkahn, 2008). Amer et al. (2013) discuss three major approaches (school of thought): (1) Intuitive logic, (2) Probabilistic modified trends (PTM) and (3) La prospective (the French school).

1) *Intuitive logic:* The basis of this group of techniques is their subjective and qualitative nature, where no mathematical algorithms are used. Extensive analysis is performed in the macro and micro-environment which rely on tools such as brainstorming sessions, stakeholder interviews and PESTEL analysis (Political, Economic, Social, Technical, Environmental and Legal). The generated scenarios are all equally plausible and therefore no probability of likelihood of happening is assigned. The scenarios are often in the form of a narrative. This group of techniques is referred to as the "Shell approach", and dominates the scenario generation techniques in many countries (Cardoso & Emes, 2014);

2) *Probabilistic modified trends:* This methodology type uses two groups of techniques for building a scenario: Trend Impact Analysis (TIA) and Cross Impact Analysis (CIA). Both techniques use data related to the indicated focal issue. This data can be extrapolated into the future according to the different events identified, creating different possible futures (Bishop et al., 2007). Within this type of methodology there are probabilities assigned to the occurrence of the different scenarios;
3) *La prospective:* This type of methodology is quantitatively and mathematically based. First, an in-depth study is executed of the external environment after which these are mathematically used to create multiple scenarios. This methodology is more often used within the public sector than the corporate environment as the scope of the scenario is often narrowly focused.

The process of selecting the right methodology depends on various characteristics of the environment in which the scenario is created. Cardoso et al. (2014) try to classify the different methodologies based on the time scale and complexity. The proposed framework uses these scales to indicate the position of different industries (figure 2.6).

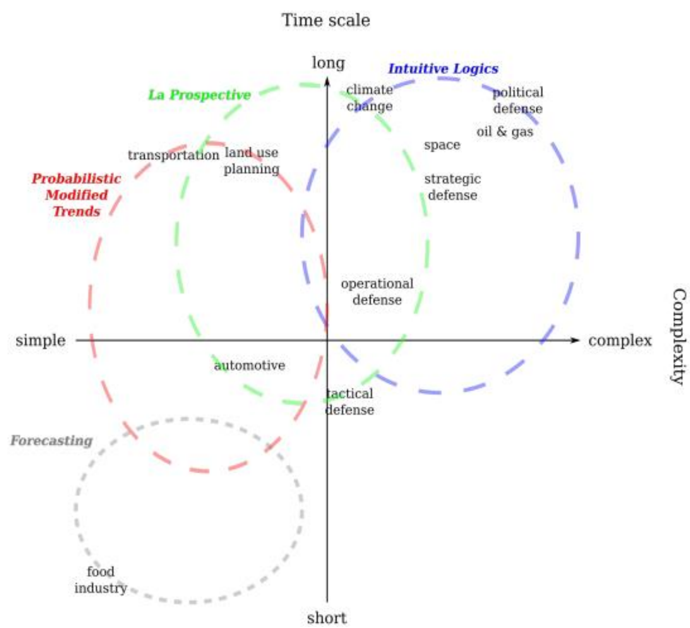


Figure 2.6: Framework for selecting scenario generation methodology (Source: Cardoso et al., 2014)

As the energy industry is seen as a highly complex industry with a long-time scale, the best approach according to the framework would therefore be the intuitive logic. Taking this into account, the remainder of this research, therefore, focuses on scenarios generated using the intuitive logic. This highlights the fact that a scenario is qualitative in nature. However, as these scenarios are used to evaluate strategies, multiple additional steps must be executed, including quantification. Nonetheless, no models or complex calculations are used to translate these qualitative scenarios into quantitative scenarios.

Industry view

Although there are many different methodologies discussed in the reviewed literature, scenarios generation within practice is sometimes different as the internal factors of an organization influence the process of generating these scenarios (Benedict, 2017; Pillkahn, 2008). This section, therefore, briefly discusses the practical view, within the energy industry, to understand the different type of scenarios generated.

The energy industry is an ideal target for using scenarios as part of their strategic thinking with its fast-changing environment and long-term investments, which highlights the fact that there is high uncertainty about the future. It can take up to ten years to bring a refinery on stream (so the capital investment is large and often sunk), after which they are used for multiple decades. This means that choices made now have a large impact on the long-term future of a company.

The use of scenarios for strategic decisions requires extensive time and financial resources and is therefore not available for many organizations. Companies who have the available resources are naturally reluctant to show their complete methodologies for generating scenarios, as these are confidential and contain sensitive information used to shape and evaluate their strategies (Chermack et al., 2001). For companies who do not have the time and financial resources, there are many energy consultants offering their services to provide the outputs and context of their generated scenarios. Energy consultants indicate that clients use their scenarios to support investments, market design or policy decisions. Additionally, they point out that their scenarios are based on extensive analysis of the energy markets, trends and macroeconomics (Aurora Energy Research, 2018; Baringa, n.d.; IHS Markit, n.d.-a; Pöyry, n.d.-b).

Although no essential differences are seen with the methodologies of the energy consultants and the reviewed literature, the most important insight when looking at the scenarios of these energy consultants, is that they often generate a high, medium and low case (Aurora Energy Research, 2018; Baringa, n.d.; IHS Markit, n.d.-a; Pöyry, n.d.-b). A low case can represent the quadrant in the lower left corner (- -) within the framework provided in figure 2.3, while the high case represents the high right corner (+ +). These three scenarios would resemble three completely different worlds which is highlighted in the test case, Part I, Section 5.3.2.1. Moreover, the industry often uses a reference case that resembles a business as usual world in which a similar situation as today is extrapolated into the future. Within Appendix A, more information about two energy consultants and their scenarios can be found (Aurora Energy Research, 2018; Baringa, n.d.; IHS Markit, n.d.-a).

2.1.2 Validation criteria

Whichever approach is chosen, scenarios are not generated in a linear fashion as iteration is needed. Some storylines will not work as they are in conflict with other aspects of the scenarios or seen as irrelevant (Royal Dutch Shell, 2008). Therefore, after generating scenarios, their validity needs to be tested. If they fail to meet the validation criteria they have to be reworked or disregarded (Cardoso & Emes, 2014). Within the scenario literature, many researchers identified scenario validation criteria. Amer et al. (2013), summarized these criteria in a table based on author and validation criteria identified.

Table 2.1: Validation criteria identified by different authors (Amer et al., 2013)

Source	Scenario validation criteria						
	Plausibility	Consistency/ coherence	Creativity/ novelty	Relevance/ pertinence	Importance	Transparency	Completeness/ correctness
Alcamo and Henrichs [133]	X	X	X	X			
Van der Heijden [9]	X	X	X	X			
Durance and Godet [8]		X	X	X	X	X	
Bradfield et al. [13]	X	X		X			
Porter et al. [31]	X	X					X
Intuitive logics methodology [13]	X	X	X	X			X
La prospective methodology [13]	X	X					X
Burt [76]	X	X					
de Brabandere and Iny [19]	X	X	X	X		X	
Paul Schoemaker [15,51]	X	X					
Peter Schwartz [10,50]	X	X					X
Peterson et al. [135]	X	X					
Wilson [114]	X	X	X	X			
Vanston et al. [118]	X	X		X			
Kosow and Gaßner [136]	X	X				X	X

As table 2.1 shows, consistency, relevance and plausibility are the most acknowledged criteria. Therefore, in the remainder of this research, these validation criteria are used to validate scenarios. A short description of the meaning of these validation criteria's is discussed below:

1. *Consistency:* The consistency of a scenario refers to the combination of drivers for this scenario. These drivers should be compatible, may not be internally contradicting and should form a coherent whole (Cardoso & Emes, 2014). A method to measure this consistency is to use a consistency matrix (Amer et al., 2013). As it is outside the scope of this thesis, a description of the use of this matrix has been added to Appendix B1.
2. *Plausibility:* The plausibility described by Amer et al. (2013, p.36) is as follows: *"the selected scenarios have to be capable of happening."* A method used to check the plausibility of the generated scenario is the morphological chart. This chart helps to form a basis for evaluating different concepts within a storyline. Making the process explicit helps to think about the different possible scenarios. As it is outside the scope of this thesis, a description of the use of this chart has been added to Appendix B2.
3. *Relevance:* The generated scenarios should be applicable to the industry they try to describe, and it should contribute to specific insights (Cardoso & Emes, 2014). This means that the scenarios should not be a different version of the same story. Discussing the generated scenarios could highlight if each of the scenarios add a different perspective.

Amer et al. (2013) and Pillkahn (2008) indicate that it is especially important to check the validity if many different scenarios are generated. Within the test case the scenarios were already generated, therefore, it is assumed that they meet the indicated validation criteria. However, as this thesis is looking into updating the generated scenarios, the scenarios may change. It is therefore important to check the validity of the scenarios after an update to see if the scenarios are still consistent, plausible and relevant before being used as a basis for making decisions.

2.2 Scenarios as a tool for evaluating strategies

The course of using scenarios for making decisions was already introduced in Section 1.1.3, where four steps were outlined to indicate how this process is structured (e.g. Qualitative scenario, Quantitative scenario, Model and Output). Having discussed the entire process briefly, the focus within this section will be on the first two steps concerning the scenarios itself. Discussing these steps in greater detail helps to understand the proposed framework as the solution uses the insights presented here.

As described in, Section 2.1, the main benefits of using scenarios are: (1) widening the perspective of a manager's current thinking, i.e. let managers think about possible other futures and (2) helping to evaluate strategies given different future perspectives. To reach the first goal, the process of generating the storylines (qualitative scenario) is the most important step. This process lets decision makers think about multiple possible futures and challenges their thinking to arrive at this future (Chermack, 2004). To reach the second goal, Chermack et al. (2001) argue that the stories scenarios tell should be altered before being used into a process of evaluating strategies. The process of generating qualitative scenarios is, therefore, different from that of using the scenarios for strategic planning. The generation process of a qualitative scenario is about widening your scope and accepting that the external environment is changing, in our case qualitative in nature. While using these scenarios for strategic planning, is a process of making decisions on which area to focus, increasing the amount of detail and reducing the level of uncertainty, and requires quantification.

Altering qualitative scenarios

As a strategy is a detailed description of a course of action within the company, the scenarios must represent the same level of detail to evaluate such strategies. The macro-level perspective, presented in the qualitative scenarios, is therefore not detailed enough (IPCC, 2005). Qualitative scenarios already significantly reduce the level of uncertainty as assumptions about the future must be made to generate a coherent storyline. However, to evaluate a strategy using these scenarios, this uncertainty needs to be reduced even more, thereby creating quantitative scenarios (Schoemaker, 1991). Uncertainty is reduced when analyses are performed, choices are made, and focal areas are indicated (figure 2.7).

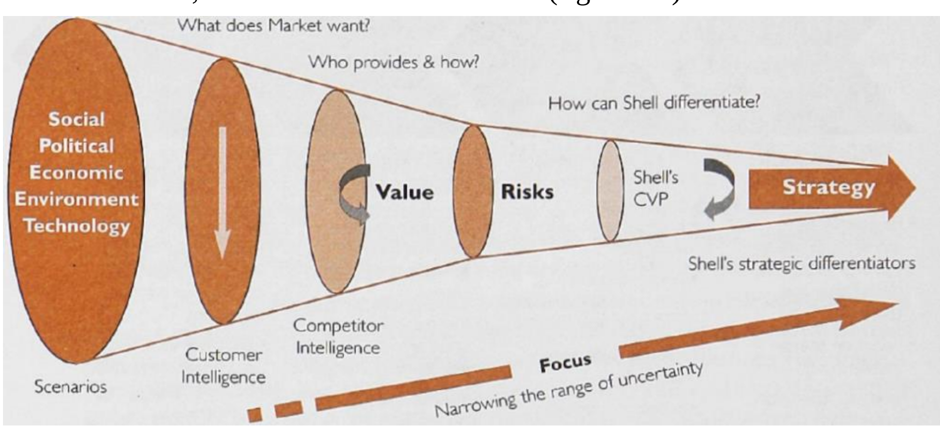


Figure 2.7: Process of using scenarios for evaluating strategies within Shell (Source: Cornelius et al., 2005)

The long-term, macro perspective view within the storylines thereby form the context in which the quantitative scenarios are constructed (Cornelius et al., 2005).

To reduce this uncertainty several steps need to be executed. Cardoso & Emes (2014) propose that one way to reduce some of the uncertainty is to execute a detailed market analysis. This might indicate what customers want within the depicted scenarios and thereby create a focus area. To reduce uncertainty even further a comprehensive risk analysis of the environment for each scenario can be done after which a strategy can be formulated. However, Cardoso & Emes (2014) do not go into detail on how this process should be executed.

Schoemaker (1991) argues that to say anything about possible strategy options, the macro-economic perspective that the scenarios represent, needs to be translated to the industry and firm-level (figure 2.8).

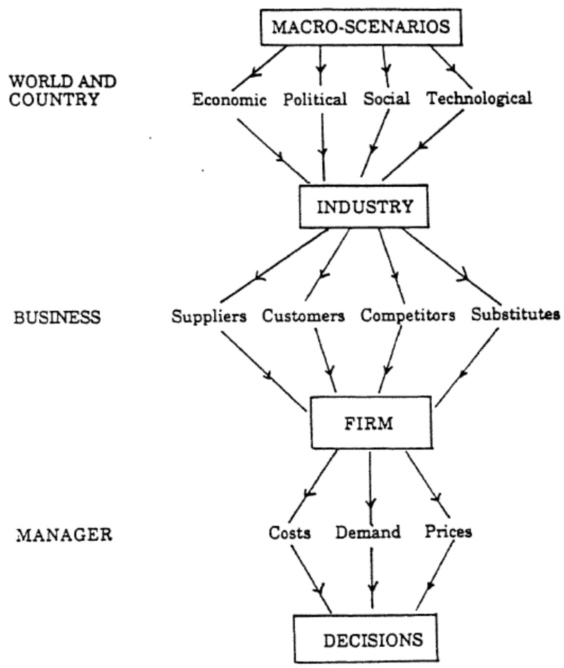


Figure 2.8: Method for increasing level of detail in qualitative scenarios (Source: Schoemaker, 1991)

This process is partly intuitive and only people with detailed knowledge about the industry are able to translate these general scenarios into firm-level information that could be used for decision making. As the level of detail increases during this process, complexity increases as well. To reduce this level of complexity, choices must be made on which aspects to focus as the complexity otherwise becomes too large.

After reducing the level of uncertainty, the scenarios can support the process of evaluating the different strategies formulated. Schoemaker (1991) indicates that the most common technique used to do this is the pay-off matrix, in which the pay-off of each strategy within a specific scenario is calculated. As there is still uncertainty present within each scenario the outcome would not be a single number, but a “zone” which indicates the depicted possible pay-offs. These zones can be quantified by a probability distribution using a standard Monte Carlo simulation that relies on repeated random sampling (Harrison, Granja, & Leroy, 2010). This is often done using models and is therefore out of scope within this research.

The previous section has shown that, before scenarios are used for strategic decisions, several steps are executed to quantify these storylines and generate meaningful insights. Therefore, within a single scenario a more long-term macro perspective is present, qualitative in nature, addressing critical issues within society such as political stability, and a more focused perspective, quantitative in nature, discussing the consequences of the critical issues for the world or industry. The qualitative scenario is related to the long-term macro perspective, creating the context for the rest of the scenarios, while the quantitative scenario quantitatively represents the long- and short-term observations in more detail. When executing this process, choices need to be made on which aspect to focus as complexity otherwise become too high. Understanding that the storylines represent the scenario components in a different way than the quantitative scenarios is important as it is a vital part of the proposed solution.

2.3 Current state-of-the-art for updating scenarios

This section will indicate how the need for keeping scenarios up-to-date is described within the literature, how scenarios are currently kept up-to-date and why this is not satisfactory. The main goal of this literature search is to identify the current state-of-the-art for updating scenarios and provide a critical review of this topic.

Compared to the abundance of literature on scenario generation methodologies, relatively few historical studies mention the fact that scenarios should be reviewed over time or that new information should be considered. Schoemaker (1991) states that forecasts require to be updated frequently, while scenarios provide a general view for a longer period of time. "An Explorer's Guide" published by Shell (2008), talks about reviewing generated scenarios over the period of a few years. They do not state how this should be done but highlight that over a period of time, if the assumptions on which the scenarios were generated have changed, new scenarios should be produced. No suggestion is given to take new information into account within the already generated scenarios. Cardoso & Emes (2014, p.27) recognize scenarios thinking as a continuous process and state: *"Scenario thinking should be addressed as a continuous activity at various levels of strategy definition and decision-making in order to clarify available options and think about their implications."* However, no attempt was made to explain how this could be done. There is no explanation or discussion on whether they incorporate new information into their already existing generated scenarios or whether they generate new scenarios.

Several studies do go into more detail about how an update is performed, however, a clear and structured way for executing this process still seems to be missing (Creutzig et al., 2017; IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010).

The International Energy Agency (IEA), an intergovernmental non-profit organization working as a policy advisor to ensure reliable, affordable and clean energy, does recognize the need to incorporate new information into their generated scenarios as they publish their World Energy Outlook (WEO) on a yearly basis, updating their previous version (IEA, n.d.-a). The WEO provides a detailed analysis and insights on trends for the energy market (IEA, 2014). The IEA points out that within their updates, new policies, implementing measures affecting the energy market and relevant policy proposals are considered (IEA, 2014). However, they fail to fully define why certain new assumptions are taken into account while others are not, and why they are only considered in certain scenarios and not in all of them. The IEA differentiates between political changes as some scenarios only incorporate formally adopted changes to create a baseline picture: *"current policy scenario",* while the *"new policy scenario"* also incorporates policy proposals.

The IEA (2014) discusses that to determine which policy proposals are included, case-by-case judgement is used. However, they do not offer any explanation on how this process is done or should be structured. It is unclear if this judgement is made by one person, or if they have a procedure to guide this judgement. They clearly compare the changes against last year's view, however, they fail to define how these changes are incorporated or assessed.

Van Vuuren et al. (2010) also clearly indicates the relevance of updating scenarios and has highlighted several points of attention when an update is performed. One of the most important insights from the paper is that a relationship is indicated between the nature of a change and how they should be treated during an update. New information may simply require some parameters within the scenarios to be altered, while other information may challenge the "original critical assumptions" of the scenarios and require new scenarios to be generated. It is argued that the difference is related to the speed of change regarding these variables. For example, market prices are subject to daily variations while variables related to the amount of available land may change slowly. The speed of change influences how scenarios are affected and therefore require different approaches. The authors conclude: "*the performance of long-term scenarios should be evaluated against appropriate long-term variables and trends*" (p. 636). This is perfectly described by the following example: *"Climate change is about the forces shaping long-term averages and not specific weather events"*(p. 639). It is argued to evaluate the long-term assumptions in these scenarios using appropriate long-term trends and should therefore not be influenced by short-term observations. This indicates the importance of differentiating between the changes in the external environment and how they impact scenarios. Some small short-term changes might influence some components within the scenario while new long-term trends might require an entirely new set of scenarios to be created. However, besides indicating the relevance for evaluating scenarios and addressing ways to accurately do so, how to perform an update using this information is not described.

Additionally, Van Vuuren & O'Neill (2006) also highlight the importance of evaluating the consistency of the generated scenarios with new information. Again, it is indicated that the information on which these scenarios were built may simply have become outdated or a trend towards another future than represented within the scenarios is identified or even the question for which these scenarios were generated might have changed. They demonstrate this process using new information to assess the consistency of the generated IPCC scenarios developed between 1996 and 1999. In their conclusion, they justify that there is no need for large-scale IPCC led updates at the scenario levels but that smaller-scale updates in individual research teams might be useful. Therefore, a distinction is made between the components within a scenario and the need for an update. Some parts of the scenario might require updates while other, more high-level, components are less subjected to change. Although the authors do go into detail in terms of whether an update needs to be performed, *how* this update should be performed is not discussed.

Creutzig et al. (2017) also critically examine the validity of scenarios using new information. Creutzig et al. (2017), however, do not look at the entire scenario but validates the assumptions made on a single component. Creutzig et al. (2017) thereby identify that the potential of solar energy has been systematically underestimated within energy scenarios. Indicating the underestimated growth of solar energy provides insight for updating this factor, however, changing this factor might also influence other components of the scenarios as they are highly interlinked. A weakness within this paper is that no attention is being paid to the possible consequences of considering large changes to a single factor.

One of the most extensive descriptions of an update can be found in a paper by Leggett at al. (1992). In 1990, the Intergovernmental Panel on Climate Change (IPCC), the UN body for assessing the consequences of climate change by relating it to science, requested long-term emission scenarios to analyze the impact and options to mitigate climate change (IPCC, 2019). In 1992, changing assumptions and new information that came available have led the IPCC to request for an update of their 1990 emission scenarios (Leggett et al., 1992). Leggett et al. (1992) discuss the performed update by highlighting how the assumptions, on which the 1990 scenarios are built, have changed and how new uncertainties have emerged. Taking these changes into account, six scenarios are presented. Two which represent a modification of the 1990 scenarios (IS92a and IS92b) and four scenarios considering new assumptions (IS92c-f). IS92a incorporates all new policies, affecting GHG emissions, agreed upon internationally and passed into national law. This scenario, therefore, only considers certain new information. IS92b includes also proposed GHG policies not yet agreed upon. The other scenarios explore other plausible assumptions not considered within the 1990 scenario. Within these four scenarios, a medium-low and medium-high scenario can be distinguished, incorporating different gradations of the assumptions. It is important to notice that all updated scenarios are built using the scenarios from 1990 as a basis. Leggett et al. show that the scenarios IS92a-b are very similar to the original 1990 scenario while the other scenario provides a broader range of future trends.

Leggett et al. (1992) extensively discuss what new information and assumptions are considered within the different scenarios, however, they make no attempt to address how these changes are assessed or why they are taken into account in a certain way. The question of why certain assumptions are only considered within a specific scenario is not elaborated on. The authors do state that the relatively certain information was taken into account for creating scenario IS92a-b and new uncertainties were considered within scenario IS92c-f, however, they do not mention how these new uncertainties were assessed. These new uncertainties were translated into assumptions, but why certain new uncertainties require a new scenario to be generated is unclear. As some uncertainties were relatively simple, such as the revision of population forecast which includes changing a specific parameter, others are more difficult to consider e.g. political events and economic changes in the former USSR, eastern Europe and middle east. Subsequently, as stated, they provide four new scenarios. However, the authors offer no explanation for why this amount was sufficient to capture all new uncertainties. Another important point requiring attention is that no indication is given as to why the update was performed after two years and not at another timeframe. Within a year also new information and events have emerged, why not perform an update then? Moreover, in 1996, after the evaluation of the 1992 scenarios, the IPCC decided to develop a set of new scenarios. It was argued that due to significant changes in the driving forces on which the scenarios were built, new scenarios needed to be developed (IPCC, 2000). However, they do not indicate why an update, in this case, would be insufficient. Lastly, they do not indicate any methodology for executing this update. Was there a structured way of executing this process? How did they choose which information to consider? Is there a method for assessing these changes and how these should be taken into account within the scenarios? Did they discuss this in a group or was this process performed individually? A structured method could, not only, help provide guidance for how to incorporate changes, but also track changes over time and see when an update should be performed or when new scenarios should be constructed.

Industry view

Moreover, the energy consultants also recognize the need for keeping scenarios up-to-date. As these scenarios are used to evaluate strategies that may incorporate large costly investments, the information considered within these scenarios must be as accurate as possible. This means that when new information becomes available there is a need to take this into account. As strategic decisions are not made in vacuum but in an increasingly rapid changing environment, it highlights the fact that scenarios need to be regularly updated. The methodologies for generating scenarios differ between companies as explained in Section 2.4, however, all recognize the need for keeping their scenario up-to-date on a regular basis by incorporating technical, economic and political changes (IHS Markit, n.d.-a). *Aurora energy research* publishes their updated global energy scenario report every six months and distributes their country-specific power market forecasts, which they use to generate their country-specific scenarios, on a quarterly basis (https://www.auroraer.com/). Aurora energy research indicates they incorporate laws agreed upon internationally and enacted into national law, into their reference case, which forms a basis for the rest of the scenarios, while uncertain policies are considered within a specific policy scenario (A. Esser, personal conversation, 5 June 2019). However, how they assess other uncertainties is unclear. *IHS Markit* differentiates between the type of change for how regularly they update their global energy scenarios. On a quarterly basis they update key data elements, which include the changes in fuel prices and GDP growth rates, and they assess global events. They provide an annual update explaining the changes in key drivers on which the scenarios are built. For their industry-specific scenarios, they provide twelve scenarios a year and therefore a monthly update is provided (IHS Markit, n.d.-a). *Pöyry* ensures quarterly updates on their market projections which are used for generating their long-term country-specific scenarios, however, also no information is found on how these updates are executed (Pöyry, n.d.). As the updates of these consultants are part of the offering to their customers, they will not be keen on publicly sharing their methodology. This results in the fact that no information is found on how this process is executed

Taken together, these studies support the notion that there is a need for incorporating new information and emerged events. They address that the assumptions on which the scenarios are built change over time and therefore require to be updated. Nevertheless, many make no attempt to give an adequate explanation for how to incorporate new information and uncertainties into scenarios, therefore, the main weakness of the studies discussed in this literature review, is the lack of information on how changes are assessed and why these changes are considered in a certain way within the scenarios. Moreover, no structured process is found on how new information and uncertainties should be considered into scenarios.

2.4 Experts knowledge

All studies reviewed suffer from the fact that no method is found on how to incorporate new information and uncertainties. However, to validate the claim that there is no method within literature to structurally incorporate change into scenarios, some highly valued energy scenario experts are asked for their knowledge of a specific method for doing so. Additionally, their expertise was used to provide input on improvements for the proposed framework. In total three experts were questioned: Prof. dr. Detlef van Vuuren, Prof. dr. Gert Jan Kramer and Dr. Oreane Edelenbosch. Within Appendix C, a short outline of their work experience and achievements is provided. Below a brief summary of the main outcomes of the conversations is provided.

First, it is emphasized that each expert individually mentioned the relevance of this research and highlighted the originality of the work. Prof. dr. D. van Vuuren and Dr. O. Edelenbosch are currently involved in generating scenarios and encountered similar problems when updating. Additionally, all provided some relevant input for updating the framework, which was incorporated into the research. Dr. O. Edelenbosch has pointed out the relation of my topic with the social-technical approach of Geels (2002) and highlighted the fact that the qualitative perspective in scenarios highly influences the quantitative scenarios. Additionally, she mentioned the importance of a general framework but also indicated the difficulty in formulating such a framework as she thought there will always be exceptions in how an update should be performed. Prof. Dr. D. van Vuuren indicated the difference between updating small parameters in a scenario and generating new scenarios, concluding some changes can be incorporated relatively easy while others require much more time. Additionally, he indicated the difficulty in communicating large changes made to people not having extensive background in formulating the scenarios. Prof. Dr. GJ Kramer indicated the importance of the high-level storyline not being subjected to the fast-changing environment. Subsequently, the most important insight from the conversations and also the main goal, was that none of the experts had read or heard of a method to structurally incorporate new information and uncertainties into scenarios. This confirms my own findings of the literature review. Prof. dr. D. van Vuuren even mentioned the updating process of the IMAGE model, of which he is one of the owners, is rather unstructured.

2.5 Conclusion

The use of scenarios has increased significantly during the last decades across all layers within our society and is being acknowledged as a relevant tool to help navigate through a highly uncertain future (Amer et al., 2013; Shell International BV, 2008). This study has identified two main benefits of using scenarios: (1) widen managers current perspective and (2) evaluate strategies given different future pathways (Varum & Melo, 2010). Many techniques for generating scenarios have been developed, however, the focus within this thesis is on intuitive logic. This highlights the fact that generating scenarios is qualitative in nature and no complex calculations are used. Subsequently, as scenario generation does not happen in a linear fashion, it is important to validate the generated scenarios (Royal Dutch Shell, 2008). When performing an update, taking new information into account, the validity of the scenarios must be re-assessed as the scenarios have changed. Within this thesis three validation criteria are used to check the validity of the scenarios: (1) consistency, (2) plausibility and (3) relevance (Amer et al., 2013).

An important insight generated from the literature review was, when scenarios are used as a tool for evaluating strategies, the qualitative scenarios need to be altered. Additional steps must be executed to reduce the level of uncertainty, i.e. making choices and performing extensive analysis on focal areas (Cornelius et al., 2005). It is therefore concluded that within a scenario a more long-term macro perspective, qualitative in nature, and a more short-term focused (macro and micro) perspectives, quantitative in nature, is present. Van Vuuren et al. (2010) stress the importance of differentiating between these forms when performing an update. Small short-term changes might influence some components within the scenario while new long-term trends might require an entirely new scenario to be created. However, currently, no distinction is made between layers in a scenario. Therefore, this will be indicated as the first research gap: different parts within the scenario will be influenced differently by changes, however, currently no distinction is made between layers within a scenario.

Subsequently, the literature review presents a critical review of how scenarios are currently kept up-to-date. The need to update scenarios is clearly recognized within literature, as new information and uncertainties have emerged which influences the assumptions on which the scenarios are based (Creutzig et al., 2017; IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010). First, the assumptions on which the scenarios are built should be checked if still being valid (Van Vuuren et al., 2010). All findings highlight that if the assumptions on which the scenarios are built significantly change, the scenarios require an update. Additionally, newly emerged uncertainties need to be considered. The IEA (2014) and Leggett at al. (1992) state that policies enacted into national law should be considered in all scenarios and proposed laws in their policy scenario. Moreover, Van Vuuren et al. (2010) highlight there is a relation between the nature of changes and how they should be treated during an update, and thereby indicates the importance of differentiating between changes in the external environment and how they impact your scenarios. Van Vuuren & O'Neill (2006) stress the fact when evaluating scenarios, some components of the scenario might require updates while other more high-level factors are less subjected to change. However, the reviewed literature fails to explain how a structured update should be performed, therefore, two additional research gaps are indicated.

The second gap identified in the literature is that no tool is found to assess which changes need to be considered and why these are considered in a certain way. The literature clearly makes a distinction between how changes are incorporated into scenarios, however, fail to address how they execute this assessment.

The third research gap indicates that there is no structured process on how new information and uncertainties should be incorporated into scenarios. The value of a structured process to execute an update is recognized (Prof. Dr. D. van Vuuren, personal communication, 28 June 2019; Prof. Dr. G.J. Kramer, personal communication, 1 July 2019; Dr. O. Edelenbosch, personal conversation, 3 July 2019). However, in the view of all that has been mentioned so far, one may suppose that no method is present within literature on how to execute this process in a structured way.

How to proceed?

In the remained of this thesis the author attempts to solve these gaps by providing a framework. Currently, no method is found within the literature, however, the literature review does provide some ideas that can give guidance in configuring a solution. The literature review indicates that in order to use the storylines (qualitative scenario) for evaluating strategies some additional steps need to be executed, thereby, altering the scenario. As the qualitative and quantitative scenario represent society in different ways, new information and uncertainties will influence these scenarios in a different way. However, currently, no distinction is made between different layers within a scenario. It is therefore important that some distinction is proposed to be able to incorporate new information in a structured way. Secondly, the nature of the change also influences how scenarios are affected when incorporating these changes. Depending on the nature of the change, the different parts of the scenarios will be influenced. It is, therefore, necessary to distinguish between changes. However, currently it is unclear how this should be done and, therefore, a solution needs to be proposed. The next chapter will highlight how these ideas are used to develop the proposed framework.

3
Introduction of concepts

Although the reviewed literature suggests that incorporating new information, emerged events and new uncertainties into scenarios can be a suitable mean to deal with the fast-changing environment, none of the reviewed literature goes into detail on *how* this process should be structurally executed. I propose that to configure a solution two important building blocks need to be introduced 1) the scenario consists of a multi-layered structure, each having own characteristics and 2) changes considered should be classified according to their impact and uncertainty, as the nature of the change will influence how the scenarios are affected. Based on this classification, changes can be incorporated into the different layers distinguished within scenarios. As the ideas presented here are at the fundament of the framework proposed, it requires an introduction on how these ideas were generated.

Section 3.1 will first discuss the layers distinguished in a scenario. Before performing any alterations, it is important to first understand the current structure of the scenarios. Dividing scenarios into different layers does not only give insight into how scenarios are currently structured but also provides a common language on *how* changes need to be incorporated. As dividing scenarios into different layers is a novel idea. A similar research subject within the field of technological transitions will be used as a source of inspiration to define the characteristics of these different layers.

Additionally, Section 3.2, discusses to classifying changes according to their uncertainty and impact on the business environment. Classification of changes based on their uncertainty and impact is not a new concept as this is a well-established approach to identify critical uncertainties used to generate scenarios (Amer et al., 2013; Benedict, 2017; Cardoso et al., 2014; Pillkahn, 2008). However, within this thesis it will be proposed that the impact-uncertainty matrix is used as a tool to indicate in which layer changes need to be incorporated.

After introducing the two building blocks, they are combined in Section 3.3 to create an approach on *how* changes should be structurally incorporated into scenarios. Finally, conclusions are drawn and a reflection on the limitation is provided.

3.1 Multi-layered scenarios

The fast-changing environment brings challenges for making long-term future-oriented projections. Recent developments and new uncertainties must be considered for the scenarios to remain plausible. As part of the solution, I propose to divide scenarios into four different layers: *Framework*, *Storylines*, *Industry specific fundamentals* and *Numbers*. Identifying these layers within a scenario helps to think about their current structure in an orderly manner before performing any alterations. This is important as the structure of a scenario influences how changes need to be incorporated. Therefore, to gain insight into *how* changes should be incorporated into scenarios, it is important to differentiate between layers in scenarios.

To define the characteristics of these layers, this thesis will use a socio-technical approach to transitions as a source of inspiration. This approach was also highlighted during the conversation with Dr. O. Edelenbosch (personal conversation, 3 July 2019), as she mentioned the theory being linked to the proposed framework. The theory of Geels (2002), the Multi-Level Perspective (MLP), is recognized as a useful framework and makes a distinction between different layers in society to indicate how society develops over time. It thereby acknowledges that external changes influence society at different levels (Geels, 2002). The MLP integrates a top-down long-term vision (climate change, changing environmental values) and bottom-up influences (technological developments) to view technological transitions (Van Bree, Verbong, & Kramer, 2010; Xu, Yuan, & Xu, 2017). The theory of Geels is shortly discussed after which, the proposed layers and their characteristics are introduced. The figure of the multi-level perspective and an example of using the theory of Geels can be found in Appendix D.

3.1.1 Multi-level Perspective

The basic idea of the multi-level perspective is that a technology does not exist as a separate entity within society. A dominant technology within society is a function of social, technical and institutional factors who are highly interdependent (Geels, 2002; Whenua, 2012). A radical new technology does not only have to compete with the current technology dominating the market but also with the system (political, legal etc.) supporting that technology. The multi-level perspective indicates that a transition towards sustainability will not be linear since the already existing highly institutionalized system creates path dependencies (Fuenfschilling & Truffer, 2014). The MLP, therefore, recognizes changes to society as transitions from one layer to another and is a process over time. These different layers represent different concepts of the society we live in. Geels (2002) distinguished three different layers in society:

1) *The socio-technical landscape* refers to the "highest" level within society. It forms the context in which our society functions and is outside of the direct influence of the other layers. It is characterized as the macro-economics, deep cultural patterns, and macro-political developments within our society. Changes within this layer happen very slowly (years/decades) (Geels & Schot, 2007; Steward, 2012). Examples from the energy industry could be climate change and public awareness of energy issues.
2) *The socio-technical regime* is the middle layer and compromises the mainstream activity and structures within society. *"The socio-technical regime forms the 'deep structure' that accounts for the stability of an existing socio-technical system."* (Geels, 2011, p. 5). This layer discusses the current rules, actors and culture within the industry and incorporates all elements of production, distribution and use of the current dominant technology (van Bree et al., 2010). The important part of this layer is the interdependency of the different factors within this regime. We "lock" ourselves into the dominant solution, which makes it difficult for new technologies to break through within society. For example, driving a regular fossil fuel car. Our producers, users, rules, culture and infrastructure are built around this technology (Whenua, 2012).

3) *Niche-innovations* is the micro-level where new ideas are introduced. This level is subjected to rapid changes as this layer presents new products and processes outside the current socio-technical regime (Olesson, 2012). The niche innovation might disrupt the regime structure and compete with the dominant technology for market share. The socio-technical landscape puts pressure on the regime to incorporate certain favorable changes, for example, incorporating cleaner energy generation technologies to combat climate change. The timing is therefore important for the niche innovation to break through (Geels & Schot, 2007; van Bree et al., 2010).

The higher layers provide the boundaries in which the lower layers are defined. A consequence of this interdependency is that although changes may in the beginning influence one layer, they might evolve to eventually influence other layers as well. Changes to society are therefore seen as an iterative process.

