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# Assignment of master’s thesis

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| **Title:** | Evolvability of the grid; An investigation of mechanisms to minimize the ripple effects due to increased use of distributed energy sources. |
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| **Branch / specialization:** | Digital Business Engineering |
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## Instructions

This design science thesis aims to address the evolvability of the electricity grid by investigating mechanisms to minimize ripple effects resulting from the increased integration of renewable Distributed Energy Resources (DERs). After this research, the thesis ends with the design and implementation of an analytical tool for assessing the influence of the dynamic pricing paradigm on electricity grid stability.

1. Introduction into the problem and content of the thesis
2. Relevance Cycle: The design challenges that ripple through the electricity grid due to the integration of distributed energy resources.
3. Rigor Cycle: Techniques and mechanisms proposed to deal with these design challenges
4. Design Cycle: Design and Implementation of an Analytical Tool for Assessing the Influence of Dynamic Pricing Paradigm on Electricity Grid Stability
    4.1: dynamic pricing paradigm
    4.2 analysis of the problem and solution, stating the functional and non-functional requirements
    4.3 high-level and low-level design of the tool
    4.4 the implementation of the tool in Python, using the PyPSA toolbox
    4.5 Testing the tool - use of unit tests
    4.6 Discussion of the findings
5. Conclusion

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Master’s thesis

# Evolvability of the grid

## An investigation of mechanisms to minimize the ripple effects due to increased use of distributed energy sources

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# Declaration

I hereby declare that the presented thesis is my own work and that I have cited all sources of information in accordance with the Guideline for adhering to ethical principles when elaborating an academic final thesis. I acknowledge that my thesis is subject to the rights and obligations stipulated by the Act No. 121/2000 Coll., the Copyright Act, as amended, in particular that the Czech Technical University in Prague has the right to conclude a license agreement on the utilization of this thesis as a school work under the provisions of Article 60 (1) of the Act.

In Prague on November 22, 2023 …………………………………..

# Abstract

This master's thesis in design science research aims to address the evolvability of the electricity grid by investigating mechanisms to minimize ripple effects resulting from the increased integration of renewable Distributed Energy Resources (DERs). The thesis identifies design challenges related to the physical structure, economics, and intelligence of the grid through interviews with practitioners and a comprehensive literature review. It explores technologies such as Digital Twin Technology (DTT) and Virtual Power Plant (VPP), balancing mechanisms, and pricing mechanisms to tackle these challenges. Through the application of the reasoning behind Normalized Systems Theory (NST), a novel perspective on the design of the electricity grid is presented. Additionally, the proposed mechanisms are evaluated by a practical implementation, through the design and implementation of an analytical tool for assessing the influence of dynamic pricing paradigm on electricity grid stability. The thesis concludes by highlighting its contributions in terms of applying NST to the grid, as well as to software development, and providing a general approach for achieving an evolvable grid design. Furthermore, the developed analytical tool contributes in the critical analysis of popular paradigms in the current electricity market. Overall, the thesis contributes to resolving the challenges associated with integrating DERs into the electricity grid, aiming for a more sustainable and efficient energy future.

# Table of contents

# Table of Figures

# 1 Introduction

In recent years, the urgent need for sustainable and clean energy solutions has propelled the integration of renewable energy sources (RES) into the electricity grid to the forefront of global attention (Anees, 2012). This need has led to a critical transition from using conventional finite sources, such as fossil fuels, to renewable sources to produce energy. This transition is promoted by many nations across the globe. There have been set nationwide objectives to lower greenhouse gas (GHG) emissions and increase the adoption of RES (Muhanji et al., 2018). To illustrate, the Paris Agreement, an international treaty on climate change, legally binds nations worldwide to combat climate change and limit global warming (Obergassel et al., 2016).

In the context of this transition, Belgium has witnessed a notable evolution, with renewable energy (RE) production accounting for 24.9% of total electricity production in 2022 compared to 14.1% in 2013 (Elektriciteitsproductie | Statbel, n.d.). This shows a rise of 10% over a decade. Solar and wind energy have emerged as the primary RE sources in Belgium, contributing to 76% of the total RE production (Maandelijkse Elektriciteitsproductie, n.d.). Therefore, when mentioning RES in this thesis, the emphasis lies on these two sources. Another term, instead of RES, that is widely used when discussing this topic is Distributed Energy Resources (DERs), small-scale energy resources, mostly renewable, that are often situated close to the loads (IEA, 2022). This term emphasizes the distributed nature of the RES, such as Photovoltaic (PV) systems for residential use. These RES and DERs are promoted with a vast amount of benefits as driving force. As mentioned above, decarbonization and a more sustainable future is one of them. Additionally, DERs would allow consumers to be more independent from the electricity grid and produce according to owners' needs (IEA, 2022).

However, integrating these DERs into the electricity grid poses significant challenges that cannot be overlooked. Extensive research has explored various aspects of these integration challenges, encompassing physical, economic, information technology, and chemical concerns (Anees, 2012; Eltawil & Zhao, 2010; Eltigani & Masri, 2015; Zahedi, 2011). Nonetheless, inquiries into the challenges that are of most concern for utility companies and grid operators themselves, are scarce next to the theoretical complications. When researching solutions for these challenges, the literature is extensive as well. However, research papers mostly give a vertical in-depth view of a solution for one specific integration challenge. Research applying a more horizontal approach towards the establishment of a framework, or a more general approach that contains dealing with all possible challenges in all possible categories is lacking. Without a holistic framework to tackle these challenges, achieving a widespread penetration of renewable energy will remain constrained.

The primary objective of this thesis is to contribute to the design of an electricity grid capable of effectively integrating DERs, with a particular focus on developing a modular and evolvable grid. By adopting a modular approach, the grid can be scalable, flexible, and optimized for the efficient utilization of renewable energy resources. The concept of evolvability ensures that the grid can adapt and evolve to meet the evolving demands and challenges associated with DER integration (Mannaert et al., 2016). To achieve this objective, and due to the fact that this work serves as a design science paper, this thesis follows a structured approach based on the design science research framework with its design guidelines proposed by Hevner et al. (2004), and the three-cycle view (Hevner, 2007). The framework discusses that when performing design science research, one should scan the contextual environment for needs, challenges or opportunities that would be handled by the design in order to ensure research relevance. Next, it states that while conducting this research, one should apply methods, mechanisms, technologies, and theories from the knowledge base. This would ensure the research rigor. With both types of results, the ultimate design can be performed (Hevner et al., 2004). Fig 1. Illustrates this framework, including the three design cycles regarding the research activities. The sections in this thesis will each deal with one cycle. By adhering to this framework, the thesis aims to provide a comprehensive and complete design proposal to manage the design challenges posed by the integration of DERs.

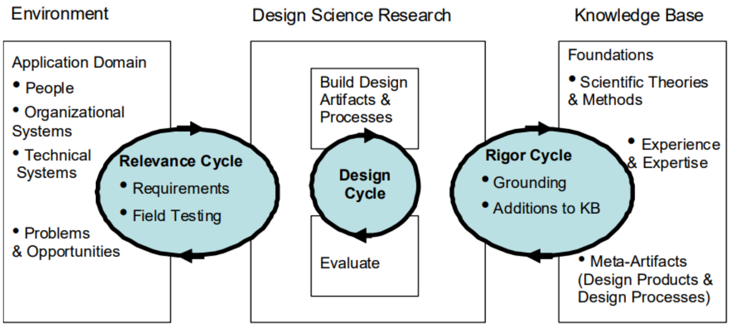

*Figure 1: Design Science Research*[1]

This thesis unfolds in three main stages, with its own objectives. Firstly, section 2 identifies and categorizes the design challenges related to the physical structure, economics, and intelligence of the grid, with a focus on challenges that have ripple effects throughout the electricity grid. To construct this list of challenges, interviews were conducted with practitioners to scan the contextual environment and define its needs. The knowledge obtained through the interviews is backed by a literary analysis. This section adheres to the Relevance Cycle (Hevner, 2007). Secondly, section 3 explores technologies, mechanisms, and theories from the knowledge base to address these design challenges and to later serve as a grounding for the design. This section adheres to Hevner's Rigor Cycle. This section is divided into the same three categories as the challenges. First the knowledge base is consulted for technologies related to the intelligence of the grid, next economical mechanisms are researched. In the last subsection, a theory is applied to the electricity grid to obtain a general approach towards dealing with design challenges in the electricity grid. Since section 2 focused on the design challenges that create ripple effects, the specific objective in dealing with these challenges is to deplete these rippling impacts. For this matter, Normalized Systems Theory is applied. Coupling modes are identified that cause the ripple effects, followed by the identification of cross-cutting concerns to elaborate on encapsulating mechanisms or technologies to integrate these concerns and deplete the ripple effects. This way the evolvability and modularity of the electricity grid would be ensured. In a last section, a high-level design of the electricity grid is presented through a simulation of a residential grid, demonstrating the application of the mechanisms and techniques identified to tackle the design challenges.

To conclude this introduction, some notes about the scope and purpose of this thesis must be made. First, as mentioned above, RES are often referred to as DERs. In this paper, I will use

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[1] Hevner (2007)

both terms, depending on the characteristics that I want to stress. Concerning the purpose of this work, it is crucial to note that this thesis is developed within the Double Degree Program between the University of Antwerp (UA) and the Czech Technical University. Chapter 2 and 3 were submitted as part (15 credits) of the Master's thesis portfolio at the UA to obtain the degree of Master of Digital Business Engineering. This complete paper covers the thesis (30 credits) to obtain the Master's degree of Informatics at the Czech Technical University (CTU). This work contains a literary study, as well as interviews with field experts, and the design and implementation of a software program.

# 2 Design Challenges

With this chapter, the goal is to construct the Relevance Cycle of the design science research framework brought forward by Hevner (2007). This cycle defines the contextual environment of the research project and links it with the design plan. Hevner et al. (2004) define this contextual environment as a problem space filled with systems and people with their problems, goals and opportunities. In this context, business needs can be identified by the researcher. Thus, through this environment the requirements that are used as input for the design research are provided (Hevner, 2007). Keeping this line of reasoning in mind, I can construct the purpose of this first part. The objective is to obtain a clear overview of the design challenges present in the electricity grid when increasing the amount of DERs in the grid. The contextual environment can be defined as the electricity grid with its grid users. The business needs of the grid are defined as design challenges in this chapter. These challenges are especially of crucial importance when they exhibit signs of being ripple effects. I will therefore focus on those design challenges in the electricity grid that create ripple effects.

In order to find and identify these ripple effects caused by the injection of electricity generated by DERs into the grid, the concept of ‘ripple effects’ needs to be clearly defined. Cambridge Dictionary describes ripple effects as ‘a situation in which one event produces effects which spread and produce further effects’. Important is the notion of an event that causes other events to happen. Normalized Systems Theory (Mannaert et al., 2016) defines ripple effects as events or effects within a structure that propagate changes throughout this entire structure. This propagation has no bounded impact, implying that the effects of one small issue can grow increasingly, limitlessly large. In this clarification of the concept, a first crucial aspect is the mention of a ‘structure’ or a system in which these ripple effects occur. A second important element is the unboundedness of the ‘rippling’ of problems. After retrieving the most important aspects of the concept of ripple effects, one can define this concept applied to the scope of this thesis. Let us define the system in this context as the electricity grid. A ripple effect would then be a certain event happening within the electricity grid that is triggered by the introduction of DERs, and that can propagate through the entirety of the grid. This event could cause a, possibly unbounded, impact on the functioning of the grid, i.e. the generation, distribution or transmission of electricity in the grid.

This chapter has been divided into three subsections, in order to sort the issue according to the subject areas where they cause challenges. First, the design challenges that one can consider to be related to the physical structure of the grid are discussed. Next, the economic concerns are investigated. Lastly, the challenges related to the intelligence of the electricity grid are elaborated. To emphasize the occurrence of ripple effects, all three subsections discuss the same three topics that entail changes when integrating DERs into the electricity grid. These three elements are the main features that distinguish DERs from conventional power plants. The first feature is the intermittency of the new resources. I will look into what this intermittency means physically, economically and intelligence wise for the grid. The second feature is the design or architecture of this new electricity grid. The same three subject areas will be discussed for this matter. Lastly, the DC-AC conversion that occurs with the integration of DERs will be explored in these three areas.

The findings in the literature concerning these various challenges were presented to, discussed, and confirmed by professionals in the renewable energy sector. Interviews were conducted with the following practitioners:

- Louis Plancke, Head of IT Architecture at ENGIE Global Markets.
- Geert Haerens, Agile and Architecture ENGIE IT.
- Peter van der Stock, business development director at Cast4All Technologies, a company specialized in monitoring solution for sustainable energy.

By researching the contextual environment through a literary analysis and interviews, this part adheres to the second research guideline established by Hevner et al. (2004), the problem relevance. This guideline describes how the business needs for which a solution is being found, must be important and relevant.

## 2.1 Design challenges related to the physical structure of the grid

### 2.1.1 Intermittency of renewable energy sources

In this first subsection, a highly straightforward concern regarding the integration of renewable DERs into the electricity grid will be discussed, i.e. the dependency of the sources on the weather. Given that RES make use of nature's resources to generate power, this generation is dependent on weather conditions. More precisely, photovoltaic systems only produce when there is sun and thus a certain level of solar irradiance, while wind turbines only generate power given a certain amount of wind. This fact implies a non-continuous power generation, with an output varying over time, assigning RES the characteristic of intermittency. When a high penetration of RES into an electricity grid is considered, it is imperative to take account of this variable or intermittent nature since this phenomenon raises the concern of a potentially less reliable power supply (Zahedi, 2011). The lack of a generator that has neither a constant generation nor one on demand induces a discrepancy between the electricity production and its local consumption. It is apparent that this property brings a high level of uncertainty to the grid when integrating RES. Due to this uncertainty, the importance of and need for accurate prediction was strongly emphasized by L. Plancke (personal communication, November 10, 2022). He highlights the dependency of the renewable generation technologies on the weather and thus the need for forecasting. This was reaffirmed by the literature, stating that in traditional power generation, the need to forecast the load, or consumer demand, has already been prominent for quite some time. Nonetheless, the intermittent nature of RES and their weather dependency, calls for a forecast of the production possibilities as well, and thus for a highly accurate weather forecast (Botterud, 2017). A lack of decent prediction enlarges the discrepancy between the power supply and demand, as mentioned above. This can be defined as grid imbalance, bringing us to the first issue resulting from the RES intermittency (Atzeni et al., 2012 & Alam et al., 2020).

An essential feature of conventional power generation plants is their 'dispatchability'. This term entails that electricity producers can alter production to the demand they are supposed to meet. Production of these generation systems can be increased or decreased accordingly (Joskow, 2011). The intermittent nature of renewable sources implies that the dispatch ability of these sources is rather limited. This brings about the inability to keep the grid balanced, called grid imbalance, and may cause troublesome instability of the grid. This can be an economic instability, which translates into unstable electricity prices as discussed in section 2.2.1, or a more physical instability where grid imbalance leads to cascading blackouts (Miller et al., 2012).

However, even in the case of a balanced grid, a different issue due to weather dependence and related to meeting consumer demand might occur. Weather conditions play a role in deciding the placement of the RES. There might, for example, be a stronger wind flow on the northern side of the grid, or a stronger irradiance on the southern part. This would lead to a placement of wind farms and PV systems accordingly. Nonetheless, the entire grid needs to be provided with an adequate amount of power, which will be supplied through transmission lines. It might occur that these power flows from one side of the grid to the other, exceed the line capacity, thus impeding the ability to meet consumer demand. This phenomenon disrupts the interconnection of the grid and is called congestion. (Singh et al., 1998 & Førsund et al., 2008). These congested transmission lines may then lead to the curtailment of the renewable power, meaning that the RES inject less power into the grid than their output capacity. Curtailment due to congestion is a more typical problem when using RES, than with the use of conventional power plants. The reason for this is that conventional power plants are placed strategically, centralized in the grid in order to transmit the power through multiple different paths to all corners of the grid. This way, no lines forming a path will get congested. However, with RES, the placement depends on the weather conditions within the grid, possibly leading to a suboptimal placement for transmission. This placement might entail a great distance between the power plants and the center of electricity demand. This would mean that a large amount of power from a conceivably sizable power plant will have to be sent to the other side of the grid. Hence, with a high penetration of RES in the grid, a distributed placement of these sources instead of a concentrated cluster is required to minimize curtailment due to congestion (Hitaj, 2015). This phenomenon is illustrated by Førsund et al. (2008), who describe the congestion problem in Norway. Since Northern Norway is prone to stronger winds and thus produce a higher power quality, plants are placed in that region. This leads to congestion on the transmission lines to other Nordic regions. Closer to home, L. Plancke (personal communication, November 10, 2022) suggested this problem is also happening in Germany. This country has a vast amount of wind farms in the north, and great industrial activity in the south. Germany therefore experiences similar congestion problems, trying to bring power from north to south.

### 2.1.2 Grid design

The traditional electricity grid is characterized by two important attributes. For one, the power generation in the traditional grid is centralized. A few sources, or even just one, generate the power that is distributed in the network. Secondly, this power flow is unidirectional. Distribution occurs from power plants and substations to passive loads. These two characteristics, centralization and unidirectionality, are challenged by the integration of RES into the grid (Canova et al., 2009 & Muhanji et al., 2018). To reiterate, RES can be appointed with the term DER, which implies a presence of multiple, smaller generators distributed over the grid. Additionally, consumers with their own RES can also inject the generated power back into the grid, leading to a power flow in the other direction. Atzeni et al. (2012) distinguish two types of end users in the grid. The end users of the traditional grid are passive users. These are just energy consumers. The bidirectionality of the grid makes way for a second type, the active users, i.e. prosumers. Having their own generators, they are connected to the grid and actively participate. Active users generate electricity mostly for their own consumption. However, they can inject any surplus back into the grid to be used by other consumers (Atzeni et al., 2012). Integration of RES thus makes the grid a decentralized and bidirectional network. This change in the design of electricity grids comes with its own challenges.

As already mentioned in the previous subsection, the decentralization of the grid leads to a challenging transmission of power. The placement of the RES within the grid must be well-considered as to not provoke any congestion and ultimately curtailment.

Concerning the bidirectionality, this characteristic may lead to a need for a voltage output restriction. This restriction is due to the voltage rise at the Point of Common Coupling (PCC). The PCC is defined as an interface, the place where the interaction between the power provider and the consumer takes place. For an active user with PV systems, their distribution panel may be considered the PCC (Eltawil & Zhao, 2010). When an active user of the grid wants to inject its generated power back into the grid it does so at the PCC. At that exact moment, the total power supply of the grid increases. Hence, the voltage rise in the PCC. If this voltage rise is too extreme and the voltage value exceeds the overvoltage relay setting, i.e. the voltage surpasses the imposed voltage constraint of the grid, that generator will be disconnected from the grid. This leads to a loss of the power that the active user was trying to inject into the grid, which is economically undesirable. Therefore, every generator in the grid would need an output restriction to comply with, in order to avoid this power loss and maximize the power production and usage of the grid (Canova et al., 2009). This phenomenon has been confirmed by P. van der Stock (personal communication, November 7, 2022). He elaborated on the fact that in neighborhoods, or even streets, where a high number of PV systems is installed on various rooftops, it is a common occurrence for inverters to switch off at the end of the street due to the overriding of the voltage restriction.

Furthermore, the fact that a large number of users have the possibility to inject power back into the grid, leads to another challenge. When power is injected into the grid, this is done in a sinusoidal voltage waveform. Due to the fact that the electricity grid operates in this AC mode, and therefore due to the characteristics of AC power, it is necessary for every generator to synchronize their voltage output. This means that the output of all users needs to be synchronous with the grid. If this is not the case, these output waves will collide and cancel out, leading to voltage fluctuations and thus instability of the electricity grid. This is referred to as the synchronization problem (Edwards, 2009).

A second issue that can be caused by the change to a bidirectional grid is unintentional islanding. This phenomenon occurs when a part of the distribution grid, containing load and generator, gets isolated from the entire grid. In case of islanding the RES keeps generating power and tries to inject it into the disconnected grid. The isolated part thus stays energized on its own (Eltawil & Zhao, 2010). Islanding can be intentionally done or can happen unintentional, for example during fault occurrence. To illustrate, when this happens in a grid with PV systems, these generators get disconnected and isolated from the rest of the grid. However, the PV systems keep injecting power into the load, leading to a so called ‘energized bubble’ (Farhoodnea et al., 2012). This can have a detrimental impact on the grid for various reasons. When part of the grid is unexpectedly and strongly energized during a fault in the grid, this might bring danger of electric shocks to line workers. Another important consequence of unintentional islanding is the fact that the high voltage in the isolated part might damage equipment from the consumer or utility lines. The bidirectionality of the grid, and thus the presence of a multitude of connections and lines, makes the occurrence of unintentional islanding particularly hard to find. In a traditional unidirectional electricity grid, this issue is rather improbable, since there are no generating entities in the distribution system, making the occurrence of unintentional islanding highly unlikely. The problem can thus be attributed as an emerging issue with the integration of RES into the grid (Mahat et al., 2008).

The concerns around these two changes in the grid design have been confirmed by a practitioner. The decentralization causes a more chaotic injection into the grid. With DERs, power injection happens everywhere in the grid, instead of at a few central points. The bidirectionality causes a need for prediction capabilities. With that many parties extracting energy from and injecting energy into the electricity grid, a prediction of when and how this will happen is needed to keep the grid balanced (Plancke L., personal communication, November 10, 2022).

### 2.1.3 DC-AC conversion

A third matter is conversion. Considering DERs, it is possible that they output Direct Current (DC) power. This is the case for PV systems, but not for other renewables such as wind and hydro power (Planas et al., 2015).However, since the discussion of implementing PV systems in the residential area is a highly significant topic in this paper, the matter of conversion is important to discuss.

A PV panel converts sunlight to DC power. However, the current electricity grids operate on Alternating Current (AC) power, as well as our households, the loads, do. Conventional power plants inject AC power directly into the AC grid. Now, with the introduction of PV systems into the same grid, the generated DC power needs to be converted to AC. This DC-AC conversion is done by an inverter, a type of power electronic (PE) converter (Farhoodnea et al., 2012 & Petinrin & Shaaban, 2016). Thus, the integration of certain DERs often leads to a need for additional equipment, i.e. an inverter. This device transforms the received DC into AC. With this conversion, it produces a sinusoidal output current that can be injected into the power grid. This way, the inverter is designed to deliver AC power in phase with the grid. One could therefore say that the inverter is the key physical instrument in enabling renewable energy integration into the conventional grid. However, the higher the penetration of DERs, the more operating pressure will be on the device and the more critical it gets to the grid. The optimal working, and thus current technology of these inverters may therefore be cause of concern (Eltawhil & Zhao, 2010).

However, this two-step process is not seamless. First the conversion itself, followed by the injection of the power into the grid, exhibits challenges that need to be faced. Considering the conversion, its performance can be measured by determining the inverter efficiency. This measure expresses the amount of DC power converted to AC power percentage-wise. A high quality inverter operates with an efficiency of about 90% (Fedkin & Dutton, n.d.). Since the efficiency is never 100%, one detects the presence of conversion losses. These energy losses imply that the input into the inverter, i.e. the DC power was higher than the AC that will be injected into the grid (Park et al., 2020). Thus, due to the introduction of RES, a new type of power losses can be distinguished.

Next, I consider the power injection into the grid. Recall that the inverter is designed to produce a sinusoïdal output that is synchronous with the AC grid. However, achieving this is not straightforward since the inverters have a tendency to distort the voltage waveform. This is called harmonic distortion (Simmons & Infield, 2000). Thus, harmonic distortion, or harmonics, occurs when the ideal sinusoidal waveform is different from the shape of the supply voltage waveform (Arrillaga & Watson, 2004). This phenomenon occurs due to the utilization of inverters, and is considered to be a serious power quality problem, arising from the DC-AC conversion. Farhoodnea et al. (2012) discuss the negative consequences in the physical structure of the grid that come from harmonic distortion. Problems such as resonances and overheating in transformers are said to decrease the reliability of the power grid. Even though these consequences are outside of the scope of this paper, they illustrate how the DC-AC conversion ripples through to harmonics, onto reliability concerns.

### 2.1.4 Synopsis

To conclude this first subsection about the design challenges related to the physical structure of the grid, a diagram about its content is presented in Fig. 2. The purpose of this graphic representation is to illustrate how these three main characteristics of RES has different effects rippling through in various aspects of the electricity grid. In the diagram, one can also clearly see that the effects of these three matters are intertwined, and thus coupled, presenting an extra dimension of interconnection of these challenges.

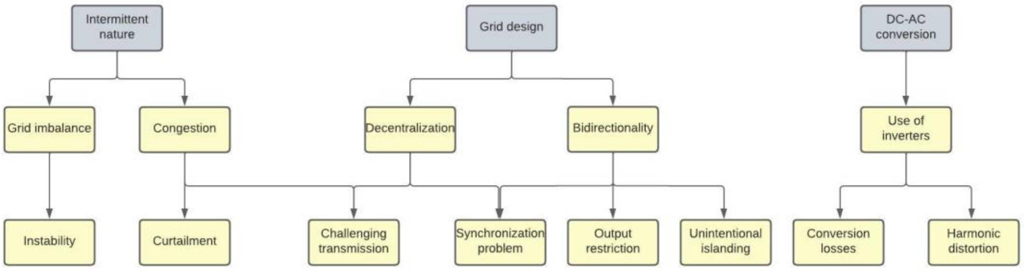


*Figure 2: design challenges related to the physical structure of the grid*

## 2.2 Design challenges related to economical aspects of the grid

In the following part, the economical impacts of the integration of RES in the grid will be discussed. Since our focus lies on issues rippling through the grid, this section will have the same set up as the previous one. First, any economical implications that arise from the fact that RES have an intermittent nature will be discussed. Next, I will look at what changing the grid architecture means for the energy market. Lastly, DC-AC conversion will be approached from an economical point of view.

However, in order to be able to discuss the economic design challenges, a short introduction into the energy market is needed. The energy market is unique in the way that the product you buy, i.e. electricity, can not yet be stored economically after purchase. In financial markets on the other hand, you can store your product, meaning that current and future prices are linked. This is not the case in the electricity market. Current prices are not linked to future prices, leading to a cyclical movement in electricity prices in tune with the supply and demand (Edwards, 2009).

Another remarkable aspect of the energy market, is a distinction between a short-term market, the spot market, where energy is delivered immediately, and the long-term forward market, with a scheduled delivery. A crucial challenge in the spot market, even with conventional power production, is that the demand is an erratic matter. Energy demand of consumers needs to be met immediately, and there is no way for producers to know the exact amount in advance. However, production has to be scheduled in advance and an estimation of the demand has to be made to determine the spot price of electricity. Due to this inelastic, short-term demand and the fact that reality can turn out different from the estimation, spot prices are volatile and the cyclical pattern of the price is created, even with conventional power production (Paraschiv et al., 2014). On the forward market on the other hand, producers and buyers negotiate energy amounts, distribution and prices in advance. This negotiation is called energy trading and is captured in a trade, which mitigates the price volatility (Edwards, 2009). However, this stability is challenged again with the introduction of renewables.

### 2.2.1 Economical design challenges arising from intermittency

The first group of ripple effects I established in section 2.1, were due to the intermittency of the RES. Likewise, this characteristic also has some implications on the energy market. The establishment of energy trades, as mentioned above, is supposed to deal with the volatility of the price due to an unpredictable demand. However, due to the intermittency of RES, their production cannot be exactly known in advance either. Thus, when integrating RES into the grid, supply and demand are both unpredictable, making energy trading even more difficult. Milstein & Tishler (2011) define a course of actions to come to the short-term market price when RES are involved. In a first stage, producers decide for each plant the generation capacity it has. This is done without any certain knowledge and solely based on the estimations of electricity demands and weather conditions. In a next step, the demand and weather of that day is taken into account, and the producer decides upon his daily production. With this information, a market price is created. However, the probability of the demand or the supply being different in reality is still significant, leading to the conclusion that an energy trade that involves RES is a more uncertain matter. This has been reaffirmed by G. Haerens (personal communication, October 27, 2022). He stated that establishing trades becomes more complicated with the introduction of RES since producers might now fail to deliver what was agreed upon in the trade. In this case, another producer has to step in and deliver. These situations have to be anticipated, making trading a highly complex matter.

Thus, the intermittency of the RES combined with a demand that cannot be completely managed causes load and/or supply fluctuations, which in turn causes price spikes and increased volatility in energy prices (Milstein & Tishler, 2011). However, the literature does not agree on the unambiguity of this causal relationship. To illustrate, Green & Vasilakos (2010) state that the integration of RES does not automatically lead to price volatility. In the context of integrating wind power, they conclude that this effect on prices can occur when the variation in output is sufficient and the demand and price are strongly related.

In section 2.1.1, the need for decent forecasting has already been highlighted. This is also crucial in terms of the energy market. Correct forecasting is needed to compose energy trades. In case of forecasting errors, market participants will be penalized with an extra cost to compensate the difference between the forecasted and the real value. This issue does not just apply to renewable sources, but to conventional ones as well (Vergados et al., 2016). However, an individual supply from one smaller distributed source and individual consumer demand is much harder to predict than the supply of conventional plants. The forecasting errors are thus prone to be larger when integrating distributed RES.

Other ripple effects due to intermittency that have been defined in section 2.1.1, were grid imbalance and congestion. Now, these physical grid concerns ripple through to the energy market and form economical concerns. To reiterate, grid imbalance happens when the generation, and thus supply, of energy sources does not match the overall grid demand. This could mean a demand that is not met, or a generated surplus. The latter is not only an adverse event for the producer due to missed revenue, but even implies an extra cost. Both grid imbalance and congestion can imply that there is more energy produced than is demanded in the grid, or in a specific part of the grid. Due to the operation costs of shutting down and ramping up generation units, a producer might opt for other solutions that achieve short-term balancing. One option is offloading. In this case, the producer sells the surplus to a neighboring country. This implies transmission between different electricity grids, with different economical regulations. L. Plancke illustrated this option with the case of Germany. As mentioned in section 2.1.1, this country is dealing with congestion problems. As solution, Germany offloads energy to neighboring countries which again leads to another issue. By doing so, they might actually use up the cross boarder capacity, leading to a neighboring country being isolated and prevented from offloading themselves (Plancke L., personal communication, November 10, 2022). Another option would be to let the spot price of the surplus energy to become negative. This negative electricity price can be an opportunity for the consumer. However, the producer is now paying to generate power for which he would normally receive revenue (Chen et al., 2021; Gatzert & Kosub, 2016; Paraschiv et al., 2014).