This theory is focused on technical transitions within society. However, as this theory is used as inspiration for defining the characteristics of the different layers within scenarios, it is argued that these characteristics also apply to other transitions (political changes, structural changes, economic changes, etc.).

Important points to take away from the MLP

The most important finding from the MLP is that to understand technical transitions, different layers within society must be distinguished. As a scenario is a future representation of a society, it is argued that a scenario also represents different layers. Besides this point, some other important insights were subtracted that could help to define the characteristics of the layers indicated. These will shortly be discussed below:

1) First, the layers represent different parts of the society we live in and are therefore differently subjected to changes. The top layer, macro-perspective view, is not subjected to rapid changes and changes within this layer happen very slowly (decades), while lower layers are more subjected to the fast-changing environment where new ideas are introduced. The middle layer discusses the mainstream activities in society in which the interdependency between the different factors is important. Additionally, the higher layers are outside of the direct influence of the lower layers but highly influence lower layers.
2) Subsequently, another important point indicated by the MLP is that the layers are interdependent. The higher layers put pressure on the lower layers. However, over time the lower layers may also put pressure on the higher layers. It is therefore important that the process of incorporating changes is seen as an iterative process.
3) Moreover, changes evolve over time. As some changes might not influence any layer at this moment, they might evolve and have an impact on society. It is therefore important to check the evolution of these changes to see if they become of any influence.

Lastly, Geels & Schot (2007) also highlight that radical changes within society will influence layers depending on the timing and nature of the change. These are therefore seen as important indicators that need to be considered when developing a framework on how to incorporate changes into your scenarios. It is believed that these indicators are of such importance that these concepts will be elaborated within a specific section (nature of change, Section 3.2; timing, Section 3.2.4).

3.1.2 Introducing layers

The literature research, chapter 2, indicates that before the qualitative scenarios can be used as a tool for making strategic decisions, the scenarios need to be altered and multiple steps must be executed. Although qualitative scenarios discuss possible long-term futures, they are relatively static in nature, while quantitative scenarios are more subjected to the fast-changing environment. As these steps alter the scenarios, this process is used as a leading thread to indicate the different layers. Additionally, the ideas introduced by Geels provide a source of inspiration to define the characteristics of these layers.

Important to note is that within each step of the generation process, assumptions on how the future might develop are formulated (e.g. future growth rate) to reduce complexity and uncertainty. As over time some of the uncertainty is resolved and new uncertainties emerge, it is important to examine the consistency of the assumptions with more recent data. Changes within the assumptions are an indication for an update. Proper indication of assumptions made within each layer is, therefore, essential to update accordingly.

The goal of defining the different layers within a scenario is three-fold:

1) Defining these layers allows people to think about the current structure of the scenario before performing any alterations. This is important as the current characteristic of these layers affect how changes need to be incorporated;
2) It highlights the fact that the layers are interdependent and that changing one layer might influence other layers over time. Incorporating change is therefore an iterative process;
3) It creates a common language for *how* changes can be incorporated into scenarios.

The proposed layers are shown in figure 3.1.

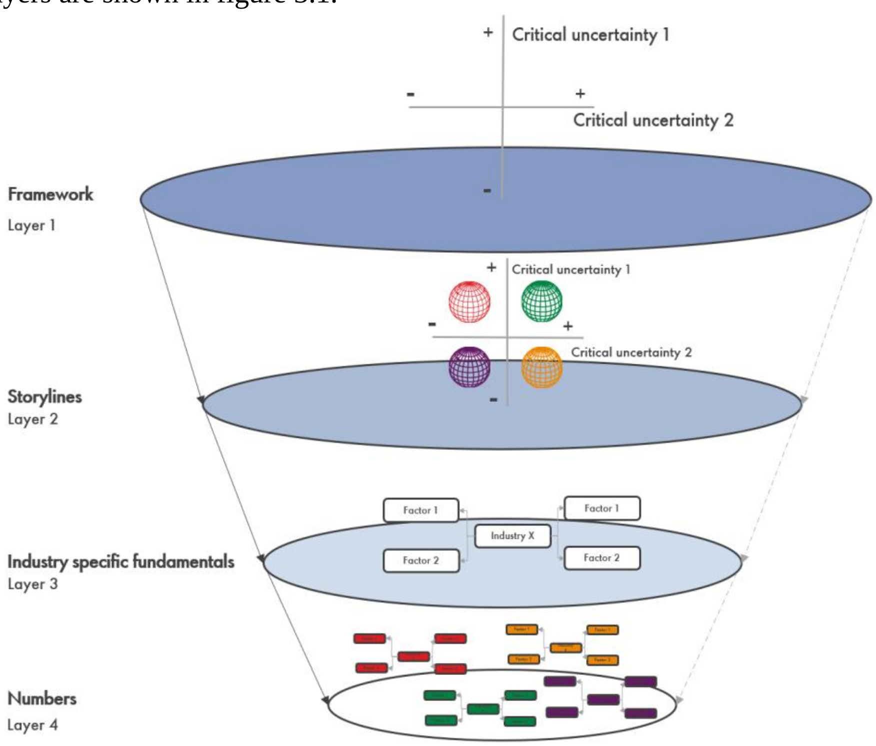


Figure 3.1: Interrelationship between different layers within scenarios

As dividing scenarios into layers is not explicitly stated within literature and is therefore a novel idea; every layer is individually discussed. First the characteristics of the layer is elaborated on, subsequently, the goal of defining this layer is explained and how changing this layer influences the rest of the scenario. Additionally, the assumptions made within each layer and the validation process after incorporating changes is briefly discussed. Finally, a summary is provided to highlight the main points per layer.

Layer 1 - Framework

The top layer, *Framework*, is the first layer distinguished within a scenario and forms the basis on which the scenarios are constructed. This layer represents the critical uncertainties affecting the business and provides the context in which the rest of the layers are formulated. When generating scenarios, it is important to first express the critical uncertainties or trends that are explored. As many things are uncertain in the future, choices must be made about the issues that really matter within the industry. These are developments or problems that are long-term, highly uncertain and have a high impact on the business environment. The relatively stable nature of this layer means that this layer is not subjected to rapid changes and provides a long-term macro-perspective view. Moreover, as this is the top layer, it is outside of the direct influence of the lower layers. Defining this layer highlights the basis of the scenarios and how they are constructed. This indicates that if these critical uncertainties change, an entirely new set of scenarios need to be constructed, thereby also changing all lower layers.

A commonly used approach to generate this *Framework* is the minimal approach in which two critical uncertainties are chosen (Amer et al., 2013). Indicating the extremes of these uncertainties on a two-by-two matrix generates the *Framework*, providing four different quadrants, which forms the basis for the qualified scenarios (figure 3.2).

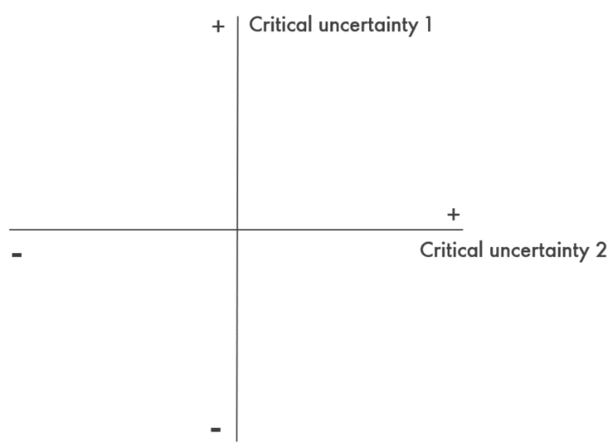


Figure 3.2: Layer 1 - Framework

Examples of critical uncertainties could be: degree of decarbonization, generation mix in the future or political stability. It should be noted that the axes within the framework are defined by a + and –, which do not represent a high and low situation but define the extremes of the chosen critical uncertainties, which *can* be high or low.

Assumptions

As the focus within this thesis is on deductive scenario only two critical uncertainties are chosen. Therefore, other uncertainties that are thought to be less important are neglected. It is important to write down why these critical uncertainties were chosen to check if these are still valid during an update.

Validation after changes

After incorporating changes into this layer, an entire new set of scenario needs to be constructed as this changes the entire basis of the scenarios. The validation process after this step is therefore the same as within the process of generating new scenarios. As generating new scenarios is out of scope of this research, this will not gain additional attention within the test case.

Output when defining this layer

- Framework indicating two critical uncertainties and their extremes
- Assumption on which this layer is built

Layer 2 - Storyline

The second layer represents the *Storylines*, qualitative scenarios, generated using the *Framework* defined in layer one. This layer discusses multiple perspectives on how the world might evolve in a qualitative way. The resulting set of scenarios all represent the same critical uncertainties, however, within each scenario, this uncertainty unfolds differently (Cardoso & Emes, 2014). The context of these different storylines is therefore characterized by the extreme values of the critical uncertainties and can be plotted onto the *Framework* (figure 3.3).

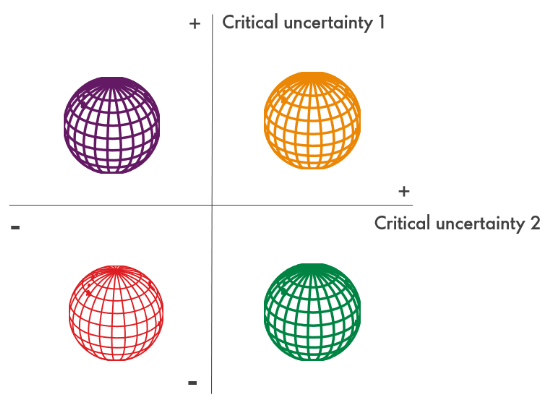


Figure 3.3: Layer 2 – Storyline (Qualitative scenarios)

As these qualitative scenarios discuss the world's evolution from the present to the end state indicated, other uncertainties, besides the chosen critical uncertainties, are considered (Van Vuuren & O'Neill, 2006). This layer, therefore, defines in more details how a world, in which these critical uncertainties play out differently, will look like. Thereby discussing the macro-perspective view of these future worlds. This layer is not directly influenced by the lower layers but is highly influenced by the top layer. Because of the macro-perspective view, these storylines are not subjected to rapid changes (years). As within this layer, multiple assumptions are made, uncertainty is reduced compared to the first layer. Therefore, this layer is more subjected to changes than the first layer as these assumptions might change over time. Defining this layer highlights the structure of the storylines defined and how these scenarios stand relatively from each other by plotting them onto the framework. Changes within this layer may influence one or multiple qualitative scenarios, which then would require to be redesigned. As this layer provides the context for the two lower layers, changing the storylines would require the lower layers to also be redesigned.

It is important to note that these storylines do not have to present the exact extremes of the critical uncertainties. They can therefore lay anywhere on the framework, as long as they form a plausible future. However, it is often highlighted that the different scenarios generated lie in multiple separate quadrants to make sure the different scenarios contribute to specific insights for possible future pathways.

Assumptions:

Within the second layer, multiple assumptions about the future are made to create a coherent set of storylines. Some assumptions can be the same across different scenarios, but a specific combination of assumptions provide different scenarios. As these assumptions form a basis for generating the storylines, they are important to explicitly state. Changes within these assumptions are an indication for an update.

Within this layer it is important to indicate the differences between the qualitative scenarios, thereby highlighting the “type” of scenario it represents. As plotting the scenarios on the framework already highlights some of the differences, namely how the critical uncertainties might play out, differences between assumptions made must also be stated. Some scenarios will assume the future will look a lot like today’s and is referred to as the *reference case*, while other scenarios will indicate a low case for many assumptions. It is of high importance to indicate the differences between the qualitative scenarios as changes in the external environment might influence these scenarios in different ways. For example, a scenario with a low degree of decarbonization will be more subjected to changes in policies addressing climate change than a scenario incorporating a high degree of decarbonization already assuming these policies might become reality.

Another representation for indicating the differences between scenarios can be seen in figure 3.4.

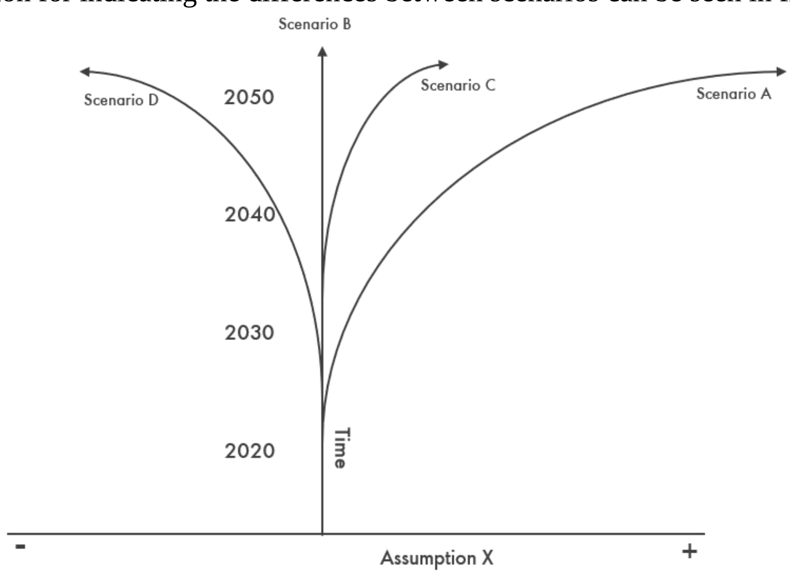


Figure 3.4: Identifying differences between scenario based on assumptions and time

This representation helps to express the relationship (and differences) between the scenarios. The X-axis represents a specific assumption. Until 2025 this assumption is the same for all scenarios, but after 2025 the assumptions are highlighted in scenario A and C and negatively indicated in scenario D.

Validation after changes

The scenarios generated need to form a coherent whole. Therefore, it is important that besides changes within a single scenario are validated, also the scenarios should be validated relatively to each other to ensure the different scenarios still contribute to specific insights. Plotting the different scenarios onto the framework provides an overview of how they are currently related to each other and allows seeing how they might have changed relative to each other after an update is performed. If two scenarios moved close to each other onto the framework, this could be an indication to redesign a scenario to make sure the generated scenarios still add different perspectives.

Output when defining this layer

- Short outline of storylines (indicating differences, type and what these storylines represent)
- Storylines plotted onto *Framework*
- Scenario-specific assumptions

Layer 3 – Industry specific fundamentals

The third layer provides the building blocks for translating the qualitative scenario into a quantitative scenario. If we, quantitatively, want to indicate the possible development of an industry, it is important to understand by which factors the industry is influenced. These often highly interdependent factors can be indicated by a flowchart showing the structure of this specific industry (Figure 3.5).

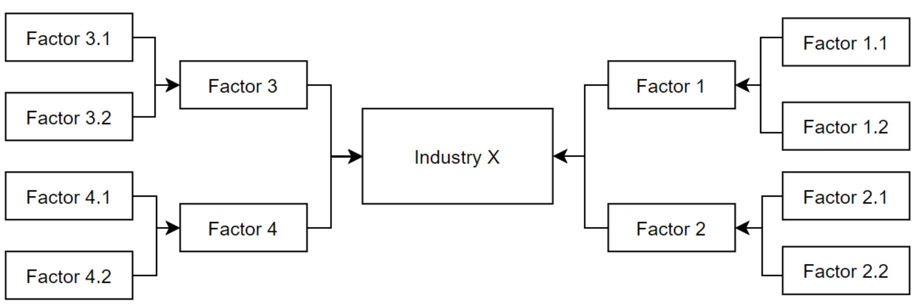


Figure 3.5: Layer 3 – Industry specific fundamentals

This provides an overview and creates a foundation for translating the *Storyline* into *Numbers*. As this process goes into more detail, again, choices must be made as the complexity otherwise becomes too high. Therefore, the most important factors must be chosen which influence the evolution of this specific industry. For example, demand, supply and fuel prices are important components within the electricity market. To understand the evolution of this market, we need to understand how these factors might change. The granularity of the flowchart is a trade-off between complexity and level of detail.

This layer is subjected to relatively fast changes as new technologies, who gained some market share, will influence how this market is structured (e.g. electric vehicles). Changes within this layer are therefore characterized by changes within the industry structure. Additionally, the interdependency between the different factors within the industry is important (also highlighted by Geels within the socio-technical regime). Changes within one factor might influence other components in this market and should be kept in mind when changes are incorporated. Defining this layer helps to create a structured overview of the factors that influence the evolution of the industry. This also helps to visualize and highlight the importance of the interdependencies between the factors. Changes incorporated within this layer influence all quantitative scenarios and therefore also includes changing the lowest layer. Moreover, incorporating many changes in this layer might, over time, influence the layer above and should be monitored.

To illustrate this layer clearly, a short example of a possible flowchart is provided below (figure 3.6). The power market is chosen as the relevant industry as this market will also be used within the test case. The different connecting lines show the relationship between the different factors. This is only a simplified version; the entire flowchart is shown in the test case.

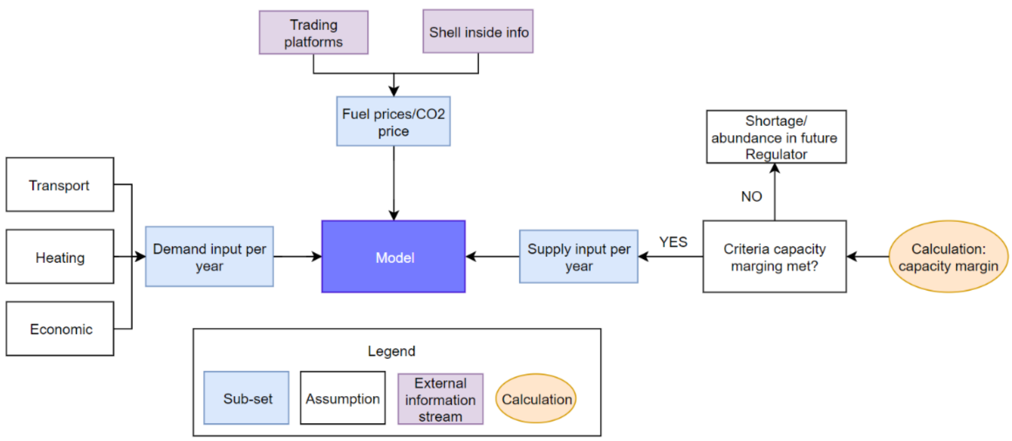


Figure 3.6: Example flowchart layer 3 – electricity market

Assumptions:

Normally, if all possible factors are considered, the flowchart becomes too complex, therefore, a selection of relevant factors should be made. It is important to highlight the assumptions made to select these factors, as changes in these assumptions might indicate an update is needed. Additionally, assumptions made on the relationship between the different factors are also important to highlight, these will be referred to as criteria. To give an example, within the power market supply needs to satisfy demand. If a power plant is closed, new capacity needs to be built to satisfy demand. It should therefore be checked that after changing a certain factor, the criteria still hold.

Validation after changes

The validation of this layer refers to validating if the factors indicated still add up to representing the industry structure. Is the flowchart still plausible? Changing one factor might influence other factors as well.

Output when defining this layer:

- A flowchart showing industry structure.
- Assumption on which this layer is build.

Layer 4 - Numbers

Within the fourth layer, *Numbers*, the qualitative scenarios are translated into quantitative scenarios using the *Industry specific fundamentals* indicated with layer three. External data is used to add numbers to the different factors indicated. This data is retrieved from different sources such as IEA, World Bank, United Nations Forecasts (Leggett et al, 1992). For each individual scenario these numbers should be altered based on the trends highlighted within this specific scenario. For example; a forecast of the percentage of electric vehicles in 2050 is 60%. In a scenario with high pressure for decarbonization, this percentage is thought to be 75%, while a scenario in which decarbonization is not a pressing topic this percentage could be 40%. Altering the forecasts based on the *Storylines* using the flowchart, creates different quantitative scenarios (Figure 3.7).

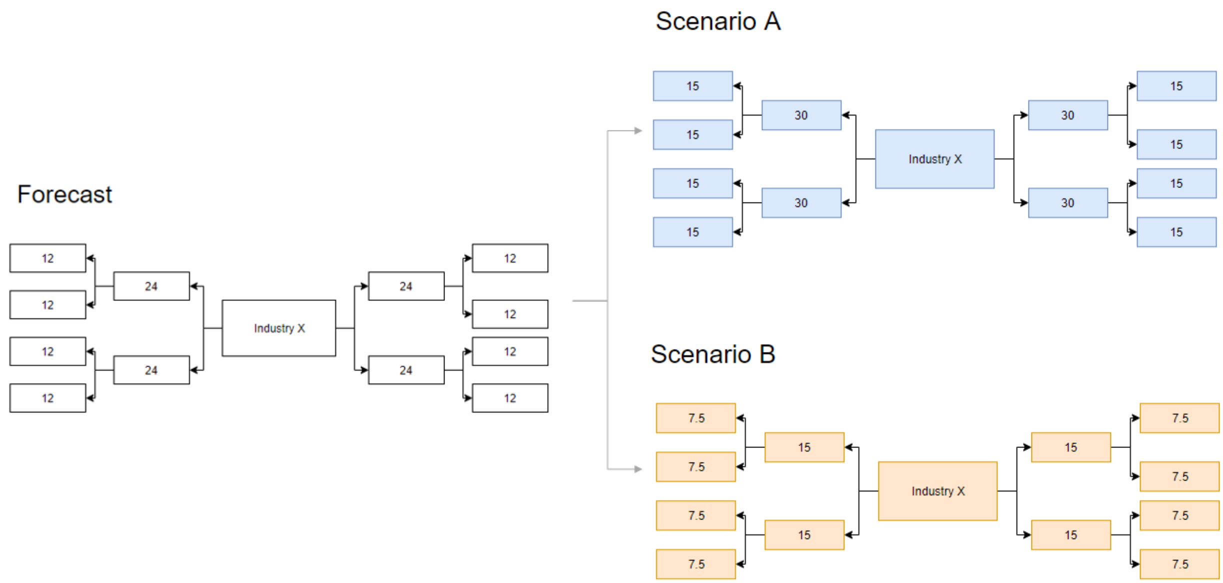


Figure 3.7: Layer 4 – Numbers (Quantitative scenarios)

It is especially important to indicate the source of the data used for defining this layer as an update would require checking whether the numbers are still plausible and relevant. Recording these sources provides the opportunity to easily retrieve historic data, gather updated data from the same source and check if the decisions made are still valid.

This layer is subjected to rapid changes as new information becomes available every day. The qualitative scenarios represent not only the macro-perspectives the storylines tell but also the micro-perspective of a certain industry. This layer is influenced by all the above layers, therefore, changes to any of the above layers requires alterations within this layer. However, as changes within this layer happen very frequently, updating this layer on a daily basis is not needed as these changes might have a relatively low impact on the outcome of the scenarios. Therefore, an update might be performed after a period of time (e.g. months). Defining this layer helps to think about how the different numbers in the quantitative scenarios are constructed and related to the storylines. Changes within this layer will influence one or multiple quantitative scenarios.

Assumptions

The fourth layer represents the highest amount of detail compared to the above-mentioned layers and, therefore, requires additional assumptions to reduce complexity. Moreover, almost all assumptions are scenario-specific, as a specific set of assumptions represents the differences between the scenario. It could therefore be argued this layer consists of only assumptions.

Validation after changes

After changing the qualitative scenarios, it must be checked if they still correctly represent the storylines. However, as these changes have a smaller impact on the business environment, it is less likely the scenarios require any additional changes. Moreover, it is important to check if changing one factor also influences other factors. Additionally, as the quantitative scenarios also need to present a plausible, relevant and consistent whole, it must be checked if this is still the case.

Output when defining this layer:

- Numbers attached to flowchart, specific for each scenario
- Sources used to formulate scenario-specific numbers
- Scenarios specific assumptions

Short recap

Scenarios can be divided into four different layers: *Framework*, *Storylines*, *Industry specific fundamentals* and *Numbers*. The MLP of Geels (2002) is used as a source of inspiration to formulate the characteristic of these layers, as this theory makes a distinction between layers in society to indicate how society develops over time. As a scenario is a future representation of a society, it is argued that a scenario also represents different layers. Formulating these layers enables you think to about the current structure of the scenarios before performing any alteration. This provides the ability to take new information into account in an orderly manner. The first and third layers represent building blocks on which the scenarios are built, the other two layers (two and four) represent the qualitative and quantitative scenarios. It is important to understand the characteristics of the different layers to gain insight into how scenarios could be updated. Table 3.1 represents a summary of the different layers discussed above.

1. Layer	2. Goal of defining this layer	3. Main characteristics of layer	4. Output when defining this layer	5. Impact of changes in this layer on scenario	6. Validation after change
Framework Layer 1	Let's you think about the basis on which the scenarios are built (extremes of critical uncertainties) and provides inside on context defined for other layers.	• Defines most pressing issues within industry (high impact & high uncertainty) • Long-term problems • Not subjected to rapid changes - decades - (relatively stable layer) • Outside direct influence of other layers • Macro-perspective – discusses problems effecting entire market	• Framework indicating two critical uncertainties and their extremes • Assumptions why these critical uncertainties are chosen	The entire set of scenarios need to be checked and/or redesigned and therefore all lower layers change.	Same validation process as when generating completely new scenarios
Storyline Layer 2	Let's you think about how the storylines are currently structured and how these scenarios differ relatively from each other. This layer defines in more detail (compared to layer 1) how the future might unfold.	• Describes qualitatively how the future might develop form present to end state • Defines how critical uncertainties might evolve in different ways • Macro-perspective • Not subjected to rapid changes – years. • Outside of direct influence of lower layers but highly influence by top layer	• Short outline of storylines (indicating differences, type and what these storylines represent) • Matrix with scenarios plotted representing how critical uncertainties unfold per scenario • Scenario-specific assumptions	One or multiple qualitative scenarios would need to be redesigned. As a consequence of these changes, the lower two layers also need to be changed.	Check each individual scenario if still present plausible future & check how they have changes relative to each other and if they still add different perspectives
Industry specific fundamentals Layer 3	Let's you think about which factors influence your industry and helps to visualize the interdependency of these factors. Additionally, it creates insight into how the qualitative scenario is translated to the quantitative scenario.	• Visualized structure of industry/factor of interest • Shows interdependencies between factors • Highlights current technologies used • Subjected to relatively fast changes – months, years – • Changes are related to industry changes • Focal points indicated relate to pressure of higher layers	• Flowchart visualizing industry specific fundamentals and their relations • Assumptions on which this layer is built	All quantitative scenarios need to be redesigned. Besides that, if multiple changes are incorporated the storyline might also be influenced (over time)	Check if factors indicated still add up. Does the flowchart still represent the industry structure in a plausible way
Numbers Layer 4	Let's you think about how the different numbers in the quantitative scenarios are constructed.	• Describes quantitatively how the future might develop form present to end state • Subjected to rapid changes – days, months • Macro- and micro perspective • Pressure from all layers above • New innovations are introduced here but might not directly influence industry structure	• Numbers attached to factors in flowchart specific for each scenario • Assumptions on which this layer is built • Sources used to formulate scenario-specific assumptions	Change one or multiple quantitative scenarios.	Check if the quantitative scenarios still represent a relevant, plausible consistent set.

Table 3.1: summary of different layers within scenario

3.2 Classifying change

The second factor that significantly influences how changes should be considered within scenarios, is the nature of the change. The nature of the change is referred to as its *uncertainty* and *impact* and will be explained in detail below. Some changes might influence society as a whole, e.g. political instability, and should be considered, to a certain extent, within all scenarios while other changes, e.g. announced closure of a single coal plant in the Netherlands, only influence the details within a single scenario. Therefore, to gain insight into *how* changes might influence the different scenarios depicted, it is important to classify these changes. Additionally, the ability to classify changes also allows tracking their evolution over time, as Geels (2002) highlights that uncertainties might evolve.

3.2.1 Classifying change is not a new subject

As our environment is complex and unpredictable, we are constantly subjected to change. One of the first and most important steps within the scenario generation process is identifying critical changes which are used to specify the themes around which the scenarios are generated (Pillkahn, 2008). Identifying and classifying these changes is a time-consuming and challenging process, but crucial in trying to understand future situations (Benedict, 2017; Pillkahn, 2008). Classifying change is therefore not a new subject within the scenario generation literature and multiple tools have been developed to structure this process (Amer et al., 2013; Benedict, 2017; Cardoso & Emes, 2014; Pillkahn, 2008).

3.2.2 Methods for classifying change

The simpler approaches to classify changes are often based on a structure with two dimensions (Pillkahn, 2008). Three dominant methods will be shortly discussed:

1) Wilson (1983) developed the *"issue-priorities matrix"* which classifies changes according to the impact on the business environment (issue) and the probability of happening (priority). Using this tool, the first step is to determine the probability that the change will develop in a significant issue for the business. The second step, given the assumption that an issue develops, is to determine how large the impact of that issue will be on the enterprise. To evaluate the dimensions, Wilson suggests the categories "low," "medium," and "high." If both dimensions are indicated with "high", the highest priority for the enterprise is assigned (figure 3.8).

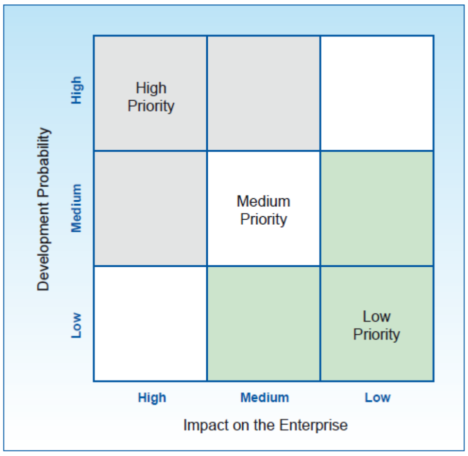


Figure 3.8: Issue-priorities matrix (Wilson) (source: Pillkahn, 2008)

2) Schwartz (1991) does not use a graphical representation of the changes but makes a distinction between three categories: *"driving forces," "predetermined elements"* and *"critical uncertainties."*

The driving forces are related to the macro environment that drives society. These are highly uncertain but have a large impact on how a specific future will play out. In contrast, the "*predetermined elements*" meet the requirements of being certain, irrespectively of which scenario is chosen. This, therefore, indicates that they should be considered within all scenarios. Schwartz talks about "*critical uncertainties"* when the assumption about the predetermined elements are being questioned. However, he makes no attempt to give an adequate explanation what he means with this term. Important is to note that the *"critical uncertainties"* are the matters with a high impact and uncertainty and therefore similar to the definition used within this thesis (see Terminology).

3) Van der Heijden (2005) combines the approach of Wilson (1983) and Schwartz (1991). He takes a similar approach to Schwartz as he also indicates "driving forces" and "critical uncertainties" to characterize changes. Additionally, to indicate which changes have the highest priority to the enterprise Van der Heijden uses an impact-predictability matrix similar to the one of Wilson. Van der Heijden evaluates the dimensions on the scale "high" and "low" and creates a two-by-two matrix. Amer et al. (2013) indicates that even though the matrix developed by Wilson and Van der Heijden is similar, the matrix of Wilson is considered better as this creates a three-by-three matrix.

More complex approaches include the Cross-impact analysis and Trend-impact analysis. Both techniques are quantitative in nature and require the development of models (Amer et al., 2013; Bishop et al., 2007). As this is out of this scope for this research no details about these techniques will be discussed.

3.2.3 Impact-uncertainty matrix

The most often used method to classify changes, and therefore well known, is an adapted version of the matrix of Wilson (1983) using two dimensions; impact and uncertainty (Pillkahn, 2008). This matrix will be used within this thesis as a tool to classify changes. The impact refers to the current impact on the drivers of the organization or the current impact on the key factors of project success (Krueger, Casey, Donner, Kirsch, & Maack, 2001). The uncertainty is considered as: *"the level of variation in the range of possible evolutions of the driver itself"* (Speziale & Geneletti, 2014, p. 3).

The impact-uncertainty matrix presented here (figure 3.9) is not divided into different rectangular blocks but curved areas, to highlights the fact that classifying a change is not limited to nine possible combinations.

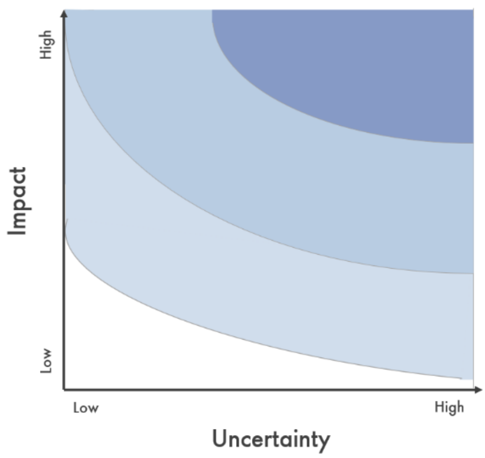


Figure 3.9: Impact-uncertainty matrix (Source: adapted from Wilson 1983)

3.2.3.1 Assigning a level of impact and uncertainty

To utilize this impact-uncertainty matrix, the changes need to be assigned with a certain impact and uncertainty level. Identification and classification of a change is often an iterative process including plenary sessions and experts' opinions and is, therefore, partly subjected to opinion (Krueger et al., 2001; Quiceno et al., 2019). It is important to note that classifying changes is a relative subject. Every change is important and has some degree of uncertainty. However, relative to each other, some will have a higher degree of uncertainty and are more critical to a certain business (van der Heijden, 2005).

3.2.3.2 Impact-uncertainty matrix as a basis for making scenarios

Within the literature, the impact-uncertainty matrix tool is used to identify critical uncertainties, high impact and high uncertainty, around which the scenarios are built (Pillkahn, 2008). As already discussed within Section 3.1, when formulating the qualitative and quantitative scenario, multiple other uncertainties are considered to differentiate between scenarios. Krueger et al. (2001) provide a tool to indicate, based on the classification of their impact and uncertainty, how these 'other' uncertainties are considered when generating scenarios (figure 3.10).

Degree of uncertainty

Low	Medium	High	Level of impact
Critical planning issues Highly relevant and fairly predictable (can often be based on existing projections). Should be taken into account in *all* scenarios.	**Important scenario drivers** Extremely important and fairly certain. Should be used to differentiate scenarios. Should be based on projections but potential discon-tinuities also should be investigated.	**Critical scenario drivers** Factors and forces essential for success and highly unpredictable. Should be used to differentiate scenario plots and trigger exit strategies.	**High**
Important planning issues Relevant and very predictable. Should be figured into most scenarios.	**Important planning issues** Relevant and somewhat predictable. Should be present in most scenarios.	**Important scenario drivers** Relevant issues that are highly uncertain. Plausible, significant shifts in these forces should be used to differentiate scenario plots.	**Med**
Monitorable issues Related to the decision focus but not critical. Should be compared to projections as scenario is implemented.	**Monitorable issues** Related but not crucial to the decision focus. Should be monitored for unexpected changes.	**Issues to monitor and reassess impact** Highly unpredictable forces that do not have an immediate impact on the decision focus. Should be closely monitored.	**Low**

Figure 3.10: Grid on impact-uncertainty matrix indicating how to incorporate uncertainties when generating scenarios (Source: Krueger et al., 2001)

The grid indicates the critical issues (shaded areas) are key drivers within all scenarios. The rest of the grid-points indicate how they influence the different scenario and roughly discusses in how many scenarios they should be considered. However, it is rather vague in explaining how this should be done. As the goal of this thesis is to structurally incorporate new information, emerged events and new uncertainties instead of formulating new scenarios, the grid provided by Krueger et al. (2001) are used as a source of inspiration to formulate how changes, classified with a certain impact and uncertainty, should be considered into the different layers of the scenarios. The matrix indicates uncertainties with a low impact should *not* immediately be considered within a scenario but should be closely monitored. Additionally, the level of uncertainty determines (assuming the issue is classified with a medium impact) in how many scenarios it is considered. Lastly, if the impact is high, it is always incorporated within the scenarios to a certain extent.

3.2.4 Tracking changes over time – 3rd dimension

As highlighted by Geels (2002) and Krueger et al. (2001), uncertainties can evolve and impact the scenarios differently over time. For example, the presence of coal in the generation mix 15 years ago was much more certain than it is now due to climate change mitigations, therefore, coal is currently differently being incorporated within scenarios differently. An important part of my solution is the ability to track uncertainties over time, therefore, time is suggested as a third dimension to the impact-uncertainty matrix (figure 3.11).