### 2.2.2 Economical design challenges arising from new grid design

In section 2.1.2, I defined two opposing grid designs. The one being the traditional centralized, unidirectional grid. The other, with the implementation of RES, a decentralized bidirectional grid. These two architectures bring forward an economical trade-off. The more decentralized the grid, the lower the transmission costs. That is, if the grid is efficiently designed and generation plants are distributed close to the loads. However, in the literature, the conventional central power plants have a higher generation efficiency, leading to lower generation costs. The trade-off that is being made here is thus transmission costs versus generation costs (Edwards, 2009).

However, in order for transmission costs to be actually lower and for the new grid architecture to not have economical disadvantages, the design of the energy market has to change as well. The conventional electricity market does not take the distributive character, such as generation variability and site specificity, of RES into account. In this case, the grid is still inefficient, requiring a high transmission and thus giving rise to high transmission costs. If the energy market would follow the tendency of the new grid architecture, and become more localized, then efficiency would increase and transmission can be reduced. This would lead to lower generation and lower transmission costs (Ampatzis et al., 2014 & Ilic et al., 2012). Grid localization, e.g. through the implementation of microgrids, will be mentioned in section 3.3.

In section 2.3, there will be discussed into detail how grid bidirectionality and decentralization will lead to a need for extra communication infrastructure. Economically speaking, this leads to additional equipment and maintenance costs for this new equipment.

### 2.2.3 Economical design challenges related to DC-AC conversion

After discussing physical implications of the DC-AC conversion when integrating RES into the grid, this subsection will handle the economical implications. Section 2.1.3 expressed the need for inverters to perform this conversion. To start, this additional equipment that is needed when integrating RES, evokes an additional cost for producers (Planas et al., 2015). However, since the introduction of RES into the grid allows for bidirectionality and active participation of prosumers, the additional equipment is an extra investment for the active user as well.

However, it is not only the installation of the inverter that contributes to additional costs. Its risk of failure contributes to the economic challenge that investing in RES is. A study performed by Formica et al (2017) reveals that the inverter has the highest failure rate among all elements in a PV system, and is thus the most unreliable component. The likelihood of the inverter failing has been confirmed by manufacturers. This has implications on the pay back period of a renewable generation system, such as a PV installation, and decreases its return on investment (ROI).

A last economic concern is related to grid efficiency regarding power conversion. Section 2.1.3 mentioned that the DC power generated by renewables is converted to AC power, to feed into the electricity grid. However the evolution in power electronics has changed the load profile of consumers. Modern appliances, such as laptops, phones and electric vehicles, operate with DC power. This implies that in order to transport generated power to the load, it first goes through the inverter for DC-AC conversion and is put on the grid. In a next step, it is then inserted from the grid into a AC-DC converter to feed the load. In this process, conversion losses occur twice (Kaushik & Pindoriya, 2014). Therefore, the economic losses due to these conversion losses are doubled. In addition, the inefficiency of this double conversion might lead to higher energy prices for the consumer.

### 2.2.4 Synopsis

Once more, a diagram was made to represent the contents of subsection 2.2. In this illustration, one can clearly distinguish macro-economic from micro-economic implications. It appears that the intermittency of RES has more macro-economic implications, since it impacts the energy market greatly. The new grid design and the need for DC-AC conversion, rather affects individual economic agents directly. Costs and investment implications for the energy producers and consumers, i.e. all grid users arise from these two matters, which are more micro-economic considerations.

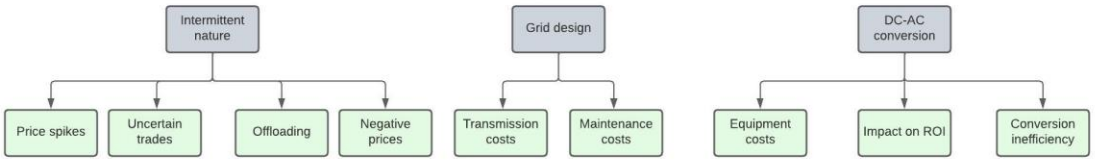


*Figure 3: Design challenges related to economical aspects of the grid*

## 2.3 Design challenges related to intelligence of the grid

The increase of grid complexity, due to an increased integration of DERs, and an increase in energy demand, there is a need for an electricity grid that is better equipped with intelligent capabilities, a so called smart grid (He, 2010). The development or expansion of the grid towards one with more computational intelligences, brings its own design challenges. In this section, the reason for a need for an intelligent grid will be discussed. In doing so, the design challenges of implementing more intelligence into the grid are defined.

### 2.3.1 Need for intelligence due to intermittency

In section 2.1.1, the need for accurate weather and power prediction was already highlighted. In order to improve prediction quality, a great amount of data is needed to process and learn patterns from. This data could be weather related (temperature, wind power, irradiance, geographic information) or related to the generation of electricity (power density, generation efficiency, output rate). To capture this information, IoT devices, such as sensors or smart meters can be used. The amount of data needed brings forward a scalability issue which is twofold. On the one hand, for each generator, or generation site, a substantial amount of data is needed on that single entity. This brings forward a challenge in the sense that this large amount of unstructured data needs to be stored and processed in some way (Fuller et al., 2020). On the other hand, the number of entities that has sensors and delivers data increases vastly with the integration of RES. In order to be able to control and integrate all this distributed data, scalability is an essential requisite (Muhanji et al., 2018). This is a challenge linked to the decentralization of the grid, which will be discussed further in section 2.3.2.

Not only the magnitude of the data calls for concern, its content brings up an issue as well. Data about supply and demand of generation units and consumers can be sensitive, personal information. Therefore, cybersecurity becomes a crucial topic in order to deal with the threat of attacks on this data. Next to this, since data of consumers will be shared and used for predictions, the issue of data ownership and privacy becomes one to take into consideration (Agüero et al., 2017).

### 2.3.2 Need for intelligence due to new grid design

As already discussed in section 2.1.2, the bidirectionality of the grid distinguishes active users. However, it is not only the two-way distribution that characterizes the new grid design. Some form of bidirectional communication infrastructure is also needed for consumers to become active participants (Atzeni et al., 2012). This way, data is brought to the producers about demand and weather conditions to establish their optimal supply. On the other hand, data can be brought to the consumer. An active user, generating its own power, can this way receive information about its own output and the opportunities to sell its power to the grid. Thus, an enabling infrastructure is crucial in order to obtain consumer participation (Agüero & Khodaei, 2018).

Next to the bidirectionality of the electricity grid, a tendency towards decentralization due to the integration of RES was also identified. This brings a shift in the intelligence concern of the grid. First, it must be noted that some degree of automation and implementation of smart technologies has already been implemented into the grid. However, this has mostly been on the level of the transmission system. Transmission System Operators (TSO's) in the traditional grid have already been concerned with the planning of transmission capacity. On the medium to low voltage level, where the distribution system operates, the introduction of intelligence is less pervasive (Gaviano et al., 2012). However, the integration of distributed RES implies power injections straight into the distribution system of the grid. Therefor, the IT infrastructure present in the electricity grid right now, is in need of an update in order to be able to handle IoT infrastructure. Next to this, the integration of new and old infrastructure, is also an issue (Fuller et al., 2020). Coordination between the two will be needed for an optimal operation. In addition, the decentralization of the grid due to the presence of distributed RES leads to a need for coordination as well. Since, the new grid has more individual active users and generation units, there is much more information that needs to be transferred and brought together (Henderson et al., 2017).

A last issue related to intelligence and the architecture of the grid is a matter of maintenance. To recap once more, the integration of RES leads to a vast increase in distributed generators. An example would be a district where active users have PV installations on their roof. Every installation is a different generation plant, and every panel a different unit. This distributed architecture can make it difficult to locate and repair faults or failing generators for a grid operator. Nevertheless, faults are a significant inhibitor of system availability and performance, and lead to huge maintenance costs. They must be detected as fast as possible. An intelligent way for fault diagnosis in a distribution grid is therefor a crucial aspect for the grid performance (Jain et al., 2019).

### 2.3.3 Need for intelligence due to DC-AC conversion

In section 2.1.3, it was discussed how the use of inverters for DC-AC conversion could be a threat for power quality into the grid. This was attributed to the waveform distortion a inverter could cause, leading to harmonic distortion in the grid. It is important to note once again, that this can lead to damage of the equipment and endanger the power quality. Therefore, an intelligent controlled grid would be highly valuable to minimize these threats. Through intelligent power control, the grid could handle the optimization of the generators' output (He, 2010). To do so, simulations are needed to test output levels and find the optimal power control. This brings me back to the design challenge of data volume, which was already discussed in section 2.3.1.

### 2.3.4 Synopsis

For this third type of design challenges, being intelligence related, a third diagram was made. Fig. 4 illustrates the problems or challenges that are encountered when one tries to develop or expand the intelligence of the grid in order to contain the effects of the RES feature in question. In this diagram, except for privacy concerns, the challenges appear to be strictly seperated. However, when considering the intelligence as a whole, no matter what topic of interest one is examining, the challenges appear everywhere and are thus intertwined. Considering privacy, this is clearly an overall concern since handling personal data and its communication over a network call for attention towards the data's protection.

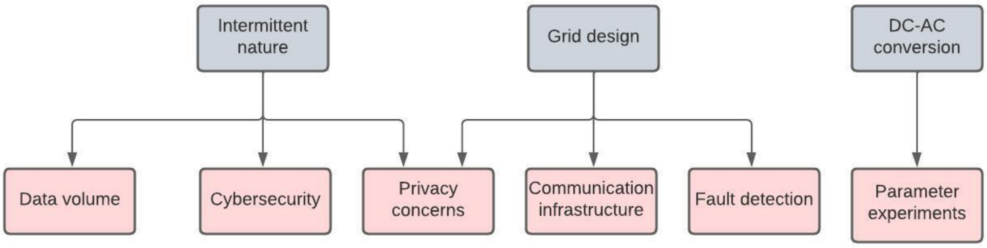


*Figure 4: Design challenges related to the intelligence of the grid*

## 2.4 Summary grid design challenges

In order to summarize this chapter about design challenges in the electricity grid related to the integration of DERs, a final diagram was made, combining all previous illustrations. Fig 4. reveals the interconnection between all challenges, no matter the subject field. In order to fully emphasize the complexity of the matter, each subject field is added underneath the other. In grey are the three main characteristics of DERs or RES. These immediately have effect on the physical structure of the grid, shown in yellow. These physical changes impact the economic operations of the electricity grid, illustrated in green. From these two fields, the challenges related to the intelligence of the grid are obtained in red. The physical and economical problems ask for an enhanced intelligence of the electricity grid, which in its turn, leads to a whole new set of challenges, influencing each other. One can thus define an arrow as 'leads to the challenge of …'. The clutter of arrows clearly shows how one new characteristic can have effects rippling through all different fields of the electricity grid. This diagram of ripple effects will be the starting point to investigate mechanisms that could contain these effects.

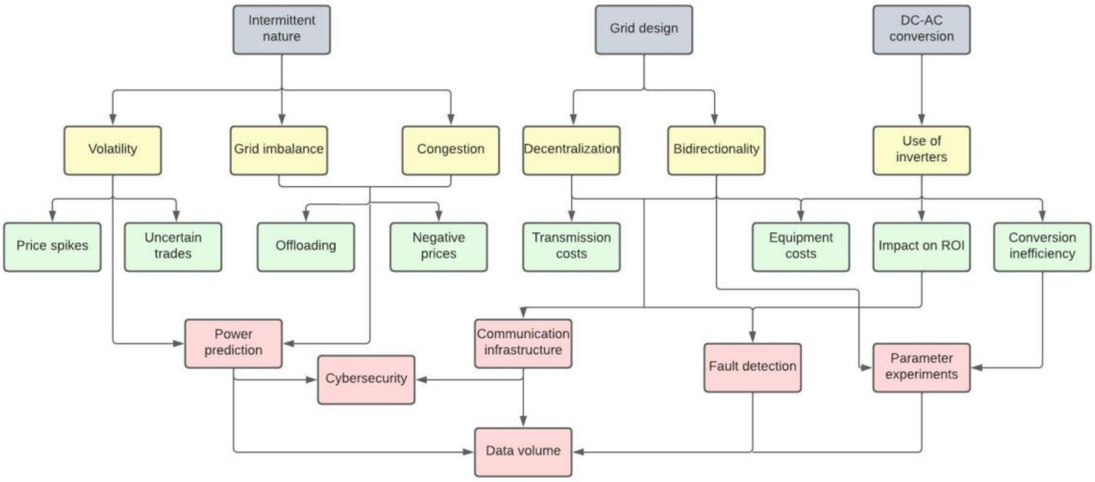


*Figure 5: Grid design challenges*

# 3 Techniques and Mechanisms

This chapter of the thesis will focus on the Rigor Cycle brought forward by Hevner (2007). According to his design science framework, this stage of the research is reserved to investigate the knowledge base to provide the appropriate materials for design. The knowledge base exists of foundational theories, frameworks, constructs, models, and methods. The appropriate application of this knowledge ensures the rigor of the research (Hevner et al., 2004).

When applying this line of reasoning to the topic of this paper, the same three disciplines as mentioned in the previous chapter can be enforced. Since the design challenges were divided into these three fields of expertise, it is only sensible to do the same in the rigor cycle. Therefore, in this chapter, the knowledge base concerning intelligence-related design will be consulted first. In a second subsection, a look into economy-related design practices for the grid will be performed. Lastly, since the physical aspects of the grid touch upon a most holistic view of the grid design challenges, this knowledge base research will be conducted last. However, as stated in Chapter 2, the design challenges could not be strictly separated into these three disciplines, but were intertwined instead. It would therefore not be lifelike to consult the knowledge base of a discipline with only the design challenges of that discipline in mind, and I will thus respect this interconnectedness.

This chapter adheres to the fifth research guideline established by Hevner et al. (2004), which is the research rigor. This guideline provides the assurance that rigorous methods are applied for the effective design-science research.

## 3.1 Information technology to enable grid intelligence

The first category of mechanisms or technologies that will be researched and discussed are the ones related to intelligence of the grid. More specific, the knowledge base will be consulted to find out how information technology can enable grid intelligence. In a first subsection, a short recapitulation of the intelligence-related needs and design challenges will be made. Next, two technologies will be explored. First, the general concept of Digital Twin Technology (DTT) will be discussed and applied to the electricity grid. The second technology is specifically established to handle DERs, this is the technology of a Virtual Power Plant (VPP)

### 3.1.1 Intelligence-related needs

Throughout Chapter 2 of this paper the collection of design challenges seem to convergence to three general intelligence-related needs for an improved grid operation when integrating DERs. The first one is a need for power prediction, due to the intermittency of the sources. Second, a need for predictive maintenance, due to the new grid design. The third need is a need for simulations and arises from the threat of frequency disturbance due to voltage fluctuations and harmonics from conversion.

The need for power prediction has already been mentioned in 2.1.1, where it was described how the intermittency of sources led to a need for precise weather forecasting, and, using this forecast, an accurate power output prediction. The need for predictive maintenance, includes fault diagnosis and was discussed in section 2.3.2. Here it was discussed how the decentralized design of the electricity grid leads to the concern of faults in generators staying undetected. When faults go undetected and are not prevented, they can lead to the downtime of the grid and to serious maintenance costs (Jain et al., 2019). The impact of the failure of the inverter on the ROI of a system, mentioned in section 2.2.3, also reveals this need for fault prediction, since this might detect the problem that could lead to a failing inverter and prevent it. Lastly, the need for simulations has been made clear by the problem of harmonics, mentioned in section 2.1.3. If different output voltage levels and other parameters could be explored in simulations of the grid, the design challenges related to the voltage output might be phased out.

To give a clear overview of what I am looking for in the knowledge base, related to grid intelligence, Fig. 6 is provided as an illustration.

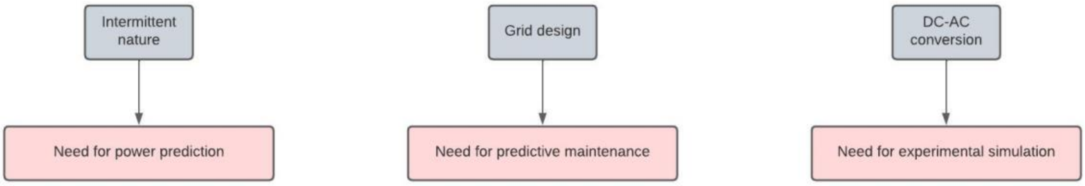


*Figure 6: intelligence-related needs*

Evidently, when searching for an instrument or method in the knowledge base that can support these three needs, the clear intelligence-related design challenges that were established in section 2.3 need to be kept in mind. To reiterate them, an optimal instrument succeeding in attending to these three needs will have to be able to handle vast amounts of data, which might also be prone to privacy concerns. Therefore, cybersecurity and a decent communication infrastructure for this data handling are of utmost importance. This communication infrastructure refers to a more general challenge of managing the distributed sources within the grid in an efficient and structured way.

### 3.1.2 Digital Twin Technology

A construct worth exploring is DTT. The relevance of this technology can be shown by its selection for Gartner's Top 10 Strategic Technology Trends for 2019. On the other hand, since this term was coined by Michael Grieves in 2003, a period of 20 years of theoretic research ensures its rigor (Barricelli et al., 2019). In this subsection, I will first explain the concept of DTT in general, followed by an application of the technology on the electricity grid. To conclude, the impact of DTT on the intelligence-related needs will be discussed.

In 2003, M. Grieves defined a Digital Twin (DT) as having three core components; the real space with physical products, the virtual space with its virtual counterpart, and the link between the two by connections of data and information. More extensively, DTT takes a physical entity, an object or process, and mirrors, simulates it as a virtual model (Barricelli et al., 2019). This is done through the connection, the third element of Grieves, and vast amounts of collected data of the physical entity. To collect this data from the physical object, sensors and other smart devices are used. An important note is that, in DTT this data collection is happening real-time (Liu et al., 2021). In order to ensure this continuous data exchange, networking devices are needed to send this dynamic, real-time data about the status and operation of the physical object (Barricelli et al., 2019). A framework for this network is shown by Fahim et al. (2022). In this work, a cloud-based DT of a windfarm is established by connecting the physical and virtual entities through a 5G-Next Generation-Radio Access Network (NG-RAN). In this case, the real-time data is sent through a 5G network to a private cloud where the DT is established. A next step in DTT is data processing. When this dynamic data, combined with historical data is gathered, analytics can be performed. Since DT technology encompasses Artificial Intelligence, learning algorithms can be applied to the data to perform multiple activities. Predictive analytics are performed to predict future activity of the object. With prescriptive analytics, decision about the operation of the object can be made. Lastly, optimization algorithms can enhance performance (Barricelli et al., 2019).

Since the electricity grid is a physical entity, DTT can be applied to it. To do so, the three component view of M. Grieves can be expanded to the 5-dimensional modeling approach of DTs suggested by Tao et al. (2018). I will apply these dimensions to the structure of the grid. The first dimension is again the physical entity, in this case the electricity grid. The grid consists of a multitude of physical objects, all part of this dimension. The virtual representation of the electricity grid is the second dimension. This virtual counterpart mirrors the behavior of the grid (Barricelli et al., 2019). The third dimension are the services for the physical and virtual entity. An example for the grid would be power output monitoring of the distributed plants, i.e. physical objects, in the grid. The fourth dimension is the data, the central part of the DT. Recall that this data has to be collected in real-time, and comes from the three dimensions above. Examples of data in the grid could be active and reactive power of generators, frequency, currency, load profiles (Cioara et al., 2021). The last dimension is the connection dimension. This entails all communication between the previous dimensions and illustrates the dynamic nature of the technology. All connections between dimensions must be bidirectional (Tao et al., 2018). The application of DTT on the electricity grid is described by Cioara et al. (2021) and by Zhou et al. (2019). The DT of the grid represents the DERs and other possible energy assets. Power cables and transmission systems can be represented, as well as inverters and PV systems. To illustrate this, Song et al. (2020) developed a DT of an inverter based on neural networks. This virtual representation enhances many grid management processes. Examples defined by Cioara et al. (2021) are production monitoring, load prediction, balancing supply and demand, and operation optimization.

When considering the intelligence-related design challenges once more, it can be pointed out that the DTT encompasses mechanisms to deal with all of them. The smart devices mentioned to collect the real-time data are designed to deal with a large volume of unstructured data

(Cioara et al., 2021). Considering the communication infrastructure concern, this has been taken into account in modelling approaches (Tao et al., 2018) and an example to deal with this was mentioned with the 5G NG-RAN cloud-based DT framework by Fahim et al. (2022). Data security in the grid can be handled by Machine Learning (ML) based security assessments (Zhou et al., 2019).

To conclude this chapter, the significance of DTT concerning the intelligence-related needs mentioned in section 3.1.1 will be discussed. The first need was the one of power prediction. Through the use of DTT, the output of the DERs could be predicted. Power predictions can be made for the individual generators, as well as for the grid as a whole (Bergler, 2020). This way, information is provided that enables grid operators to plan the energy supply and deal with the intermittency of the sources ("The key to electricity sector 4.0: the digital twin", 2021). The next need of predictive maintenance encompasses fault diagnosis. Through the data collection of sensors, which is then fed to ML algorithms, the DTT has the predictive power to detect faults. Jain et al. (2020) proposed for example an approach for fault diagnosis within a PV system. Not only fault prediction of a generator can be performed, but of the whole grid. Potential failures and security concerns can be timely detected and diagnosed by the DTT (Cioara et al., 2021). The capability of fault prediction would have an impact on the economic design challenges as well. A reduction in maintenance costs can be appointed as a positive consequence (Rasheed et al., 2019). The last need that was defined in 3.1.1 is experimentation through simulation. To clarify, the virtual counterpart of the physical object can be defined as a simulation of that object. On this simulation, experiments can be performed by altering certain parameters. This way scenario and risk assessments can be performed in the shape of ‘what-if’ analyses. The response of the grid to various alterations can be studied (Rasheed et al., 2019). Examples are researching different load profiles, output voltage levels etc. This way, various design challenges could be managed, such as the occurrence of harmonics or output restriction, as well as high voltage levels harming equipment, leading to equipment costs.

### 3.1.3 Virtual Power Plant

With DTT, a general technology was found which can be applied to the operations of the electricity grid. However, it is also possible to specify and look into mechanisms and technologies constructed solely for the optimal operation of the electricity grid with the integration of DERs. To do so, I will focus on the design challenges related to the new grid design, decentralization and bidirectionality. Recall that the conventional grid is not designed for the extensive integration of decentralized and distributed generators, since the conventional energy provision went through a central power plant (Werner & Remberg, 2008). To deal with this, one could aggregate these DERs into one VPP. This technology is designed to handle the grid design challenges. With a VPP, distributed generators are consolidated into one virtual plant, so that virtually, these act as one central power plant (Saboori et al, 2011). The DERs combined in a VPP appear as one operating profile and have the same visibility and controllability than a conventional central power plant (Pudjianto et al., 2007). A VPP consists of a multitude of IT components. First, and most important, is the Energy Management System (EMS) of the VPP. It controls the power that flows from the different DERs and coordinates their operation. A next component is forecasting systems that predict the loads and the weather, and thus the generation of sources,. Lastly, a communication system is needed so that the DERs can communicate with the EMS of the VPP (Werner & Remberg, 2008).

Considering these VPP components, one should take note of the similarities between DTT, described in section 3.1.2, and VPP. Both these technologies describe a virtual entity related to the electricity grid. For both, a communication infrastructure is needed for the physical grid entities and the virtual entity. Lastly, both concepts include output and load prediction and are thus in need of vast amounts of data. One could therefore use certain components of the DT to model and ultimately obtain a VPP.

The benefits a VPP provides can be divided into two categories, technical and commercial. The technical aspect of a VPP is that DERs are now visible for system operators, they operate as a whole and their capacity can thus be optimally used. Commercially, DERs become visible on the energy market, thanks to the VPP and prosumers are given the opportunity to participate in this market (Saboori et al., 2011). To conclude, a VPP brings a solution to the challenges of the new grid design with the introduction of DERs. The technology is not based on adapting the grid to the change, but adding a layer of information technology to reshape this grid modernization to fit into the conventional operation. With this, a VPP enables an effective integration of RES (Dielmann & van der Velden, 2003).

## 3.2 Economic mechanisms to overcome economic concerns

In this section, the knowledge base concerning economic mechanisms, theories and frameworks to deal with the design challenges is looked into. First, I will go over the economic-related design challenges, their underlying matters, and the needs they reflect. In the next subsection, balancing mechanisms on a national scale will be explored as a means to handle previous mentioned design challenges. Lastly, a pricing mechanism on the scale of the consumer is discussed to support grid balance.

### 3.2.1 Economic needs

As mentioned in subsection 2.2.4, a distinction can be made between macro-economic and micro-economic challenges. These micro-economic concerns, of direct importance to individual grid users and including maintenance and equipment costs, impact of inverter failures on the ROI of a system, were discussed in section 3.1.2. In that section, the conclusion arose that DTT would be able to handle and contain these micro-economic challenges. Therefore, these concerns will not be elaborated on anymore in this section. Instead, the macro-economic challenges will be handled in this section. These concerns, i.e. price volatility, uncertain trades and negative prices, are all direct consequences of grid imbalance and instability due to the intermittency of the DERs. Therefore, a need for an economic mechanism to deal with this matter of grid imbalance can be defined. First, I will explore this need on a national scale by looking at what can be done high-level to balance out the grid. Next, I look at price driven demand-response as a mechanism to diminish or stabilize the energy cost of end users.

### 3.2.2 Balancing mechanisms

The need for balancing the grid can be explained as follows. As mentioned in section 2.1.1, the integration of renewable energy increases the variability of the grid due to the intermittent nature of the sources, which leads to grid imbalance. When this occurs, a grid frequency decrease occurs in case of a higher consumption than production, or a frequency increase when production is higher. Grid imbalance threatens the reliability and stability of the electricity grid. This leads to a need for ancillary services and, more specific, a mechanism to stabilize the frequency and balance the grid (Giovanelli et al., 2018). The balance of the grid is managed by a TSO that requires every energy producer participating in the grid operation to maintain an output that ensures the balance. For the Belgian grid, the TSO is Elia (“Balancing Energy Markets,” n.d.). When an imbalance occurs nonetheless, balancing power is used. This energy is purchased by the TSO in balancing energy markets. On this market, Balancing Service Providers (BSP) offer balancing flexibility through various mechanisms that can be procured by the TSO (Keeping the Balance, n.d.). Three mechanisms will be discussed; Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), and manual

Frequency Restoration Reserve (mFRR). In order to prove their rigor as well as their relevance, the concepts will be explained by means of literature, as well as exploring their implementation in Europe.

These three reserves can be distinguished by their reaction time in case of a frequency deviation due to grid imbalance. The FCR is the first reserve that will be called upon. This power reserve is an automatic response to a deviation in real-time, activated within 30 seconds. By continuous monitoring of the grid frequency, FCR can automatically intervene and limit the deviation. The second measure that is activated, with a reaction time of five minutes, is the automatic FRR. It replaces the FCR after five minutes and restores the balance automatically. By receiving setpoints about the balance status when the aFRR is activated, the grid operator can adjust the reserve as needed. When a grid imbalance lasts for over 15 min, the mFRR is activated manually and replaces the aFRR. This way, large and prolonged deviations, and thus grid imbalances, can be met by these reserves (“Balancing Energy Markets,” n.d.; Firoozi et al., 2020; Merten et al., 2020). The operation of the balancing energy markets is rather straightforward. In case of a need for an aFRR or mFRR intervention, the TSO will select and activate the market participants with the lowest energy prices until the demand is met and the balance is restored (Camal et al., 2018). For the FCR, the market enforces a requirement for the participants of a bid of 0.1MW, in order to reach an adequate capacity (Giovanelli et al., 2018). In order to standardize and enable the exchange of this balancing energy, the European Network of Transmission System Operators for Electricity (ENTSO-E) developed European platforms. A first one is the mFRR platform ‘MARI’. This platform serves for the exchange of energy from mFRR across multiple countries to restore frequency and balance the grids. Second, the aFRR platform is called ‘PICASSO’. On this platform the aFRR bids and needs across TSO’s from European countries will be exchanged, to balance their grids (ENTSO-E, 2022).

Now, let RES enter this topic. How are these reserves provided currently, and can this be done by RES? The resources that provide these three reserves are currently large conventional power plants (Firoozi et al., 2020). Due to the intermittency and thus production uncertainty of RES, TSO’s have mostly kept them out of providing ancillary services (Camal et al., 2017). However, the literature present about the topic indicates this to be a feasible possibility, all providing the same crucial condition. Recall the minimum required bit. A DER cannot provide this on its own, which means that, in order to use DERs to provide these reserves, an aggregator is needed to coordinate these distributed sources and trade in a coordinated way on the balancing markets (Giovanelli et al., 2018). This aggregator could be provided by the use of a Virtual Power Plant, which was discussed in section 3.1.3. Various studies about the use of RES to provide stabilizing reserves have been performed. Concerning the FCR, Giovanelli et al. (2018) construct a coordination scheme for FCR provision through consumer aggregation. Concerning the aFRR, Camal et al. (2017) study the provision of a reliable day-ahead offer of aFRR by a VPP that aggregates PV and wind power plants. The provision of mFRR services is discussed by Firoozi et al. (2020). They describe a two-stage model of how a local energy community with PV systems, electric vehicles and battery energy storage systems can provide mFRR services. The use of RES to provide ancillary services is however not only studied in literature. In Europe, the Restable project starts from the assumption of a high level integration of RES into the European electricity grid. It focusses on the development of a VPP in order to demonstrate that RES have the ability to provide these frequency control reserves to the European grid (Restable Project – Grid Stability and Ancillary Services, n.d.).

Lastly, I will discuss how these balancing mechanisms positively influence design challenges. Important is to note that these mechanisms are mostly advantageous for the business side of grid participation. (The end user's wellbeing will be discussed in the next subsection.) As already mentioned, the TSO's benefit from these mechanisms is that they enable the grid to stay balanced. Fig. 2 showed how grid imbalance leads to instability, which would be avoided by using the reserve mechanisms. Another party that highly benefits from the reserves are energy producers and traders. In situations where the reserve price to sell energy at is higher than the average price for energy, it would be economically speaking more interesting for the energy trader to participate in the balancing energy markets. Participation in both the energy and the reserve market leads to an increase in revenue for energy traders (Camal et al., 2017). Recall the occurrence of negative energy prices, mentioned in section 2.2.1. If an energy producer would trade on the balancing energy market as well, this would prevent them from having to sell their surplus energy at a negative price in case of a grid imbalance. Instead, they would have the opportunity to sell the surplus as a reserve. However, this would only be possible in two cases. Either the reserve markets operate with Energy Storage Systems (ESS), which would enable the storage of this surplus production for reserves (Nitsch et al., 2021). ESS will be shortly discussed in section 3.3. However, they are mostly out of the scope of this paper. Another possibility would be for reserve markets to span over multiple electricity grids. In this case, an energy producer who would normally sell to one grid, could sell to the reserve market. This market would then transfer this energy to a grid with shortage. This is however close to the concept of offloading.