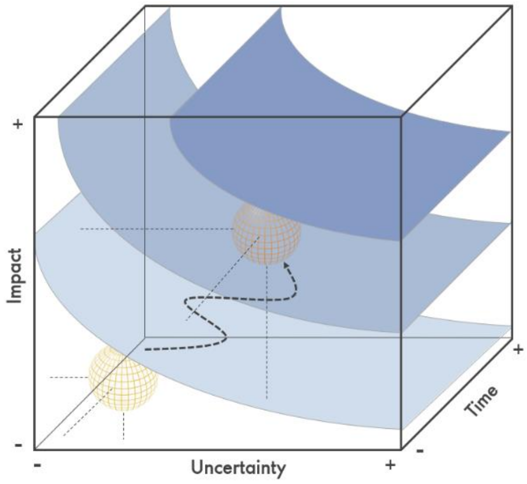


Figure 3.11: Impact-uncertainty-time matrix

Tracking the evolution of these uncertainties increases insight into if these changes are becoming more important to incorporate in higher layers or if they become less important and should be considered within lower layers or even be left out altogether. Certain patterns can be distinguished which could help steer the discussion on the development of these trends. If a certain trend shows a strong path of becoming more impactful it might be important to increase the attention towards this change and execute some additional analysis. Moreover, adding this third dimension allows visualizing how these changes have evolved and thereby their impact on the scenario. An important note is that within the remaining of the thesis, this third dimension will not be used, as the timeframe of this thesis is not substantial enough for trends to evolve it is not possible to show their evolution. Therefore, within the additional sections, time will not be included, and a two-dimensional matrix is used. However, when using the proposed framework, the third dimension must be considered.

3.3 Linking the impact-uncertainty matrix to layers indicated

The purpose of the framework proposed is to indicate how new information and uncertainties should be considered within the generated scenarios. The impact and uncertainty level assigned to the different changes is used as a guideline to determine in which layer the change should be considered (figure 3.12).

Assigning a certain impact and uncertainty to the changes in the external environment forces the scenario planners to structurally think about how these changes might impact the scenarios. The lines within the matrix provide a *suggestion* onto which layer the changes need to be incorporated and should not be seen as conclusive as filling in the impact-uncertainty matrix is subjective in nature. Depending on the group of people classifying these changes, their impact and uncertainty may be indicated differently.

For the different areas to be linked to the layers indicated the findings of the literature review, the matrix provided by Krueger et al, 2001 and experts opinion are used. If the impact is high the uncertainty should be incorporated within layer 1 or 2, if the impact is low layer 3 or 4 should be considered. Depending on the uncertainty, layer 1 (high uncertainty) or 2 (low uncertainty) and 3 (high uncertainty) or 4 (low uncertainty) is chosen (figure 3.11). It is therefore fair to say that first the impact should be determined before a level of uncertainty is assigned. It could therefore be argued that the impact provides more weight to providing input in which layer it should be considered. Additionally, Prof. Dr. G.J. Kramer (personal communication, 1 July 2019) states that changes seen as certain must be considered as the *"common core"* and should be taken into account within every scenario. However, to what extent these are considered in the different layers depends on its impact. Moreover, Van Vuuren et al. (2010), clearly indicate the storylines in the scenarios are only subjected to new information who challenge the original assumptions within the scenarios, while other information might require some parameters to be changed.

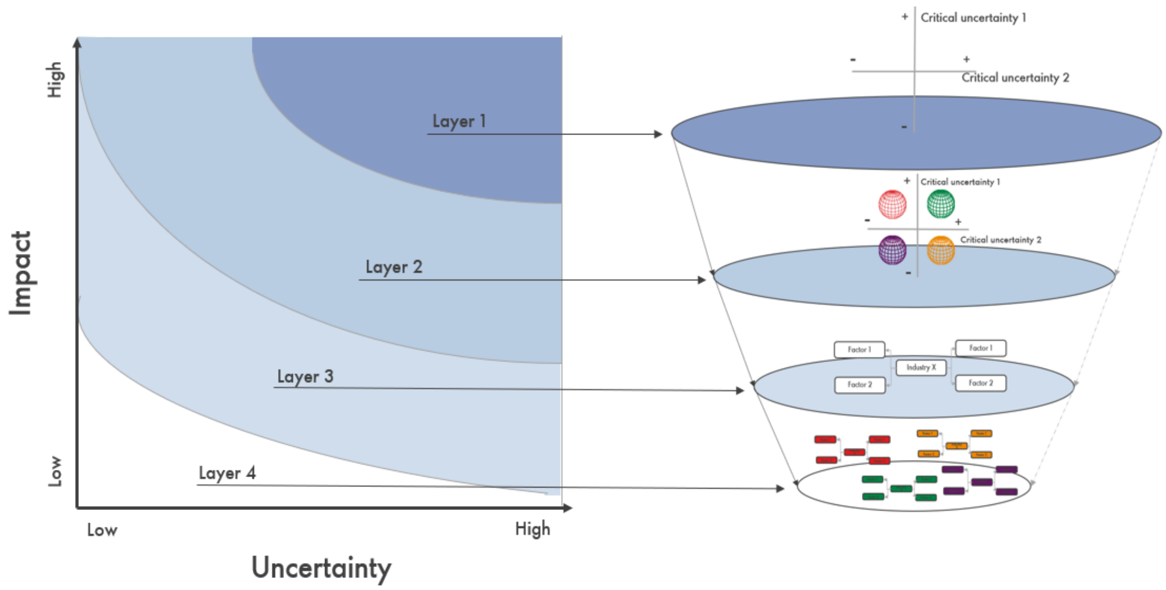


Figure 3.12: Linking the impact-uncertainty matrix to the layers indicated within scenarios

The different levels will be discussed below. First, it is indicated in which layer these changes, with a specific classification, should be incorporated and why. Secondly, the characteristics of these changes and to what extent they should be considered within the different scenarios are elaborated on. The consequences of considering changes into a specific layer are already highlighted in Table 3.1 column six.

Layer 1 – High impact & High uncertainty

Changes assigned with a high impact & high uncertainty are classified as critical uncertainty and therefore influence layer 1 (*Framework*). The level of variation in the possible futures of these uncertainties is high (high uncertainty), but they certainly have a high impact on how the future business environment evolves. These are issues which are long-term (trends), not subjected to fast changes and influence the entire industry. These changes do not appear from one day to another and evolve slowly, therefore, early indication is possible. As only two critical uncertainties are chosen to form a basis for the *Framework*, other (less) critical uncertainties need to be considered within the *Storylines* (layer 2) of the different scenarios. Additionally, as these changes are found highly unpredictable and important, these critical uncertainties should be considered within all scenarios to a different extent.

Layer 2 – Medium impact & High uncertainty || High impact & Medium-Low uncertainty

Changes classified with a Medium impact & High uncertainty or High impact & Medium-Low uncertainty need to be incorporated in the second layer (*Storyline*). These issues influence the qualitative scenarios and are not subjected to fast changes and are incorporated differently to differentiate between scenario storylines. Changes with a medium impact but high uncertainty should be considered within some scenarios as they will not influence the entire business environment, while changes classified with low uncertainty, but a high impact should be incorporated within all *Storylines* as they are fairly certain and have a high impact on the business environment. However, within each scenario, the change is incorporated to a different extent.

Layer 3 – Medium impact & Low uncertainty || Low impact & High uncertainty

Changes classified with a Medium impact & Low uncertainty or Medium/Low impact & High uncertainty need to be incorporated into layer 3 (*Industry specific fundamentals*) or closely monitored. As this layer provides the building block for translating the qualitative scenario into the quantitative scenario, changes with a medium impact and low uncertainty need to be considered within all scenarios (to a certain extent). Changes with a low impact but high uncertainty should be considered within one scenario or closely monitored as they do not have an immediate impact on the business environment but are highly unpredictable (Krueger et al., 2001).

Layer 4 – Low impact & Low uncertainty || (very) Low impact & High uncertainty

Changes classified with Low impact & Low uncertainty or (very) Low impact & High uncertainty need to be closely monitored or not considered at all. Changes with a Low impact and Low uncertainty are not considered within the scenario but closely monitored to see if unexpected changes happen. Changes classified with a (very) Low impact & High uncertainty are disregarded. However, during the next update, it is important to re-classify them to see if any changes have occurred. It is important to note, that although new changes classified in layer four are not considered during an update, layer four *can* change. If changes in higher layers are incorporated, layer four will also change. Additionally, if during an update it is noted that the assumptions within layer four have changed, these also need to be altered. Subsequently, it was highlighted that the layers are interdependent, therefore, if one layer changes the lower layers must also be redesigned. Moreover, as discussed in Section 3.2.4, over time it should be checked if changes have evolved and need to be considered within another layer.

3.4 Conclusion

This chapter was dedicated to introducing the building blocks for the proposed framework to structurally incorporate the changing environment into scenarios. Two things were found important when incorporating changes: (1) the current buildup of the scenarios and (2) the type of change considered. By extending the literature and combining existing ideas, I propose a tool to categorize uncertainties and directing them, based on this categorization, to the different layers identified.

First, the different layers were defined and discussed. The different steps of generating scenarios were used as a leading thread to indicate four layers. Additionally, I extend the literature using Geels (2002) his theory by creating an illustrative tool to define the layers within a scenario into a general concept. Identifying these layers within a scenario helps to think about the current structure in an orderly manner before performing any alterations. In total four different layers are defined, *Framework*, *Storyline*, *Industry specific fundamentals* and *Numbers*. The relatively stable top layer within scenarios is not subjected to rapid changes, while the parts that are subjected to more rapid change are related to the lower, more detailed layers. The interdependency between the different layers is highlighted as the higher layers provide the context in which the lower layers are defined. Additionally, incorporating changes into one layer influence the lower layers but over time, they may also influence higher layers.

The second building block provides a tool, the impact-uncertainty matrix, for classifying uncertainties based on their impact and level of uncertainty, as the nature of the change will influence how it affects the scenarios. Classifying changes according to their impact-uncertainty is not a new concept but using this matrix as a tool to identify how changes should be incorporated within scenarios is. The novelty, therefore, lies in combining different theories. Additionally, the ability to classify changes also allows tracking their evolution over time, as Geels (2002) highlights uncertainties might evolve. Therefore, a third dimension, time, is added to the impact-uncertainty matrix that allows visualizing this evolution.

Lastly, the two presented ideas were linked together to guide the user *how* changes, based on their impact and uncertainty, should be incorporated into the different layers of a scenario. Visualizing the interdependency between the layers helps to understand how the rest of the scenarios is influenced by incorporating changes. The tool proposed in this chapter provides a structured way of incorporating new uncertainties and helps to think about the consequences of incorporating these new elements into scenarios.

How to proceed?

This chapter has described two concepts, forming the building blocks for the framework proposed. For these ideas to be used in practice, additional steps must be executed. The next chapter moves on to describe the steps within the framework and provides, in greater detail, how this tool can be used within practical context. Discussing the entire framework provides the theoretical and practical basis needed for the test case.

4
Dynamic scenario framework

In the previous chapter, two important elements of the proposed framework were introduced. Based on the level of impact and uncertainty assigned to a change, the user is directed to consider the change into a specific layer within the scenarios. To apply these elements in an update, several steps need to be performed. This chapter discusses the steps that together form the proposed theoretical framework and attempts to close the gap within the literature by proposing a structured process for taking the changing environment into account within scenarios; a topic that is currently under-explored.

The conceptual framework presented here provides a step-by-step guide on how new information and uncertainties should be considered within scenarios, thereby improving the reporting process, increasing transparency and the ability to track changes over time. Within this process the defined scenarios evolve as the external environment is considered, thus making the scenario dynamic. The proposed framework is therefore referred to as the dynamic scenario framework.

Figure 4.1 presents a flowchart of the entire process consisting of seven steps. The first two steps are performed to understand the current set of scenarios and their buildup. The combination of steps 3 - 7 is referred to as performing the update. Step 3 is executed to understand the changing external environment and provides the required input for performing an update by evaluating this information. The 4th step is the first part of incorporating the external environment into scenarios by adjusting the assumptions on which the current scenarios are built. Within step 5 and 6, new trends and new uncertainties not yet considered within the scenarios are dealt with by using the concepts from chapter 3 to determine *if* and *how* these should be considered within the scenarios. Lastly, the changes are validated in step 7.

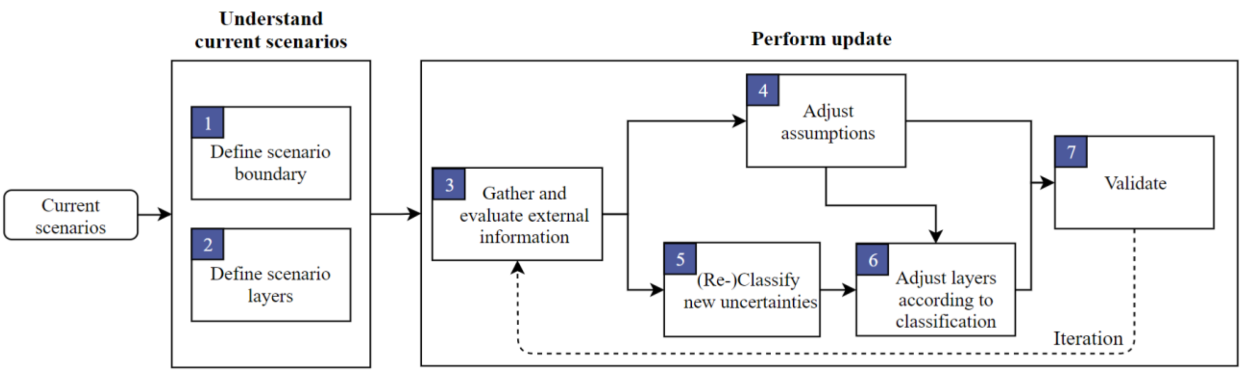


Figure 4.1: Dynamic scenario framework

Before proceeding to explain the different steps within the framework, the two routes that could be taken within the framework are shortly highlighted (figure 4.2). Step 1 and 2 are not incorporated within the routes as they should be executed, regardless of the route, before performing the actual update.

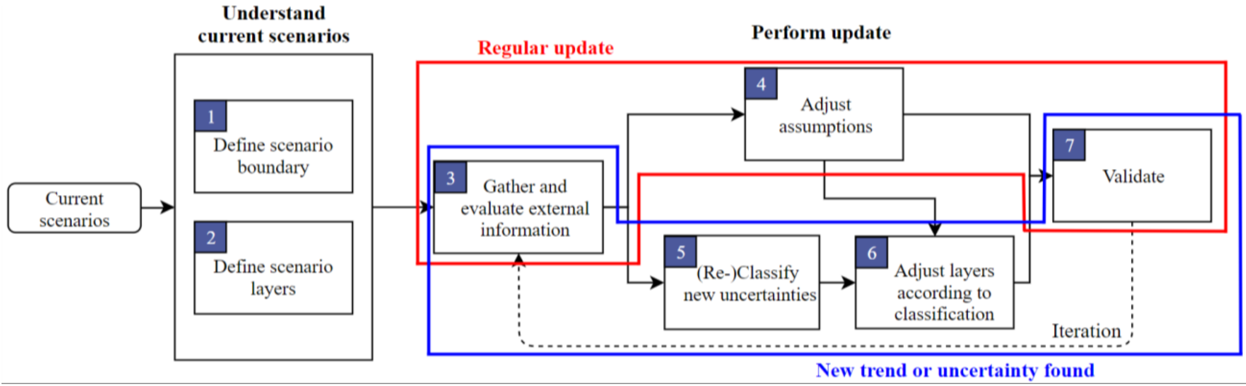


Figure 4.2: Different possible routes within framework

1) The first route (red, step 3-4-7) is referred to as a *"regular update"* and incorporates the changing environment by updating the assumptions in layer 4, *Numbers*. New information will be added to the existing assumptions within the scenarios, therefore requires minimal adjustments. Steps relating to this route are explained but not expanded upon as this is not the focus of this thesis.
2) The second route (blue, step 3-5-6-7) should be taken if a new trend or uncertainty, not yet considered in the scenarios, is found. In particular, to understand how these new trends and uncertainties should be incorporated, the concepts introduced in chapter 3 should be used to help categorize them such that the most relevant ones are selected and incorporated into the scenarios. This second route is primary the focus of this thesis as research on this topic is limited and there is currently no methodology in the literature that provides a structured process for incorporating new trends and uncertainties into scenarios. Moreover, this also highlights the academic and societal contribution of the proposed framework.

Since it is likely that the assumptions in lower layers have changed, the first route must always be performed to adjust the scenarios accordingly. Additionally, when new trends and uncertainties are found the second route should also be performed.

The proposed steps within the framework are discussed separately by a dedicated section. Each section discusses what the step constitutes, how this step should be executed and the advantages of defining this step. After discussing all the steps, conclusions are drawn and further steps are deliberated.

4.1 Define scenario boundary – step 1

Explanation of step: Before incorporating the external environment, it is important to understand how the current scenarios are structured. The first step within the framework is to define the boundary of the scenarios**.** The boundary of the scenarios discusses the context in which the scenarios were generated. The scenarios might be focused on a specific industry, country or continent and discusses a specific timeframe. Additionally, the goal of generating the scenarios and the insights expected to be subtracted from the scenarios should clear.

Implementation: Defining the scenario boundary is done by discussing the scope and focus area within the scenarios. The scope can refer to a geographical location and timeframe, while the focus area is related to what is found important within the scenarios. Additionally, the objective of defining the scenarios should be highlighted. Moreover, if the scenario is to be shared with people that do not have background knowledge on the topic discussed within the scenarios, it is important to provide some information on how this market is structured and what is currently happening within this market. This step, therefore, also provides a basic understanding of the topics discussed within the current scenarios.

Advantage: Since the scenarios are already defined, the boundary of the scenarios should be known. Explicitly stating the boundary before executing an update provides insight into which changes should be included during an update and what is out of scope. As many things might have changed, the choice on which changes to focus is important. Defining the boundary might give some guidance when making this choice and helps to keep focus when performing an update. Moreover, by repeating the goal it justifies these choices made.

4.2 Define scenario layers– step 2

Explanation of step: The second step within the framework is to define the scenario buildup. As argued, the structure of the current scenarios should be identified before performing any changes. This is done by recognizing the four layers discussed in chapter 3 (*Framework, Storylines, Industry specific fundamentals* and *Numbers)*. Each layer should be individually formulated to indicate their characteristics. Additionally, it is important to highlight the interdependency within and between the layers. An input of this layer is the current set of scenarios.

Implementation: Since the scenarios are already formulated, it is important to structurally think about how these scenarios were created. Start by defining the top layer, *Framework,* discussing the critical uncertainties used as a basis for formulating the qualitative scenarios. The second layer should discuss the *Storylines* and highlight the differences between each qualitative scenario. Additionally, the multiple assumptions made within this layer, to differentiate between the scenarios, should be clearly indicated. The third layer discusses the *Industry specific fundamentals* by generating a flowchart elaborating on the structure of the market as used within the scenarios. This not only creates a simplified visualization of the scenario components but also indicates the structure of how the qualitative scenarios are translated into the quantitative scenarios. Each component within the flowchart should be individually discussed to understand what they represent and where they are positioned in the flowchart. This understanding is especially important as during an update it is argued which and how these factors change when new uncertainties are considered. Lastly, layer four, *Numbers,* is defined. As the scenarios are already generated it should be highlighted how these scenario-specific numbers were generated. Thereby, it is especially important to elaborate on which sources were used to generate these numbers. This allows to easily check their relevance and plausibility when performing an update.

Advantage: Identifying the different layers within the scenarios before performing any alterations provides the basis of being able to structurally perform an update as this structure influences how changes should be incorporated. The four layers help to identify how the scenario is currently built up. Additionally, it highlights the interdependency between and within the layers to highlight that changing one part of the scenario might influence other parts as well. As the first three layers are also represented visually, it helps to create a compact overview and fosters easy communication.

Important to note is that step 1 and 2 are executed once when the framework is used for the first time. When the boundary and the different layers are indicated, these can also be used as a basis during other updates.

4.3 Gather and evaluate external information – step 3

Explanation of step: Before being able to perform an update, information on changes within the external environment should be gathered. This step consists of two parts: 1) gathering information on assumptions made within the scenarios and 2) gathering information on new uncertainties not yet considered within the scenarios. When the information is gathered on the assumptions made it should be evaluated if a regular update suffices (step 4) or the impact-uncertainty matrix is needed to include these changes into scenarios, indicating a new trend is found (step 5 and 6). New uncertainties, not yet incorporated within the scenarios, always require the use of the impact-uncertainty matrix (step 5 and 6) and, therefore, do not require any further analysis here.

Within this step, it is important to obtain multiple different views to understand the different opinions surrounding the possible evolution of these uncertainties. Retrieving information is a continuous process within organizations, however, during an update, extensive research should be performed.

Implementation: This step requires extensive research in the field of interest using multiple different sources. First, information should be gathered on the assumptions made. These assumptions were generated using multiple sources, specified in step 2, which can be used to provide updated information. Subsequently, extensive research can highlight new uncertainties not yet incorporated within the scenarios.

The information on assumptions is further analyzed to indicate if a regular update suffices or if the impact-uncertainty matrix is needed. The assumptions form the basis of the scenarios and were generated using the information available at that time. During an update, time has passed and new information on these assumptions has become available. The questions that should be answered here is: are alterations needed, and if so how?

It is recommended to systematically evaluate the different assumptions by starting at the bottom layer. Starting at the bottom layer is important as the fourth layer is subject to rapid changes and the assumptions within this layer are most likely to change, while the assumptions in higher layers can still be valid. To evaluate these assumptions several steps need to be performed. First, a list of all the scenario-specific assumptions made should be provided (generated in step 2). Secondly, the actual values should be stated. Lastly, the difference between the scenario-specific assumption and the actual values need to be indicated. An example is provided in table 4.1.

Table 4.1: Example evaluating scenario-specific assumptions layer 4

Scenario	Assumption made in 2015 for 2018	Actual values in 2018	%Difference
	Installed capacity of wind in GW	GW	%
Scenario 1	10	32	-69%
Scenario 2	20		-38%
Scenario 3	30		-6%
Scenario 4	40		25%

The table presents the assumptions made in 2015 for 2018 and the actual values in 2018. Subsequently, the table clearly indicates the difference between these values and thereby which scenario was closest to predicting its actual value. Since the values for installed capacity of wind is much higher than average expected, it might be needed to adjust not only the values for the years 2015 - 2018 but also the view within the future by re-classifying its uncertainty onto the impact-uncertainty matrix. However, it is important to check this with external information as short-term changes might not be compared to long-term trends (Van Vuuren et al., 2010). If this is the first year the values are significantly different, adjusting current values might be appropriate. However, if over time the actual values are an extreme case of our scenario-specific assumptions, alteration of our entire view is needed for the scenarios to provide different plausible future perspectives.

In most cases, changes made at a lower layer will not necessarily impact any of the layers above. If an update is performed after a short period of time (couple of years), the second layer may not need any alteration as this layer discusses the more long-term macro perspective. Nonetheless, if a lower layer is often being updated, this might highlight a possible trend that is currently being ignored at a higher layer. Re-evaluating the assumptions within higher layers may then be needed to capture this trend, indicating the lower route within the framework must be taken. This, therefore, requires the uncertainty to be re-classified onto the impact-uncertainty matrix and re-evaluate all the assumptions made related to this uncertainty. A short example is provided below (figure 4.3 - 4.5). Figure 4.3 illustrates last year's situation (2018, grey dot) and four different scenarios (colored dots) all having their own paths that lead to the different worlds depicted. If we see that during an update, the actual values are moving in a certain direction (figure 4.4), it might be that a certain scenario is no longer found relevant and changes in higher layers might be needed or even a new scenario should be created (figure 4.5).

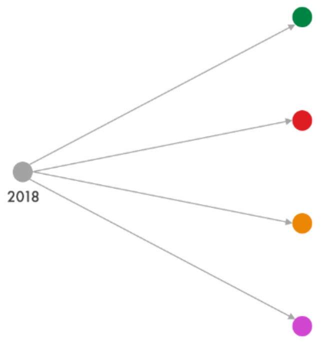


Figure 4.3: Last year's situation (grey dot, 2018) and four depicted scenarios (colored dots) and the path towards these scenarios

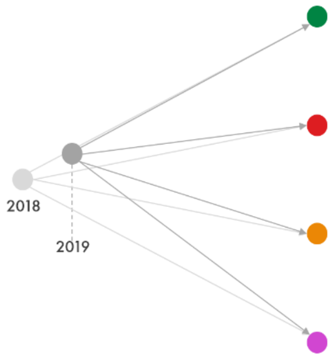


Figure 4.4: Current situation (dark grey dot, 2019) and the four depicted scenarios and the path towards the depicted scenarios, indicating a trend to the upper scenario

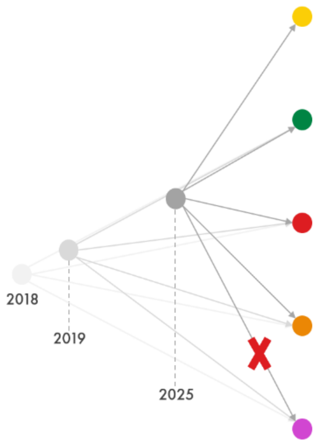


Figure 4.5: Future situation (dark grey dot, 2025) and the four depicted scenarios and the path towards these scenarios. The clear upward trend makes the purple scenario implausible. It can hence be disregarded.

If a new trend is discovered when analyzing the *Numbers*, or radical changes have occurred, this can be seen as a change in uncertainty. Therefore, this requires the uncertainty to be re-classified onto the impact-uncertainty matrix and re-evaluate all the assumptions made related to this uncertainty. If the uncertainty is still classified in the same layer, the assumptions in this layer need to be evaluated if still being plausible and relevant.

Advantage: Without retrieving any new information, an update cannot be performed. The main goal of retrieving this information is to understand the changes within this market and the impact of these change on the scenarios. Moreover, it generates insight into, *if* and *how* an update should be performed and it provides the input for executing this update. By analyzing each change, you determine a certain path throughout the framework and adjust the layers accordingly.

4.4 Adjust assumptions – step 4

Explanation of step: Step 4 is the first step of incorporating new information into the scenarios by updating the assumptions in layer 4 (*Numbers)* and is referred to as performing a regular update. During an update, time has passed and new information on these assumptions has become available. To make sure the scenarios remain plausible and relevant, this new information should be added to the existing numbers of these assumptions. If radical changes or trends have been identified when evaluating the assumptions, these will be dealt with in step 5 and 6 and are not discussed here. The alterations performed here simply update the old assumptions instead of generating new assumptions.

Implementation: Within the previous step, step 3, it was evaluated which assumptions should be adjusted. New information will be added to the existing assumptions and, therefore, requires minimal adjustments. During an update in the fourth layer, alteration can consist of two options: 1) update values with actual values, thereby altering only a couple of years, and the same for every scenario and 2) alter numbers until the end of the timeline and differentiate between scenarios. How the numbers need to be adjusted will depend on the information retrieved and personal opinion of the scenario planners, and is therefore subjective in nature. It is important to start with this lowest layer as an update, most of the time will involve changing the numbers of particular assumptions, rather than changing the assumptions themselves. Additionally, it is especially important to consider the interdependency between the different factors, which would require making changes to the numbers of other assumptions. The flowchart defined in layer 3, is used to determine which factors might be influenced and whether a certain interdependency exists.

Advantage: Within this step, external information is considered within the scenarios by adjusting the assumptions in layer 4, thereby performing the first part of the actual update. If the assumptions on which the scenarios are built are not relevant anymore, the scenario does not represent a plausible future and becomes useless for strategic thinking. Updating the current assumptions within the scenarios makes sure the basis of the scenarios are relevant and plausible before incorporating new uncertainties. The advantage of updating assumptions using the proposed framework is to reduce the complexity of the process by defining which assumptions need updating and highlighting the interdependencies that might affect other assumptions. This not only increases time efficiency but also guarantees that the interdependencies are captured.

4.5 (Re-)Classify new uncertainties – step 5

Explanation of step: As the external environment changes, new uncertainties may have arisen. Within this step, a certain level of impact and uncertainty is assigned to these external changes to understand how the scenario updaters view the importance of these new uncertainties. As these uncertainties are currently not yet incorporated within the scenarios, the impact-uncertainty matrix is used to evaluate *if* and *how* these uncertainties must be considered within the scenarios. Additionally, if a trend is found when analyzing the external information, this should also be treated as a new uncertainty and requires re-classification onto the impact-uncertainty matrix. Moreover, if a historical update was already performed using the impact-uncertainty matrix, it should be checked if these uncertainties are still assigned with the same level of impact and uncertainty. Uncertainties not found relevant during the last update might have evolved and become more relevant, moreover, some relevant uncertainties might have become less relevant. This highlights the importance of tracking changes over time. To answer these questions the buildup of the scenarios, previously plotted uncertainties and the external information retrieved is used as an input. Important to note is that it might happen no new critical uncertainties are indicated. If also no trend if found, step 5 and 6 do not have to be executed.

Implementation: As stated in chapter 3, classifying these uncertainties is subjective in nature and depends on personal opinions and assumptions of the ones classifying the changes. However, when assigning the impact and uncertainty it is important to understand the different views surrounding these changes. It is recommended to question multiple experts, in addition to those making the update, to evaluate the classification. Discussion on the impact and uncertainties of these changes is important as it stimulates multiple opinions to be compared and evaluated. The research executed within step 3 can provide basic information to familiarize oneself with the topic and different opinions. However, additional research might be needed.

Advantage: Classifying these changes forces the scenario planners to think about its impact and uncertainty and thereby the possible influence on the business environment. It ensures that the right problems are addressed in the right way (in the eye of the scenario planners). Using the impact-uncertainty matrix lets you think about uncertainties in a structured way and helps to determine in which layer the changes need to be considered. It thereby creates a tool for incorporating new uncertainties (or evolved uncertainties) in a structured way. The classification justifies why uncertainties are considered in a specific layer and thereby provides easy communication. Additionally, since classification is done during every update, it visualizes the evolution of these changes which could help to recognize certain trends and indicate the need for additional research.

Important to note: The impact-uncertainty matrix provides a *suggestion* into which layer these uncertainties must be considered and different experts may have differing views. It is indeed possible that one expert is convinced that the uncertainty should be considered in a different layer to another expert. Additional attention is being paid to this point in Section 7.1.

4.6 Adjust layers according to classification - step 6

Explanation of step: Step 6 performs the second phase of incorporating the external environment into scenarios to ensure they resemble plausible and relevant future visions. This step requires significant changes to the scenarios compared to a regular update. First, the top layer is adjusted, if needed, after which the lower layers are altered. Important to note is that these new uncertainties may also influence the assumptions already incorporated within the scenarios. It is therefore vital to think about how these new uncertainties might influence the rest of the scenarios and consider the interdependency within and between the layers.

Implementation: The previous step, step 5, has indicated which layers are affected by incorporating these new uncertainties. To understand how these layers are affected, the information retrieved (step 3), and the partly updated scenarios after step 4 are used as an input. Moreover, as we now know which layers are affected, additional research can be executed to gain more information on how these changes might influence the scenarios. Incorporating changes into each layer is shortly discussed.

Layer 1

If layer 1 is adjusted, the basis of all scenarios change. Therefore, when incorporating changes into this layer an entirely new set of scenarios need to be constructed. It is recommended when generating these new scenarios, the different layers are immediately indicated to save time during the next update. Within the test case only a brief explanation is provided on how this process is structured as no new critical uncertainties are indicated, moreover, generating scenarios is beyond the scope of this research.

Layer 2

When incorporating new uncertainties into layer 2, a specific part discussing this uncertainty and how they might play out in the different scenarios should be added to the storylines. Additionally, scenario-specific assumptions on the evolution of this uncertainty should be formulated. Moreover, it should be indicated *if* and *how* this uncertainty affects the rest of the storylines using the information retrieved. For example, incorporating hydrogen vehicles into the scenarios will reduce the share of fossil-fueled based cars. If a trend is found when analyzing the information, the uncertainty is already considered within the scenarios but the assumptions on this uncertainty should be adjusted. For example, scenarios discussing the generation mix in the Netherlands. In one scenario, coal may be actively phased out while in the other scenarios, coal may not be actively phased out. However, if the Netherlands plans to actively phase-out coal, as is the case with the current ambitions (De Wetgevingskalender, 2019), then any scenario that does not actively phase-out coal may no longer be considered accurate and should hence be adjusted. All scenarios would then consider a coal phase-out, but the uncertainty could now relate to the speed of the phase-out. However, if all coal plants are completely phased out this assumption should be disregarded and taken out of the storylines. Subsequently, as changes within this layer also affect lower layers, these should also be adjusted. This is done by first analyzing the flowchart to understand *which* factors are affected, thereafter, layer 4 discusses the question of *how* these factors are affected.

Layer 3

Updating the third layer discusses the question of *which* factors are influenced by introducing a new element into the scenarios. The flowchart provides an overview to structurally incorporate new elements by visualizing the different factors discussed within the scenarios and their interdependencies. When a new uncertainty is incorporated within this layer, it is important to run through the entire flowchart to discuss *if* and *how* the uncertainty influences each factor. The assumptions made are related to choices of the factors within the flowchart and the different interdependencies within this layer. It may happen that two factors that were interdependent no longer are, or less so. This provides you with the basis on how changes should, quantitatively, be incorporated into the scenarios and provides additional insight into which information needs to be retrieved to provide reasonable *Numbers*. Additionally, layer 3 is also influenced by changes in layer 1 or layer 2, when the entire market structure is affected.

Layer 4

New uncertainties classified with a low impact and low uncertainty or (very low) impact & high uncertainty are not considered within the scenarios. Therefore, new uncertainties only influence layer 4 if incorporated within higher layers. However, layer 4 is always adjusted in step 4 when the current assumptions, already present within the scenarios, are adjusted. Within this layer, the question is answered *how* the factors indicated in layer 3 are quantitatively affected.

Advantage: This step provides the second phase of updating the scenarios to make sure the scenarios stay plausible and relevant. By executing this step the scenario planners are reminded that besides executing a regular update, updating assumptions already present within the scenarios, new uncertainties might have evolved and are important to incorporate. Additionally, it provides a structured way of doing so. By starting at the top layer, it reminds the scenario planners of the interdependency between and within the different layers and makes sure this interdependency is considered. Additionally, it reduces some of the complexity within the updating process, thereby increases time efficiency and transparency.

4.7 Validation and Iteration – step 7

Explanation of step: Step 7 involves validating the changes made such that the scenarios still represent a plausible relevant future and shows consistency within and between the scenarios. If after performing an update, the scenarios represent a slightly different version of the same story, the scenarios need additional changes to ensure to end up with unique and diverging scenarios. Additionally, if a trend towards a certain future is seen, different from the current view within the scenarios, the scenarios need to be rethought as they may no longer be relevant (figure 4.3 – 4.5).

Implementation: There are multiple different methods to check the validity of the scenarios (Section 2.1.2). As these validation methods are often organization-specific, some methods are briefly discussed to give a general idea of how this step might look like.

1) *Plot the scenario onto the Framework.* As each scenario should provide a distinct possible view of the future. Plotting the scenario again onto the *Framework*, after an update is performed, shows how the scenarios differ from each other regarding the critical uncertainties. If they have moved "too close" to each other, a scenario might need to be disregarded and a new scenario should be created. However, the meaning of "too close" is subjective and is determined by the scenario planners.
2) *Does the lower layer still represent higher layers*? This process indicates checking whether the *Storylines* still represents the lower layers correctly. After performing alterations within the third or fourth layer, they should still represent the second layer accurately. During each update the fourth layer will change, however, executing this process multiple time might change the fourth layer significantly over time. Therefore, one should check during every update whether the second layer still represents the view in the fourth layer or if alterations in the second layer are needed.
3) *Validate with other scenarios*. Another way to validate the changes made is to cross-check with other scenarios. Multiple organizations provide their scenarios publicly (e.g. IEA, IRENA and IPCC). Scenarios that have the same focus or topic could be used to validate changes made. If there are significant differences between assumptions made, additional research should be executed. It is important to note that if the line of thought is different, it does not mean that one of them is better than the other. It is simply an indication to check the assumptions made again. If upon further research the generated assumptions are still thought to be plausible, no alterations are needed. For example, if all external sources assume a coal phase-out in the Netherlands in all their scenarios but ours do not, it might be important to check whether this assumption is still plausible.
4) *Run model*. The scenarios, within this thesis, form the input parameters of a model. Running the model will provide insights into how the input parameters play out. This could highlight specific unwanted or unrealistic situations such as an unrealistically high increase in emissions, for instance. If this is the case, additional alterations might be needed.

Advantage: During an update, new information and uncertainties are considered, altering the scenarios content-wise and relatively from each other. By validating the changes made, it ensures that the scenarios provide a plausible, relevant and consistent future and therefore a sound basis for making decisions.

Iteration

If during the validation process, the validation criteria are not met, iterations are needed. This indicates that the scenarios need to be altered until the validation criteria are met.