### 3.2.3 Real Time Pricing Mechanism

In the previous section, balancing mechanisms were discussed to alter the supply in order to meet demand. However, it is also possible to approach grid balance from the demand point of view. If this is the case, we are talking about demand response. This response can be event-driven or price-driven. I will focus on the latter. Price-driven demand response (PDDR) can be described as consumers altering their consumption patterns, and thus energy usage, because of changes in the energy price. By doing so the peak load can be shifted and PDDR can impede voltage instability by providing ancillary services (Yan et al., 2018). One of the possible PDDR techniques is real-time pricing (RTP). In this case, the energy price is not predetermined and established in advance, but varies continuously. The exact value of the energy produced in a period is calculated real-time, so the energy price is based on real-time production cost. These real-time prices are made public only an hour or day in advance, when the current period begins (Samadi et al., 2010). This way, the energy price reflects the behavior of supply and demand, and the influence of random events or consumers' reaction on previous prices will be embedded into the current real-time price (Roscoe & Ault, 2010; Samadi et al., 2010). The goal of this pricing strategy is for consumers to adapt their consumption behavior accordingly, and consequently flatten the peak load to stabilize the grid balance, and lower energy costs for consumers (Yan et al., 2018). By monitoring the electricity prices throughout the day, a consumer can stay away from high energy use during peak load moments during the day and shift their consumptions to moments with a lower price. This will lower their electricity bill (Tsui & Chan, 2012).

This pricing technique is especially valuable with the use of DERs. Since these sources could be located closer to consumers than conventional power plants, there might be no need for transmission and distribution, which would eliminate these costs. In addition, as seen in section 2.2.1, there is the intermittency of the sources that creates production and thus price volatility. These unique aspects are not captured by the wholesale energy price, decided in advance, and leads to inaccurate pricing and possibly unfavorable energy prices for consumers (Beck & Martinot, 2016). Since RTP is based on real-time data on energy generation and consumption, this pricing techniques captures a more accurate value.

This rigorous pricing technique has been the topic of research for quite some time. To illustrate, Samadi et al. proposed an optimal RTP algorithm for demand side management already in 2010. However, the relevance of the topic is a rather recent trend, due to the introduction of smart meters. In residential areas, smart meter infrastructures are essential to use the RTP technique, since the real-time consumer consumption needs to be measured to construct the price (Yan et al., 2018). The need for smart devices has already been mentioned in section 3.1.2, in order to obtain a Digital Twin. The conclusion can thus be drawn that by the modernization of the grid, and the implementation of modern technology, intelligence of the grid can be enhanced. This would in its turn lead to economical advantages.

## 3.3 Normalized Systems Theory to enable grid stability

In this last subsection about techniques and mechanisms, the design challenges concerning the physical structure of the grid are addressed. As seen in Fig. 5, these challenges are the basis for all other concerns. Because of this, it is important to find a theory or mechanism that can really be applied to the entirety of the grid, down to its core basic structure. One theory that focuses on the structural integrity of artefacts is Normalized Systems Theory (NST), established at the University of Antwerp. The objective of this subsection is to look at the physical structure of the electricity grid through the eyes of NST. First, an introduction into NST itself will be provided. Subsequently, this theory will be applied on to the electricity grid. Lastly, encapsulation mechanisms are defined to ensure the minimization of the identified ripple effects.

### 3.3.1 Normalized Systems Theory

Normalized Systems is a theory established to enhance the agility and evolvability of software through modular system design. The need for evolvability stems from changing requirements for software. This software evolvability however is inhibited through the presence of combinatorial effects. When a modular system is not carefully designed, change can lead to ripple effects, which are defined in section 2. These rippling changes propagate through the system and create instabilities, leading to combinatorial effects. The objective of NST is to identify these ripple effects and deplete their propagation, to overcome the fact that their impact can become unbounded. This reasoning is based on system theory, considering the artefact design as an evolving system (Mannaert et al., 2016; Oorts et al., 2014). The ripple effects are in fact a manifestation of an underlying mechanism, i.e. coupling. Coupling is a way to measure the degree of dependency between modules in a system. Ripple effects reveal the presence of a highly coupled design (Mannaert et al., 2020). To identify and immediately deplete these ripple effects, NST presents four design theorems. These theorems start from the assumption and requirement that ripple effects due to basic changes must be avoided, and thus that basic changes must be identified and dealt with in an appropriate way. They enable modular software design that ensures evolvability of the system. The four theorems are Separation of Concerns, Data Version Transparency, Action Version Transparency, Separation of States (Mannaert et al., 2016). Since these theorems are specific to software, I will not go into further detail about them.

However, even if these NS theorems are specific to software, the reasoning behind ripple effects and their depletion is not. The fact that basic changes in modular structures might lead to ripple effects, whose propagation must be immediately depleted in order to enable an evolvable design, can be applied to any modular system or artefact. To do this, it is not the specific NS theorems that must be followed. But rather one must detect the relevant basic changes, the coupling modes that lead to these ripple effects and construct a way to encapsulate them. This general reasoning behind NST can be applied to the electricity grid (Mannaert H., personal communication, March 16, 2023). In order to do so, the cross-cutting concerns of the system must be defined. These are concerns that are present and relevant throughout the whole artefact and thus ‘cut across’ its structure. Through identifying these in a modular system, the dependency of the modules and thus coupling of the system can be addressed. By rightly encapsulating the cross-cutting concerns of a system, the coupling modes can be contained and their ripples effects avoided, which will ultimately lead to the ability of designing an evolvable system (Mannaert et al., 2020).

### 3.3.2 NST grid application

To reiterate, when applying the reasoning behind NST to the grid a couple of steps must be followed. First, the basic changes in the electricity grid must be identified. Next, the coupling modes must be addressed by whom the basic changes lead to ripple effects. Then the cross-cutting concerns in the electricity grid are determined. Lastly, mechanisms to encapsulate these cross-cutting concerns are established to contain the coupling modes and deplete the rippling of basic changes. It is important to note that when listing basic changes, coupling modes, cross-cutting concerns, and encapsulation mechanisms, that these lists are not exhaustive. They serve as a personal interpretation of applying the NST to the electricity grid and can of course be extended.

First, the basic changes. Since the scope of this work is the impact of the integration of DERs into the electricity grid, I define the basic changes with respect to this. The following changes can be identified:

- The introduction of an additional distributed generation unit
- The replacement of a conventional power plant by a distributed generation unit
- The introduction of a connection to another grid for import external production or export internal production
- The introduction of an additional communication infrastructure

These are, in my view, the four main changes occurring in the grid when focusing on the integration of DERs. Next, the coupling modes in the electricity grid are defined. These are the modes that initiate ripple effects when introducing the basic changes mentioned above. Concerning the coupling modes, different groups can be defined. First, grid imbalance and synchronization problems are modes of coupling that ripple through to impact the power quality and stability of the grid, as mentioned in section 2. These coupling modes can all be reduced to one general need in the grid, one concern that cuts across the entirety of the electricity grid, which is frequency stability. By rightly encapsulating the mechanism to ensure frequency stability in the grid, these coupling modes can be minimized and their effects depleted. Other coupling modes are harmonics, or the use of inverters. These coupling modes are present in relation to another cross-cutting concern, conversion. When integrating DERs such as PV systems, there is a need for DC-AC, and probably AC-DC conversion throughout the grid, making it a cross-cutting concern. The encapsulation of the provision of this concern, should deplete the impacts from harmonics and any inverter-related issues. A last group of coupling modes that leads to the definition of another cross-cutting concern is related to the grid design. If not dealt with correctly, the bidirectionality of the grid is a coupling mode since the two-way energy provision and communication leads to additional links and coupling. The decentralized grid design, is also a coupling mode since a higher amount of units must be connected to the grid. However, this bidirectionality and thus the 2-way communication can also be defined as a cross-cutting concern since the need for this concept can be found throughout the grid and for every grid participant. With a mechanism to rightly encapsulate this concern, the coupling modes that could be present due to these characteristics will be contained, and will not ripple through to the impacts mentioned in section 2.1.2.

### 3.3.3 Encapsulation mechanisms

After identifying three cross-cutting concerns, mechanisms must be found to integrate them in a way that minimizes coupling. Mannaert et al. (2020) define three design guidelines to integrate cross-cutting concerns into an hierarchical system. The first one is encapsulation. The cross-cutting concern should be integrated in an encapsulated way. The next guideline is interconnection, which implies that the concern should be implemented in a relayed way through an interconnection instead of implemented in each module itself. Lastly, the guideline downpropagation is mentioned. This addresses the fact that the implementation of the cross-cutting concern should happen on the lowest aggregation level possible. With these three guidelines in mind, I define three techniques to integrate the defined cross-cutting concerns into the grid. It is relevant to note that I will not go into technical details about these techniques. The objective of this section is merely to demonstrate how applying the NS reasoning can lead us to find solutions that deal with the rippling design challenges mentioned in section 2.

The first concern to address is frequency stability. To integrate this into the grid while adhering to the design guidelines, Energy Storage Systems (ESS) can be considered. One of the main challenges that kept returning in section 2 was grid balance, and related challenges such as congestion, peak loads, synchronization problems, output restriction. With the possibility of energy storage during times of high production and low demand, and dispatch from these storage systems during peak loads, the output can be stabilized. This way, the combination of RES or DERs with ESS would enhance the reliability of the grid (Palizban & Kauhaniemi, 2016). The integration of ESS can be done in a distributed or aggregated way. When distributed, each generating unit would be connected to its own ESS. When aggregated, the whole system, the grid, would have one ESS to support the grid operation. The guideline of interconnection advocates for an ESS on an aggregated level as to avoid implementation duplication. However, the guideline of downpropagation mentions the provision of the concern to the lowest level possible, and advocates thus for the integration of ESS in a distributed way (Mannaert et al., 2020). The discussion on which option is best for a modular and evolve grid design is outside of the scope of this paper.

The second cross-cutting concern mentioned was the one of conversion. To deal with this concern, we start with the assumption of a residential grid where households use PV systems for electricity generation. This residential grid can be considered a microgrid. However, it is not stand-alone. In case of a shortage of generated energy, this ‘subgrid’ is connected to a bigger entity, the electricity grid. Recall how in section 2.1.3, it was mentioned that there was a need for DC-AC conversion since PV systems generate DC but the grid is AC. There was however also a need for AC-DC conversion, since many modern appliances function on DC. Conversion is thus embedded throughout the whole grid structure in, what seems to be, a redundant way.

When considering the design guidelines, with a focus on interconnection, one could conclude to elevate the conversion to the level of the grid instead of every separate unit. A technique that would do this is the implementation of DC microgrids. In a DC microgrid, the common carrier is DC. This implies that the DC-AC-DC conversion mentioned above would not be necessary on the distribution level, which would prevent substantial energy losses (Justo et al., 2013). The DC-AC conversion would now happen on grid level, where an encapsulated and interconnected inverter would transform the DC power of the microgrid to AC to link to the electricity grid’s higher-voltage transmission lines. The integration of a DC microgrid would also deplete the coupling modes related to frequency stability, since there is no need for synchronization or compensation of harmonics in DC mode (Gaur, 2021).

The last cross-cutting concern identified, is the bidirectionality or two-way communication. Let’s consider the design guidelines again. The integration of this two-way communication should be encapsulated, as to not give rise to extra coupling. It should be downpropagated, meaning that this communication should be provided to the lowest level possible. In other words, it should be possible for each generating unit to have a communication capability. Lastly, the integration should be performed through interconnection, meaning that the concern of providing this infrastructure should be realized in a relayed way (Mannaert et al., 2020). With this in mind, I propose an integration and encapsulation mechanism or technology that was already identified in this paper. For this, I consider the Virtual Power Plant (VPP) introduced in section 3.1.3. Through the consolidation of DERs into one virtual entity, the concern of two-way communication is relayed to a separate module, ensuring interconnection. However, communication is provided to every unit, meaning that every unit is connected to the VPP, ensuring downpropagation.

Through the integration of these three mechanisms, i.e. ESS, DC microgrids, and VPP, a more stable modular grid could be designed that would impede the ripple effects of basic changes, thus handling all design challenges brought forward in section 2. This would enable the electricity grid to stay evolvable and effectively cope with the high penetration of renewable DERs.

# 4 Design and Implementation of an Analytical Tool for Assessing the Influence of Dynamic Pricing Paradigm on Electricity Grid Stability

In this section, a design science contribution is proposed through the design and implementation of an analytical tool for assessing the influence proposed mechanisms in section 3 on the evolvability of the grid.

With this design contribution, the third and last cycle, the Design Cycle, introduced by Hevner (2007) is addressed. In this cycle, the actual design is constructed by developing alternatives, evaluating, and adapting them to a final result. For this design, the needs and design challenges from the relevance cycle are applied as input, as well as the mechanisms and technologies learned in the rigor cycle.

To document the development of said tool, the steps of the waterfall model will be followed, a model brought forward for software development. However, the waterfall model is based on a sequential execution of the steps, whereas this work is conducted with a more iterative approach towards the different steps. The knowledge gained about this model and provided in this various steps is derived from the course '*System Design*', taught by Jan Verelst at the University of Antwerp in the Bachelor Digital Engineering: Management of Information Systems.

The following section will first discuss the specific mechanism that is focused on in this design cycle and why. Afterwards, as mentioned above, all steps of the waterfall model are discussed.

## 4.1 Dynamic Pricing Paradigm

In the previous part of this thesis, the third chapter offered theories, technologies and mechanisms to provide the right materials to design a solution for the challenges mentioned in the second chapter. In other words, the mechanisms that were introduced, try and minimize the problems rippling through the electricity grid when DERs are integrated. This fourth chapter will maintain a more practical approach. Now that theoretical solutions are offered to cope with the ripple effects of the challenges related to DER integration, it would be beneficial to examine what this would actually mean in reality.

In order to do so, real data is needed and the trends in renewable energy sector should be investigated. In doing so, a trend towards the use of dynamic pricing contracts can be noticed. Recall how in section 3.2.3 these kind of mechanisms were already mentioned. The term Price-driven demand response (PDDR) is used when end users of the electricity grid, the consumers, respond to a changing energy price by altering their consumption patterns throughout the day and thus shifting peak load (Yan et al., 2018). A possible technique to invoke PDDR is dynamic pricing (DP). With this approach, the electricity prices are dynamic, changing continuously so that the consumer pays for its electricity usage the price of that moment (Théate et al., 2023). In Europe, the hourly electricity prices differ per country and are made available a day in advance. These day-ahead prices can be consulted on the ENTSO-E platform (Data view, ENTSO-E). The fact that introducing DP contracts into the electricity market in Europe is a rising trend can be proven by a proposal filed by the European Commission in March 2023 for a change in regulation to improve the Union’s electricity market design. In this proposal, DP contracts are offered as a response to volatile electricity prices, and are meant to strengthen consumer protection against it (European Commission, 2023).