4.8 Conclusion

Chapter 4 has described multiple steps to structurally perform a scenario update. This chapter began by outlining the entire framework and the possible routes that could be taken, thereafter, each step was individually discussed. To structure this chapter, each section began by first discussing what the step constitutes, its implementation explaining how this step should be executed and what the advantage is of performing the step. Steps 1 and 2 are dedicated to understanding the current scenarios before any alteration is performed. It thereby lays a basis for incorporating new information in a structured way. Additionally, it reminds the scenario planners what the scenarios contain, how they are related and what their differences are. Step 3 looks at the external environment and the changes that have happened compared to the last update (or when the scenarios were generated). Understanding the changes helps to imagine how the future, and therefore the scenarios, might have changed and provides the input for performing the update. Subsequently, using this external environment, the different assumptions made within the scenarios can be evaluated. This will test the basis of the scenarios by indicating how relevant and plausible the scenarios currently are and provides insight into whether these assumptions need to be adjusted. Adjusting these assumptions with new information helps guarantee that these scenarios remain plausible and relevant (Step 4). Additionally, as new uncertainties may also have arisen, these also need to be considered. To understand *if* and *how* they should be incorporated into the scenarios, they are classified with a certain level of impact and uncertainty (Step 5). Within step 6, the new uncertainties are considered based on their classification. It is important to notice the interdependencies between the assumptions within a scenario, as well as between the scenarios themselves. Changing one factor might also change other factors and incorporating changes in higher layers also influences lower layers. The last step, Step 7, is executed to validate the scenarios. This ensures the scenarios still provide a plausible and relevant view while being internally consistent. If not, iterations are needed until the validation criteria hold.

How to proceed

Thus far, this thesis has theoretically argued for a framework to incorporate the external environment into scenarios. It is claimed that this framework can be used within a practical context. To validate this claim, the next chapter presents a test case in which four scenarios are updated using the framework proposed. The four scenarios discuss to the European power market on a timeframe from 2016 to 2050. Since the environment within this market is rapidly changing, it represents a relevant example for testing the proposed framework. Additionally, as the author was not present at the time the scenarios were generated, it is a perfect opportunity to test if an update can be performed without prior knowledge of the scenarios. Moreover, it is argued that the framework increases the ability to communicate changes. As this update is performed alone it can easily be tested if others understand the changes made.

5

Test case – part I

Scenarios discussing the European power market

The previous chapter has described the proposed dynamic scenario framework and the steps that need to be completed to structurally perform an update. This chapter will now provide the practical dimension of this thesis by applying the framework to four scenarios discussing the European power market. The main goal of presenting this test case is to illustrate how the framework should be used within a practical context, consequently highlighting the benefits of using such a framework, while at the same time uncovering any of its limitations.

In total, four scenarios will be explored during this test case: *Base case, Regulator, Factory and Rocket.* Each scenario describes a plausible unique pathway of the European electricity market and was generated in 2016. While these scenarios are inspired by the publicly available Shell scenarios (e.g. Sky, Mountains, Oceans), they are completely fictitious and do not represent Shell's view. The scenarios used within this thesis are not modified after 2016 and are taken as they are. The choices made when generating these scenarios (e.g. context or critical uncertainties) are used as a starting point and are not questioned within this thesis. As these scenarios were generated a few years ago, since then, new uncertainties have arisen, and new information has become available. By executing the different steps within the framework, it is shown that the information retrieved needs to be considered in different ways.

It is important to note that the presented test case is a simplified version of an entire update as a complete update would be a lengthy process and require multiple resources that are simply not available for this project. However, as the main goal is to illustrate how the framework is applied in a practical context, this goal is not significantly affected by the simplification. As normally multiple assumptions and new uncertainties are considered, within this test case only a small number is demonstrated. To provide a complete overview of how the framework should be used, the test case illustrates an example of taking changes into account within each layer. However, as considering changes in the first layer requires a new set of scenarios to be generated, this is only briefly discussed.

Outline of test case

Before proceeding to demonstrate the dynamic scenario framework, it is important to first get a general understanding of the European power market. Therefore, a brief introduction to this market is given to provide the context in which the scenarios were generated. The sections that follow then explain the framework proposed following the steps presented in Chapter 4. As a complete update for all factors within the scenarios is too time-consuming, within this test case, one example is provided to indicate the process of evaluating and adjusting the assumptions. This example will refer to the assumptions made on installed capacity for solar PV. Additionally, three new uncertainties are considered, i.e. nuclear fusion, hydrogen and a coal phase-out in Germany. These uncertainties are currently not yet considered within the scenarios. The example of incorporating hydrogen into the scenarios is the most extensive example as the impact-uncertainty matrix shows it needs to be considered within the second layer. Since this example therefore also shows the process of incorporating changes into layer 3 and 4 the additional examples will be less extensive. After executing the test case, validation is executed and conclusions will be drawn.

Due to the length and complexity of the test case, the steps within the framework are divided into two different chapters:

Part I) **Chapter 5 - Introduction to the current scenarios and the changing external environment.** The first part of the test case will execute step 1-4 within the framework, thereby, discussing the current structure of the scenarios, the changes that have happened within the external environment and how they should be treated within the scenarios. Additionally, it is briefly shown how a regular update is performed (step 4), as this is not the main focus within this thesis.

Part II) **Chapter 6 – Incorporating new trends and uncertainties into scenarios** The second part of the test case investigates how new trends and uncertainties should be considered within the scenario (step 6). By using the impact-uncertainty matrix it is determined *if* and *how* the update should be performed and uses this information to take the changed external environment into account. Thereafter, the changes made are validated. Part II will therefore discuss step 5-7.

Short case introduction – Scenarios European power market

As stated in the introduction, due to climate change mitigation, electricity is thought to play a much bigger role in the future. The International Energy Agency (2018), predicts demand for power to increase by 60% by 2040 compared to 2018, reaching a share of one-quarter of final global energy consumption. Consequently, this market is undergoing large changes. Additionally, the power market is fundamentally different from other energy markets. Electricity is grid-bound and must always be balanced in real-time, while storage on large scale is not yet possible, at least not in an economically viable way (Schwenen, 2018). Due to the increasing importance of power markets and their fundamental differences resulting in high complexity, there is a need to translate the uncertainty surrounding the development of power markets into meaningful scenarios. Power market scenarios for European countries help steer the companies in the right direction throughout the energy transition by supporting them to investigate new business opportunities. As the changes within this market happen at a fast pace, this influences the plausibility and relevance of the generated scenarios. The scenarios used within this test case are, therefore, a perfect subject for testing the framework.

5.1 Background information European power market

5.1.1 History European power market

Formerly European power markets were characterized as tightly regulated often state-owned monopolies, where a single company was responsible for generation, transmission, distribution and selling electricity to the consumers (Deen, 2019). The reason for this structure was that electricity is seen as an essential good for the public and is needed for a functioning economy (Serena, 2014). These power companies were monopolies because of the high initial investment cost that created a barrier to entry for competitors. As this monopoly structure is characterized by a lack of competition, they can ask prices well above their marginal costs. Tight regulation made it possible to ensure that every citizen has access to electricity.

In the last two decades, there has been a transformation in European electricity markets, in which regulated monopolies were vertically unbundled. The energy directive in 1996 was the first attempt to liberalize the European electricity market, later, two other legislative packages (2003, 2009) were introduced to gradually increase competition in this sector (KU Leuven Energy Institute, 2015). However, this liberalization process is not yet complete. Currently, generators and sellers compete in a liberalized market, while transmission and distribution are, largely, still regulated monopolies. The ultimate goal is to create an integrated market with high competition, in which the energy sector is cost-efficient (Sioshansi, 2006).

5.1.2 Power market - structure

The electricity system consists of, on the one hand, the physical infrastructure and, on the other hand, the market structure in which the electricity is traded. The infrastructure can be related to the physical flow of electricity and the market structure to the flow of money (European Parliament, 2016). This section shortly discusses both systems.

Physical infrastructure (figure 5.1)

There are several steps involved from generation of electricity to electricity usage by the end consumer. These are referred to as (European Parliament, 2016):

1. *Generation:* Electricity can be produced using different sources and comes in various sizes, from large generation plants to solar panels on rooftops.
2. *Transmission:* The transmission network is referred to as the power lines transporting electricity on a national and international level using high voltages to reduce losses.
3. *Distribution:* The distribution network takes the electricity to the end consumers using a lower voltage. This is also the system which transports electricity from smaller generation sources.
4. *Consumption:* Consumers are referred to the ones using electricity. These can be households but also larger consumers such as industrial companies.

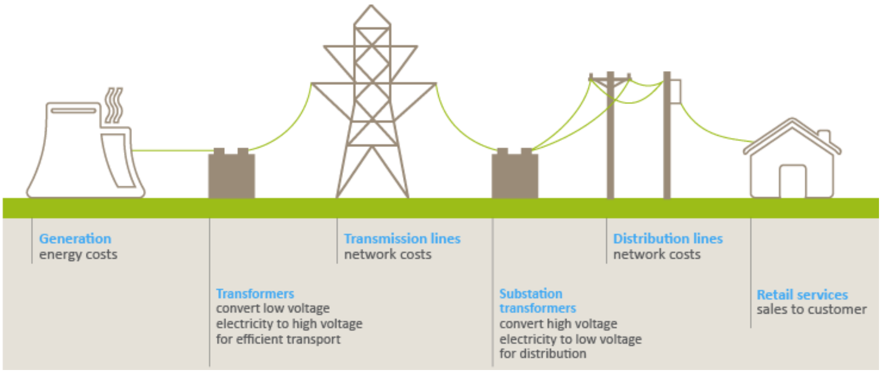


Figure 5.1 Physical structure electricity supply (Source: Queensland Competition Authority, n.d.)

Market structure (figure 5.2)

As stated, the market structure can be related to the flow of money. The structure of this market is shown in figure 5.2. Generators produce electricity and sell it either via bilateral contracts or over-the-counter on the wholesale market to retailers or large consumers. The sold electricity is transported via the transmission lines operated by a Transmission System Operator (TSO), who owns the transmission lines

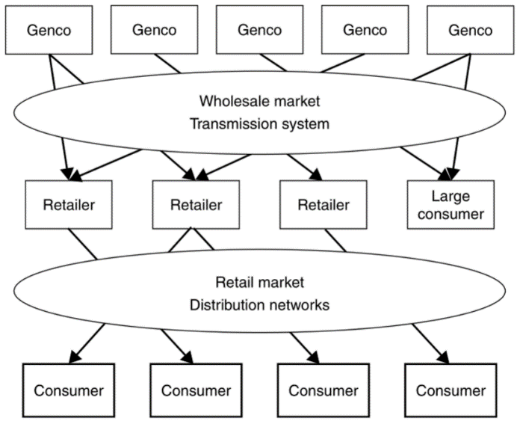


Figure 5.2: Overview different electricity markets with timeline (Source: Schwenen, 2018)

and is paid for long-distance transport. Retailers that have bought electricity sell it to end consumers on the retail market. This electricity is distributed to the end consumers via the distribution network, owned by the Distribution System Operator (DSO). They are paid for delivery of electricity to consumers. Consumers pay for the electricity to the retailers, which includes a fee for the distribution network. The functioning of the entire market is overseen by the regulator. The rules are set by an independent national organization, at EU level this is the Agency for the Cooperation of Energy Regulators (ACER) (European Parliament, 2016). The focus of this test case will be on the wholesale market as within this market, prices are often set based on supply and demand economics.

5.1.3 Different markets for balancing supply and demand

One of the specific characteristics of electricity is that supply and demand must always be balanced in real-time for the system to function. Since producers and consumers are not able to perfectly predict how much they consume and produce it is necessary to have different markets to balance (Schwenen, 2018). These markets have different timelines and start long before delivery while other markets operate in real-time (figure 5.3). The real-time markets are needed to recover for the imbalances from other markets.

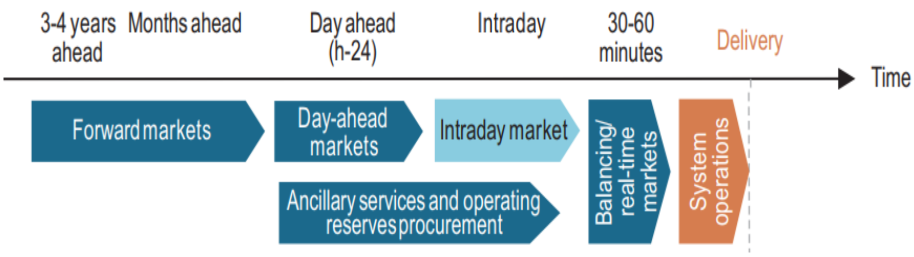


Figure 5.3: Market structure electricity market (Source: Shell)

Below the markets will shortly be discussed:

1. *Forward market:* this market runs from years until days before delivery. The motivation for this market is to reduce the risks of being exposed to price fluctuations. The products (often large amounts of electricity (100 -1000MWh)) are traded via customized or standardized bilateral contracts (Schwenen, 2018). As the products traded on this market do not have to be related to the physical electricity, therefore difficult to model, it will be out of scope for this research.
2. *Day-ahead markets:* within this type of market, electricity is traded a day before delivery. Producers and purchases send in their bids to a market platform which are then ordered by a central entity,

often, the TSO. These bids are based on forecasts about electricity production and consumption. The intersection point between supply and demand sets the market price on an hourly basis for the next day. The market is cleared once a day after which the producers and purchasers know how much electricity they must produce and how much electricity they get for a set price (Cornélusse, 2017). This market is called the spot market in which supply, and demand are matched based on the allocation rule. This rule indicates that the cheapest unit to satisfy demand wins the auction (Schwenen, 2018). This market is chosen as the main focus within this test case since the day-ahead market price is one of the most important revenue streams for power generating assets and can be modelled using fundamental theory of energy economics.

3. *Intra-day market:* within this market electricity is continuously traded after the day ahead market is closed and allows market participants to correct changes in their day ahead schedule. This can be for example the unexpected increase of lack of renewable energy generation or unexpected maintenance.
4. *Balancing market:* since the actual generation and demand deviates from the forecasted, the imbalances must be corrected for the grid to function properly which is organized by the TSO. The position of each generator is evaluated, this means that the actual generation minus the electricity sold (forecasted electricity) is determined. If this is positive the generator is treated as if it sells at the balancing market and receives a real-time price for its electricity. If the difference is negative the generator is treated as if it buys from the system at a real-time price. This is the same as for the consumers. First, their position of their imbalances is determined. If positive, it buys electricity at a real-time price, if negative, the consumer is treated as if it sells at a real-time price (Schwenen, 2018).

5.1.4 Matching supply & demand

As the focus of this thesis will be on the day ahead market, a short introduction into the market platform setting the market price is provided. This platform is a merit order type in which the aggregated supply and demand are plotted. The intersection between those curves indicate the market-clearing price for a specific hour the next day. This market is based on the lowest cost principle: the generators who provide energy for the lowest cost can supply. The price is set equal to the last power plant needed to satisfy demand (intersection point). All the power plants producing will receive the same price for their delivery. Generators submit their bids based on marginal cost of production. This is the cost for producing one additional unit of output, also referred to as the short run marginal cost (SRMC). This cost is based on the raw material price, the CO_2 price and the efficiency factor of the power plant. As these costs differ for different power plants, the submitted bids will differ. However, since the raw material price is the same for a certain type of power plant, the aggregated supply curve is often grouped by type of power plant (figure 5.4). As the costs for their production differs and the producing units will all receive the same energy price, the amount of net revenue will also differ. The difference between the SRMC and the power price is called the marginal rent of a specific power plant. However, this does not mean that the power plants on the left side of the merit order will always make large amounts of profits. The power plants must also retain their fixed costs. The breakeven cost of a power plant, called the LCOE (levelized cost of energy), refers to the minimum price per MWh of electricity at which the output must be sold over its lifetime to ensure the investment made of this installation pays off.

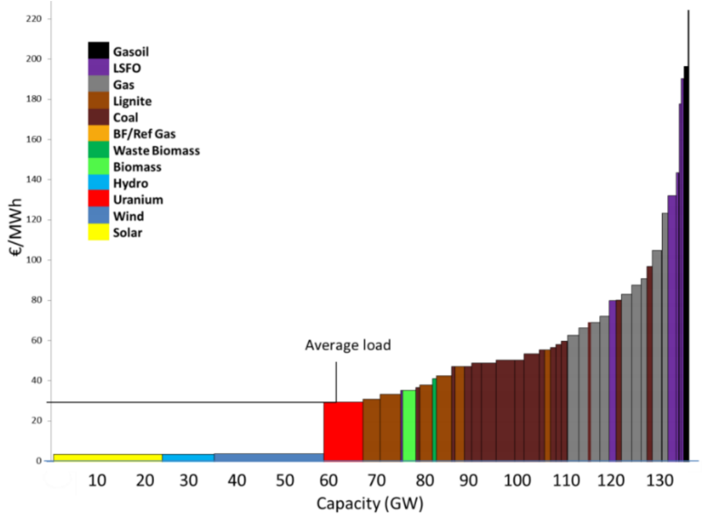


Figure 5.4: Aggregated supply curve indicating the different power plants and their marginal cost (European Parliament, 2014)

The height of the electricity price depends on multiple factors. The baseload is referred to the minimal level of demand; when demand is low, there is still a certain amount of energy required. The electricity price of this baseload is relatively low since the cheaper power plants can satisfy the demand. Peak load is referred to as the highest demand required within a specific time period. As the market price depends on the intersection between supply and demand, the electricity price will usually be higher when demand is higher. The mechanism behind these price fluctuations is shown in figure 5.5.

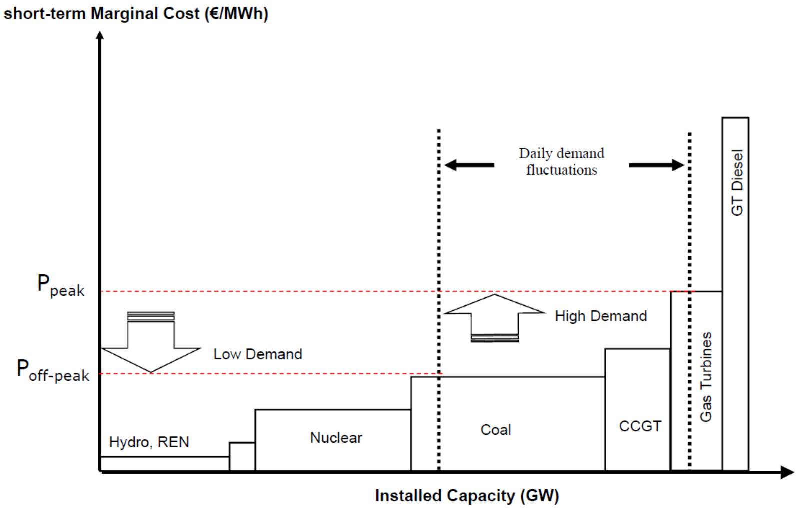


Figure 5.5: Implications demand fluctuation for electricity price (Source: Shell)

This electricity price is of high importance for the evolution of the market. If day-ahead prices are high, investments are more attractive while low prices reduce the possibility for profit. The day-ahead price is therefore of high importance for investors and is often one of the main focus points when generating scenarios.

5.1.5 Trends electricity market

As stated in the introduction, it is necessary for the world to explore other types of energy sources, and therefore, our energy system is likely to change in the coming decades. Certain trends in the electricity system can be identified related to these changes which are shortly discussed in this section.

Electricity is thought to play a big role in reducing the amount of greenhouse gasses currently produced. Therefore, the percentage of electricity in total energy use is expected to increase (especially within the transport and heating sector). This requires significant changes to the energy system which rely on very large investments. The challenge is how these investments are going to be made while maintaining security of supply (threatened by the intermittent nature of renewables) and keeping electricity affordable (European Parliament, 2016).

According to the European Parliament (2016), the drive for a low-carbon future means a growing amount of renewable energy sources, focus on energy efficiency and a greater role for the consumers, being able to generate electricity themselves. Additionally, active participation of the consumer in balancing the grid is thought as one of the solutions to deal with the intermittent character of solar and wind. This also means that large utilities might not dominate the entire market anymore.

These trends bring many challenges and opportunities that need to be considered when looking at future electricity systems. New policies or technological advances could help to overcome these challenges and seize the opportunities, but also create an uncertain environment. Scenarios help consider potential implications of how these uncertainties might play out and imagine possible responses to these situations, however, only when being plausible and relevant. Within the following sections, the dynamic scenario framework will be used to update power market scenarios generated in 2016 with new information and uncertainties for these scenarios to stay plausible and relevant.

5.2 Step 1: Scenario boundary

The first step within the framework proposed is to define the boundary of the scenarios. As the scenarios are already generated in 2016, the boundary of these scenarios is known. However, in order to ensure easy communication on why certain choices are made during an update, the boundary should explicitly be stated. First, the focus area and scope will be elaborated on. Thereafter, it states the goal for generating the scenarios which might help to keep focus while performing an update.

5.2.1 Scope and focus areas

The scenarios explore the evolution of the European power market for the period 2016-2050. In total there is a coverage of six countries: Great Britain, Denmark, Netherlands, Belgium, Germany and France, as highlighted in figure 5.6. These countries were chosen as they share large offshore renewable resources and have significant power interconnectivity. These markets are therefore an integrated power market. Due to lack of data the other EU countries were not incorporated within the scenarios.

Figure 5.6: Countries of interest within scenarios

The focus areas of these scenarios include the development of electricity demand, capacity mix, generation patterns, fuel mix, carbon intensity and power prices. As these countries are based in the European Union, the EU legislation regarding the power market is of interest as well as country-specific regulations. The technologies of interest within the generated scenarios are conventional and renewable generators, demand response, storage and interconnectors.

A summary of the focus area and scope is provided in table 5.1 below.

Table 5.1: Summary focus area and scope

Focus area and scope within scenarios	
Scope	North-West European power market
Timeframe	2016 – 2050
Countries	Great Britain, Denmark, Netherlands, Belgium, Germany and France
Properties	- Well interconnected power market - Large share of renewable resource
Focus area	- Electricity demand - Capacity mix - Generation patterns - Fuel mix - Carbon intensity - Power prices - Storage - Interconnectivity
Legislations	Country specific regulations and EU regulations
Technologies	Conventional & renewable generators, demand response, storage, interconnectors

5.2.2 Goal of defining scenarios

As stated earlier, the scenarios form input parameters for the model by offering distinct views on the evolution of the electricity system. These input parameters can be divided into three different groups:

1) Fuel & CO_2 prices,
2) Development of capacity mix (supply) and
3) Electricity demand.

The model explores the evolution of the European power market to better understand the opportunities for Shell and New Energies. The goal of defining these scenarios is to provide a wide range of possible future pathways in order to understand the possible consequences of these diverse futures on the electricity market. The scenarios are different depicted worlds that then translate to how you perceive the input parameters to the model. Although the model is out of scope within this thesis, it is important to understand that the scenarios are an input for the model, therefore, all the parameters discussed within the following sections are inputs of the model.

5.3 Step 2: Define scenario layers

There are currently no layers explicitly defined within the scenarios, therefore, the second step is to formulate the four layers according to the proposed methodology: *Framework, Storylines, Industry specific fundamentals,* and *Numbers*. This provides a structured basis when performing an update and clearly indicate how the scenarios are currently organized. As the scenarios are already generated, all information should be present. As stated, in total four scenarios will be investigated. As these scenarios, especially the lower layers, can consist of many thousand data points, some examples will be discussed to show how such a layer could look like when being defined (instead of discussing every detail within this layer). A summary of the characteristics of each layer can be found in table 3.1.

5.3.1 Layer 1 – Framework

The first layer represents the critical uncertainties around which the scenarios are constructed. A short explanation is provided on what these critical uncertainties mean and why these were chosen. The two critical uncertainties discussed here were chosen after extensive research and discussion with multiple experts in the field of electricity. These uncertainties formed the basis when the different scenarios were generated in 2016 and are therefore important to discussed to understand the structure within the scenarios. The output after defining this layer is a matrix indicating two critical uncertainties and their extremes cases.

5.3.1.1 Two critical uncertainties

The critical uncertainties represent the problems that have a large impact on the electricity market while being highly uncertain about *how* they are going to impact this industry. These problems are long-term, macro perspective and are not influenced by rapid changes. Due to the transition towards a low carbon future and the increasingly important role of electricity, the power market is very likely to change within the coming decades. However, how this market is going to change is highly uncertain. *The degree of decarbonization* (critical uncertainty 1) realized is of high importance for the structure of this market as for high decarbonization other technologies are needed than for low decarbonization. Additionally, for the energy transition to take a certain direction, *the level of government intervention* (critical uncertainty 2) is found to be of high importance. On a social level, Scholten and Bosman (2016) argues that the current political pressure makes it more interesting for countries and companies to shift their focus towards renewable energy systems, however, also creates a great deal of uncertainty as there is no consensus on how these policies should be formulated or how the objectives set should be reached. The two chosen critical uncertainties are discussed below. Additionally, a short explanation is provided indicating their extremes. Moreover, as the different scenarios do not have to represent the exact extremes of the critical uncertainties an example in between the extremes is given.

Table 5.2: Critical uncertainty 1

Critical uncertainty 1: Rate of decarbonization The rate of decarbonization refers to the degree to which decarbonization is realized. As the scenarios are deductive and not normative in nature, there is no constraint to reach a certain level of decarbonization, therefore, they aim to cover broader themes.		
Low degree of decarbonization is connected to a slow transition. In a world with slow transitions the attention shifts from climate change to a more short-term concern: the worldwide recession that was heralded by increasing geopolitical tensions. The energy sector responds to the increased uncertainty by reducing long-term investments, perpetuating the status quo. Consequently, investments in low-carbon technologies decrease, which in turn slows down cost reductions by technological learning.	**Gradual decarbonization** The energy transition picks up pace as it has been doing in the last few years but faces serious societal and economic hurdles. For every two steps forward there is one step back due to tension between short-term affordability and long-term benefits. The power sector largely decarbonizes, except for the last – most expensive – steps.	**High degree of decarbonization** The sharp cost reduction is the 'engine' that drives low-carbon investments at a rate faster than the natural replacement rate. Especially in Europe, countries try to get a competitive advantage (and mitigate cross border effects) by decarbonizing faster than their neighbors.

Table 5.3: Critical uncertainty 2

Critical uncertainty 2: Government intervention		
Minimal policy intervention Within Europe, emerging populist movement frustrate the energy transition by destabilizing institutions – first and foremost the EU itself – and sharply reducing governmental support for the energy transition. As a consequence, existing power plants are not actively phased-out. The deployment of renewables is market-based, and day-ahead market revenues are sufficient to cover investment costs.	**Gradual intervention** EU targets drive the decarbonization plans of the individual states, which results in moderate policy interventions in the energy sector. Threading unknown ground, the effectiveness of these policies is mixed. There is consistent support for low-carbon technologies. This level of support is sufficient to drive additional RES deployment beyond a minimal policy scenario but does not cause major disruptions. Coal power plants are actively phased-out.	**Active policy intervention** Propelled by pressure from society, courtroom and international policies, nation states step up their decarbonization efforts. This results in concerted policy interventions in the energy sector, which are more often successful than not. Coal plants are actively phased-out and CCS is applied to gas.

5.3.1.2 Visualization Framework

Visualizing the *Framework* is important as the four different quadrants forms the basis for the qualitative scenarios. Additionally, it provides the opportunity to plot these scenarios to see how they stand relative to each other. The framework is shown in figure 5.7.

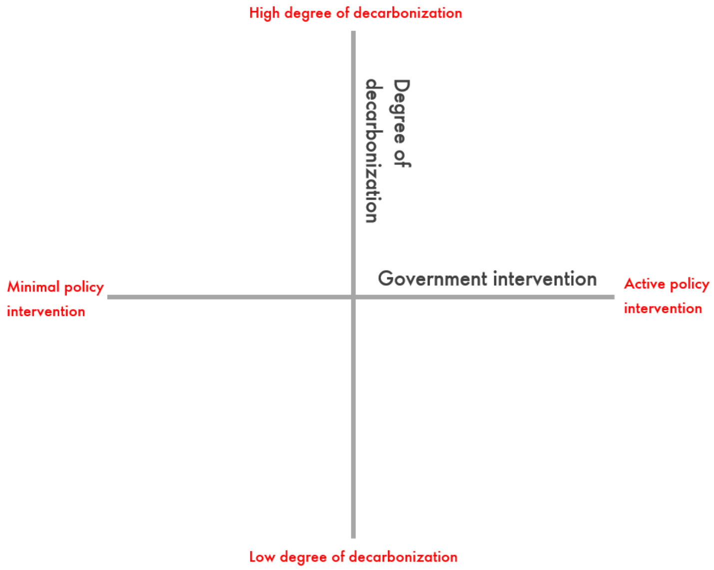


Figure 5.7: Layer 1 - Framework

Assumptions

Within this layer, there is only a small amount of assumptions made. The assumptions relate to the choice of the two critical uncertainties. If, after an update, it appears that another (new) critical uncertainty is found to be more important, this will replace one of the dimensions of the *Framework*, thereby changing the basis of the scenarios which would require a new set of scenarios to be formed.

5.3.2 Layer 2 – Storyline

The second layer describes how the future might develop from present to end state in a narrative form, thereby, representing the qualitative scenarios. As the energy transition is of high influence for the evolution of the power market, the different scenarios will partly reflect the speed in which this energy transition happens. The goal of defining this layer is to think about how the storylines are currently structured and differ relatively from each other. The output after defining this layer is as follow:

- Short outline of storylines, indicating differences.
- *Framework* onto which the qualitative scenarios are plotted.
- Assumptions on which these storylines are built

In total four distinct scenarios were generated in 2016 that all represent different plausible futures of the European power market: *Base case*, *Rocket*, *Factory* and *Regulator*. These worlds are thought to be equally plausible and important and therefore require further investigation. First, a short narrative of the scenarios is presented. Secondly, the *Framework* will be shown onto which the different qualitative scenarios are plotted. This will highlight the difference between the scenarios regarding the two chosen critical uncertainties. Additionally, other differences will be highlighted by providing a list of scenario-specific assumptions made.

5.3.2.1 Storylines

Base case represents a central view on the evolution of the power market, in line with current trends. The energy transition picks up pace as it has been doing in the last years. Under this scenario, the governments continue to pursue a balanced energy policy attempting to meet the sometimes-competing demand of security of supply, competitive market structure and environmental sustainability. Due to government intervention focused toward energy transition, coal is actively phased-out in a few countries. Until 2030, decarbonization happens at a relatively fast pace, similarly to the *Regulator* scenario, but then flattens as we move towards 2050, due to the additional costs of reducing carbon intensity. CCS for gas is introduced around 2035 but with a delay compared to *Rocket* and *Regulator* scenarios. There is a steady shift from gas to power consumption due to electrification but no radical changes. This scenario is the "reference scenario".

Rocket is a world in which decarbonization takes precedence and is pursued across all sectors through a diversified mix of low carbon generation. The low-carbon investments are driven by sharp cost reduction which thereby happens faster than natural replacement and drives renewables share to a high extent. This world is policy driven but there is less government intervention than within the *Regulator* scenario. Coal plants are actively phased-out in all countries and CCS is applied to Gas. Additionally, due to the sharp shift towards clean technology, electrification drives increased power and decreased gas demand. This also requires a high increase in flexible demand to mitigate the fluctuating intermittent renewable energy sources. Due to the large investments in renewable energy there is a steep drop of carbon intensity until 2040 after which the decline is moderate. This scenario is the only one that achieves the Paris agreement target of a 2-degree world as decarbonization is actively pursued. This scenario can be seen as the "high scenario".

Regulator is a policy driven world in which decarbonization occurs through large-scale low carbon generation (CCS, nuclear & offshore wind). This world results in an intensive policy intervention in the energy sector which are more often successful than not. Coal plants are actively phased-out in all countries and CCS is applied to gas. This world results in the second highest decarbonization. Until 2035 the decarbonization pace is relatively the same as *Base Case*. However, after 2035 there is a steep reduction which results in the same carbon intensity in 2050 as *Rocket.* Additionally, due to the large amount of large-scale decarbonization there is a medium increase in flexible demand. Within this world the electrification drives increased power demand. As of the large share of large-scale renewables, gas generation in the future is an important part of the generation mix.

Factory is a consumer driven world in which delayed decarbonization occurs through small-scale low carbon generation. Within this world the attention shifts from climate change to a more short-term concern: worldwide recession due to increasing political tension. Additionally, government intervention is low as the EU is destabilizing which reduces governmental support for the energy transition (e.g. no active coal phase-out). The energy sector responds to the increased uncertainty by reducing long-term investments, perpetuating the status quo. Consequently, investment in low-carbon technologies decreases, which in turn slows down cost reduction by technological learning. The deployment of renewables is market-based, and day-ahead market revenues are sufficient to cover investment costs. As decarbonization is delayed, there is almost no changed demand for electricity or gas. This results in a low increase in flexible demand. This scenario is the “low scenario”.

5.3.2.2 Categorizing scenarios according to layer 1: Framework

It is important to clearly indicate the differences and similarities between the scenarios depicted as an update might change the scenarios relative to each other. Plotting the different scenarios onto layer 1: *Framework*, highlight the differences in terms of the two chosen critical uncertainties (figure 5.8).

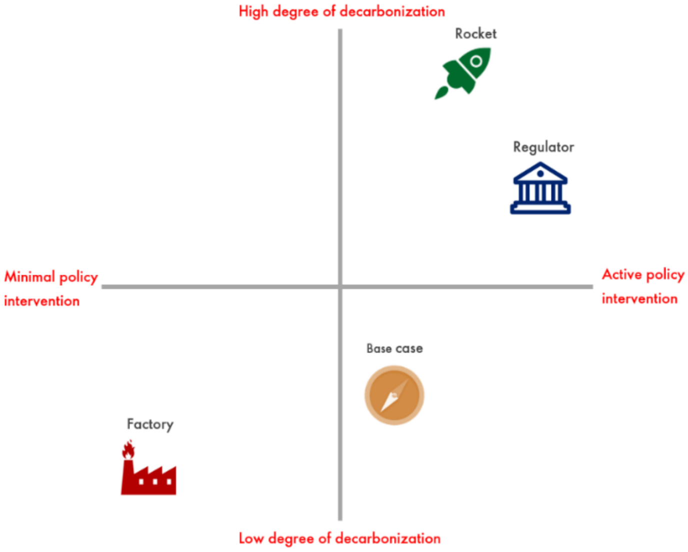


Figure 5.8: Scenarios plotted onto *Framework*

The *Rocket* scenario reaches the highest reduction in carbon intensity and has the second-highest government intervention. *Regulator* is a world in which there is a high degree of government intervention but reaches the second-highest reduction in carbon intensity. *Factory* is the opposite of these scenarios as there is a low degree of decarbonization and minimal policy intervention. *Base case* is the middle scenario.

As can be seen from the plot, no scenario covers the upper-left quadrant. An explanation could be that the scenario generators did not think this would be a plausible or interesting future and therefore left it out. Moreover, the different scenarios do not represent exact opposites of each other, the area that they represent can be seen as a diagonal line from the left down corner to the upper right corner.

5.3.2.3 Assumptions

Additionally, there are multiple other differences between the scenarios besides the two critical uncertainties discussed. These differences are a result of the scenario-specific assumptions made and are important to highlight in order to structurally perform an update.

Within Appendix E the scenario-specific assumptions are provided in table 9.1. Changes in these scenario-specific assumptions due to changes in the external environment are an indication for an update as these scenarios are built on these assumptions. Additionally, other assumptions, nonspecific to the electricity market, are made for the storylines to represent a coherent whole (e.g. GDP growth, population growth, demographic developments etc.). As these assumptions are taken directly from the World Energy Model (WEM) provided by Shell, these are considered to be out of scope. The WEM model is designed to quantify long-term scenarios of the transformation of the energy system and are updated within other Shell departments (Royal Dutch Shell, n.d.-d). These assumptions are therefore assumed to be up-to-date.

5.3.3 Layer 3 – Industry specific fundamentals

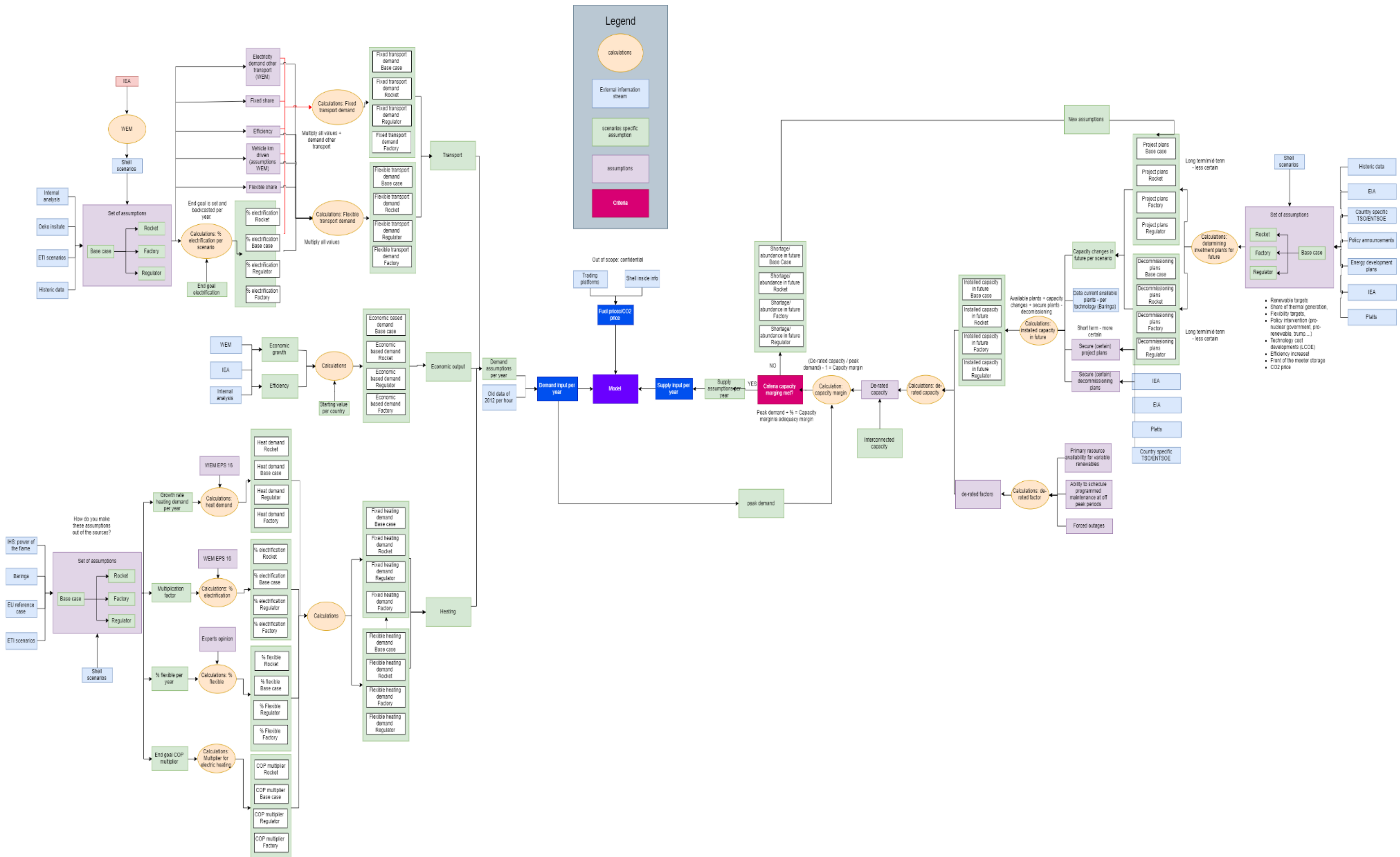
Within the second layer, four distinct worlds were qualitatively defined to explore different possible futures. For these narratives to be translated into quantitative scenarios, the *Industry specific fundamentals* need to be defined. The goal of defining this layer is to think about which factors influence the evolution of the relevant industry and helps to visualize the interdependency between these factors. Additionally, it provides the structure for how the qualitative scenarios were translated into the quantitative scenarios.

Outline flowchart

Within these scenarios, the evolution of the electricity market is thought to be influenced by three major factors: supply, demand and fuel prices. Given the confidential nature of future price views (e.g. price of gas, coal, oil and carbon) these are excluded from this thesis. Demand and supply are individually explored to indicate the factors influencing these sub-sets. The constructed flowchart can be seen in figure 5.9. Each factor is shortly discussed in the section that follows. At the end of each branch, different sources are indicated which were used to retrieve the required information to define a set of scenario-specific assumptions. As these are used to formulate layer 4, these will not be discussed here.

It should be noted that the flowchart can have many different forms like the one provided here, for example, it could have a more or less granular structure. This is the choice of the organization itself in which personal assumptions and interests are considered. The flowchart provided here is merely an example of how it could look like.

Figure 5.9: Flowchart – Industry specific fundamentals



5.3.3.1 Demand – Left side of flowchart

Demand is referred to as the electric energy consumption of the European power market, often provided on an hourly basis by public sources, such as ENTSO-E (ENTSO-E, n.d.). To formulate yearly demand until 2050 for each scenario, yearly demand changes are formulated based on scenario-specific assumptions. Data on current demand in Europe is available, adding the additional demand for each scenario provides the scenario-specific yearly total demand. The sub-set demand is thought to be influenced by three major factors: Transport, Heating and Economic. "Transport" is referred to road passenger transport; "Heating" as services and residential heating and "Economic" as heavy industry, which can include agriculture, rail passenger transport, rail freight transport, road freight transport, lighting & appliances, etc.

Before discussing the different factors, the terms flexible and fixed demand are shortly defined as the demand within the flowchart is divided into these sub-sets. An important criterion within the electricity system is that demand should always be satisfied (Schwenen, 2018). Conventionally, non-flexible generators provide baseload generation, while flexible generators are used to meet peaks in demand. The increased share of intermittent sources, such as wind and solar, requires more flexible generation or demand, as these sources produce when there is sun or wind and do not follow the pattern of demand. One solution for this increased difficulty in balancing is to increase the level of flexible demand. Flexible demand is referred to the ability to mitigate the use of electricity, in times of scarcity, to another point in time (e.g. charge your EV during the night instead of during the day). As flexibility is thought to play an important role in the future, sub-sets transport and heating are divided into fixed and flexible demand.

i. Section transport

As electrification of transport is happening and is likely to further increase, this could significantly influence demand for electricity. The increased demand for electricity resulting from the electrification of transport can be determined by looking at five different factors (% electrification per year, flexible/fixed share, vehicle km driven, efficiency and demand other transport). Adding these numbers will provide total demand from transport.

To calculate flexible demand, the following formula is used:

*Flexible transport demand = % electrification per year * Flexible share * (vehicle km driven * efficiency)*

Flexible transport demand refers to the amount of TWh of electricity that can be considered as flexible demand within transport. To say something about the yearly percentage of electrification within the different scenarios, a scenario-specific end goal for 2050 is defined. This is back casted to indicate the *% electrification per year* for a given scenario. The *flexible share* is the number of cars that can be charged in a "smart" way and can be adjusted to peak demand in order to reduce fluctuations. As the number of cars does not say anything about the amount of electricity used, these factors are multiplied with the average of *vehicle kilometers driven* and the amount of electricity needed (TWh) per billion kilometers (*efficiency*).

To calculate the fixed demand, the following formula is used:

*Fixed transport demand = % electrification per year * Fixed share * (vehicle km driven * efficiency) + demand other transport*

The only difference compared to flexible demand is *demand other transport*. This refers to the electricity demand from trains and trucks.

Important to note, within the flowchart some assumptions are scenario-specific while others are the same for every scenario.

ii. Section economic (electricity demand from industry activities)

Economic-based demand is electricity demand from industry activities. Economic based demand is calculated by determining the *economic growth* and *efficiency*. Multiplying the current demand from industry activities by the economic growth and efficiency each year gives the economic based demand per year.

iii. Section heating

Heating is another sector in which electrification is expected in the future. In total four factors need to be investigated before the fixed and flexible electricity demand for heating can be calculated. The formula for fixed and flexible demand is the same except for the percentage of (flexible/fixed) demand. The following formula is used:

*Flexible (Fixed) heating demand = (Heat demand * percentage electrification) / (COP multiplier * percentage flexible (Fixed))*

- *Heat demand* refers to the expected demand for heat, now and in the future. This value changes with a certain yearly scenario-specific growth rate. Multiplying the current heat demand with the growth rate per year gives the expected heat demand in the future.
- *Percentage electrification* within heating: refers to the % of electrified heating. As heating is expected to be increasingly electric, this percentage is thought to grow. This value is scenario-specific.
- *Coefficient of performance (COP) multiplier* refers to the efficiency of the system. The higher the coefficient the more efficient the system. Within all scenarios, the efficiency is expected to grow but to what extent is scenario-specific.
- *Percentage of flexible demand* discusses the amount of electrified heating that can be used in a "smart" way. This refers to the amount of electrified heating that can be shifted to another point in time when electricity is scarce.

5.3.3.2 Supply side – Right side of flowchart

Supply of electricity consists of all available electricity generators in a specific hour. To say something about how the supply side might evolve in the future, it is important to gain knowledge about the possible future project plans and decommissioning plans. Project plans refer to plans for building new electricity generators. Additionally, as plants are getting older, decommissioning might be needed. Moreover, as some scenarios will highlight renewable energy targets, decommissioning of power plants might be done before the end of their lifetime (i.e. coal phase-out). These project- and decommissioning plans are partly scenario-specific. Some plans are already announced and are relatively certain, these should be incorporated within all scenarios and can be seen as short-term plans. However, over a longer time period, scenario-specific plans will determine the generation mix. To understand how these plans might be derived for the different scenarios, a set of scenario-specific assumptions are provided based on the following subjects, each an input for formulating the scenarios:

- Renewable targets
- Share of thermal generation
- Flexibility targets
- Policy intervention (pro-nuclear, pro-renewable, denying climate change etc.)
- Technology development costs (LCOE)
- Efficiency increases per technology
- Front of the meter storage
- CO_2 price

From these assumptions, scenario-specific decommissioning and investment plans can be subtracted. This provides in-sight in scenario-specific capacity changes per technology. Together with the data about current available capacity, future scenario-specific installed capacity can be determined.

However, as the installed capacity does not provide full information about how much each plant is able to produce at a specific moment in time, it should be multiplied by the de-rated factor. The de-rated capacity is the average capacity available in a year and is plant and technology-specific. Additionally, as can be seen from the flowchart, another factor that influences de-rated capacity is the interconnectivity with other countries outside the countries of interest.

Using the de-rated capacity, a capacity margin can be calculated.

Capacity margin = (de-rated capacity / peak demand) -1

As stated at the beginning of this chapter, the power system must always be balanced in real-time. The de-rated capacity should, therefore, be a certain percentage above peak demand to secure supply i.e. capacity margin. This criterion must always be satisfied and is indicated in the flowchart. It must be checked if the criterion (e.g. capacity margin) is met with the indicated scenario-specific assumptions. If this is not the case it means that there is a capacity shortage or abundance in the future and the scenario-specific plans for decommissioning or investments should be altered. This process is therefore seen as iterative.

5.3.4 Layer 4 - Numbers

The flowchart from the previous layer provides us the structure to translate the narratives of the qualitative scenarios into quantitative scenarios. Layer 4 discusses these qualitative scenarios. These numbers not only represent macro- but also the micro perspectives of the relevant industry. As the numbers were already generated in 2016, it is especially important to indicate the source of the data used as an update would require checking whether the numbers are still plausible and relevant. Recording these sources provides the opportunity to easily retrieve historical data, gather updated data from the same source and check if the decisions made are still valid. The output of this layer is as follow:

- Numbers attached to flowchart, specific for each scenario.
- Sources used to formulate scenario-specific numbers (indicated in *Flowchart).*
- Scenario-specific assumptions.

Each sub-set (demand & supply) was individually explored using the sources indicated in the *Flowchart*. The sources used can consists of, for example, scenarios, forecasts from institutes or internal analysis. Using these sources, a set of scenario-specific assumptions was defined that were used as input for translating the qualitative scenarios into quantitative scenarios.

As this layer, consists of multiple thousands parameters (for example, every power plant existing within Europe), these are not provided within this thesis. However, to indicate how this layer could look like after defining, an example is provided within Appendix F. The example refers to the factor % electrification within *Demand - section transport* in figure 5.9. Within this example the sources used to formulate the numbers and outcome of the calculations is provided. As every organization has their own scenarios specific assumption and way of formulating these numbers it is of no use to go into high detail in this step.

Assumptions

All the numbers attached to the different factors discussed within the flowchart are based on different sources and personal opinion of the scenario generators (based on what is thought to be the best representation of the future). Therefore, all the numbers attached to the factors are seen as assumptions and should therefore be checked during an update.

5.4 Step 3 – Gather and evaluate external information

Having defined the different layers of the scenarios in the step 2, we have laid out the structure of the current scenarios before any alterations are performed. Within this step new information is retrieved as the external environment has changed. The retrieved information might highlight changes in assumptions as well as new uncertainties not yet considered within the scenarios. As this test case provides an example of how the proposed framework should be implemented, only a selection of changes are considered. One existing assumption (projection of installed solar PV capacity) and three new uncertainties are debated: nuclear fusion, hydrogen, and a German coal phase-out announcement. After retrieving information on the changing external environment, the information on the assumptions should be analyzed to indicate if a regular update suffices or if a trend is found which would require re-classification onto the impact-uncertainty matrix. The procedure of selecting the topics discussed was not a formal procedure. They were chosen as these topics were recent subjects of discussion and perfectly describe a classification in each layer. However, normally, it is not straightforward how to select the uncertainties that will be discussed during an update. Many things might have changed in the external environment and not all of them can be considered. This selection procedure is partly influenced by 1) the scenario boundary defined and 2) personal opinion of the scenario planners. This subject is out of scope within this thesis and will, therefore, be highlighted within Section 8.3, recommendations for further research. Important to understand is that for a normal update, other assumptions and relevant new developments may need to be considered.

5.4.1 Assumptions

There are many assumptions formulated within the different layers to make the scenarios a coherent whole. As over time new information becomes available, the assumptions can be evaluated if still being plausible and relevant. One assumption is chosen as an example to illustrate this process: evolution of installed capacity for solar PV. In each scenario a central view for solar PV installations in the second layer and a certain yearly percentage of solar PV in the generation mix for 2016 until 2050 in layer 4 was formulated. Within the section that follows, new information (since 2016) on the evolution of solar PV is discussed. These new insights will be used to evaluate the assumptions in made layer 4 to determine if a regular update suffices or a trends is found which require re-classification onto the impact uncertainty matrix.

Development costs solar PV 2016 – 2018 (World)

There has been a dramatic decline in costs from utility-scale solar PV over the last years which has continued to do so from 2016 – 2018. According to IRENA (2019, p.20), *"The sustained, dramatic decline in the cost of electricity from utility-scale solar PV continued in 2018, with a fall in the global weighted-average LCOE of solar PV to USD 0.085/kWh – 13% lower than for projects commissioned in 2017. This takes the decline between 2010 and 2018 in the global weighted-average LCOE of solar PV to 77%."* Additionally, over 94 GW of new capacity, worldwide, was added which was more than half of the total new renewable energy capacity. Within Europe, Germany expended their solar capacity with 4 GW. This is mainly due to the ongoing decline in cost of electricity from solar PV (Figure 5.10). However, within Germany, the LCOE of new utility solar PV has increased a bit (by 2%) in 2018, due to a slight increase in installation costs (IRENA, 2019).

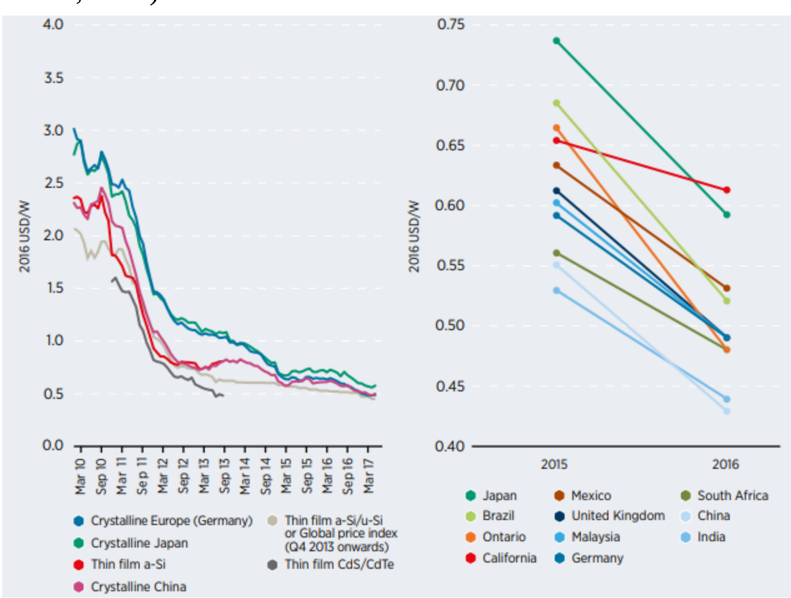


Figure 5.10: Average European solar PV prices by technology and country (Source: IRENA, 2019)

This rapid decline of solar PV costs was the largest among all clean technologies which made it a very attractive option. According to the IEA (2018), due to this increased competitiveness installed capacity of

PV will move past wind in 2025 and hydropower in 2030. However, the increasing prominence of this technology increases the importance of flexibility to secure electricity use (IEA, 2017).

Moreover, if we look at previous forecasts from the IEA, we can see that every year the IEA altered their view on global cumulative solar installations. This means that their expectations were significantly different than what they previously though would happen (Figure 5.11).

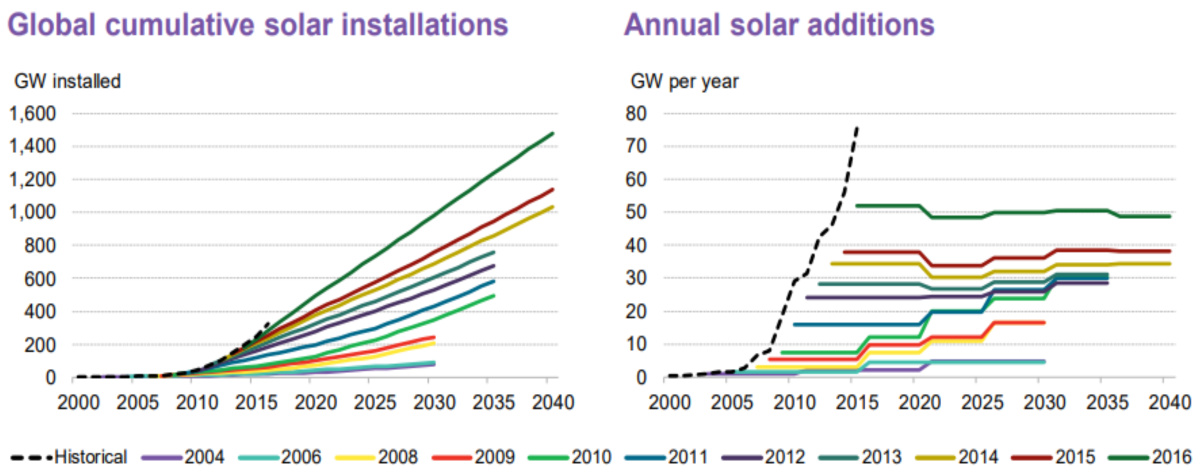


Figure 5.11: IEA solar capacity forecast evolution (Source: Liebreich, 2017)

Creutzig et al. (2017) confirm that the potential of solar energy has been systematically underestimated within energy scenarios. Indicating this underestimated growth of solar energy might be an example of a trend which would mean this uncertainty should be re-classified.

5.4.1.1 Analyze assumptions

The information on the assumptions is further analyzed to indicate if a regular update suffices or if the impact-uncertainty matrix is needed. The current assumptions on the amount of installed capacity for solar PV generated in 2016 can be seen in Appendix G. Using the retrieved information, we are able to indicate the difference between our assumptions and the actual values (table 5.4).

Table 5.4: Evaluating assumptions made with real values

Scenarios	Assumption made in 2016 for 2018	Actual values in 2018	%Difference
	GW total installed capacity European Union	GW	%
Base case	109.5	115.0[1]	5.0%
Rocket	116.5		-1.3%
Regulator	114.0		2.7%
Factory	107.5		7.0%

Table 5.4 clearly shows that the real values for GW installed solar PV capacity is closest to our *Rocket* case. Additionally, as the external information shows, the costs for solar PV have declined more rapidly than expected. These cost reductions influence the amount of installed capacity and could be an explanation for

[1] European Commission, 2019b

why the actual values are relatively high (*Rocket* scenario is high case). It is important to notice, that it does not matter if the real values are high or low, it is important that one of our scenarios is in line with the real values. This is exactly why we make multiple different perspectives and why we want to update our scenarios. It is the choice of the scenario generators if these values need alteration or if the "old" values are still in line with our current thinking. Given the above stated, and the fact that there are already large differences when only two years have passed, we have decided to update not only the values for 2018 but also alter the numbers in the future (until 2050), as most of our views are well under the actual values and we expect this rapid growth to continue in the future. This is, however, based on personal opinion and might differ from others. An additional point to note is that we have decided to alter our vision in the fourth layer but in line with the assumption made within our second layer. Over time, however, as these alterations continue in the future the second layer might need to be altered. Moreover, as we have seen a trend within the past years, underestimating the potential of solar PV (Creutzig et al., 2017), it is recommended to re-classify the uncertainty onto the impact-uncertainty matrix and show if any changes have occurred. This uncertainty is now considered in layer 2 and is still thought to be classified in layer 2. However, the assumptions made within this layer should be checked if still being plausible and valid. Currently, we have multiple different perspectives on how installed capacity for solar PV might evolve. After evaluating the assumptions made, they were still found plausible and relevant. Our *Base case* represents the situation in which the future looks a lot like today. Our *Rocket* case represents a high case regarding decarbonization and our *Regulator* case a world in which policies enable decarbonization. *Factory,* on the other hand, represents a low case. As we still want the *Rocket* and *Regulator* case to represent a "high case", the values in these scenarios will significantly increase, while the *Factory* case will represent a smaller increase.

The re-classification process is not discussed in detail here, as the process is similar to classifying the new uncertainties and does not add significant value in showing how the framework should be applied.

5.4.2 New uncertainties

As stated, the world is looking for new ways to provide clean energy as a consequence of our changing climate. Novel ideas are introduced or being developed. These developments are not yet part of our dominant technologies but may evolve to do so. In the section that follows multiple (new) developments are briefly discussed that are not (yet) considered within the scenarios. To understand what the impact of these uncertainties is, additional information should be retrieved. Within step 5, these uncertainties are classified according to its uncertainty and impact on the European electricity market based on expert opinion. This will highlight in which layer these uncertainties must be considered, if at all.

5.4.2.1 Nuclear fusion

Nuclear fusion is a chemical reaction in which two atoms react and produce one larger and one smaller atom. During the fusion, a large amount of energy is released according to the equation $E=mc^2$ (ITER, n.d.). If nuclear fusion becomes commercially viable it can provide limitless quantities of clean energy which will solve many of today's problems. Nuclear fusion is seen as a prominent source of energy, however, not yet a proven technology and according to the "European Roadmap to fusion" only possible in the long-term (at least after 2040) (EUROfusion, n.d.). It is, therefore, thought nuclear fusion will not be part of the energy transition but could provide the energy of the future.

5.4.2.2 Hydrogen

The increased demand for electricity in the future brings challenges for the grid. Electricity is currently the main energy carrier considering wind and solar energy. Balancing the grid can become an increasingly complex task with the intermittent character of these sources combined with the inability to store electricity at large scale (Schwenen, 2018). Hydrogen is an alternative energy carrier that can be produced out of water using electricity and can be stored in large quantities for long periods (European Commission, 2019a). This could help increase the flexibility of the energy system by balancing during abundance or deficits of power. Drivers for a transition to a hydrogen economy are combatting climate change, energy security, local air quality and competitiveness (McDowall & Eames, 2006).

Main applications

Hydrogen is already being used within the industry for a long period of time and this experience is now used to introduce hydrogen in civil situations (RVO, n.d.). Hydrogen is seen as a potential energy carrier to reach the climate goals set, especially on a longer time scale (Marchenko & Solomin, 2015). Hydrogen could help the following sectors to decarbonize which would otherwise be difficult to decarbonize through electrification (IRENA, 2018):

1. Industry
2. Transport
3. Heating of buildings

Hydrogen production

In total three main production methods are identified for hydrogen; green, blue and grey. Green hydrogen is seen as the emission-free method in which hydrogen is produced from water via electrolysis using electricity from renewable energy sources. Blue hydrogen refers to a climate-neutral method in which hydrogen is produced using natural gas where the released carbon is captured using carbon capture storage (CCS) (CE Delft, 2018). The most often used and least expensive method is grey hydrogen in which fossil fuels are used to generate hydrogen and is thereby also the most polluting method (Acar & Dincer, 2014).

Future hydrogen perspectives

Within the EU a hydrogen economy is already gradually developing. There are currently a numerable amount of hydrogen projects generating or implementing blue or green hydrogen, especially in Europe (New Energy Coalition & JIN Climate and Sustainability, 2019). The report, The Future of Hydrogen, prepared by the IEA (2019, p.13) for the G20 states: "*Clean hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. It concludes that now is the time to scale up technologies and bring down costs to allow hydrogen to become widely used."*

However, even though hydrogen investments are present there is a mixed view on the importance of hydrogen in the future. Dorian, Franssen, and Simbeck (2006) state that while hydrogen is attractive from an environmental point of view it is expensive to produce, transport, store and distribute and therefore requires a technological breakthrough for a hydrogen economy to emerge. Gambhir, Rogelj, Luderer, Few, and Napp (2019) found that in many scenarios, in which the goals set in the Paris agreement are reached, hydrogen is expected to play a small role. Others see a larger role for a hydrogen applications. The hydrogen council, the largest industry-led effort to develop a hydrogen economy, states that in 2050 hydrogen provides the possibility to contribute to a twenty percent reduction of the total CO_2 abatement compared to our current technologies (Hydrogen Council, 2017). Additionally, the International Renewable Energy Agency (IRENA) (2018) refers to hydrogen as the possible missing link in the energy transition.

Possible impact on electricity market

As the test case is about the electricity market in Europe, it is important to retrieve information on how hydrogen may influence the evolution of this electricity market. As stated, one of the main advantages of using hydrogen is the ability to transport over long distances and store on large scale, thereby, offering the opportunity to reduce losses over long-distance transport and balance the electricity grid during abundance or deficits (IRENA, 2018; PBL, 2011). Green hydrogen could, therefore, boost the use of solar and wind energy, allowing for increased electricity production. The hydrogen council (2017, p.10) even states that *"By 2030, 250 to 300 TWh of surplus renewable electricity could be stored in the form of hydrogen for use in other segments."* However, critique on a fully integrated market is the reduction of efficiency as losses occur when electricity is transformed into hydrogen and back (IEA, 2018; Shinnar, 2003). Besides the integration of the two economies, hydrogen is often also compared to electricity. Offer, Howey, Contestabile, Clague, and Brandon (2010) and Thomas (2009) provide some good insight on hydrogen compared to battery vehicles and have different points of views on which energy carrier should be preferred. If hydrogen is preferred it could mean that, when produced from fossil fuels, it would reduce demand for electricity. According to McDowall & Eames (2006), the adaption rate of hydrogen technologies is largely a function of their relative costs compared to alternative technologies and policy interventions.

However, all recognize that a hydrogen economy is still far away. Although the very positive view of the hydrogen council (2017), they indicate that to realize their vision, the infrastructure should be deployed, and manufacturing capacities should be scaled up to achieve cost reduction and mass-market acceptance. The IEA recognized that "great effort" is needed to realize a significant scale-up of hydrogen needs to be realized and is not going to happen without policy support for research as well as the creation of new market-based instruments (IEA, 2018).

5.4.2.3 Coal phase-out announcement Germany

To reach the goals set in the Paris agreement, countries must rapidly reduce their emissions. As coal is the most polluting fossil fuel, contributing a significant portion of total emissions, multiple European countries have announced the closure of their coal plants (Climate Action Network Europe, 2019). In June 2018, Germany appointed a coal commission that was tasked to propose an end date for coal usage. They presented that a complete coal phase-out should be finished at latest 2038 and is already possible by 2035. At the beginning of 2019, the government announced it will implement the recommendations presented by the end of 2019 or 2020. However, as the electricity produced from coal is significant, other options must be explored before the plants are closed (Agora Energiewende, 2019).

Possible impact on electricity market

While the announcement of a coal phase-out significantly reduces the uncertainty of a coal phase-out happening, there is still much uncertainty present surrounding the decisions on how and when this coal phase-out will be executed. The German government is aiming to implement the phase-out in 2019-2020, however, a single coal exit strategy is not yet determined. It is still uncertain if this start date will be met (Clean energy wire, 2019). Additionally, as demand should always be satisfied, alternatives for generating electricity is needed. The German government has announced that this deficit will mostly be provided by renewable energy: *"The decline of electricity generation from coal-fired power plants is to be replaced primarily through renewables by increasing the share of renewable electricity generation to 65 per cent of gross electricity consumption by 2030"* (Agora Energiewende, 2019, p. 5). However, the intermittent character of renewable energy sources opposes grid balancing problems and creates uncertainties on how demand is met in times when there is little wind or sun. Decommissioning of coal plants will only be performed if security of supply is met. Moreover, the decrease in coal and increase in renewable generation will influence the electricity prices. However, *how* the electricity price will be influenced is still uncertain. Lastly, as more countries announce the abandonment of coal, they might stimulate other countries to also commit to a phase-out. As all European countries of interest have already announced a coal phase-out this is not relevant in this test case, but it shows how uncertainty might develop over time.

5.4.3 Conclusions of gathering and analyzing external information

Within this test case, only a selection of changes is considered. For each change, it should be determined if a regular update suffices or if the impact-uncertainty matrix should be used to understand *if* and *how* they should be considered within the scenarios. As new uncertainties should always be classified onto the impact-uncertainty matrix only the information on installed solar PV capacity was further analyzed. There is a trend found but after further analysis, it was determined a regular update in layer 4 would fit. None of the findings were really shocking (in the eye of the scenario planner), therefore, adjusting the assumptions in layer 4 would suffice for the assumptions on this uncertainty to remain plausible and relevant. Within step 4 it is determined how the assumptions in layer 4 should be adjusted.

5.5 Step 4 - Adjust assumptions (regular update)

Within the previous step, we have decided to alter the *Numbers* for the different scenarios regarding the installed capacity for Solar PV. As the regular update is not the focus within this thesis, a brief example is provided on a possible way to update these numbers, using the external information retrieved and the analysis performed. A regular update incorporates adding the new data on top of the existing data. The numbers for the years 2016 – 2018 are, therefore, the same for each scenario as it is known for these years how much solar PV was installed. Additionally, the numbers for the years 2019 - 2050 are slightly altered according to the new insights and information gathered in step 3. Since our *Rocket* and *Regulator* scenarios represent our high view, these scenarios will have the largest increase while the *Factory* scenario has a small increase. The alterations can be found in Appendix H. It should be noted that the alterations are based on the personal assumptions of the author and can be different from others. This example is just provided to indicate how this process is structured.

Additionally, it should be considered that, because the factor installed capacity solar PV changes, other components of the scenarios might also be influenced. The flowchart provides a good structure to check which other factors may be influenced. As our demand is assumed to stay the same, there will be an excess of installed electricity in the future. An abundance of installed capacity is unwanted as some power plants will not make profit. In the long-term, the increase in solar PV will reduce the installed capacity of other generation technologies. Altering these factors would require additional research, however, is out of scope within this thesis.

5.6 Discussion of chapter 5 and introduction of chapter 6

This chapter has described step 1-4 within the framework, thereby, discussing the current structure of the scenarios, the changes that have happened within the external environment and how they should be treated during an update. By doing so, it has created a basis to indicate *if* and *how* an update should be performed. For each change, it was determined if a regular update suffices or classification onto the impact-uncertainty matrix was needed. Subsequently, it was briefly shown how a regular update, requiring minimal adjustments, is performed by altering the assumption on installed capacity solar PV (step 4). The following chapter will discuss the more radical changes, requiring classification onto the impact-uncertainty matrix (step 5) to determine how they should be considered within the different layers of the scenarios (step 6). This will not only highlight the scientific but also the societal contribution of the proposed framework.

6
Test case – part II
Incorporating new trends and uncertainties

The second part of the test case elaborates on step 5-7, discussing the more radical changes. It first elaborates on, *if* and *how* the indicated new uncertainties should be considered (step 5) and uses this information to incorporate the changing external environment into the scenarios (step 6). Subsequently, multiple ways to validate the changes made are discussed (step 7). Having demonstrated the different steps within the framework, validation of the test case is performed, thereby, highlighting the societal contribution. Finally, conclusions are drawn.

6.1 Step 5 – (Re-)Classify new uncertainties

In total three new uncertainties were further examined that might have an impact on the European electricity market. To determine *if* and *how* these uncertainties should be considered within the scenarios discussed, multiple power experts within Shell were asked to discuss how they would assess its uncertainty and impact on the European electricity market. The following section briefly discusses the outcome (figure 6.1).

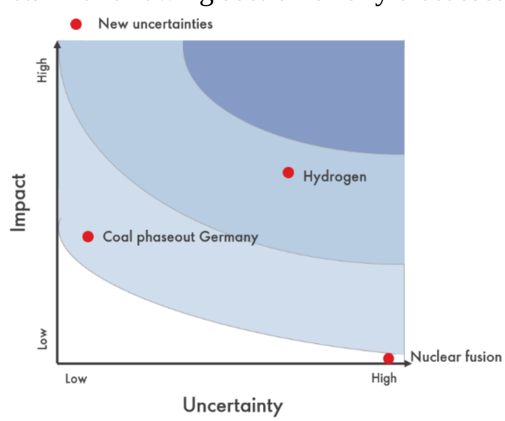


Figure 6.1: Matrix with new uncertainties classified

It should be noted that the position of the uncertainties on the matrixes is based on personal assumptions of experts and, therefore, might differ from the opinion of others. Within the conclusion section of this chapter, the process of classifying these uncertainties is elaborated on. Additionally, a section in chapter 7, discussion, is devoted to discussing this process.

Nuclear fusion

Nuclear fusion is not thought to play a role in the energy transition, therefore, its current impact on the electricity market is very low. Additionally, as nuclear fusion is not yet a proven technology, the range of possible evolutions is large. Therefore it is classified as very uncertain. Concluding, nuclear fusion will not be considered within any of the scenarios. However, in the future, this might change. During the next update, its impact and uncertainty need to be determined again to track its evolution. However, as the classification is both very low, its development is likely to be quite slow and not considered to have an imminent impact; hence its monitoring can be gradual.

Hydrogen

While the impact of hydrogen on the electricity market can, as stated in Section 5.3.1, be relatively high, there is no one answer on how hydrogen applications will evolve in the future. The uncertainty is, therefore, classified as medium-high while its impact on the electricity market is relatively high. As there are multiple methods to produce hydrogen, it is not only the question of *if* a hydrogen economy will emerge but also *how* this hydrogen will be produced. The purpose of taking hydrogen into account within the different scenarios is to discover multiple pathways hydrogen could take and how such a future will look like in order to deal with this uncertainty. Therefore, hydrogen should be considered within layer 2 (*Storylines).*

Coal phase-out Germany

The impact of a coal phase-out in Germany on the European electricity market is classified as medium while the uncertainty is relatively low. The reduction of coal plants within Germany is relatively certain, however, uncertainty surrounding, for example, the speed of the coal phase-out, the alternatives or consequences for the electricity prices remains. To mitigate the uncertainty surrounding the coal phase-out, it is important to take these into account within the different scenarios. Therefore, a coal phase-out in Germany should be considered within layer 3 (*Industry specific fundamentals).*

Note on timing: Over time, the uncertainty surrounding a coal phase-out in Germany has changed significantly. Before appointing the coal commission, a coal phase-out was still relatively uncertain. However, over time as plans have been developed, this uncertainty has significantly been reduced. As stated in Section 3.2.4, timing is important. A coal phase-out is a good example to indicate this importance. Seven years ago, a coal phase-out should maybe have been considered within one scenario, however, now it should be incorporated within all scenarios as the certainty of a coal phase-out happening is high, however, how and when is remains highly uncertain. Incorporating different coal phase-out pathways into the scenarios helps considering the implication of these pathways and imagine possible responses.

6.2 Step 6 – Adjust layers according to classification

As the goal of this test case is to provide a practical example of using the framework, it is helpful to show an example of considering changes into each layer. However, as no new critical uncertainties are indicated within this test case, an imaginary world provides an example for layer 1. Considering changes within the first layer requires to create an entirely new set of scenarios, which is out of the scope of the thesis and therefore will only be discussed briefly.

6.2.1 Example Layer 1 – Nuclear fusion becomes real

Within this example, we assume that nuclear fusion has become commercially available and is providing large quantities of energy. The example that is given here is purely imaginary and should be treated as such.

Today, nuclear fusion is not considered within our scenarios. Figure 6.2 presents the situation used in this example. In the year 2050 we might have altered our vision for nuclear fusion and consider it within one of the *Storylines*. If in the future, let's assume year 2100, nuclear fusion has become commercially available this will be considered within all scenarios as a basis. However, if nuclear fusion would be available on a large scale one could imagine the world looks different than today. Degree of decarbonization and government intervention might not be critical uncertainties anymore, but geopolitics and R&D might. Who has access to this technology and are countries willing to share energy at reasonable costs? How is the relationship between different countries? Our entire energy system might have to be redesigned, and flexibility issues might not be an issue anymore. Additionally, *if* this type of energy is only being produced in certain places, efficiency losses due to long-distance transport might be a problem. Technological improvements might become more important and more focus is being placed on R&D.