According to Théate et al. (2023), an important assumption that needs to be made concerning DP, is that consumers are equipped with smart metering devices for their installations. This way, the communication of the price signal and production or consumption measures can be performed. Next to this, the DP paradigm would be more beneficial if the end user would have a battery to store electricity, and maybe a PV installation to generate electricity himself.

The question that rises with this popular paradigm, is its effect on grid stability. In the previous part of this thesis, pricing mechanisms were mentioned to shift the peak load and thereby securing voltage stability. However, if all consumers were to make use of this DP paradigm to the fullest, by having a generating unit and an Energy Storage System (ESS), would they not be exhibiting highly similar behavior, thus creating peaks all over again? What is the influence of this on the stability of the electricity grid?

## 4.2 Analysis

### 4.2.1 Problem Statement

The previous section ended by composing a hypothesis. What is the influence of DP induced consumer behavior on the stability of the electricity grid? Does exhibiting this similar behavior lead to a new set of peak demand moments?

To test this hypothesis, real data is needed from such households in order to simulate similar behavior that could be shown when having a DP contract. To be able to perform this analysis with the needed data, and to gain some expertise from skilled professionals about the matter, I worked closely with Cast4All Technologies (or short, Cast4All), a Belgian energy monitoring company. This company provided me the needed data to analyze my hypothesis, guided me through the concept of the DP paradigm with the related subsequent behavior, and introduced me to the possible functionalities to implement that would help consumers optimize their PDDR through their smart metering devices. The process of this data acquisition will be further discussed in section 4.2.5.

After retrieving data about households, what else would be needed to test this hypothesis? The power flow that occurs in a grid with these households needs to be analyzed. Thus, a grid simulation must be established using the acquired data. Afterwards, a power flow analysis (PFA) needs to be performed. In a PFA, a set of equations need to be solved in order to obtain information about the set up network or system. This analysis provides information about each bus in the network and its loads, generators and lines. The information entails voltage angles, magnitudes, power flow on the lines, voltage conditions etc. (Mukherjee et al., 2012). After establishing a PFA of the original data, this should be performed on data with DP induced behavior as well.

A next concern to address related to the problem statement is the stability of the electricity grid. How will this be evaluated with the available information? For this, the voltage angles that are obtained through the PFA can lead to a conclusion concerning the grid stability. Voltage angles or phase angles are the difference between voltage waveforms at different points in a system. It refers to the timing between waveforms or the voltage supplied in an AC grid by different buses. This way, they are a key element in evaluating the stability of the grid, since they are essential in keeping a balance between generation and consumption. (electricschool, 2018; Von Meier, 2006)

A voltage angle is a relative concept. It is the relative contribution to the real power in the system, and its value is in reference to the slack bus. The slack bus is the generator in the system, or grid that is assigned to do load following. This means that when the loads in the grid ramp up or down, the slack bus's task is to do everything in its power to follow this new demand or injection and balance the grid. The voltage angle at the slack bus is a constant, in order to keep this balance. The angles at the other buses are thus the relative value to the slack bus. These values, and thus differences from the slack bus, are a crucial component in verifying the balance and thus stability of the grid. The bigger the differences in voltage angles, the bigger the danger for grid imbalance and thus instability. In real power grids, this difference has a limit. If this limit is exceeded, the grid loses synchronicity. (Von Meier, 2006)

The short breakdown on voltage angles above explains its importance in evaluating the influence of DP behavior. If the hypothesis holds, and DP behavior causes a sudden rise of similar behavior, and thus of peak activity, these voltage angles might lose their stability.

Another way to evaluate the situation, is through investigating the power flows immediately. A sudden change in power flow can also be cause for concern since this clearly entails a peak offtake or peak injection. Yan et al. (2018) states that peak loads are a threat for grid balance and should thus be flattened, by for example pricing mechanisms. An imbalance in the grid, even for a short period can ultimately cause instability in the grid (Giovanelli et al., 2018).

To conclude the problem statement around this hypothesis, data is needed to create a grid simulation in order to be able to simulate DP induced behavior. A PFA is needed to obtain power flows and voltage angles, which will serve as indicators for grid stability issues.

### 4.2.2 Solution: Analytical tool

As mentioned above, in this design cycle of this thesis, an analytical tool will be developed to test the hypothesis that was made. What is the impact of the dynamic pricing paradigm on the stability of the electricity grid? The problem statement defined some necessities for a tool to explore this hypothesis. First of all, data is needed to simulate a grid with real input. Additionally, the construction of a PFA on this grid simulation is needed to evaluate the voltage angles and the power flow on the lines. Lastly, it has to be possible to manipulate the data according to certain behavior that consumers with a DP contract would exhibit. In order to design and implement the actual tool, some assumptions must be made:

**ASSUMPTION 1**: The needed data has to be real data from households. The assumption is being made that households within the grid all make use of an ESS, a battery, and are thus able to store electricity, as to fully make use of their dynamic contract. In section 3.3.3, ESS were proposed as an encapsulation mechanism to enhance the cross-cutting concern frequency stability. By making this assumption, I cannot only explore DP behavior to the utmost, but I can also analyze the influence of two proposed mechanisms of chapter 3. The one mechanism being ESS, the other the DP paradigm.

**ASSUMPTION 2**: The household data used contains households with PV installations. This way, the key topic of this thesis will be adhered to, the integration of DERs into the grid. If the data captures grid behavior with DERs, the reason for analyzing the influence of DP will stay clear. This mechanism was brought forward to deal with ripple effects due to the integration of DERs. It is therefore highly logical that the simulation features DERs as well.

**ASSUMPTION 3**: Certain specific actions might be taken due to having a DP contract. These will be discussed in the design step. It is however important to note that performing certain behavior one hour will influence the consumption pattern and thus the data for the rest of the day. Nonetheless, since I will focus on this specific action and behavior, I will make abstraction of the further influence throughout the day. The tool will thus only manipulate the data at the moment of a specific DP related action being taken.

**ASSUMPTION 4**: As mentioned in the previous section, voltage angles are in relation to the slack bus. This means that the grid simulation should be in possession of a slack bus. This is understandable, considering that the grid offtake measured at households needs to come from some source. I therefore make the assumption that the simulated grid with real household data, contains a central power plant. This power plant takes on the role of slack bus and is responsible for maintaining the grid's stability. The power plant will ramp up and down immediately depending on the grid offtake and injection of the households. The voltage angles at the household buses have a value in relation to this power plant. In order to easily analyze this relative value, the constant voltage angle of the power plant will be set to 0.

With these assumptions in mind, the actual requirements of the tool can be explored. The problem statement and the solution section made clear what the problem behind the hypothesis is, and what would be needed to research it. The next step is to translate this into a requirement specification. This can be organized into functional and non-functional requirements. In doing so, the needed data becomes more clear and an analysis of the data acquisition can be made. These will be the following steps of this thesis.

### 4.2.3 Functional requirements

Functional requirements define the functionality that is necessary for the new application, system, or in this case, tool. By writing down functional requirements, the features and functionalities that the new tool needs to have, are listed clearly. In doing so, a requirement specification is established to serve as a guideline throughout development and a checklist during testing.

**Extract, Transform, and Load (ETL) functionality:** It is necessary for this analytical tool to be able to retrieve the data from the available REST-API from Cast4All and to transform it into a data structure or type that is suitable to use for the tool.

**Store data from multiple households for different days:** The tool needs data from multiple households on different days. It is therefore necessary that there is an ability to extract, load and store that data accordingly.

**Transform various timezones:** The data in Cast4All technologies is stored for time zone UTC. Since the actual time zone in Belgium is UTC+2 in summer and UTC+1 in winter, it is necessary that the new tool can transform this offset.

**Transform time interval of data:** The data that is being provided has a time interval of 5 minutes. Since this is much too detailed and thus leads to an overload of data, it would be optimal for the tool to be able to transform this interval to an hour. This way, PFA can be performed with a more clear view.

**Calculate household consumption**: When looking at the data, there is only data available about the battery power, grid power, and PV power. There is no power measure considering the load or consumption of the household. Since the load is a crucial aspect in PFA, the tool should be able to calculate this, using the other measures.

**Create a grid simulation:** This might be the most crucial functional requirement. The tool should be able to create a simulation of a small microgrid, using the available data.

**Perform a power flow analysis (PFA):** A crucial requirement as well, after creating a grid simulation, the tool should be able to perform a PFA on this grid simulation. This way, the behavior of the grid can be analyzed.

**Simulate DP behavior:** Considering that I want to inject behavior that is related to having a DP contract into the household data, the tool should be able to simulate this behavior one way or another.

**Manipulate data according to DP behavior:** After simulating DP behavior, it is important that there is the needed functionality to manipulate the data according to this change in behavior. With this manipulated data, a PFA can be performed again.

**Analyze the results:** Analyzing the results is of course a human action. However, it would be useful if some logic were to be implemented in the tool so that it could output conclusions itself. By automizing this analysis as well, the tool is a more holistic entity.

### 4.2.4 Non-functional requirements

Non-functional requirements do not focus on the features of the application, but rather on its overall quality, on how these features are working in general and should be performed. Examples of non-functional requirements are the following: correctness, robustness, adaptability, security, etc. I will not go over all non-functional requirements, but will name the most important ones for this tool.

**Correctness/accuracy**: this requirement indicates whether the system works correct without any mistakes and according to the functional requirements that were noted. Since the tool that will be developed in this thesis will be used to confirm or reject a hypothesis, its accuracy is of utmost importance. If this tool would make calculation errors or has the wrong logic built in and comes to a wrong conclusion, the conclusions based on this tool would be wrong. Future decisions might be even made with a tool like this. It could be used to justify certain arguments or decisions concerning the use of DP, so it has to be correct.

**Adaptability**: this requirement relates to the possibility and feasibility of the system to adapt when functional requirements would change in the future. This is highly important for this tool as well. Consider, for example, other pricing related paradigms emerging for which a company like Cast4All would like to analyze its influence on grid stability. Then it would be necessary for this tool to implement other behavior without that much problem. This requirement relates to **evolvability** as well. It must be possible to implement changes to this tool and use it for variant analyses without too much trouble. To be able to do so, ripple effects in the tool must be minimized. Ripple effects occur when one change in one part of the program, or tool, leads to more changes throughout the rest of the program. If I want to guarantee this tool being able to adapt to different paradigms, situations, prices, etc., ripple effects cannot occur.

**Portability**: this requirement relates to the possibility of the system to be easily moved or adapted to different operating systems, platforms, environments without significant modification. Any analytical tool is meant to be used by different users, with different levels of technological skills, and various stakes. It is therefore important that the tool is a portable entity, to be shared between people and run in different environments, and on different operating systems. It would be highly bothersome if any user that wants to perform this analysis should adapt the code to his or her environment first.

**Integrity/security**: This requirement concerns the security of the system to avoid unauthorized people accessing certain data, or for personal data to be read by any user. Since personal data from the clients of Cast4All is being used, it is crucial that this tool ensures the integrity of this data and is therefore decently secured.

**Testability**: It is important for this tool to be easily tested. The argument behind this is similar to the importance of accuracy in this tool. Since this tool needs to be accurate and correct, this quality must be easily tested to ensure this for future users.

### 4.2.5 Data acquisition

As mentioned in the problem statement, in order to be able to obtain real data on the consumption pattern of households, I worked together with Cast4All Technologies. Cast4All provides a platform for independent monitoring through the aggregation of installations in your household. With this platform, they can monitor PV installations, batteries, grid meters, etc. The platform is equipped with a REST-API to which calls can be made to retrieve this monitored data. Throughout my cooperation with this company, I was able to receive the necessary credentials and gather the household data needed for my grid simulation. The exact data are five households, each with a grid meter, battery and PV installation, of which the power values were available to me. The consumption of the household was not part of this data but is calculatable through the available data. This historical data was available for every 5 min of the last year. However, I only retrieved the data of two dates; 21/01/2023 and 21/06/2023. This way, winter and summer data is available to analyze, in case there might be a significant difference between seasons. A more elaborate explanation on this is available in section 4.4.2.1. Note that, considering that Cast4All handles personal data, the necessary steps were taken to ensure the privacy of this data throughout the thesis.

Another necessary data component in this thesis is the day-ahead prices. In order to simulate DP behavior, it is necessary to know the electricity prices of the day that is being analyzed since consumers with a DP contract will adapt their behavior according to these prices. The day-ahead prices are the hourly electricity prices made public for the next day. These prices are the binding prices used in a DP contract. The electricity exchange in Belgium is called the 'BELPEX', provided in hourly tariffs (Day-ahead Reference Price, n.d.; Yuso, 2022). As mentioned in section 4.1, these day-ahead prices can be consulted on the ENTSO-E platform (Data view, ENTSO-E). However, in order to retrieve the BELPEX day-ahead prices from the correct day in a desired data format, I consulted the webpage of the Belgian electricity supplier Elexys. They provide a page to download the needed day-ahead prices in an excel file format (Spot Belpex, n.d.).

## 4.3 Design

In the design step of the waterfall model, the main concern is to decide upon the structure of the software that will be implemented. There is a distinction between high-level design, the software architecture, and low-level design, the details of the system and the more practical aspect of design. However, before getting into this, I will discuss the design theorems brought forward in Normalized Systems Theory (NST) for software development.

### 4.3.1 NST's Design Theorems

The line of reasoning of NST was already introduced and discussed in the first part of this thesis. However, this theory was developed with software development in mind and entails 4 design theorems that minimize dynamic instabilities in the software. Attempting to adhere to these principles would therefore enhance system stability (Mannaert et al., 2016). This subsection describes these principles because I will strongly attempt to adhere to these theorems in the design and implementation phase.

#### 4.3.1.1 Separation of Concerns

The first design theorem, brought forward by Mannaert et al. (2016), is called Separation of Concerns (SoC). This principle states that tasks should be separated into different constructs. The reason for this is that when you would compile various tasks into one module or construct, variations in one task would lead to a multiplication of the other tasks. Changes in tasks would then multiply as well throughout various constructs. When designing and implementing code, it is therefore important to encapsulate utilities and functionalities to ensure maintainability of the code.

#### 4.3.1.2 Action Version Transparency (AVT)

The second design theorem focusses on constructs (functions) invoking or calling each other. When functions are dependent on each other this way, it is important to properly encapsulate the interface. If a function would not have a version transparent interface, a change in the function would lead to changes all over the system, in those functions calling the changed function. The second conclusion is thus to ensure stable, version transparent interfaces (Mannaert et al., 2016).

#### 4.3.1.3 Data Version Transparency

The third principle, Data Version Transparency (DVT) discusses the passing of data between entities (functions). Functions passing data to other functions are dependent on that data. If this data is not well encapsulated, a change to the data structure would entail a change in the code of those functions passing the data. The third concept to adhere to is thus version transparent data. This entails the avoidance of data coupling (Mannaert et al., 2016).

#### 4.3.1.4 Separation of States

Lastly, Mannaert et al. (2016) propose the principle Separation of States (SoS). The state that your code or system is in has to be stored. If not, new errors or exceptions will have to be reacted upon by invoking code.