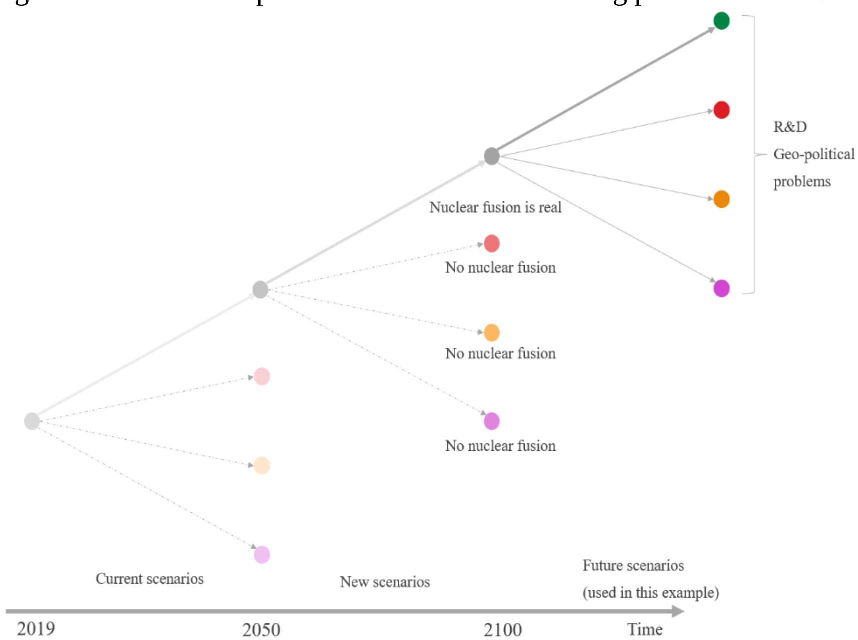


Figure 6.2: Example of future scenario developments over time

The most stringent problems discussed now, might not be relevant anymore. Therefore, changing the basis of our scenarios (layer 1). An example of two possible new critical uncertainties is shown in figure 6.3.

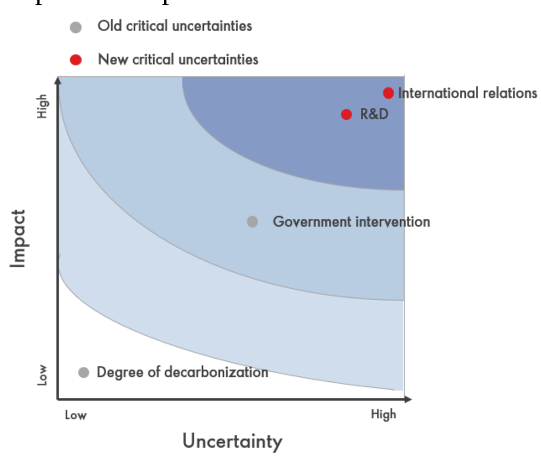


Figure 6.3: Example new critical uncertainties

Therefore, an entirely new set of scenarios need to be developed to address the new pressing issues and mitigate for their uncertainty. During the generation of these scenarios, it is recommended to distinguish the different layers immediately as this would save time at a later stage.

It should be noted that new critical uncertainties evolve slowly over time. For example, the issues raised by climate change were not introduced into our society over a short period of time but took years to enter the political agenda. Before this world would become a reality, many changes would have already occurred. This highlights the importance of tracking changes over time. If a certain trend is developing, it might be important to pay additional attention to this development to understand how it might develop in the future.

6.2.2 Example Layer 2 - Incorporating hydrogen

Hydrogen should be incorporated within the second layer of the scenarios and, therefore, changes the storylines. It is not the question if we will use hydrogen, but how "big" it will be, how we will generate it, and where we are going to use it (industry, heating or transport). Moreover, as the second layer changes, the third and fourth layer also need additional analysis.

6.2.2.1 Adjusting layer 2

As hydrogen is only a small part of the entire storylines, the part that is added to the existing storylines is discussed below. These storylines are constructed using the external information retrieved and fitted into the different worlds the scenarios represent.

Rocket

Due to the large increase of intermittent solar and wind, exploring options to use hydrogen for balancing the grid has grown. From 2030, there is a steady increase of green hydrogen use as a result of sharp cost reductions due to technical improvement and cheap electricity from renewables (lower cost of production). Additionally, efficiency (from transforming electricity to hydrogen and back) has improved which increases the attractiveness of using green hydrogen. Especially within the heavy-weight transport sector the use of hydrogen increases, as this is more efficient than electric vehicles. Due to this increased use of green hydrogen, electricity demand increases. However, as hydrogen is less stimulated by the government than within *Regulator,* hydrogen will take a slower introduction into the market.

Base case

Due to the advantages of hydrogen to balance the grid, there is a slight increase in hydrogen use, however, not enough to push down costs to make it available on large scale. Hydrogen is mostly produced using cheap gas. Within industry blue hydrogen is stimulated over grey hydrogen to reduce pollution, but only after 2040. Additionally, there are multiple small initiatives, driven by real business cases, that finds market share, however, without any real impact (e.g. forklifts that use hydrogen). Therefore, no large-scale projects are realized. The government stimulates the use of hydrogen attempting to improve security of supply and environmental sustainability but due to large costs and lacking efficiency a hydrogen economy does emerge.

Factory

Due to the lack of government support and decarbonization low on agenda, hydrogen is not explored extensively. Off-grid small scale hydrogen is used as an initiative to store electricity produced from solar panels, however, large investments, to push down costs are lacking. While grey hydrogen is increasingly being used within the industry (as this infrastructure is already largely in place), the government tries to stimulate blue hydrogen to push down emissions but fails in doing. Main barriers to implementations of green hydrogen are large sunk investments needed and efficiency losses.

Regulator

Due to large increase of intermittent energy sources and strong government intervention, hydrogen will be steadily adopted on large scale from 2030 (with significant share in 2040), therefore, cost of hydrogen has decreased steadily. Large investments are done mainly due to government support which gave a boost to infrastructure and made large scale movement of hydrogen possible. As of the large increase in the use of hydrogen, from 2030 blue and sometimes grey hydrogen is used, however, due to environmental pressure, the use of green hydrogen increases rapidly and replaces grey hydrogen completely.

Assumptions

Additionally, multiple scenario-specific assumptions are formulated and shown in table 6.1.

Table 6.1: Scenario-specific assumption for hydrogen - layer 2

Scenario		Base case	Rocket	Factory	Regulator
Category	Sub-category				
Supply	Total hydrogen	Small growth	Medium growth 2030 after which large growth	Small growth	Large growth
	Green hydrogen	Small growth (mainly within industry but only after 2035)	From 2030 medium growth after which high growth from 2040	No growth	High growth after 2040
	Blue hydrogen	Medium increase from 2035	Small increase from 2030	Small increase	Steady increase from 2030
	Grey hydrogen	Small increase	Large decrease from 2035	Small increase	Small increase in 2030 but large decrease around 2035
Efficiency	Green hydrogen	Small improvements	Large efficiency improvements	Small improvements	Delayed efficiency improvements

6.2.2.2 Adjusting layer 3

As hydrogen is considered within the second layer, it also influences the third layer. Updating the third layer discusses the question of which factors are influenced by introducing hydrogen into the market. The sub-sets demand & supply both require attention by introducing hydrogen into the scenarios. Increased usage of green hydrogen can boost electricity demand. Consequently, this increase in electricity must be produced which affects the supply side. However, if grey and blue hydrogen production increases, electricity demand might slightly reduce. The flowchart provides us with the structure of the steps that need to be performed and are briefly elaborated on in the section below.

1. Demand side

As the demand side provides an input criterion for the supply side, this side is first examined. The question that must be asked when looking at the demand side of the flowchart is what the impact of hydrogen can be on the demand for electricity. This will depend on the extent to which a hydrogen economy emerges and how this hydrogen will be produced. Following the flowchart, demand is divided into three different factors that will be discussed separately regarding the question of how hydrogen might impact these factors.

1.1 Transport – section i.(figure 5.9)

To understand how demand for electricity from the transport sector might be influenced by introducing hydrogen, we must look at the six factors influencing electricity demand from transport. As only a brief literature search is executed on the possible development and influence of hydrogen, during a real update additional information must be gathered. The influence of hydrogen on the factors that together from electricity demand from transport will be briefly discussed:

1) *% Electrification end goal 2050.* As stated in Section 5.4.2.2, hydrogen may increase electricity demand in two different ways. First, hydrogen provides the ability to balance the grid, therefore, an increase in renewable energy sources is possible without balancing problems. Secondly, if hydrogen is produced in a green way, demand might also increase. Both reasons might influence the path towards the *percentage of electrification end goal 2050*. The growth of electricity demand by hydrogen might increase the pace of electrification. However, this factor is scenario-specific and therefore depends on how the scenario depicts a hydrogen economy. A scenario in which grey hydrogen is extensively used, the percentage of electrification might even slightly reduce as it steals some market share of electricity.
2) *Vehicle km driven* is not necessarily influenced by the amount of hydrogen used, nonetheless, an abundance of very cheap hydrogen may lead to an increase in the amount of km driven. However, this effect is not considered here.
3) *Demand other transport* refers to the electricity demand from trains and trucks. The external information has shown that hydrogen is especially thought to have an impact on long-range heavy weight transport (e.g. trucks and trains), as the efficiency of this types of transport is thought to be higher for hydrogen-powered transport compared to electric-powered vehicles. It might, therefore, compete or be complementary to electric powered vehicle. When produced using green hydrogen, demand might increase while blue or grey hydrogen might reduce electricity consumption within this sector. In Section 6.4.2.3, adjusting layer 4, changes in electricity demand from trains when considering hydrogen into the scenarios, is used as an example to indicate how this process is structured.
4) *Flexible and fixed share* refers to the percentage of transport that can be flexible charged. It is argued that less flexibility within the system is needed if a hydrogen economy emerges. However, this is only the case if green hydrogen is used. The percentage of flexibility is therefore not influenced when hydrogen is introduced, but the need for this flexibility is. Therefore, the need for flexibility when introducing hydrogen becomes a scenario-specific factor.
5) *Efficiency:* in TWh/billion kilometers driven, refers to the amount of electricity used within BEV. This factor is therefore not influenced by introducing hydrogen.

1.2 Economic output – section ii (figure 5.9)

Two factors are influencing electricity demand from the industry (e.g. economic output): economic growth and efficiency. Grey hydrogen already plays a significant role within many industrial processes; oil refineries, chemical manufacturing and steel production (IEA, 2018). The IEA states (WEO, 2018, p.407) that within the industry, hydrogen is extensively being used for ammonia production and *"Switching from natural gas to electrolysis for around 5% of global ammonia production creates 110 TWh of additional electricity demand."* Electricity demand from this factor might, therefore, significantly be influenced when green hydrogen is used. To what extent these factors might be influenced within the different scenarios would require extensive research and out of scope within this research.

1.3 Heating – section iii. (figure 5.9)

The flowchart indicates that electricity demand from heating is influenced by four scenario-specific factors:

1) *Growth rate heating demand:* The demand for heat itself is not influenced by hydrogen as the amount of heat needed will stay the same when hydrogen is introduced.
2) *% Electrification* refers to the percentage of heat generated by electricity. Hydrogen can be used to heat houses via a fuel cell. As the usage of green hydrogen to heat houses is indirectly provided by electricity, green hydrogen might boost the amount of electricity used for heating. However, if hydrogen is produced using grey or blue hydrogen this might reduce the amount of electrification. Additionally, an easy way of reducing the amount of gas used is injecting hydrogen into the gas grid. *"A 20% blend of hydrogen in the European natural gas grid today would reduce CO_2 emissions by around 60 Mt (a 7% reduction)"* (IEA, 2018, p.69). This is a quick way of reducing emission and could delay the electrification within the heating sector (IRENA, 2018). However, if a larger percentage of hydrogen is added, alteration behind the door need to be performed and is unwanted. Moreover, using only hydrogen to heat houses without producing it back to electricity is not thought to be economically feasible (M. Oostveen, personal communication, 1 August).
3) *% flexible per year*. A key advantage of this so-called "power-to-hydrogen" over electricity is the fact that hydrogen can be stored on large scale, which enables the system to cope with large swings in demand as well as allowing for inter-seasonal storage to meet seasonal demand peaks (e. g. heat in winter) (IRENA, 2018). This means that there is a reduced need for flexibility and could therefore lower the % flexibility needed. However, it will not influence the % of flexibility within the system.
4) *End goal COP multiplier* refers to the efficiency of the system. As heating using hydrogen will be used via a fuel cell (transforming it back to electricity), there will be a significant loss of power and therefore lowers the efficiency of the system. This is not yet considered within the goal COP and could, therefore, change if hydrogen would be extensively used for heating.

2. Supply side

The sub-set Supply might be influenced in two different ways when introducing hydrogen into the scenarios: (1) change in demand (which requires a change in supply) and (2) allowing more intermittent energy source to be built. Both options are discussed using the structure of the flowchart.

1) If the change in demand is significant, capacity margin will not be met, resulting in a shortage (in case of increasing electricity demand) or abundance (in case when hydrogen competes with electricity for market share). Based on this shortage or abundance, new project or decommissioning plans must be determined. To do this, the set of scenarios specific assumptions must be reviewed using external information to understand the possible influence of hydrogen on these assumptions. For example, depending on the scenario, decommissioning plans might be delayed (e.g. coal and gas plants are used to generate hydrogen), while in a scenario with high pressure for decarbonization more renewable project might be introduced. These plans influence the future installed capacity and using the de-rated capacity factor, capacity margin can be calculated and looked upon if being met. If this is not met, iteration is important and new assumptions must be formulated.
2) As hydrogen provides the ability to balance the grid, additional investments in renewables are possible without balancing problems. In a scenario in which hydrogen does not become significant, not much will change, however, within a scenario in which green hydrogen rapidly increases the supply side might change significantly. Decommissioning plans of carbon-intensive plants might become possible in an earlier stage and provide more room for solar and wind (long/ mid-term plans). An example would be a scenario in which coal is phased out faster than normal and replaced by renewable energy sources. As hydrogen will only take place in a medium time-space (next decade). Secure project plans will not change. Alterations in project and decommissioning plans will also change the installed capacity within the future. Therefore, it must be checked if capacity margin is still met. Otherwise, additional project or decommissioning plans need to be defined.

6.2.2.3 Adjusting layer 4

The fourth layer translates the qualitative scenarios into the quantitative scenarios using the structure of the flowchart. The question that will be answered here is to what extent hydrogen influences the factors discussed in layer 3. Due to time constraints, extensive research to provide reasonable numbers for all factors discussed in the previous section is not possible. Therefore, one factor is chosen as an example to illustrate this process. The factor that is more closely examined is “demand other transport.” This refers to the electricity demand from trains and trucks. However, within this example we will only look how hydrogen might influence electricity demand from trains. To mitigate for the uncertainty, we will differentiate its impact between the scenarios. Electricity demand from trains is chosen as an example as the literature on this topic was manageable in the limited amount of time. Nonetheless, the process for other factors is the same, however, more time needs to be spend to retrieve external information.

First, as the example refers to the transport sector, a short introduction is provided on how hydrogen might influence this sector and how hydrogen might influence electricity demand from trains. Secondly, current numbers within the scenario for electricity demand from trains is briefly discussed. Lastly, the numbers are updated to take hydrogen into account.

Influence of hydrogen on transport

Vehicles fueled by hydrogen, fuel cell electric vehicles (FCEVs), are a low-carbon mobility option when fueled with hydrogen produced from renewables (IRENA, 2018). Recent study by the hydrogen council (2017) has shown that FCEVs could complement Battery Electric Vehicles (BEVs) to achieve large decarbonization in all segments of transportation. The hydrogen council (2017, p.8) even states that in 2050 *"more than 400 million cars, 15 to 20 million truck and around 5 million busses"* could be powered by hydrogen. FCEV's are thought to have a larger impact on long-range heavy weight transportation, e.g. trucks, buses, trains, aviation and ferry boats. This segment also has a large share in abatement and could therefore benefit immensely from decarbonization: "*While trucks and buses would account for only 5% of all FCEVs in 2050, they could achieve more than 30% of hydrogen's total CO_2 abatement potential in the transport sector" (*Hydrogen council, 2017 p.9). Therefore, in this perspective, they can expand the scope of electric mobility by providing advantages where today's batteries face limitations (IRENA, 2018). According research by IRENA (2018) each segment has clear advantages or disadvantages for either FCEVs or BEVs (figure 6.4).

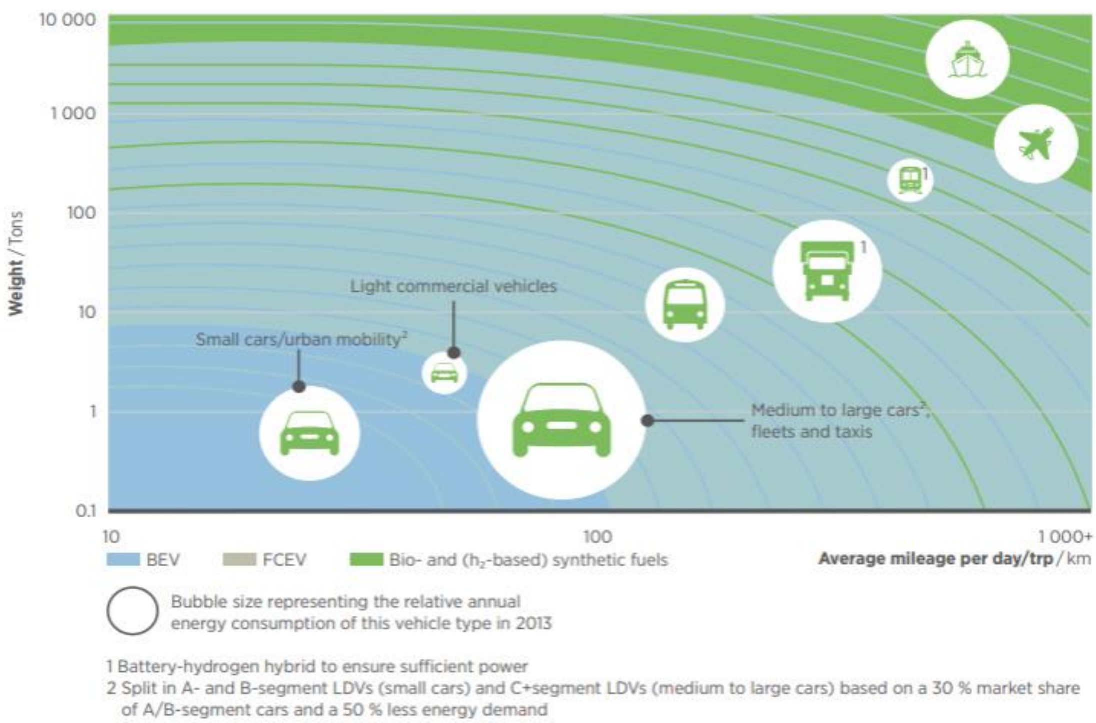


Figure 6.4: Advantages FCEVs and BEVs per source (Source: IRENA, 2018)

Figure 6.4 shows BEVs have the largest advantages in small to medium light commercial vehicles that travel smaller distances, while FCEV could provide an advantage for more heavyweight long distances. IRENA (2018) states that FCES might even be the most commercial option in the long term as it can combine the flexibility of hydrogen with the higher efficiency of BEVs. Today FCEV busses, medium-sized cars and forklifts are already commercially available and within the coming years trucks, vans and trains will likely to be added (Hydrogen Council, 2017).

Influence of hydrogen on electricity demand from trains

The question within this example refers to how hydrogen might influence the electricity demand for trains in Europe. To answer this question, a brief outline of different prospects is provided. Thereafter, the update number will be provided.

Hydrogen powered trains - prospects

Hydrogen powered trains are an attractive alternative for diesel powered trains, especially on non-electrified railways (roughly 55.000 locomotives in the US and Europe today) (hydrogen council, 2017). Hydrogen is able to match the performance of diesel trains and is the preferred fuel choice for long range transport as recharging batteries on long drives is not optimal and refuelling time is short (Hardy & Harner, 2018). Additionally, hydrogen is preferred on currently non-electric railways as electrification would require large capital expenses for new overhead wires (IRENA, 2018; Hydrogen Council, 2017). Northern-Germany was first to introduce hydrogen powered passenger trains at the beginning of September 2018, and other countries have similar plans (IRENA, 2018). The UK has announced it wants to phase-out all diesel trains by 2050 (Hardy & Harner, 2018) and the France government has said it wants to have the first hydrogen train by 2022 (The Guardian, 2018). For hydrogen trains to be developed on a large scale, technical improvements are needed and are likely to become available on a commercial scale in the next five years (Hydrogen Council, 2017). The hydrogen council (2017) estimated that by 2050 around 20% of the trains could be driving on hydrogen with a commercial increase from around 2030. As this increase is realized for currently non-electric railways, hydrogen could be additional to the electrification of trains, thereby, increase decarbonization. When produced in a green way, this could therefore increase electricity demand.

Current numbers

Before performing any alternation, the current prospect of electricity demand from trains without incorporating hydrogen into the scenarios should be provided. Since these are confidential these are not provided here. However, as hydrogen trains would complement to electric trains, the additional demand from hydrogen trains should be added to our current view.

Updating the numbers

From the research executed, we know that hydrogen fueled trains have a high potential in non-electric railway with a commercial increase around 2030 (Hydrogen Council, 2017). It is thought not to compete with electricity but might complement electrified trains, therefore, resulting in a boost for electricity demand if produced using renewables. The updated numbers would therefore be an addition to our current view. As can be seen from figure 6.4, the market for hydrogen within the train sector is relatively small. To calculate how much electricity demand is additionally generated, we use the information retrieved and the storylines from the scenarios to formulate the percentage of total trains power by green hydrogen (table 6.2).

Table 6.2: Scenario-specific assumption on % of trains power by green hydrogen

% of trains fueled by green hydrogen								
Scenario	2016	2020	2025	2030	2035	2040	2045	2050
Base case	0%	0%	0%	0%	1%	2%	3%	5%
Rocket	0%	0%	0%	1%	4%	6%	11%	16%
Regulator	0%	0%	0%	2%	5%	8%	15%	20%
Factory	0%	0%	0%	0%	0%	0%	0%	0%

Within the *Regulator* scenarios, hydrogen is thought to play the most significant role, therefore, has a 20% hydrogen powered trains in 2050 (Hydrogen Council, 2017). The *Factory* scenario is the opposite as within this scenario a hydrogen economy will not emerge, therefore, in 2050 the percentage of hydrogen trains will be zero. The *Base case* and *Rocket* scenario are in between those extremes. *Rocket* is thought to also have a (relatively) high share of hydrogen, while within the *Base case* the percentage in 2050 is still low.

To calculate the effect of hydrogen powered trains on the electricity demand, the following formula is used:

*Additional electricity demand from hydrogen trains = (% of trains fueled by green hydrogen * (total km driven by trains * hydrogen usage per km * kWh of electricity per kg h2 production)) / 1000*

The following data is used to calculate additional electricity demand from hydrogen powered trains.

Table 6.3: Additional information to calculate electricity demand from hydrogen trains

Total Km driven by train[2]	
in million	
Belgium	59
Denmark	63
France	260
Germany	573
Netherlands	116
UK	371
Total	**1442**

kWh of electricity per kg H2 [3]		Comments
2017	54	Average taken
2030-2050	45	

hydrogen usage [4] [5]		Comment
kg hydrogen per km		For lightweight or passenger transport
2018	0.3	
2030-2050	0.25	

Using the values provided in table 6.4 and the formula indicated. The additional total electricity demand from hydrogen for each scenario is calculated and shown in table 6.4.

Table 6.4: Additional electricity demand from hydrogen power trains

Additional electricity demand from hydrogen powered trains								TWh
	2016	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base case	0.00	0.00	0.00	0.00	0.00	0.16	0.49	0.81
Rocket	0.00	0.00	0.00	0.16	0.65	0.97	1.78	2.60
Regulator	0.00	0.00	0.00	0.32	0.81	1.30	2.43	3.24
Factory	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[2] European Rail Research Advisory Council, 2016
[3] IRENA, 2018
[4] Shirres, 2018
[5] Roland Berger, 2019

The outcome provides us with the additional electricity generation from trains when introducing hydrogen and can be viewed in Appendix I. The influence of hydrogen on the total electricity demand from trains is small in all scenarios. However, this was expected as the literature search already indicated a small market for hydrogen trains as many trains are already electric. As these numbers are complementary to our previous view they should be added to our current view of electricity demand from trains to provide the final updated numbers.

Within this example, only one factor in the entire flowchart is investigated. However, during a real update, every factor should be closely examined. To do this the same procedure applies. It should be noted that although much external information is required, the information required can often be used from the same data sources. Therefore, it would take significantly less time to investigate how hydrogen influences other factors.

6.2.3 Example Layer 3 - Incorporating a German coal phase-out

As a coal phase-out in Germany should be considered within the third layer, the first and second layer not require any changes. However, it should be noted that assumptions on phasing out coal in Europe are already incorporated within the second layer as there are assumptions on whether a coal phase-out in the EU might happen, and if so, at what speed. However, the example here only refers to the German coal market and is therefore only incorporated in the 3^{rd} layer. As this is an additional example of how the framework could be applied, this example will be less extensive than the hydrogen example.

6.2.3.1 Adjusting Layer 3

A coal phase-out only influences the supply side of the electricity prices. Therefore, we should take a closer look at the right side of the flowchart (figure 5.9).

As a coal phase-out is not an event happening at one point in time but may take multiple decades to fully be executed, we have to distinguish between short- and medium/long-term plans. As the uncertainty of a coal phase-out happening in the near future is significantly reduced by the German coal commission's announcing to phase-out coal, we can alter the secure (certain) decommissioning- and project plans. Some coal plants, which are at the end of their lifetime, might be decommissioned earlier or new project plans might be cancelled. These short-term plans will be the same for all scenario. However, as these plans influence the amount of installed capacity, this will also affect the de-rated capacity. As capacity margin is calculated using the de-rated capacity, the capacity margin may not be met, and additional plans need to be built to make sure there is enough de-rated capacity to satisfy future peak demand. As it is unclear how this capacity will be replaced and to what extent, alternative new built capacity might therefore differ between the scenarios.

Additionally, when we move further in time, increased uncertainty around the coal phase-out arises and the speed of phasing out coal might differ between the scenarios (e.g. long- and medium-term project and decommissioning plans will change and are scenario-specific). New assumptions should be formulated, on how fast decommissioning of coal might happen and what type of plans will overcome scarcity of electricity. As Germany has announced it wishes to replace coal primarily with renewables, *"65% of gross electricity consumption by 2030"* (Agora Energiewende, 2019, p. 5), this might be difficult to reach while meeting security of supply and providing energy at an affordable price. This uncertainty must be represented within the different scenarios. Within the *Rocket* case, for example, the renewable share is met or even a higher percentage will be reached. Within the *Factory* case, a delayed coal phase-out might happen or some coal plants might not be phased out.

6.2.3.2 Adjusting Layer 4

Within this layer we, quantitatively, distinguish between the different scenario to indicate how fast coal is phase-out and what technologies will replace the deficit in capacity. The secure decommissioning plans on the short term will be the same, however, the decommissioning plans on the long-term are scenario-specific. Depending on the speed of decommissioning, if decommissioning even happens, other project plans will be made to meet the capacity margin.

As stated, at the end of 2019 beginning 2020, new project plans might be cancelled and (certain) decommissioning plans might be announced. Additional information should be retrieved to look at what the possible plans in the short-term are. Moreover, to differentiate between the different scenarios, the speed of decommissioning should be altered depending on the storylines the scenarios represent. Again, information should be retrieved to provide plausible numbers. Additionally, to make sure the plans are viable, it is important to run the model to check if electricity prices are within a certain acceptable range. If this is not the case, additional technologies to generate electricity should be determined. This will be a scenario-specific decision. In the *Factory* scenario, fossil fuels might be the cheapest alternative while in the *Rocket* case CO_2 prices might be high and renewable energy might be the better alternative.

6.3 Step 7 – Validation and Iteration

Performing an update changes the scenarios, content-wise and relatively from each other. It is, therefore, important that after an update, these scenarios are again validated according to the validation criteria. The goal of this validation is to make sure each scenario still provides a plausible and relevant view while being consistent. As a complete update is not executed within this test case, validation is difficult as this would require looking at the updated scenarios as a whole. In the section that follows, therefore, multiple options for validation will be discussed.

1. *Compare scenarios with other sources*

Within this test case, an example of changing assumptions on the installed capacity of solar PV was provided. To validate our changes made we use the IEA scenarios made in 2016 and their updated view in 2018. This is only one, among many, of the scenarios that discuss assumptions on the installed capacity of solar PV. Normally many scenarios should be used for validation, however, this scenario is chosen as an example to show how this process might be structured. The numbers for installed capacity in 2016 (figures left) and 2018 (figures right) are shown below.

As can be seen from the data, the IEA also significantly increased the installed capacity of solar PV within all scenarios. Additionally, within their New policies scenario (blue graph), the assumptions made in 2016 compared to the view in 2018 on installed capacity for solar PV in 2040, is increased by 51.8%, while their "low" case (current policies scenario) is only increased with 38.4% and their "high" case (450 scenario) with 62.6%. This is in line with our alterations as we also increase our "high" case with a higher percentage than our "low" case.

	Electrical capacity (GW)					
	2014	2020	2025	2030	2035	2040
Total capacity	985	1 066	1 123	1 176	1 228	1 265
Coal	177	169	147	114	83	70
Oil	58	39	29	19	15	12
Gas	212	226	259	292	324	338
Nuclear	129	121	105	103	104	102
Hydro	151	157	161	166	169	171
Bioenergy	40	45	49	51	54	55
Wind	129	186	230	271	303	326
Geothermal	1	1	1	2	2	3
Solar PV	87	118	136	150	160	166
CSP	2	2	3	5	7	9
Marine	0	1	1	3	7	13

Figure 6.5: Total capacity Europe Union new policies scenarios WEO 2016 (Source: IEA, 2016)

	Power generation capacity (GW)					
	2016	2017e	2025	2030	2035	2040
Total capacity	1 024	1 040	1 151	1 266	1 295	1 320
Coal	173	170	121	84	55	43
Oil	51	50	27	20	16	12
Gas	217	217	247	272	280	284
Nuclear	127	125	105	90	89	89
Renewables	455	478	649	794	845	877
Hydro	154	155	160	165	169	171
Bioenergy	42	44	55	60	62	64
Wind	154	169	255	329	354	367
Geothermal	1	1	1	1	2	2
Solar PV	101	107	175	232	247	252
CSP	2	2	3	4	5	7
Marine	0	0	1	2	6	13

Figure 6.6: Total capacity Europe Union new policy scenario WEO 2018 (Source: IEA, 2018)

	Electrical capacity (GW)					
	2020	2030	2040	2020	2030	2040
	Current Policies Scenario			450 Scenario		
Total capacity	1 064	1 171	1 275	1 060	1 181	1 312
Coal	172	129	95	164	98	55
Oil	39	19	12	38	18	11
Gas	229	329	411	219	255	272
Nuclear	121	97	89	125	123	125
Hydro	157	165	170	157	169	176
Bioenergy	45	50	53	45	53	60
Wind	183	241	282	187	292	381
Geothermal	1	1	2	1	2	4
Solar PV	114	134	146	120	161	195
CSP	2	4	8	2	7	15
Marine	0	2	7	1	4	19

Figure 6.7: Total capacity Europe Union current policy and 450 scenarios WEO 2016 (Source: IEA, 2016)

	Power generation capacity (GW)					
	2025	2030	2040	2025	2030	2040
	Current Policies			Sustainable Development		
Total capacity	1 150	1 182	1 259	1 162	1 280	1 478
Coal	139	111	74	103	60	27
Oil	27	20	12	25	18	12
Gas	253	280	319	232	240	263
Nuclear	105	94	93	108	112	115
Renewables	622	667	739	691	841	1 034
Hydro	160	163	168	162	168	175
Bioenergy	53	55	58	58	64	72
Wind	241	267	298	273	350	439
Geothermal	1	1	2	1	2	3
Solar PV	165	176	202	193	250	317
CSP	3	3	6	3	5	12
Marine	0	1	6	1	3	16

Figure 6.8: Total capacity Europe Union current policy and 450 scenarios WEO 2018 (Source: IEA, 2018)

2. Plot updated scenarios onto Framework after performing an update

Each scenario should provide new insights to ensure they are not a different version of the same story. Before performing any alterations, the different scenarios were plotted onto the *Framework* indicating the differences between the scenarios regarding the critical uncertainties. After performing an update, the scenarios might have changed relatively from each other. Plotting the scenarios again onto the *Framework* visualizes how they differ from each other after performing an update. If they moved too close to each other, it might be an indication to alter one of the storylines to create a new, relevant view. However, the definition of "too" close is based on the opinion of the scenario generators.

3. Check if lower layers still represent layers above

As the proposed framework suggests that changes can be incorporated into lower layers, leaving the higher layers unchanged, it is important to check if the lower layers still represent the view within the higher layers after performing alterations. An example related to the test case is the coal phase-out in Germany. Within the *Storylines* (layer 2) assumption are made on the evolution of coal within the European electricity market ranging from actively phasing out coal to not actively phasing out coal. Within the test case changes were made within the third and fourth layer, leaving the second layer unchanged. However, since all countries of interest have announced a coal phase-out, the uncertainty regarding not actively phasing coal out becomes smaller. As currently many countries have only announced a coal phase-out and not yet started the process, there is still uncertainty of a coal phase-out actually happening, however, it reduces the plausibility of this specific assumptions actually happening (see figure 4.4). During the next update when more information is available, alteration of the second layer might be needed. This highlights the findings of Geels (2002); lower layers might influence higher layers over time. When updating the fourth layer, it might be possible it does not represent our view within the second layer. It should therefore be validated if this is still the case.

4. *Run model*

Running the model and evaluating the outcome is an important part of the validation process. This will provide insight into how the input parameter (partly provided by the scenarios) play out. This could highlight specific unwanted situations such as an extremely high increase in power prices. If the outcome of the model indicates such problems, the scenarios require additional alterations and iteration is needed.

The above-mentioned methods are only a couple of examples of possible validation steps. Many organizations have their own way of validating. Therefore, it is important to mention the importance of this step but no additional research is provided here. If after validation, the scenarios do not provide a plausible and relevant view or are not consistent, iteration is needed, and the scenarios should be adjusted.

6.4 Validation of executed test case

Lastly, the executed test case was validated by experts of the Strategy & Portfolio team within Shell who have themselves executed multiple scenario updates. It was debated if the executed test case was done correctly by discussing each step and its outcome. Although the specifics of the update (e.g. scenario-specific assumptions for solar PV or percentage of trains fueled by green hydrogen within each scenario) might have been different if the update was executed by other people, it was concluded that the individual steps within the test case were executed correctly. Additionally, it was decided that communicating the changes made was simple, as the tools within the framework justified choices made on how the different uncertainties were considered. Formulating the layers and using the impact-uncertainty matrix to indicate in which layer the uncertainty must be considered, visualized and simplified the executed process. Moreover, the indicated interdependency between the layers gave a general understanding of how the incorporated changes influenced the rest of the scenarios.

Subsequently, the literature study showed there is currently no methodological process for executing a scenario update. Van Vuuren et al. (2010) stress the importance of differentiating between parts within the scenario when performing an update. However, currently no division is made between different parts within a scenario. Additionally, the literature clearly makes a distinction between changes and how they are considered within scenarios, however, fail to address how they execute this assessment. Nonetheless, multiple scenarios updates have been performed without the use of a framework. To highlight the difference in executing an update with and without using the proposed framework, it was debated how the experts would have executed the update (without using the framework). Additionally, it was questioned if they would change their process using the dynamic scenario framework knowing how it performs in practice. The insights generated highlights the societal contribution of the thesis and will therefore shortly be discussed. The experts pointed out that updating the numbers of the scenario-specific assumptions on solar PV, in this test case referred to as performing a regular update (route 3-4-7), would have been executed in a similar fashion. First, gathering information on the changes of this specific assumption, thereafter, updating the values by adding the known information from past years which are the same for all scenarios. Additionally, the experts indicated they might have debated altering the values for coming years, the same procedure as within the test case. However, for the new uncertainties discussed, not yet considered within the scenarios, the process would be quite different. The experts indicated that for these uncertainties new scenarios would need to be generated. Nevertheless, as this would require a substantial amount of time, it was likely the process of incorporating these new uncertainties would have been put on hold until more radical changes have occurred, which would then require an entirely new set of scenarios to be generated. This highlights that within the current process, there is no option for incorporating new trends and uncertainties into the already generated scenarios.