### 4.3.2 High-level design

As mentioned above, high-level design relates to the software architecture. In deciding the architecture of a system, the objective is to divide the system or tool as a whole into smaller subproblems to solve. And so, subsystems or modules are defined. This brings us to the concept of modularity, dividing the design into various modules. By focusing on modularity during this phase, complexity is bound to be reduced in the system as a whole. The system is also supposed to be of higher maintainability when it has a modular design (Mannaert et al., 2016). While defining the subsystems of the tool, it is also important to take into account how these various modules communicate. For this analytical tool, the following subproblems can be defined:

- **Data retrieval module**: extracting the relevant household data from the appropriate API, transforming it into

- **Data preparation module**: the household, as well as the day-ahead price data needs to be prepared to use in the simulation. This entails fixing the utc offset, calculating the consumption, etc.

- **Grid simulation module**: the key part of the entire tool is the simulation of a microgrid with the retrieved and prepared data. This should be done in a separate module.

- **PFA module**: on this grid module, a PFA will be performed. Since this is an activity on its own, this is a separate subproblem and thus a separate module.

- **DP behavior module**: the goal is to simulate the consumption behavior of a household with a DP contract. This functionality is a subproblem on its own and therefore receives its own module.

- **Result analysis module**: Lastly, the results from the original and manipulated PFA must be compared and analyzed. This logic will be implemented in a separate module as well.

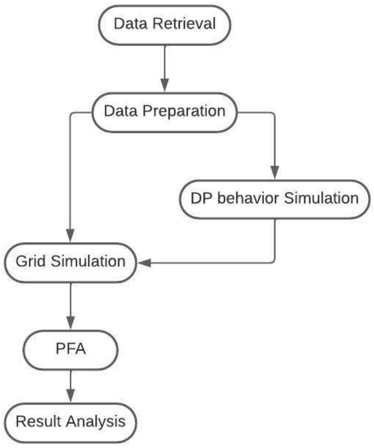


*Figure 7: module diagram - option A*

Considering cohesion, there can be concluded that each model has a very high cohesion. Within each model, there is only one functionality defined. When constructing a diagram with these modules, the mode of coupling becomes clear (Fig. 7). Since coupling needs to be minimized, the modules should be connected as minimal as possible. On the diagram, it appears that the modules of this tool are mainly coupled sequentially. Since one action follows the other, each module uses the output of the previous one and constructs input for the following. However, it might be possible to add a 'commander' module, the main module. This entity would call the other modules once the output from the previous one is returned. This way, the course of action of this tool would be centrally managed by one module, keeping track of the status of the tool. This would imply that if anything goes wrong, the main module knows exactly where. This way of working is shown in Fig. 8. The modules now only communicate with the main module, and are thus only coupled with the main entity. However, the sequential coupling is still implied. If one module fails, the rest of the tool will not be able to be executed since all modules are mere steps towards one result.

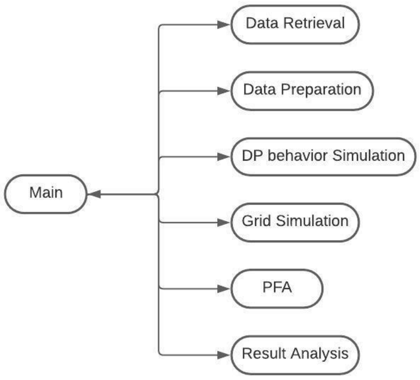


*Figure 8: module diagram - option B*

### 4.3.3 Low-level design

After designing the high-level architecture of the tool, a closer look should be taken into the details and practical design of each module. In the low-level design phase, the algorithms to perform are designed and the implementation of the non-functional requirements is being considered. The models and their design are considered carefully while keeping the design theorems, especially separation of concerns, into mind. I will discuss every module separately.

However, it is important to note that a significant amount of design choices will be only presented in the next chapter, the implementation. The reason for this is that various design choices are made with consideration of the programming language and its existing tools, making these choices part of the implementation process.

#### 4.3.3.1 Data Retriever Module

When having a more detailed look at the REST-API of Cast4All to access the data, it becomes clear that the data retrieval is a significant work load. The reason for this is that every measure of every household, for every separate day needs to be retrieved through a separate call. Every call generates a separate JSON file, resulting in a mass of data overload and number of files. After this closer look, the module should thus be separated into two separate tasks, two classes: The retrieval of the data, and the creation of one CSV file. This choice is related to the fact that this thesis works with personal data. Other parties who will use or review this analytical tool might not be able or allowed to access Cast4All's REST-API. I therefore made the design choice to construct one CSV file for every day that will be analyzed, in which all data from all households are gathered. This way, the code can still be run, starting with the CSV file.

#### 4.3.3.2 Data Preparer Module

This module performs various tasks. However, they can all be defined as a 'Data Preparation' task and can thus be taken together into the same module. Each task, however, will need its own class. The first task is to import the csv file (or another file) and store it into the correct data structure. This of course depends on the chosen programming language. Next, all alterations that need to be made to the household data are stored into the class 'HouseholdDataPreparer', where each alteration to the data is encapsulated in its own function. Lastly, alterations to the BELPEX data, are data specific as well, and thus different from the household alterations. These will thus be comprised in the class 'BelpexPreparer'.

#### 4.3.3.3 Grid Simulation Module

One module serves for the simulation of a grid. In order to be able to decently study the power flow and voltage angles of the various households, I made the design decision to encapsulate these households into an encapsulated, self-sustaining microgrid. This way, there would be no changes or influences from 'outside' and the data of these households can be decently studied.

To have an encapsulated microgrid, there needs to be a power plant within this grid. In this software module, a grid should be established, a power plant introduced, and all households need to be add with their own load, generator and storage unit. This will also be implemented in separate functions. Note how this power plant serves as the slack bus, as mentioned in 4.2.2, and will thus have a constant voltage angle of 0.

#### 4.3.3.4 PFA module

On this grid simulation, a power flow analysis will be performed. Since various tools exist to do so, it is not yet clear whether or not the code for this functionality will be abundant or not. It might therefor be a valid design choice to include the PFA into the grid simulation module. This choice will be made in the implementation phase, since it depends on the programming language and existing tools. The result of the PFA will be two datasets: the power flow between all existing lines in the grid, and the voltage angles at each bus. The reason to output the voltage angles was already discussed in section 4.2.1. This output will be used as input for the result analysis module.

#### 4.3.3.5 Dynamic Pricing Behavior Module

In the low-level design phase, it is time to define this dynamic pricing behavior. To do so, I consulted the expertise of Cast4All. The first smart metering functionality they implemented, related to the DP paradigm, was pre-charging the battery during the night. If the battery state of charge of consumers was less than 80%, the smart device would send an order for the battery to charge at night during the cheapest night hour. This way, the peak load during the morning can be captured with the battery instead of electricity of the grid, which would be very expensive at that moment. I decided to implement this feature as ‘DP behavior’ and to simulate battery charge during the cheapest hour of the night. Thus, in this module, there are two tasks. Find the cheapest hour at night, and manipulate the data according to this behavior mentioned above. These tasks will be encapsulated in a separate function.

#### 4.3.3.6 Result Analysis Module

In this step of the waterfall model, logic implemented in the software should be discussed, as has been done above. In order to be able to derive a conclusion from the PFA and the manipulation of the data, some logic needs to be implemented that leads to a conclusion. The following logic will be implemented: compare the voltage angles of the original situation and the situation after data manipulation. More specific, analyze the voltage angles during the cheapest hour of the night for each household. Check three conditions:

1. In the manipulated dataset, is the absolute value of the voltage angle $x$ times bigger than the voltage angle of the previous hour?
2. In the manipulated dataset, is the absolute value of the voltage angle $x$ times bigger than the voltage angle of the following hour?
3. Is the absolute value of the manipulated voltage angle during the cheapest hour $x$ times bigger than the original voltage angle during the cheapest hour?

Since this tool serves as a way for stakeholders to analyze the grid behavior, the decision on the level of significance of change should be made by the user of the tool. The factor $x$ should therefore be an input by the user. If all three conditions are adhered to, the change in voltage angle at that household is considered significant. This significance could be implemented as a Boolean.

#### 4.3.3.7 Main module

Recall the two diagrams in section 4.3.2. I now make the design choice to implement the tool according to Fig. 8, by using a main module. The modules, or classes, will thus not call each other. They will be getting called upon by one main module. The reason for this choice is the fact that the main module enables me to keep track of the state. When every module is only coupled to one and the same main module, this entity can keep track of the workflow of the tool (and its status) and can notify when something goes wrong and where. This way, separation of states is adhered to. The main module should also allow the user to insert two parameters when running the data. These parameters are the date for which the analysis should be run, and the factor of significance the voltage angles should be analyzed with.

## 4.4 Implementation

### 4.4.1 Programming language

In the implementation phase, the modules and their classes that were defined in section 3 will be implemented in a specific programming language, using various tools. When wanting well encapsulated object-oriented code, it would be a great option to implement the tool in Java. However, in the case of this thesis, while choosing a programming language, the main concern was the grid simulation and the ability to perform a PFA. After some research, the clear answer to this is the PyPSA toolbox. This toolbox is an open-source environment that enables energy system modelling and the performance of PFA. This toolbox was developed at the University of Berlin and is highly used in Europe to perform analyses on the European grid as well (PYPSA website, n.d.). The toolbox has a very clear documentation that explains how to initiate a network/grid and what components can be integrated. The use of this toolbox would also ensure the accuracy of the tool considering electrical knowledge, since this will be entailed in the software. Since PyPSA enables me to easily and correctly construct a microgrid and perform a PFA, the choice of programming language necessarily leads to Python.

Since Python is a dynamically, interpreted language and not a class-based programming language, the ability to implement a highly modular design and to adhere to the design theorems becomes more challenging than in Java for example. However, the abundance of tools and packages available for Python make it a highly accessible language (*What Is Python? Executive Summary*, n.d.). In order to try and construct a design as evolvable as possible, I programmed this tool in Python as close to my knowledge of the static, class-based and object-oriented language of Java.

Next to PyPSA, another tool is highly used in the implementation of my thesis, pandas. This is a Python library that enables the analysis and manipulation of data. Pandas offers the data structure ‘dataframe’, which is highly beneficial to store timeseries data, such as the data I use in this work. Using this library leads to a significant design choice. In Java, a class ‘Household’ would evidently be constructed in order to instantiate objects of this class for every household of the grid. Getters and setters would be implemented to obtain the various measures related to that household. However, the pandas dataframe, presents the ability to store this household data in a very easy-to-use data structure. This is highly beneficial to manipulate the timeseries data. It does, however, imply a step away from the class-based software design.

### 4.4.2 Module implementation

In this chapter, I will again go over certain design choices made in the implementation. This time, they are related to the Python programming languages and the used tools and libraries.

#### 4.4.2.1 DataRetriever

Within the Data Retrieval class, one function should be constructed to obtain a to access the data through the API. A bearer token is part of an HTTP authentication scheme and serves as a security key to access data through an API. Only the person in possession of a token is able to access it. Credentials to obtain a bearer token are needed (Bearer Authentication, n.d.; Jones & Hardt, 2012). As mentioned in 4.2.5, these credentials were provided by Cast4All. Since I am dealing with personal data protected by the company, the data retrieval using the bearer token will not be part of this thesis. The code of this data retriever can be found within the repository. However, it is secured and the credentials are taken out. Therefore, the file cannot actually be run and the obtained data is provided in the repository in a csv.

A second function serves to obtain the data. The header of this function should be version transparent to ensure adaptability of the code. The json files should be stored in a consistent way so that, for example, every battery power file for every household can be accessed the same way. When considering the scope of the specific REST-API of Cast4All, this class has a high reusability. It can be reused for whatever measurement data is needed from whichever household. However, outside of this scope, the class cannot be used.

The actual data that is retrieved and stored in CSV files within the repository of this thesis, is the data of 21/01/2023 and 21/06/2023. This way, one winter and one summer day are available for analysis. If this tool would be made for internal use in Cast4All, it would be possible to adapt the code so that for any day that is entered, data can be retrieved and analyzed. However, since this is a thesis, the actual data retrieval is not possible and datasets of only two days are provided.

#### 4.4.2.2 CsvCreator

Next, the CSV creator class. In this class all data from all households should be loaded and transformed into one CSV. When instantiating an object of this class, the name of the csv file should be passed as well as the directory where all data can be founded. This class is not highly reusable either, since it serves to create a CSV file with the suitable column names. When looking at the constructor of this class, it is clear that I made the choice to invoke the functions within this class from the constructor. The reason for this is that it ensures the actual creation of the CSV file when creating an object of this class. There is no reason to create an object of this class other than the creation of a CSV file, so the choice to immediately instantiate this seems valid from my point of view. Additionally, the logic required to set up the created object is now well encapsulated in the constructor. A disadvantage would be the lack of flexibility. However, as mentioned above, this class can only be used for this particular case and therefor already lacks in flexibility whether or not the functions are called from the constructor. Important to note is that this class is not part of the tool either and will not be called upon in the main class. As mentioned above, the creation of the CSV serves as a way to provide the data to the user of this tool without needing access to the credentials and personal data of Cast4All. This class was thus made to be able to provide a CSV file to run the main file securely without any data breach.

#### 4.4.2.3 DataPreparers

**DataframePreparer:** This class loads a file to transform it to a pandas dataframe. The class is used to transform the CSV file with the household data, as well as the excel file with the day-ahead prices. This class is somewhat data version transparent, in a way that a different data structure that is loaded in the class will not change the constructor. The if-clauses make sure to correctly process different file formats.

**HouseholdDataPreparer:** For this class, the dataframe with all household data is passed to perform certain alterations on. These alterations are, amongst other, adjusting the utc offset, calculating the SoC (not percentage wise but in kWh), calculating consumption, and separating the households. The households are separated so that they each form a separate dataframe. There is also a function called ‘combine_bat_powe_charge_direction’. In Cast4All’s database, battery charge is marked with charge direction ‘0’, and discharge with charge direction ‘1’. These need to be translated to the correct input for the PyPSA tool; negative values for charging and positive for discharging. Additionally, since the data is delivered for every 5 minutes, a function is made that transforms it to hourly data.

In this class, the choice was made as well to call all these functions from the constructor. The advantage again is that it encapsulates the entire data preparation process within the class, which highly simplifies the main code. This leads to a better maintainability. It also ensures that all necessary steps to make the data correct for the PFA are actually performed in a consistent order when an object of this class is created. This is in favor of the accuracy of the system. One suboptimal implementation is the hard coded battery capacity in the function ‘calculate_SoC’. The reason for this is that every household has a different battery capacity. However, this data could not be retrieved from the Cast4All database, but was part of their customers’ personal data. This is why the battery capacity is hard coded and is thus not evolvable at all.

As in most classes in this program, I made the decision to define the dataframe as a class variable in the constructor. This way the dataframe can be accessed by every function within the class without being passed in the function headers. This design choice was made because all methods within the class need to access that same dataframe to alter it. By making it a class variable, the code becomes cleaner and more readable because of the decrease in redundant code. This should also make the code more evolvable, since the data is and the operations on it are now decently encapsulated in the class. However, this means that all functions within the class are tightly coupled. This is not a concern here because all functions are called in the initiator and thus coupled anyway. If this were not the case, and all functions would be called from a main class, it would be dangerous to make the dataframe a class variable due to the high coupling.