The above stated indicate that performing a regular update, requiring minimal adjustments, would have been executed in a similar fashion. However, new trends and uncertainties would not have been incorporated and, therefore, reduces the usefulness of scenarios for making strategic decisions. The lower route within the framework (step 3-5-6-7), incorporating new trends and uncertainties, is non-existing in the current process. The framework, therefore, adds much value as it provides a structured way in incorporating these changes. Subsequently, the experts indicate that the process of executing a regular update is relatively simple, but as there is currently no structured procedure, it makes the process time-consuming and difficult to communicate. The experts have, therefore, indicated that it would be very helpful to have a structured process for executing a regular update *and* a way to incorporate new trends and uncertainties. Moreover, it was highlighted that dividing the scenarios into different layers would provide easy communication on what the scenarios constitute and how incorporating changes influences the rest of the scenarios, as this was currently a difficult discussion. The ideas presented are novel and could therefore add much value when performing an update. The Strategy & Portfolio team within Shell has indicated to change their current updating process using the dynamic scenario framework, as they see the added value of using the steps proposed. They thereby highlight the societal relevance of using the proposed framework.

6.5 Conclusion

The goal of this test case was to illustrate the dynamic scenario framework in a practical context. The conclusion discusses how successful the framework is in structurally incorporating new information and uncertainties into scenarios by judging the process of executing this test case. In the beginning, it was argued a structured process would increase time-efficiency, provide a common language for incorporating changes and would make the process more transparent. Additionally, it would reduce some of the complexity of the process. Therefore, these criteria are used to evaluate the process. Subsequently, the opinion of the experts was used to indicate additional benefits or uncover any of its limitations.

Overall benefits

The framework aims to offer the user a tool that helps think about how changes could be incorporated within scenarios in a structured way and what the impact of these changes are for the rest of your scenario. Without the framework, I would not have been able to update parts of the scenarios in this limited amount of time. I was able to perform an update in small reasonable steps as I understood how changing small parts would affect the rest of my scenario. For example, updating the electricity demand for trains was now done in isolation, however, knowing it influences electricity demand from transport. I was able to investigate the flowchart and see what information was required and what needed to be done. Additionally, the interdependency between the layers was clearly indicated and reminded me to also structurally change the other layers. During the test case, multiple advantages of using this framework were identified and are elaborated on below.

Structured way of understanding the current scenarios

Within this test case the scenarios used were generated in 2016. When I received information on the scenarios, it was very difficult to imagine how all this information was linked. There was limited information available on how the different scenarios were generated and how they were structured. This made it especially difficult to imagine how everything was connected. This highlights the difficulty in communicating these scenarios with external people (people who did not generate the scenarios). It was difficult understanding how these different scenarios were organized, however, by understanding there were multiple layers to be distinguished, a structure is provided for understanding these scenarios. Additionally, by defining these different layers, it became apparent how the entire scenarios are structured and what information was currently missing to perform an update. Moreover, by reminding what the characteristics of each layer were, it was easy to see what information should be incorporated within which layer.

Update some small components or entire view

Most of the time, updates would require changing some components in the lower layers referred to as a regular update (step 3-4-7). However, as discussed, over time the assumptions within higher layer might also change. This framework forces you to think about these small and radical changes, and how they impact the rest of your scenario. As the framework focusses on changed assumptions, identifying trends and new uncertainties, it helps to subtract useful information from the gathered data. Moreover, it provides a structured way of incorporating these changes.

Understanding the interdependencies within and between the scenarios

When performing an update, it is important to understand what the interdependencies are within and between the scenarios. By defining every layer, it does not only become apparent what the differences and similarities are between the scenarios but also what the structure is within a single scenario. This highlights the importance of when an update is performed, if one factor changes, other factors might also be influenced. Defining the entire structure of the scenarios remind the updater of this interdependency.

Use of impact-uncertainty matrix provides useful tool

The use of the impact-uncertainty matrix and its link to the different scenarios, provides a good structure to solve a difficult question: what is the influence of considering these uncertainties on the scenarios? Using the impact-uncertainty matrix and linking it to the different layers within the scenario, therefore, reduces some of the complexity of the process. Because of the link, it provides a structure in understanding how these changes might influence the scenarios. The value of this links was also highlighted by the experts as they currently have no process of incorporating new trends and uncertainties into the scenarios.

More time-efficient

As executing an update is a complex process, discussion on *if* and *how* changes need to be incorporated can be time-consuming. Using the framework proposed, this discussion is already partly structured and will therefore take less time. Additionally, as changing one factor influences other factors it takes time to understand which other factors are influenced when incorporating changes. Using this framework, it is immediately clear which other factors might be influenced. Especially the flowchart provides a good overview of which factors to focus. Of course, experts within this market will know what to change, but it saves time and makes sure no factors are forgotten. Subsequently, as some changes are suggested to be incorporated within the lower layers, it saves time reviewing every layer. This could be seen when incorporating the German coal phase-out. As this was incorporated within layer 3, we did not have to worry about changing the first and second layer. However, it must be validated if the lower layers still represent the top layers after incorporating changes. The same argument is made for updating the assumptions. The assumptions changed in the fourth layer do not immediately influence the second layer. Moreover, the framework also provides a structured way to determine if changes should be excluded from the scenarios.

Reduces complexity of the process

By providing a step-by-step process of performing an update, the complexity of such a process is reduced. As the complexity of performing an update is high, standardization is preferred as it allows the user to structurally think how to consider changes, thereby reduce possible failures. Moreover, using the framework, updating the scenarios can be divided into multiple smaller steps while maintaining overview.

Increases transparency of the process

One of the main results of the test case is that the framework increases the transparency of the updating process. Scenarios are formulated to understand the uncertainty surrounding the future and to use these insights for strategic decisions. As the people updating and formulating scenarios are often different than the ones making decisions from its outcome, communication of changes made is important. Making the process easy to understand, simple and logic, was therefore one of the objectives when generating the framework. The framework has created a common language for incorporating new information and uncertainty, thereby, improves communication. It was easy to explain which steps had been performed and why certain choices were made, as the steps are clearly indicated, and these choices were made using the tools described. Using the framework, the updating process becomes explainable and transparent. The framework, therefore, not only reduces some of the complexity of the update but also increases transparency of the process, thereby, making it easier to communicate to the outside world.

Overall improvement points

Additionally, the executed test case uncovered some of the limitation of the framework. Some points for improvements have, therefore, been identified and will shortly be elaborated on in the section below.

Classifying changes on impact-uncertainty matrix

When classifying changes onto the impact-uncertainty matrix, it was shown the opinions of the experts were not uniform. The classification represents the importance of a subject in the eye of these scenarios planners and is therefore subjected to opinion. As this is an important part of identifying in which layer the change should be incorporated, additional attention on this topic is provided in the discussion.

Acquiring information still very time-consuming

An important step within the framework is to retrieve external information. Retrieving this information was very time-consuming and sometimes difficult. Due to the abundance of information it can sometimes be difficult to understand what information is important and what not. During a normal update, organizations often use the same sources as used to generate the scenarios. This was during this update not possible and retrieving information was, therefore, more time-consuming. Additionally, many information was retrieved to understand the possible evolution of hydrogen in the transport sector. Within the test case only the parts discussing the electricity from trains was elaborated on as the other components were not considered. However, these sources could also be used to update other factors in the transport sector, which would save significant amount of time.

Not completely clear how to check if the changes in layer 4 still represent layer 2

It is important to check, after the changes incorporated layer 4, if this layer still represents the top layers. After performing this update, it was checked if the 2nd layer still represents the lower layers correctly. As this was only checked for one factor, it was easy to execute. However, if many changes are incorporated is can become more difficult which is currently not tested.

Lack of information to use framework

Additionally, when scenarios are generated, it is often not registered which sources are used to formulate the different assumptions and how conclusions are drawn. Generating the different layers, it was sometimes difficult to understand how certain assumptions were formulated as some information was never documented. It was therefore a difficult and time-consuming process to visualize and describe the different layers. However, this also highlights the need to have a structure.

7
Discussion

This chapter provides a critical review of the results of the thesis. At first, a discussion is provided on the main findings from this research. Secondly, the implications of the results for academia are elaborated on by discussing the main scientific contributions. Thirdly, societal contributions are highlighted and finally, a reflection on the research limitations is provided.

7.1 Discussion of main results

7.1.1 Use of impact-uncertainty matrix

One of the main findings of this thesis was that the nature of the change influences how an update should be performed. The literature clearly makes a distinction between different changes and how they are included into scenarios, however, fails to address how this assessment is executed (IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010). This research gap was addressed by using the impact-uncertainty matrix to classify changes, which is an important part of the proposed solution. However, the choice for this tool has several implications that require attention:

1) *How an update is performed is highly dependent on how one categorizes uncertainties onto the impact-uncertainty matrix.* Classifying changes with a specific impact and uncertainty level is subjective in nature. While performing the test case, it became clear that there were different opinions regarding the classification of uncertainties. Depending on the views of the people classifying the uncertainties, the resulting update is therefore performed differently. One could argue that on the one hand, using this tool provides structure in the way an update is performed but on the other hand the differing opinions, by which uncertainties can be classified, can highly influence how an update is performed. The question, however, is whether this should be considered a limitation. An update that requires several people will always be influenced by their views and opinions regardless of whether the impact-uncertainty matrix is used or not. While the matrix provides a tool to structurally translate these views, it does not provide a means to reach consensus in the way uncertainties should be classified and hence how an update should be performed.
2) *Difficult to assign a certain impact and uncertainty level*. Following point 1), the opinions on the level of impact and uncertainty assigned to an issue may not be uniform. It might be that people have many different opinions and do not agree with the same classification. It is important to note that a perfect prediction of the amount of impact and uncertainty would mean foreseeing the future and is therefore not possible. However, it may be important to indicate some criteria to help steer the discussion. For example, if the size of the market on which the uncertainty has an impact is small, the impact on the

entire industry might also be small. Pillkahn (2008), argues that there is a lack of suitable criteria for identifying differences between changes. Further studies need to be carried out to establish what these criteria could be.

3) *Strict classification in one layer is required.* The impact-uncertainty matrix, as it has been proposed, does not allow the possibility for an uncertainty to be classified in between two layers. A strict decision must be made on whether an uncertainty should be in one layer or another. Yet this decision might not always be so clear. If an uncertainty is classified between the first and second layer, this will not result in an issue, as only the two most critical uncertainties are considered within the first layer and the rest is considered within the *Storylines*. However, if an uncertainty is indicated on the lines between the second and third layer or the third and fourth layer, it is not immediately clear what should be done. To overcome this problem, one could reverse the process and look at the specific characteristics of the scenario layers and indicate in which layer the characteristics of the uncertainty fits best. The uncertainty has specific characteristics which might fit more accurately in a specific layer than others. For example, if an uncertainty is classified in between layer 2 and 3, but the uncertainty resembles a long-term trend, it might be important to incorporate it into the second layer as the uncertainty surrounding this trend can be mitigated between the different scenarios.
4) *Impact-uncertainty matrix may not be the only suitable tool.* Classifying change is not a new subject within the scenario generation literature and multiple tools have been developed to structure this process (Amer et al., 2013; Benedict, 2017; Cardoso et al., 2014; Pillkahn, 2008). The impact uncertainty-matrix was chosen as this is the most often used tool to indicate critical uncertainties and therefore well-known. It is simple to use and has the ability to visualize the consequences of classifying the issue with a certain impact and uncertainty. However, the impact-uncertainty matrix may not be the only suitable tool for classifying changes and directing them to the different layers indicated.
5) *The validity of one-to-one link with scenario layers.* Within this research, a one-to-one link is suggested from the impact-uncertainty matrix to indicate in which layers the issue needs to be considered. However, the question might arise if this one-to-one link is always valid. This link was made based on literature (Krueger et al., 2001; Van Vuuren et al., 2010) and the characteristics of the layers defined (Geels, 2002) and was validated during experts' interviews (Prof. Dr. D. van Vuuren, personal communication, 28 June 2019; Prof. Dr. G.J. Kramer, personal communication, 1 July 2019; Dr. O. Edelenbosch, personal conversation, 3 July 2019). The lines within the matrix provide a *suggestion* onto which layer the changes need to be incorporated and should not be seen as conclusive. It provides a tool to structurally think how the uncertainties impact the scenarios. However, as the situations discussed within an update refer to the future, testing all possible situation is impossible. It might happen scenario planners classify an uncertainty onto the matrix but do not agree with the assigned layer. During the test case, such a situation has not occurred, and it has provided a good tool to translate the opinions surrounding an uncertainty into a suggestion *if* and *how* they should be considered within the scenarios. However, as stated, not all situations can be tested, and exceptions might be possible.

7.1.2 Alternative flowchart

Besides the implication of the choice for the impact-uncertainty matrix, the choice for the proposed 7 steps within the framework also requires attention. Many other options are possible to execute an update and many options were discussed. One of the main objectives when generating this framework was the ability to increase the transparency of the process, by making the steps simple and logical. The main line of thought when generating the framework was therefore the following: if an update is performed in a structured manner, first, it is important to understand its current condition (step 1 & 2). Thereafter, understand what has changed in the external environment or in other words, why an update needs to be performed and how this must be executed (step 3). Subsequently, performing the actual update using the information from the previous steps (step 4-6) and, finally, validating (step 7). Using this general line of thought, however, still many variations are possible.

Within all the options discussed, define scenarios boundary (step 1), define scenario layers (step 2), gather external information (step 3) and validation (step 7) were the same. However, there was many variation between step 4 – 6. The most important alternative is shortly discussed below, as the rest of the variations were all very similar. The main difference within this alternative is that adjusting the layers (step 4 and 6) are taken together, without changing the assumptions within the scenario first (figure 7.1).

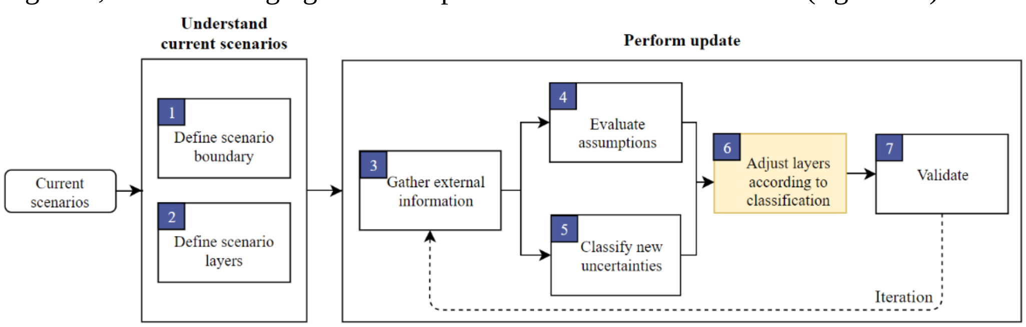


Figure 7.1: Alternative option dynamic scenario framework

Within step 3 only information is gathered. Step 4 and 5 discusses the question *if* and *how* an update should be executed. This alternative is more time-efficient, as adjusting the layers is only done once. Within the proposed framework (figure 4.1), the assumptions are first adjusted within step 4 but might also be influenced when new uncertainties are incorporated into the scenarios. Although the framework shown in figure 7.1 could save time, it also increases the complexity within the process. When taking new uncertainties into account you have to consider how they influence the existing assumptions within the current scenarios, but at the same time also understand that these assumptions itself might be outdated and require changes. For people who are familiar with updating scenarios, the above-provided alternative might be less time-consuming and a more convenient option. However, as the main goal is to increase transparency within the process, the reduction of complexity is chosen over time-efficiency. The framework proposed, figure 4.1, is therefore influenced by the personal opinion of the author. It is important to note that there is no definitive procedure for updating scenarios and it is not suggested that the framework presented is the only “right” methodological approach possible. It should be seen as a tool to help structure the complex process of updating scenarios, thereby, reducing some of its complexity.

7.1.3 Application of the framework to all kinds of scenarios

Another point that requires attention is the fact that the process of performing an update, using the framework, is still very "open". The framework is used to guide the process of keeping scenarios up-to-date, but the outcome of the individual steps and finally the update highly depends on the current set of scenarios and the people executing the update. Executing an update can be very complex. It might therefore be argued that such a general framework is of no value for updating scenarios with high complexity. However, during the interview with Prof. Dr. D. van Vuuren, 28 June 2019, he indicated that such a framework would be valuable during an update of scenarios with high complexity. Prof. Dr D. van Vuuren is one of the owners of the IMAGE model, developed to understand the long-term environmental changes based on human activities and is seen as a highly complex model (PBL, 2014). He indicated that the general line of thought (e.g. small parts might require an update leaving the general view untouched) is still valid for complex scenarios. Executing an update by incorporating new information and uncertainties might be different depending on the complexity within the scenarios, however, the thinking process of determining *if* and, in general lines, *how* an update should be executed is the same. Therefore, it is argued the framework has values for different kinds of scenarios, including complex scenarios.

7.2 Implication of results for the academic world - scientific contribution

This thesis has made four important scientific contributions: (1) it presents a critical review on how scenarios are currently kept up-to-date, (2) it recognizes that scenarios can be split into multiple layers, (3) it links the impact-uncertainty matrix to a specific layer within scenarios, and (4) it has created a novel framework to structurally incorporate new information and uncertainty into scenarios. Each contribution is briefly discussed:

1) *Present critical review on how scenarios are currently kept up-to-date.* This thesis has executed a literature study on how scenarios are currently kept-up-to-date, with the objective to clearly indicate its current state-of-art. Despite the importance of keeping scenarios up-to-date, the search of literature revealed that few studies go into detail on how an update might be executed (IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010). By analyzing and subtracting the underlying assumptions presented in these studies, two important factors were identified that influenced how an update should be performed: (1) the build-up of the current scenarios, and (2) the nature of the change being considered. These factors have provided a basis to structurally incorporate new information and uncertainties into scenarios and are not yet explicitly stated or addressed in literature.
2) *It recognizes that scenarios can be split into multiple layers.* As argued throughout the thesis, scenarios consist of multiple layers. The existence of different layers within a scenario is implicitly indicated by the process of transforming the qualitative scenarios into quantitative scenarios (Chermack et al., 2001; IPCC, 2005), and the fact that an update can be performed by altering some parameters within the scenarios without changing the high-level storylines (Van Vuuren et al., 2010). However, these layers have never been explicitly defined and is therefore novel; contributing to science. There are multiple

advantages of defining this multi-layered structured within scenarios. At first, it provides a common language for what a scenario constitutes. By acknowledging the differences within a single scenario and explicitly defining the layers, it provides a tool for communication. Secondly, defining the layers indicate the current structure of the scenarios and provide a good overview to understand the relation between the different components. It thereby increases the transparency of what a scenario is and reduces some of the complexity in understanding these increasingly multifaceted scenarios. When incorporating changes, it will help to understand the consequences for the rest of the scenario.

3) *It links the impact-uncertainty matrix to a specific layer within scenarios.* During an update, the nature of the change will influence how scenarios are affected. Currently, no tool exists for understanding which changes affect the scenarios in what way, even though literature indicates that it is crucial in trying to understand future situations (Benedict, 2017; Pillkahn, 2008). This thesis has proposed to link the impact-uncertainty matrix to the different layers proposed. The novelty, therefore, lies in combining different ideas and theories presented. The link from the matrix to the scenarios forces scenario planners to think about the consequences of the indicated issues for their scenarios, thus contributing to scientific knowledge on how to keep scenarios up-to-date. Additionally, it provides a structure to incorporate new trends and uncertainties, a process that is currently missing within existing updates.
4) *It creates a framework to structurally incorporating new information and uncertainties into scenarios.* Lastly, the framework proposed to structurally incorporate new information and uncertainties into scenarios for them to stay up-to-date is novel. Presenting this and its implementation is the main contribution of this thesis. Multiple highly-regarded energy scenario experts have confirmed the scientific value of this work (Prof. Dr. D. van Vuuren; Prof. Dr. GJ Kramer, Dr. O. Edelenbosch). Prior studies have noted the importance of keeping scenarios up-to-date (Creutzig et al., 2017; IEA, 2014; Leggett et al., 1992; Van Vuuren & O'Neill, 2006; Van Vuuren et al., 2010), however, in reviewing the literature, no single study was found that discussed a structured process of executing an update. This study has successfully developed a framework to structurally incorporate new information and uncertainties. Using the framework allows the complexity of the update to be revealed in a step-by-step process. Additionally, it increases transparency by creating a common language. Not only for understanding the structure of scenarios but also *if* and *how* changes should be incorporated within scenarios and the ability to update small steps while maintaining overview and understanding how these changes affected the rest of the scenarios. Moreover, as highlighted by the experts within Shell, there was no method for incorporating new trends and uncertainties. The framework provides a structured way of executing this process, using the impact-uncertainty matrix and the different layers defined, in order to properly update scenarios, guaranteeing the insights generated remain realistic and useful.

7.3 Implication of results for society – societal contribution

Within the MSc CoSEM, focus is on designing solutions for complex socio-technical problems. The presented framework therefore not only has a scientific, but also a societal contribution. The societal contribution of this thesis is threefold.

First, one of the main results of the test case is that the framework increases the transparency of what a scenario is and the process of keeping scenarios up-to-date. Scenarios are formulated to understand the uncertainty surrounding the future and are used to create insights for strategic decisions. As the people updating and formulating scenarios are often different than the ones making strategic decisions, correctly communicating any changes made is important. Making the updating process easy to understand, simple and logical, was therefore one of the objectives when generating the framework. Using the framework, the updating process becomes explainable and transparent on why certain choices are made. The framework therefore not only reduces some of the complexity of the update but also increases the ability to communicate to the outside world.

Secondly, as stated within Section 6.4, validation of the executed test case, a regular update (step 3-4-7), would have been executed in a similar fashion. However, new trends and uncertainties would not have been incorporated and, therefore, reduces the usefulness of scenarios for making strategic decisions. Proposing a methodological approach to incorporate these new uncertainties not only reminds the scenario planners these changes should be analyzed, but also provides a way to incorporate these new trends and uncertainties without the need to generate new scenarios. Additionally, the framework proposes a structured procedure for executing a regular update making the process more time-efficient and improves the ability to communicate. The Strategy & Portfolio team within Shell has indicated to change their current updating process using the dynamic scenario framework, as they see the added value of using the steps proposed.

Lastly, the European Union is in the process of minimizing the emission of greenhouse gasses (Erbach, 2016). The energy transition requires power markets to be decarbonized (reducing greenhouse gas emissions) while being affordable (at low cost to the consumer) and reliable (provide security of supply). To achieve this, large investments are needed in renewable energy at the lowest cost possible while making sure that there is enough capacity to meet the demand during system peaks. Using scenarios helps consider potential implications of different events and imagine possible responses to these events. However, due to the fast-changing environment, these scenarios become outdated which reduces their ability to guide the investment process. The framework within this thesis help to structure the process of keeping scenarios up-to-date, helping to contribute to increased insight for strategic and political decisions, and thereby drive forward the energy transition.

7.4 Limitations of research

This executed research has several limitations that require attention. At first, due to resource and time constraints, an entire update was not executed. It is therefore difficult to assess the complete value of using the framework. Although the main objective was to illustrate how the framework could be used in practice, which was not significantly affected by the simplification, executing an entire update using the framework is recommended. One of the advantages is the increased transparency and ability to keep overview while updating small parts of the scenario, thereby, reducing some of the complexity of the updating process. A complete update could reveal additional value of using the framework, as the increased understanding of the interdependencies between and within the scenarios might reduce more complexity than currently indicated. However, a complete update might also uncover new limitations currently not specified. Within the test case only one assumption was evaluated and adjusted, this would require other assumptions to also be checked. Due to time constraints, checking other assumptions was not possible. This resulted in a lack of insight into how the increased transparency helps to understand the impact of these changes for the rest of your scenario. Moreover, validation of the changes made could not be executed. However, as the validation process is often organizational specific there was no added value of executing this process.

Secondly, the framework was applied to a specific market (power market). As the framework is argued to apply to scenarios discussing other section of the energy industry, the generalizability of the results is currently unchecked. Therefore, no generic scientific conclusions can be drawn based on the main results. Nonetheless, the test case has indicated some important benefits that are thought to be generic. To evaluate the framework and its application for other markets, updates using the proposed framework in other industries should be executed.

Thirdly, one of the main benefits of using this framework was the ability to check the evolution of changes over time and is provided by adding a 3^{rd} dimension to the impact-uncertainty matrix. During each update, the uncertainties should be re-evaluated, thereby, following the path of each uncertainty over time which could lead to early detection of trends. Visualizing how these uncertainties evolve increases insight into the possible future. However, during this thesis, no substantial time has passed for trends to evolve. Therefore, the ability to track changes over time using the 3^{rd} dimension was not checked. An improvement would, therefore, be to execute an update over a significant amount of time to validate the ability to track changes over time.

Fourthly, the conclusions of using the framework were indicated by discussing the personal experience of the updating process during the test case. However, as the author had no previous practical experience in updating scenarios, it can be questioned how valuable this judgment is. Nonetheless, the author did gain much knowledge by reading about how the updating process is currently executed within academia and practice, additionally, by talking to multiple experts (within Shell, energy consultants, and academia) who have performed multiple scenario updates. It is therefore argued the author did have enough knowledge to judge the updating process. Additionally, the test case was also validated by multiple experts within Shell.

Finally, validating the framework is mainly done by Shell employees. They might have a specific view of what a scenario is and how the energy market is structured. This might bias the final version of the framework. However, the main outline of the framework was also evaluated during the expert interviews. It is, therefore, argued that the general line of thought within the framework is not influenced by the possible bias of Shell employees. However, the final outline of the framework might be influenced by the specific lens Shell employees look at the energy industry.

Notwithstanding these limitations, the study provides a good overview of how scenarios can be structurally kept up-to-date by addressing all research gaps indicated.

8
Conclusion & Recommendation

In conclusion, we return to the original aspiration behind the dynamic scenario framework, namely, to understand how a scenario update can be structurally performed. Scenarios play an important role in understanding the uncertainty and complexity surrounding the future. For scenarios to be used as a basis for today's policy and investment choices, it is critical for these scenarios to remain plausible and relevant. This can be done by incorporating new information and uncertainties. However, due to the increasing complexity of scenarios, this process also increased in complexity. To reduce some of this complexity, a methodological process to incorporate these changes is therefore highly valuable.

This research has successfully developed a framework to structurally incorporate new information and new uncertainties into scenarios. This allows these scenarios to be kept up-to-date, guaranteeing their plausibility and relevance. The outcome of this research therefore has the potential to play an important role in the updating process of scenarios as it reduces some of the complexity and increases transparency. This chapter revisits the four sub-questions and their results. This is used to answer the main research question: *How to structurally incorporate new information and uncertainties into scenarios, keeping them up-to-date, guaranteeing that the scenarios remain realistic and useful?* Lastly, the research is viewed from a broader perspective and recommendations for further research are elaborated on.

8.1 Research conclusions

Sub-question 1: *How are scenarios currently kept up-to-date?*

This sub-question was answered by means of academic literature and interviews with experts. Prior studies have noticed the importance of keeping scenarios up-to-date (IEA, 2014; Leggett et al., 1992; Van Vuuren et al., 2010). Nonetheless, no stepwise process was found to structurally incorporate the external environment. The results of the literature review do, however, identify important factors influencing how an update should be performed. It was concluded that within a scenario a more long-term macro perspective, qualitative in nature, and a more short-term focused (macro and micro) perspectives, quantitative in nature, is present. Due to this difference, these qualitative and quantitative parts will be differently influenced by the changing external environment. However, currently, no explicit distinction is made between these different layers within a scenario. Secondly, the literature clearly makes a distinction between changes and how they are considered within scenarios. It was, therefore, concluded that the nature of the change influences how scenarios are affected when incorporating these changes. However, no tool was found to assess which changes need to be considered and how they should be considered. Taken together, these findings lay a foundation for the rest of the thesis.

Sub-question 2: *What are important factors that need to be considered if you want to structurally incorporate new information and uncertainties?*

Based on the findings in the literature review, it is concluded that to configure a solution, two concepts need to be introduced, namely; (1) a scenario consists of a multi-layered structure, each having own characteristics and (2) changes considered should be classified according to their impact and uncertainty, as the nature of the change influences how the scenarios are affected. Based on this classification, changes should be incorporated into the different layers distinguished within scenarios. First, scenarios were divided into four distinct layers: *Framework, Storylines, Industry specific fundamentals* and *Numbers*. To define the characteristics of these layers, the theory on the Multi-Level Perspective of Geels (2002) is used as a source of inspiration. The top layer is stable and presents the long-term macro perspective view, while the lowest layer is subjected to the fast-changing environment and presents a more short-term micro-perspective view. By identifying these layers, the current structure of the scenarios and the interdependencies within and between the layers become apparent. It thereby increases the transparency of what a scenario is and reduces some of the complexity of understanding these increasingly multifaceted scenarios. Additionally, by acknowledging the differences within a single scenario and explicitly stating the layers, it provides a tool for communication. The second concept relies on using the impact-uncertainty matrix as a guide to identifying *if* and *how* changes should be incorporated into scenarios. This is done by directing the change, based on the classification, into a specific layer within the scenarios. The impact-uncertainty matrix is not a new concept but the novelty lies in combining different theories.

Sub-question 3: *Which steps need to be executed for scenarios to be kept up-to-date in a structured manner?*

To apply the concepts introduced in the previous section to structurally performing an update, 7 steps are proposed, shown in figure 4.1. The first two steps in the framework are dedicated to understanding the current scenarios before any alterations are performed. Step 3 is concerned with the changing external environment. Acquiring information on what has changed provides insight into why an update needs to be performed and serves as an input for executing the update. Subsequently, for each change it is determined if a regular update suffices or if classification onto the impact-uncertainty matrix is needed. Steps 4 is dedicated to ensuring the basis of the scenarios is correct by adjusting the assumptions made within layer 4. This is done by using the acquired information from step 3 and is referred to as a regular update, requiring minimal adjustments. Step 5 and 6 consider new uncertainties currently not yet incorporated into the scenarios. Step 5 classifies these uncertainties according to their impact and uncertainty and links them, based on this classification, to a specific layer within the scenarios. Step 6 incorporates these new uncertainties by adjusting the layers affected. Due to the interdependencies, an upper layer will always require changes to its lower layers. In most cases, changes made at a lower layer will not necessarily impact any of the layers above. Nonetheless, if a lower layer is often updated, this might highlight a possible trend that is currently being ignored at a higher layer. Re-evaluating the assumptions within higher layers may then be needed to capture this trend. The last step, step 7, validates the changes made. If the validation criteria are not met, iterations are required until all validation criteria are met.

Sub-question 4: *How does the framework perform in practice?*

To present the framework in a practical context, it was applied to four scenarios discussing the European power market. Executing the test case and validating the outcome with experts highlighted several benefits and uncovered some of its limitations. Concluding, the benefits of using the framework are the reduced complexity of executing an update, increased transparency of the process and the ability to update small steps while maintaining a good overview. Moreover, it provides a structured way of understanding the scenarios and the interdependencies between and within the different layers, thereby, reminding the scenarios planners that changing one part might influence other parts as well. Lastly, the different routes within the framework highlight that new trends and uncertainties should also be considered and provide a step-by-step procedure of incorporating these in the existing scenarios. This process is currently non-existing within scenario updates and therefore adds much value. Despite these advantages, the test case also uncovered certain limitations. Acquiring the right information is still time-consuming and difficult, nonetheless, this is essential to the updating process but not discussed within the framework. Van Vuuren et al. (2010) argue that in order to evaluate the long-term assumptions in these scenarios, it is important to use appropriate long-term trends and should therefore not be influenced by short-term observations. It is still undecided how to evaluate if the right information is used to evaluate the scenarios. Additionally, to define the boundary and formulate the layers, information on the generation process of these scenarios is required, which may not be present. Lastly, the use of the impact-uncertainty matrix has several implications, which were discussed in Section 7.1.

Main research question: *How to structurally incorporate new information and uncertainties into scenarios, keeping them up-to-date, guaranteeing that the scenarios remain realistic and useful?*

Based on answering the four sub-questions, the main research question can be answered. To structurally incorporate new information and uncertainties into scenarios, keeping them up-to-date, guaranteeing that the scenarios remain realistic and useful, the dynamic scenario framework consisting of 7 steps has been proposed. The aim of the framework is to offer the user a tool that helps to think about *if* and *how* changes should be incorporated within scenarios and what the impact of these changes are for the rest of the scenarios.

Using the framework allows the complexity of an update to be revealed in a step-by-step process. By separating the update in smaller concrete steps, understanding how these steps influence the rest of the scenario, a major part of the complexity is reduced. Additionally, for each change, it is decided if a regular update suffices or if the impact-uncertainty matrix should be used to understand *if* and *how* they should be considered within the scenarios. Incorporating new trends and uncertainties into the existing scenarios, is non-existing in the current updating process and highlights the societal contribution of the framework. Subsequently, when using the framework, the process becomes increasingly transparent. A common language is created, not only for understanding the structure of scenarios but also *if* and *how* changes should be incorporated within scenarios. The concepts introduced allow visualizing the consequences of incorporating changes in one part of the scenario for other parts. Improving the transparency of the process increases understanding of the scenarios themselves and the changes made. This results in the ability to better communicate the scenarios and the choices made during an update to people using them for making decisions. This helps in making the process explainable and justifiable why and how choices are made. Lastly, ensuring the plausibility and relevance of scenarios contributes to more accurate decision-making.

8.2 The research in a broader perspective

Climate change is one of the most important issues of our time and is influencing our political and strategic decisions (United Nations, n.d.). To combat climate change everyone must put forward their best effort to reduce their carbon footprint, not only on the political level but also companies and individuals in society. Everyone must provide his or her share to decarbonization. However, many are still ignorant and do not understand the consequences of their actions. If we are trying to understand the impact of our decision, well-grounded projection about the future are an essential foundation.

The framework proposed does not only reduce the complexity of keeping the scenarios plausible and relevant for the scenario planners but also creates a language for communicating it to a broader audience. The layers proposed triggers people to think differently about scenarios, taking a step back from the complex components and creating an overview of their main purpose and views discussed. This could help more people to better understand the scenarios themselves and their outcome, thereby creating a mutual understanding of how to combat climate change. Knowledge and insights should be shared, and collective actions should be taken to reduce environmental change. This thesis contributes, to some extent, to help better understand the consequences of our actions today for our future tomorrow.

8.3 Recommendations for further research

The work presented within this thesis has fulfilled the research aims which were initially defined. However, following the research findings and the highlighted limitations, several questions have arisen and remain to be answered. Therefore, areas exist in which further research is recommended to further develop the framework:

1) As highlighted in the discussion section 7.1, classifying a change on the impact-uncertainty matrix is subjected to opinion. As the classification should be done by multiple people, this might increase difficulty in making a uniform decision. While many articles suggest using the impact-uncertainty matrix to identify critical uncertainties, they rarely mention how this uncertainty and impact is assigned (Benedict, 2017; WSP, 2018; Quiceno et al., 2019). Pillkahn (2008), therefore, rightfully argues that there is a lack of suitable criteria for identifying differences between changes. Further research could focus on formulating criteria to help steer this discussion. This could help move forward the discussion on classifying changes surrounding many different opinions. A possible criterion could be to identify the size of the market that the uncertainty has an impact on. If the size is small, the impact on the industry might also be small.
2) The three new uncertainties further examined within the test case were not chosen via a formal procedure. The selected uncertainties clearly represented a classification within each section of the

impact-uncertainty matrix which was helpful in showing how the framework should be applied in practice. The matrix helps to understand how these uncertainties must be considered within these scenarios, but how to select the uncertainties that are classified onto the matrix is currently undecided. Many things might have changed and not all of these changes can be considered. Normally, it is not straightforward how to select the uncertainties that are discussed during an update. The selection procedure of the uncertainties further examined during an update is partly influenced by 1) the scenario boundary defined and 2) personal opinion of the scenario planners and is not discussed within this thesis. Future studies on the selection procedure of relevant changes are therefore suggested.

3) Additionally, further research is recommended to validate the choice of the impact-uncertainty matrix. There are many other tools to classify changes. The choice for this tool was the ability to link it to the different layers within the scenarios. The fact that this tool is well-known and simple to use also made this tool the preferred choice. However, other tools might also be suitable for classifying changes and linking them to the different layers within the scenario.

4) Further work needs to be carried out to execute an entire update using the framework. This could highlight additional benefits or uncover further limitations of the proposed framework. Moreover, an entire update should again be executed after a significant amount of time. One of the main advantages of using the impact-uncertainty matrix was the increased insight into the evolution of changes. This was currently not validated. Increased attention on the evolution of these uncertainties might help to better understand the development of these trends.

5) The last recommendation refers to the development of a generic framework. A natural progression of this work is to apply the framework to scenarios discussing other industries. The test case was applied to the scenarios representing the European power market. However, to confirm the generalizability of the framework, it should be applied to other markets and industries. Although the results may not be generically interpreted, using the framework, an update was successfully executed. The results provide a starting point for multiple scenarios to be structurally updated.

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Appendix

Appendix A – Scenarios of IHS Markit and Aurora Energy research.

To give some insights in the different type of scenarios generated, two energy consultants and their type of scenarios are briefly discussed:

IHS Markit Ltd is a global information provider active in energy industry (IHS Markit, n.d.-b). Scenarios developed by IHS Markit assume three completely different worlds, *Rivalry, Vertigo* and *Autonomy* and are developed from direct input of IHS Markit expert and clients, who identified key uncertainties about global economy, politics, security and energy resources. The presented narratives are quantified in data sets with different levels of detail (IHS Markit, n.d.-a). Depending on the scenario they use, the outcome will be different. A brief description of their scenarios:

- *Rivalry:* is referred to as the reference case. This is a world in which there is increase competition among energy sources and manifest itself in multiple ways: natural gas will enter the transportation; there will be a more significant role for electricity in transportation as well electricity will play a more significant role in transportation (IHS Markit, 2014).
- *Autonomy:* A world in which there is a much faster-than-expected transition away from fossil fuels, where local energy demand is satisfied to a much greater degree from local energy supply. E.g. renewables become much more cost efficient. Supply is abundant, and renewables grow much faster than in Rivalry (IHS Markit, 2014).
- *Vertigo:* Economic and geopolitical uncertainty drives volatility. Vertigo is a world where technology changes are significant. However, changes might be such significant that society is not able to keep up with the rapid changes. This can create frequent mismatches between investment, supply of energy and demand (IHS Markit, 2014).

Aurora Energy Research, a company providing data-driven analytics on European and global energy markets, uses proprietary analytics to generate a central forecast (Aurora, 2018). By changing parameters from this central forecast (reference case), they produce different scenarios, e.g. a more technology-based scenario in which there is a fast reduction of technology prices. The changed parameters depend on trends and client specific requests. Changing only a small number of parameters is seen as a sensitivity while changing inputs to create a consistent set of assumptions is seen as generating a new scenario. Therefore, not a set number of scenarios is generated, but can differ depending on the request (Aurora, 2018).

Appendix B1 – Explanation consistency matrix

It is evident from table 2.1, section 2.1.2, emphases is being placed on the internal consistency of scenarios. There are many software tools available to execute an consistency analysis, however, here the consistency matrix is shortly discussed (Amer et al., 2013). Pillkahn indicates a score of 1–5 should be assigned to each factor in the matrix (Figure 9.1) to evaluate the consistency of the scenarios (Pillkahn, 2008). A score of 1 is given if there is no consistency between the factors at all, which means it resembles an impossible combination. A score of 5 is given if these factors have a positive impact on each other and are highly linked. To assign these scores, often experts are used (Amer et al., 2013).

	C1	C2	C3	C4	C10	C11	C14	
C1								
C2	4							
C3	3	4						
C4	3	5	4					
C10	3	4	4	4				
C11	3	4	4	4	5			
C14	3	4	4	5	4	5		

1= Totally Inconsistent, 3= Neutral, 5= Supporting
2= Partially Inconsistent, 4= Slight Positive Impact,

Figure 9.1: Consistency matrix (Source: Amer et al., 2013)

Appendix B2 – Explanation morphological chart

The morphological chart helps to ensure the plausibility of the generated scenarios. By indicating the different factors and the combination that could be possible, it helps to visualize the different combinations. Ensuring the different drivers of the scenarios make a “good” combination ensure the plausibility. To provide an example, figure 9.2 shows an morphological analysis to generate scenarios (Amer et al., 2013).

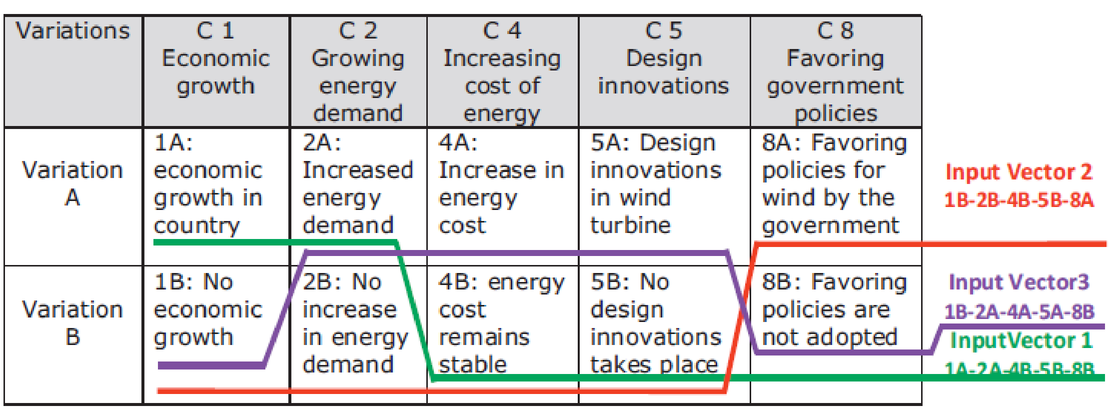

Figure 9.2: Morphological chart (Source: Amer et al., 2013)

Appendix C – Additional information energy scenario experts

In total three highly valued energy scenario experts were questioned:

"Prof. Dr. Detlef van Vuuren *is professor in Integrated Assessment of Global Environmental Change at the Faculty of Geosciences, Utrecht University and senior researcher at PBL Netherlands Environmental Assessment Agency leading the IMAGE integrated assessment modeling team. He has published more than 240 articles in refereed journals including Nature, Science, Nature Climate Change, Nature Energy, Nature Geosciences, PNAS, and Environmental Research Letters. He is listed among the most highly cited researchers worldwide*" (University of Utrecht, n.d.-a).

Prof. Dr. Gert Jan Kramer is professor in Sustainable Energy Supply Systems at the Faculty of Geosciences, Utrecht University, Member of the Scientific Board of the Netherlands Energy Research Association (NERA), advisor to shell in areas of renewable energy and energy scenarios and Member of the subcommittee ECN/Deltares/NLR/Marin of the Evaluation Committee Toegepaste Onderzoek Organisaties (University of Utrecht, n.d.-b).

"Dr. Oreane Edelenbosch is a post doc researcher at Politecnico di Milano. Previously she worked at the PBL Netherlands Environmental Assessment Agency (2012-2017), where she was involved in internationally funded research projects, such as the FP7 project ADVANCE, and contributing also to the UNEP Emissions Gap Report 2017. During her work at PBL, she obtained the Ph.D at the Copernicus Institute of Sustainable Development of the Utrecht University" (CMCC, n.d.).

Appendix D – Figure and example Multi-level Perspective

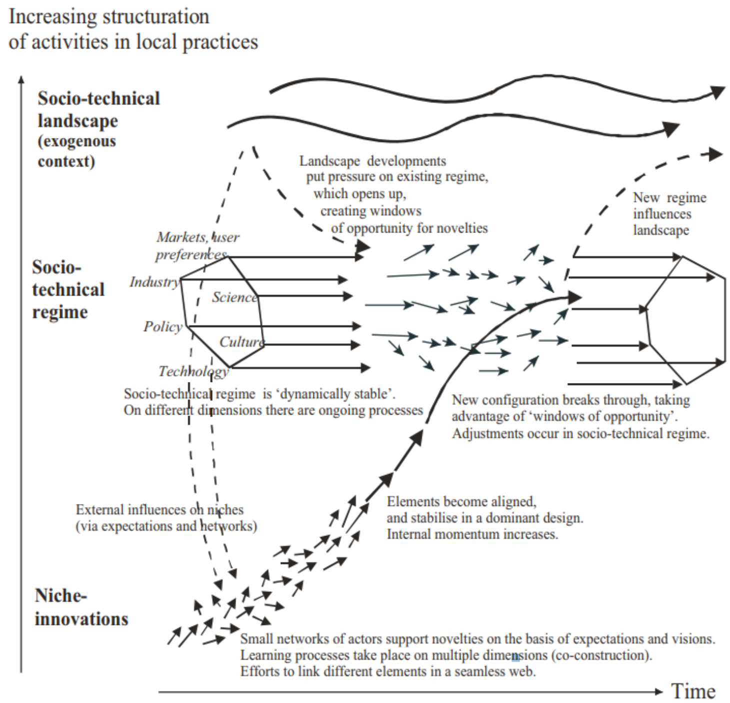

Figure 9.3: Multi-level-perspective (Source: Geels, 2002)

Example car industry

To illustrate how a transition might take place, an example from the car industry will be discussed. The fossil fueled car has become a dominant mean of transport in our society and thereby creates interdependencies with social, technical and institutional factors. These include car manufacturers, infrastructure, fuel providers, users of cars, car user policies, taxation, etc. (Whenua, 2012). This is described as the socio-technological regime in which this dominant technology is embedded. We develop habits and values that includes the use of the car as we get used to it. The question is how new innovation might succeed in competing with this dominant technology. The landscape level might put pressure on the current regime and changes our dominant values and beliefs. Increasing concern over climate change has pushed this topic onto political agendas (regime). Policies are created disrupting the position of the fossil fuel-based car. These disruptions create a "window of opportunity" for other innovations to break through to the regime and gain market share (Geels, 2007). Examples of niche-innovations are electric vehicles and hydrogen cars (Whenua, 2012).

Appendix E – Scenario-specific assumptions layer 2

Note: Some assumptions are provided relatively to the *Base case* as this presents the general view. To provide a structured overview the differences in storylines are also highlighted. The assumptions are provided per category and sometimes per sub-category. Additionally, important to note is that the assumptions are provided relatively per category. A "large" increase in flexible demand for the *Rocket* case can be an increase of 75% percent, while a "large" increase in DSR within the *Factory* scenario can be 10%. However, relative to the other scenario the increase is large.

Table 9.1: Scenario-specific assumptions - layer 2

Scenario		Base case	Rocket	Factory	Regulator	Comments
Differences in storyline						
Category	**Sub-category**					
Coal phase-out		Actively phased out	Actively phased out	Not actively phased out	Actively phased out	
Pace of energy transition		Medium in beginning, slow towards the end	High trough-out entire period	Slow	Medium in beginning, from 2035 high	
Government support for transition		Medium (consistent support for low-carbon technologies)	High (renewable deployment is ramped up, driven by government policies)	Low (no support for renewables: deployment in market based)	High (renewable deployment is ramped up, driven by government policies)	
Cost reduction of technologies		Medium	High	Low	High	
Demand for electricity and gas		Steady shift from gas to power consumptions due to electrification	Electrification drives increase power and decreased gas demand	Almost no change	Electrification drives increase power and decreased gas demand	It should be kept in mind that if demand for gas decreases, it does not mean that the capacity share for gas is reduced. If coal is out of the generation mix, gas share will automatically increase. Moreover, they do not generate as often is for example nuclear as they are on the rights side of the merit order

Assumptions						
Category	***Sub-category***					
CCS for gas		-	Large increase from 2020 until 2050	Large increase from 2030 until 2050	Medium increase from 2020 until 2050	
Offshore wind		Early and largest deployment	Early and largest deployment	Only small share of offshore wind	Late adoption but large share at end 2050	
Renewable share		High	High	Low	Medium	
Coal Share		Medium	Low (phased out almost completely by 2020)	High	Low-medium	
Annual demand for electricity	*Flexible demand*	Medium-Low increase	High increase	Low increase	Medium increase	Trends in economic growth and energy efficiency drive total annual demand while trends in transport and heating electrification drive demand flexibility
	Economic	Middle increase	Small reduction	Large increase	Flat growth rate	
	Heating	Small increase	Large increase	Small decrease	Large increase	“Economic & Other” consists of Shell WEM categories of Heavy Industry, Agriculture & Other, Rail Passenger Transport, Rail Freight Transport, Road Freight Transport, Lighting & Appliances
	% of heating demand electrified	Middle increase '(50%)	Large increase '(75%)	Small increase'(25%)	Large increase '(75%)	“Heating” refers to Services and Residential Heating
	Transport	Middle increase	Large increase	Middle increase	Small increase	Started at 15%
	% end-use energy service electrified	Middle increase '(60%)	Large increase '(80%)	Middle increase '(60%)	Small increase'(30%)	“Transport” refers to Road Passenger Transport
Supply	*Biomass*	-	High growth	High growth	Low growth	

	Coal	-	Low growth	Low growth	High growth	
	Gas	-	Base case	Base case	Base case	
	Hydro	-	Base case	Base case	Base case	
	Nuclear	-	High growth	High growth	Low growth	
	Offshore wind	-	High growth	High growth	Low growth	
	Oil	-	Low growth	Low growth	High growth	
	Onshore wind	-	High growth	Low growth	High growth	
	Solar	-	High growth	Low growth	High growth	
	PV Battery	-	High growth	Low growth	High growth	
	Grid Battery	-	High growth	Low growth	Low growth	
	Pumped storage	-	Base case	Base case	Base case	
Installed capacity	*Interconnection*	Same in every scenario	Same in every scenario	Same in every scenario	Same in every scenario	*Rocket* has growth in all types of low carbon capacity from an early stage while *Regulator* and *Factory* have later stage growth in large-scale and small-scale low carbon, respectively
	DSR	Low increase	Medium increase	medium-low increase	Large increase	
	Storage	Medium increase	Large increase	Small increase	Beginning small increase but at end larges increase	
	Solar	Small increase	Large increase	Small increase	Beginning small increase but at end largest increase	
	Offshore wind	See above	See above	See above	See above	
	Onshore wind	Medium increase over timeline	small increase in 2023- 2026 after which no new increase	flat increase	Large increase over timeline	

	Biomass	medium increase but still small share	large increase but still small share	large increase but still small share	medium increase but still small share	
	CCS	Very small increase	Large increase from beginning	Largest increase, especially from 2035	Almost non existing	
	Coal	Medium decrease	Large decrease, complete phase-out	Large decrease, almost complete phase-out	Flat increase	
	Gas	Small increase	Large decrease	Large decrease from 2035	Small increase	
	Nuclear	Flat increase	Small increase	Large increase	Small decrease	
	Hydro	Medium-Low increase	Medium increase	Low increase	Large increase	
De-rated capacity	*Interconnection*	~100% increase in 2020	~140% increase in 2020	~100% increase in 2020	~120% increase from 2020	Nuclear and gas (including CCS) are the key contributors to firm capacity across scenarios
	DSR	Small amount	Large amount	Large amount	Small amount	Capacity is de-rated by multiplying by a factor (its de-rating factor) to reflect the estimated availability of that plant at peak periods, considering factors such as forced outage rates, the ability to schedule programmed maintenance at off peak periods, and primary resource availability for variable renewables.
	Storage	Flat increase	Large increase	Flat increase	Flat increase	
	Solar	Small decrease	Medium increase	Small decrease	Large increase	De-rating means that the supply is adjusted to take account of the availability of plant, specific to each type of generation technology
	Offshore wind	Small increase	Small increase	Large increase	very small increase	
	onshore wind	Small increase	Medium increase	Small increase	Medium increase	

	Biomass	Medium increase	Large increase	Flat increase	Large increase	
	CCS	Flat increase	Very large increase	Flat increase	Very large increase	
	Coal	Medium decrease	Large decrease	Small decrease	Large decrease	
	Gas	Medium increase	Very large decrease	Medium increase	Very large decrease	
	Nuclear	Large decrease	Medium increase	Large decrease	Medium increase	
	Hydro	Flat increase	Small decrease	Flat increase	Small decrease	
Capacity changes		Large instalment in beginning which after that evenly spread	Weighted towards start	Increasing capacity installment, especially end to satisfy increasing demand	Relatively same as *Regulator* but smaller amounts	All scenarios see significant capacity growth across the time period, with Rocket weighted towards the start, *Regulator* and Factory the end, and Base case relatively evenly spread

Appendix F – Example layer 4 - factor % electrification - demand side - section transport

Sources used to formulate scenarios specific assumptions

1. Oeko institute (Öko-Institut e.V., 2016)

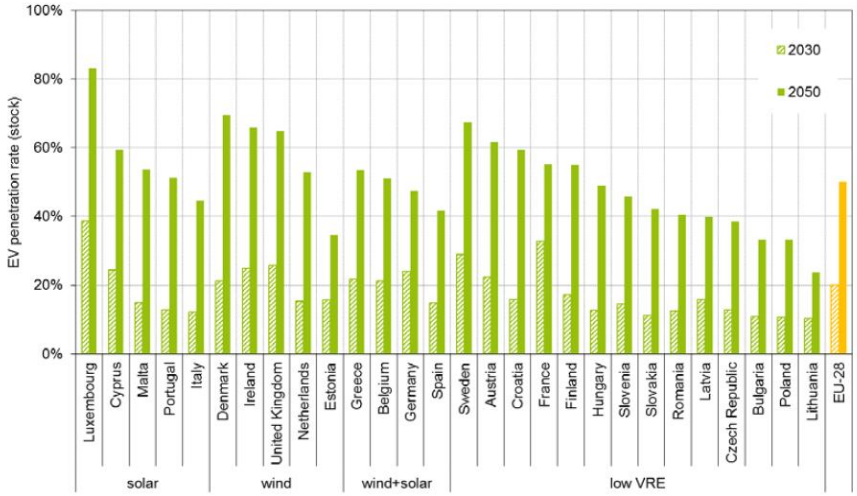

Figure 9.4: EV penetration rate of EV-mid scenario by 2030 and 2050 by country (Source: Öko-Institut e.V., 2016)

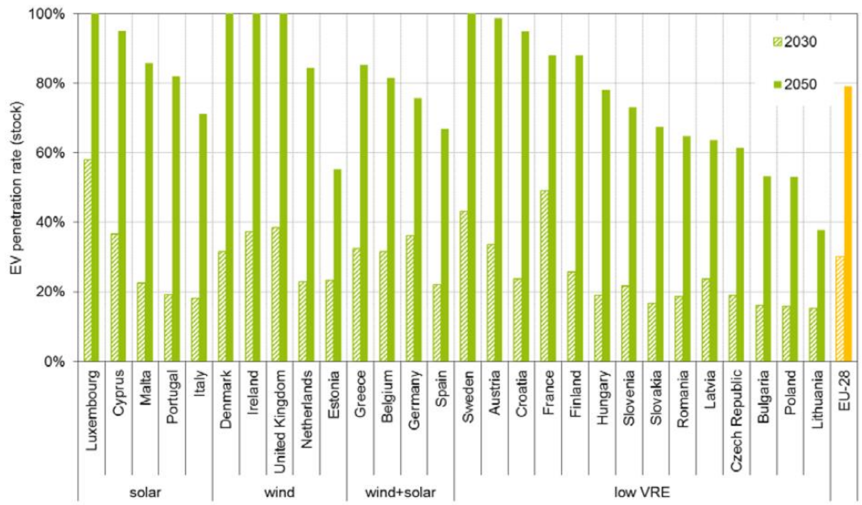

Figure 9.5: EV penetration rate of EV-high scenario by 2030 and 2050 by country (Source: Öko-Institut e.V., 2016)

Table 9.2: Summary of EV-mid and EV-high scenario (Source: Öko-Institut e.V., 2016)

	2030	2050
EV-mid scenario		
EV total share	20%	50%
BEV share in EV	50%	60%
PHEV share in EV	50%	40%
EV-high scenario		
EV total share	30%	80%
BEV share in EV	60%	80%
PHEV share in EV	40%	20%

2. Shell scenario

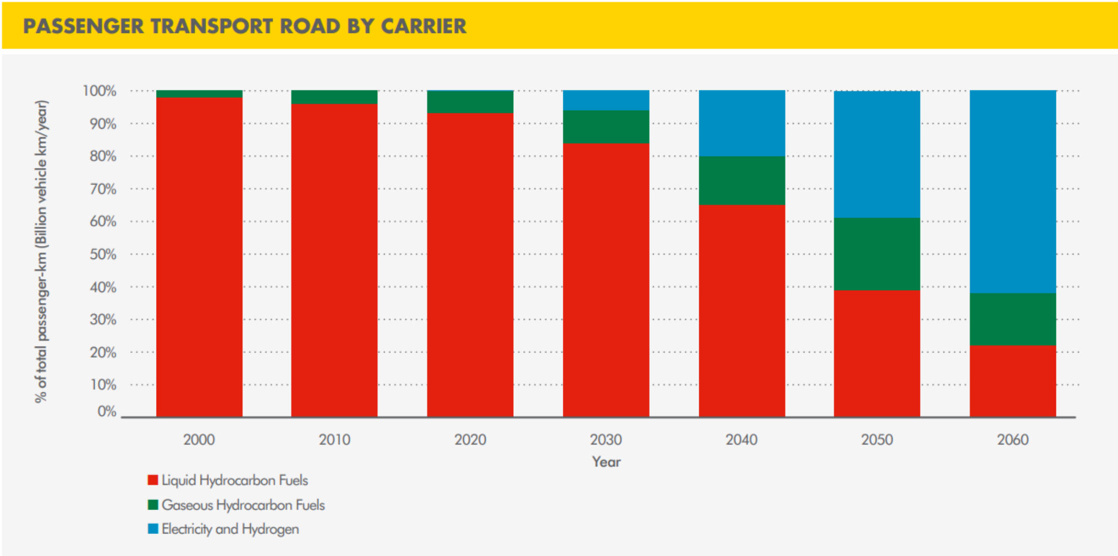

Figure 9.6: Passenger transport road by Carrier in Mountains scenario (Source: Shell International B.V., 2013)

Using the different sources, scenario-specific assumptions were formulated. The end goal is provided for the year 2070, so the value for 2050 will be slightly lower. The end goal will be used as input values for calculating the % electrification per year. The values shown here are altered from the different sources provided above to be used within this thesis and do not represent the view within Shell.

Table 9.3: Scenario-specific assumptions end goal

Base case scenario			
Country	Year 2016	Year 2037	End goal
Belgium	1%	22%	45%
Denmark	1%	22%	39%
France	1%	26%	50%
Germany	1%	24%	50%
Netherlands	1%	30%	52%
UK	1%	25%	48%

Regulator scenario			
Country	Year 2016	Year 2037	End goal
Belgium	1%	29%	81%
Denmark	1%	29%	72%
France	1%	28%	88%
Germany	1%	33%	89%
Netherlands	1%	34%	92%
UK	1%	32%	88%

Rocket scenario			
Country	Year 2016	Year 2037	End goal
Belgium	1%	33%	93%
Denmark	1%	33%	83%
France	1%	30%	101%
Germany	1%	35%	102%
Netherlands	1%	39%	106%
UK	1%	33%	101%

Factory scenario			
Country	Year 2016	Year 2037	End goal
Belgium	1%	22%	37%
Denmark	1%	22%	30%
France	1%	26%	40%
Germany	1%	24%	40%
Netherlands	1%	30%	42%
UK	1%	25%	40%

Calculations of % electrification per year

Using the assumptions defined above, the % of electrification was calculated for each year. This was done using S curve formula. This process should be executed for every factor in order to calculate the total electricity demand.

Table 9.4: Scenario-specific assumption layer 4 - % electrification per year

BASE CASE	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Belgium	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05
Denmark	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05
France	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07
Germany	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.06
Netherlands	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.08
UK	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.06
Total Base case	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.06

ROCKET	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Belgium	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.09	0.10	0.12	0.14	0.16
Denmark	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.12	0.14
France	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.09	0.10	0.12	0.14	0.16
Germany	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.10	0.12	0.14	0.16	0.19
Netherlands	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.10	0.11	0.13	0.16	0.19	0.22
UK	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.13	0.15	0.18
Total Rocket	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.13	0.15	0.17

REGULATOR	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Belgium	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.12
Denmark	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.10	0.11
France	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.08	0.10	0.11	0.13
Germany	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.10	0.11	0.13	0.15
Netherlands	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.09	0.10	0.12	0.14	0.17
UK	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.09	0.11	0.13	0.15
Total Factory	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.08	0.09	0.10	0.12	0.14

FACTORY	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Belgium	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04
Denmark	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04
France	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06
Germany	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.05	0.05
Netherlands	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07
UK	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05
Total Factory	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05

CONTINUE

BASE CASE	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0.06	0.07	0.08	0.09	0.10	0.11	0.13	0.14	0.16	0.17	0.19	0.21	0.22	0.24	0.26	0.28	0.29
Denmark	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.19	0.21	0.22	0.24	0.25
France	0.08	0.09	0.10	0.12	0.13	0.15	0.17	0.19	0.21	0.23	0.25	0.27	0.29	0.31	0.33	0.34	0.36
Germany	0.07	0.08	0.10	0.11	0.12	0.14	0.16	0.17	0.19	0.21	0.23	0.25	0.27	0.29	0.31	0.33	0.34
Netherlands	0.10	0.11	0.13	0.14	0.16	0.18	0.20	0.22	0.25	0.27	0.29	0.31	0.33	0.35	0.37	0.39	0.41
UK	0.07	0.08	0.10	0.11	0.12	0.14	0.16	0.17	0.19	0.21	0.23	0.25	0.27	0.29	0.30	0.32	0.34
Total Base case	*0.07*	*0.08*	*0.10*	*0.11*	*0.12*	*0.14*	*0.15*	*0.17*	*0.19*	*0.21*	*0.23*	*0.24*	*0.26*	*0.28*	*0.30*	*0.32*	*0.33*

ROCKET	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0.19	0.22	0.25	0.28	0.32	0.35	0.39	0.44	0.48	0.52	0.56	0.60	0.63	0.67	0.70	0.73	0.76
Denmark	0.17	0.19	0.22	0.25	0.28	0.32	0.35	0.39	0.43	0.46	0.50	0.53	0.57	0.60	0.63	0.65	0.68
France	0.19	0.21	0.24	0.28	0.31	0.35	0.39	0.43	0.48	0.52	0.56	0.61	0.65	0.69	0.72	0.76	0.79
Germany	0.22	0.25	0.29	0.33	0.37	0.41	0.46	0.50	0.55	0.60	0.64	0.68	0.72	0.76	0.79	0.82	0.85
Netherlands	0.25	0.29	0.33	0.38	0.43	0.47	0.53	0.58	0.63	0.67	0.72	0.76	0.80	0.84	0.87	0.90	0.92
UK	0.20	0.23	0.27	0.30	0.34	0.38	0.43	0.47	0.52	0.56	0.61	0.65	0.69	0.73	0.76	0.79	0.82
Total	0.20	0.23	0.27	0.30	0.34	0.38	0.42	0.47	0.51	0.56	0.60	0.64	0.68	0.71	0.75	0.78	0.80

REGULATOR	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Belgium	0.14	0.16	0.19	0.21	0.24	0.27	0.30	0.34	0.37	0.40	0.44	0.47	0.51	0.54	0.57	0.59	0.62
Denmark	0.13	0.15	0.17	0.19	0.22	0.24	0.27	0.30	0.33	0.36	0.39	0.42	0.45	0.48	0.51	0.53	0.55

France	0.15	0.17	0.20	0.22	0.25	0.28	0.32	0.35	0.39	0.43	0.46	0.50	0.53	0.57	0.60	0.63	0.66
Germany	0.18	0.21	0.24	0.27	0.30	0.34	0.38	0.42	0.46	0.49	0.53	0.57	0.61	0.64	0.67	0.70	0.72
Netherlands	0.19	0.22	0.25	0.29	0.32	0.36	0.40	0.44	0.49	0.53	0.57	0.61	0.64	0.68	0.71	0.74	0.76
UK	0.17	0.20	0.23	0.26	0.29	0.32	0.36	0.40	0.44	0.48	0.52	0.55	0.59	0.62	0.65	0.68	0.71
Total Regulator	0.16	0.18	0.21	0.24	0.27	0.30	0.34	0.37	0.41	0.45	0.48	0.52	0.55	0.59	0.62	0.65	0.67

FACTORY	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
Belgium	0.05	0.06	0.07	0.07	0.08	0.09	0.11	0.12	0.13	0.14	0.16	0.17	0.18	0.20	0.21	0.23	0.24
Denmark	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19
France	0.06	0.07	0.08	0.09	0.11	0.12	0.13	0.15	0.17	0.18	0.20	0.21	0.23	0.25	0.26	0.28	0.29
Germany	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.20	0.22	0.23	0.25	0.26	0.27
Netherlands	0.08	0.09	0.10	0.11	0.13	0.15	0.16	0.18	0.20	0.22	0.23	0.25	0.27	0.28	0.30	0.31	0.33
UK	0.06	0.07	0.08	0.09	0.10	0.12	0.13	0.14	0.16	0.17	0.19	0.21	0.22	0.24	0.25	0.27	0.28
Total Factory	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.20	0.21	0.23	0.24	0.25	0.27

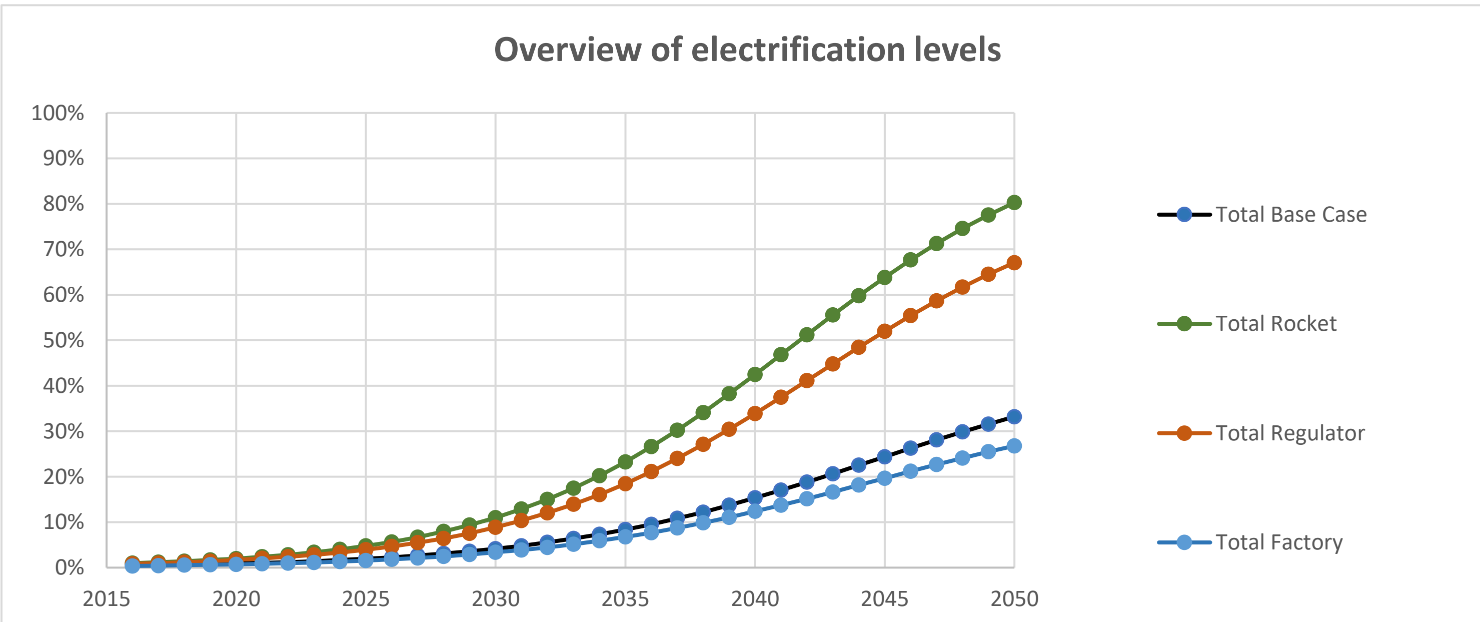

Figure 9.7: Overview of electrification levels different scenarios

Appendix G – Electricity generation by solar PV (2016 view)

The numbers provided here are altered from the IEA New Policy Scenario WEO 2016 to reflect the scenarios used within this test case. The New Policy Scenario is taken as the values for our Base case as this reflect the same line of thinking. Additionally, as the numbers are only provided for the years 2016, 2020, 2030 and 2040, the other year are provided by linearly increasing the values until 2050. The values for the other scenarios were formulated using the different worlds depicted indicating a value for 2050 and linearly dividing the increase between 2016 and 2050. *Rocket* is taken as the highest increase, while *Factory* as the lowest, the *Base case* and *Regulator* scenarios are in between. These numbers therefore do not reflect the view of Shell. In this example the countries are not separately discussed but the Europe Union in total is used as only this data was available.

Table 9.5: Scenario-specific assumptions – electricity generation by solar PV

Electricity generation by solar PV								**Source: IEA 2016**			
GW											
Scenarios	**2016**	**2017**	**2018**	**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base case	101.0	105.3	109.5	113.8	118.0	136.0	150.0	160.0	166.0	173.0	180.0
Rocket	101.0	108.8	116.5	124.3	132.0	148.3	164.7	181.0	197.3	213.7	230.0
Regulator	101.0	106.5	112.0	117.5	123.0	135.8	148.7	161.5	174.3	187.2	200.0
Factory	101.0	104.3	107.5	110.8	114.0	121.7	129.3	137.0	144.7	152.3	160.0

Red= data source (IEA, 2016)

Blue = own vision, related to the different scenarios depicted

Black = linearly divided between end and beginning values

Appendix H – Alterations of view electricity generation by solar PV

The final values for 2050 are increased for *Rocket* with 20 GW, *Regulator* with 15, *Base case* with 10 and *Factory* with 5. From there the values are linearly decreased until the values for 2018. The values for 2016-2050 are the same for all scenarios.

Table 9.7: Alterations scenario-specific assumptions electricity generation by solar PV

Electricity generation by solar PV								View from 2016			
GW											
Scenarios	**2016**[6]	**2017**[7]	**2018**[8]	**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Base case	101.0	107.0	115.0	124.4	133.8	143.1	152.5	161.9	171.3	180.6	190.0
Rocket	101.0	107.0	115.0	131.9	148.8	165.6	182.5	199.4	216.3	233.1	250.0
Regulator	101.0	107.0	115.0	127.5	140.0	152.5	165.0	177.5	190.0	202.5	215.0
Factory	101.0	107.0	115.0	121.3	127.5	133.8	140.0	146.3	152.5	158.8	165.0

[6] IEA, 2016
[7] EurObserv'ER, 2018
[8] EurObserv'ER, 2019

Appendix I – Additional electricity generation from trains when introducing hydrogen - layer 4

Table 9.6: Additional calculated electricity generation from trains when introducing hydrogen

Base case	**TWh**							
Scenario	2016	2020	2025	2030	2035	2040	2045	2050
Belgium	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
Denmark	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04
France	0.00	0.00	0.00	0.00	0.00	0.03	0.09	0.15
Germany	0.00	0.00	0.00	0.00	0.00	0.06	0.19	0.32
Netherlands	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.07
UK	0.00	0.00	0.00	0.00	0.00	0.04	0.13	0.21
Total	0.00	0.00	0.00	0.00	0.00	0.16	0.49	0.81
Rocket	**TWh**							
Scenario	2016	2020	2025	2030	2035	2040	2045	2050
Belgium	0.00	0.00	0.00	0.01	0.03	0.04	0.07	0.11
Denmark	0.00	0.00	0.00	0.01	0.03	0.04	0.08	0.11
France	0.00	0.00	0.00	0.03	0.12	0.18	0.32	0.47
Germany	0.00	0.00	0.00	0.06	0.26	0.39	0.71	1.03
Netherlands	0.00	0.00	0.00	0.01	0.05	0.08	0.14	0.21
UK	0.00	0.00	0.00	0.04	0.17	0.25	0.46	0.67
Total	0.00	0.00	0.00	0.16	0.65	0.97	1.78	2.60
Regulator	**TWh**							
Scenario	2016	2020	2025	2030	2035	2040	2045	2050
Belgium	0.00	0.00	0.00	0.01	0.03	0.05	0.10	0.13
Denmark	0.00	0.00	0.00	0.01	0.04	0.06	0.11	0.14
France	0.00	0.00	0.00	0.06	0.15	0.23	0.44	0.59
Germany	0.00	0.00	0.00	0.13	0.32	0.52	0.97	1.29
Netherlands	0.00	0.00	0.00	0.03	0.07	0.10	0.20	0.26
UK	0.00	0.00	0.00	0.08	0.21	0.33	0.63	0.83
Total	0.00	0.00	0.00	0.32	0.81	1.30	2.43	3.24
Factory	**TWh**							
Scenario	2016	2020	2025	2030	2035	2040	2045	2050
Belgium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Denmark	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
France	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Germany	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Netherlands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00