**BelpexPreparer:** In this case, the same reasoning was applied as in the previous preparer. Since the Elexys data was not clean, a function was constructed to clean to columns so that they would only consist of the price of the electricity. Next to this, every electricity supplier has its own additional costs (fixed and variable) added to the BELPEX prices. The additional costs that were used are obtained through Cast4All, they made the formulas available of one specific electricity supplier. This gives me the following offtake and injection prices:

$$offtake = BELPEX * 1.038 + 3.93$$

$$injection = BELPEX * 0.988 - 16.83$$

#### 4.4.2.4 GridSimulator

The GridSimulator class actually creates the virtual microgrid. In the constructor, the network is initialized, the snapshots are created, and the powerplant is added to the network. This all is done in the constructor, since there cannot be a grid without the initialization of a network, and without a power plant. However, adding the households does not happen in the constructor. In the future, it might be the case that there is a preference to analyze the grid first with only a power plant, or to not add all households immediately. This is why the function that adds a household is called separately from the main function. It makes the code more flexible. Within this function, the flexibility is somewhat decreased again. The code makes the assumption that a household being added always has a generator or a storage unit. The code would be more scalable if different components could be chosen for each household. However, since in this scope it actually is the case that each house has a generator and a storage unit, I made the choice to decrease code flexibility in order to enhance the cleanliness of the code.

Some important parameters to note in this class are the following: the powerplant is defined as the ‘slack bus’, the reason behind this was mentioned in the problem statement. The household buses have a standard voltage of 230 V. The lines have a series reactance of 0.01 since this value cannot be 0 (Von Meier, 2006).

Next, I made the design choice to perform the PFA in a function within the GridSimulator class. The reasoning behind this is that a PFA cannot be performed without the instantiation of a grid object. It makes therefore sense to include this short code block in this class. However, it is not called by the constructor. This way, the PFA can be called and performed whenever suits best.

#### 4.4.2.5 DynamicPricingBehavior

The actual behavior that would be implemented here, was already explained in section 3.3.5. The module is divided into two classes that are coupled through data passing.

A first class looks for the cheapest hour during the night. Here, the choice was made again to make the data a class variable, with the same argumentation as above. The function returns the cheapest hour, which is then passed to the Manipulator class. Since this class is coupled with the previous class through data passing, as well as getting data from the main class, there are checks implemented to validate the passed data. This should enhance the performance and accuracy of the code. This class manipulates the household dataset according to the DP behavior, so that there is new input for the GridSimulator. The logic in the manipulator class is the following: Consider a charge capacity of 50% of the total battery capacity (Cast4All, 2023). This means that when charging the battery for one hour, 50% State of Charge (SoC) is added. For this, if-conditions are constructed. If the SoC is less or equal than 50%, 50% of the total capacity is added, and the battery is charged with a power of half the total capacity. If the SoC is between 50% and 80%, the battery is charged until full, with a power correctly relating to this amount of charge. If however, the SoC is higher than 80%, it is not worth the effort to charge the battery.

#### 4.4.2.6 ChangeChecker

There is not much to add to the implementation of this class that was not mentioned in section 4.3.3.6. One exceptional thing is that there is no constructor defined in the class. The reason for this is that functions in this class are called separately from the main class. Right now, there is only one function, the check_voltage_angle_change function. However, in the future, it might be possible that someone wants to check other outputs from the PFA, like the voltage magnitudes or the power flow at the lines. When this occurs, a function to do so should be implemented in this class. This new function would need other parameters in its header. For the scalability of this tool it is crucial that these functions can be added to the class without changing too much. Therefore, this class uses a default constructor without instantiating any variables. The needed variables for a specific check are just provided in the function call.

Concerning the implementation of this function, the three 'checks' mentioned in section 4.3.3.6 are implemented. The significance_list is a list of Booleans, stating whether the change in voltage angles is significant for the households.

#### 4.4.2.7 Main

All previously explained classes are now sequentially called from this main class. To implement the idea of 'state keeping', a highly rudimentary implementation was presented. After every step is completed, the 'current_state' variable is changed. The calls are put in a try-except block. This way, in case something fails, the code will return the current_state as well. The outputs of the various functions called are instantiated as global variables. This way, they can be consulted (e.g. in the variable explorer when using Spyder) if needed. When running the main file, two inputs are expected; the day to be analyzed, and the factor of significance to analyze the change in voltage angles. Note that, considering the date, there are only two possibilities to insert: '21_01_2023' and '21_06_2023'

## 4.5 Testing

A last step in the waterfall model before actually rolling out the software for use, is testing. Testing knows two dimensions, verification and validation. Verification entails checking whether the tool works correctly. In this dimension, one looks back at the requirements constructed in the analysis phase and checks whether the code was developed accordingly. Verification can be performed through the use of unit tests and by throwing exceptions throughout the code. The other dimension is validation. Validating the tool means examining whether the correct tool was actually built. In this dimension, one looks back at the original problem statement and check whether this has been answered by the built tool. In this section of the thesis, both dimensions will be discussed.

The used knowledge concerning the verification of the built Python code, was obtained through a course from Codecadamy: *Learn Intermediate Python 3: Exceptions and Unit Testing*. Any information about concepts in this section will thus implicitly refer to this source.

### 4.5.1 Verification – Exceptions

One way to verify whether the code is working correctly is through the implementation of exceptions. In python the word *'raise'* can be used to throw an exception. This can be implemented together with a condition. If a certain condition is not fulfilled, a certain error is raised. When this happens, the program stops running and outputs the error message attached to the raised error.

However, there are cases in which one would want the program to keep executing. In this case, an error is not raised but 'exception handling' is performed through the implementation of try-except block. In this case, the code that needs to be executed is put inside the 'try' clause of the block. If an exception occurs in this block, the except block is executed. This except block might raise an error anyway, or just print a statement.

In order to catch any possible exceptions occurring in the building and executing of this tool, error or exception raises and try-except blocks can be found throughout the code implementation. To demonstrate and clarify this, two examples will be discussed in this section.

- The first example can be found in the *DataFramePreparer* class. This class contains a function called '*file_to_dataframe*' which transforms a datafile into a pandas dataframe. This function can handle CSV files, as well es Excel files. However, if another data structure were to be passed in this function, a ValueError would be raised. This raised error serves to catch the passing of an unsupported file format. If this happens, the code would stop executing and throw this exception. Additionally, this function contains a try-except block as well. It might be possible that the problems is not related to the file format, but that the file just cannot be found. In this case, no conditions of the if-clause are satisfied because the file cannot be accessed at all. An exception is thus found in the try-block and shown in the except block. The code will stop running here as well, and a FileNotFoundError will be raised.

- For a second example, I refer to the *DynamicPricingBehavior* class, containing the '*manipulate_data*' function. A try-except block can be found here as well. The line of reasoning behind implementing a try-except block here, is that multiple columns within a dataframe need to be accessed and altered. However, it might be possible that not all of the columns are successfully accessed. It would thus be favorable to execute the entire code block, and being notified at the end if there where any columns missing or inaccessible and which ones. In order to know all problematic columns, a try-except block is inserted instead of raising an exception immediately. If a column raises a concern, a keyError exception occurs.

Even though the implementation of exceptions is a great way to find any problems in the code, it does not warn you when the code is being executed problem-free but does not do what you were visioning it to do. To check this, unit tests can be used.

### 4.5.2 Verification – unit testing

Unit tests serve as a way of verifying whether a single unit of the written program functions the way it is supposed to. These individual tests focus on the smallest unit possible that needs to succeed within a class. In the repository of this thesis, a test folder can be found. Here all tests relating to the same class are bundled in one file, with the same name as the class name and the word 'test' in front of it.

Unit tests can be performed in Python through the use of their unit testing framework. This can be found in the module 'unittest' and works highly similar to unit testing in Java. Through the implementation of various functions, each serving as a unit test and containing assert statement, the correct functioning of the code can be thoroughly tested. I will again refer to an example within this thesis. In the test repository, a file 'TestGridSimulator' can be found. In this file, all tests are gathered that test the functionality of the GridSimulator class. I will go over each function separately:

- setUp: the setUp function in unit testing serves to set up all data that is needed by all tests in the class. If there is data only needed by one test, it is specified there. If all tests need it, the setUp function avoids redundant code. Here, the date and the simulator object are defined in the setUp function.

- Test_snapshots_are_set: since the tool analyzes the powerflow throughout a day, snapshots are crucial in the correct working of the simulation. This function checks whether they are set or not.

- Test_powerplant_is_added: During the initiation of a grid simulation, the power plant needs to be added immediately to the grid, since a grid cannot exist without a plant. This test verifies the actual addition of the power plant.

- Test_household_is_added: key to a grid simulation is that the households can be added without any problem. This test makes sure that this is the case.

- test_failed_household_addition_without_powerplant: If there is no power plant established in the grid simulation during initiation, the households are not supposed to be added since there has to be a line between the household and the power plant. Without a power plant, the household would thus be added incorrectly. This test verifies that an exception is actually raised when the power plant is missing.

The other test files have the same logic implemented and will thus not be discussed here. By running the test files, one can check that these tests are succeeding.

### 4.5.3 Validation

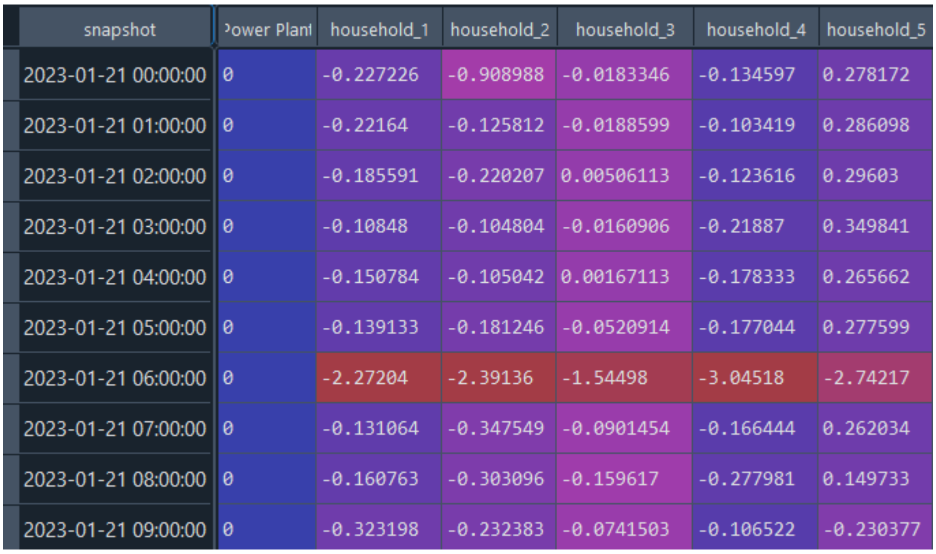
For the validation of this tool, I need to refer to the problem statement. There, the hypothesis was mentioned for which the analytical tool constructed should serve as a way of researching this hypothesis. The hypothesis was the following: *What is the influence of DP induced* *consumer behavior on the stability of the electricity grid? Does exhibiting this similar behavior lead to a new set of peak demand moments?* The question to ask during the validation of the built system is whether or not the tool indeed served as a way to deal with and possibly answer this hypothesis. To answer this, I will go over the functional requirements again. The tool indeed extracted and transformed the necessary data. It stored data from multiple households for different days (using the CsvCreator). The time zone offset was handled in the HouseholdDataPreparer class, as well as the transformation of the time interval and the calculation of the household consumption. A grid simulation was indeed created and a PFA performed in the GridSimulator class. The DynamicPricingBehavior class defined and simulated DP induced behavior and manipulated the data accordingly. The ChangeChecker class then analyzed the resulting voltage angles. To summarize, every functional requirement was met in the implementation of this tool. The goal was to be able to analyze grid stability after integration DP behavior. Since the final output of the tool is whether the change in voltage angles is significant with a chosen factor, this concluding output can be used to indeed analyze the influence of DP behavior on the grid stability. The validity of the built system is hereby thus endorsed.

## 4.6 Findings – discussion

In this section the findings after implementation of the analytical tool will be discussed. The section is divided into three parts, considering three different topics need attention for discussion. The first one is related to the actual content of the tool. In a next part, the obstacle of ETL will be discussed. Lastly,  the act of software engineering in Python will be discussed.

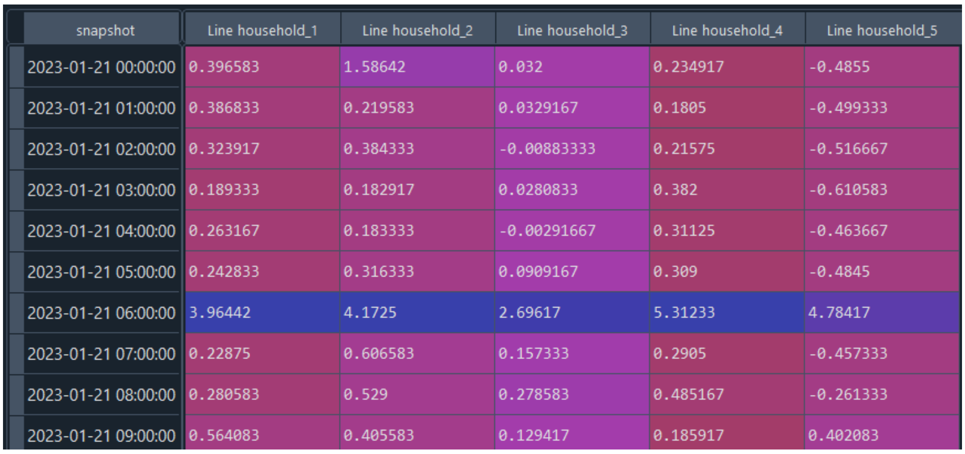
### 4.6.1 Results

After performing the analytical tool on the data of both the winter and summer day, a significant change in voltage angles can be found during the cheapest hour of the night, when the battery was charged.  A screenshot of the dataframes that resulted from performing the tool on 21/01/2023 prove this (Fig. 9 and Fig. 10).



| snapshot | ower Plant | household_1 | household_2 | household_3 | household_4 | household_5 |
|---|---|---|---|---|---|---|
| 2023-01-21 00:00:00 | 0 | -0.227226 | -0.908988 | -0.0183346 | -0.134597 | 0.278172 |
| 2023-01-21 01:00:00 | 0 | -0.22164 | -0.125812 | -0.0188599 | -0.103419 | 0.286098 |
| 2023-01-21 02:00:00 | 0 | -0.185591 | -0.220207 | 0.00506113 | -0.123616 | 0.29603 |
| 2023-01-21 03:00:00 | 0 | -0.10848 | -0.104804 | -0.0160906 | -0.21887 | 0.349841 |
| 2023-01-21 04:00:00 | 0 | -0.150784 | -0.105042 | 0.00167113 | -0.178333 | 0.265662 |
| 2023-01-21 05:00:00 | 0 | -0.139133 | -0.181246 | -0.0520914 | -0.177044 | 0.277599 |
| 2023-01-21 06:00:00 | 0 | -2.27204 | -2.39136 | -1.54498 | -3.04518 | -2.74217 |
| 2023-01-21 07:00:00 | 0 | -0.131064 | -0.347549 | -0.0901454 | -0.166444 | 0.262034 |
| 2023-01-21 08:00:00 | 0 | -0.160763 | -0.303096 | -0.159617 | -0.277981 | 0.149733 |
| 2023-01-21 09:00:00 | 0 | -0.323198 | -0.232383 | -0.0741503 | -0.106522 | -0.230377 |

*Figure 9: voltage angles - 21/01/2023 - DP behavior*



| snapshot | Line household_1 | Line household_2 | Line household_3 | Line household_4 | Line household_5 |
|---|---|---|---|---|---|
| 2023-01-21 00:00:00 | 0.396583 | 1.58642 | 0.032 | 0.234917 | -0.4855 |
| 2023-01-21 01:00:00 | 0.386833 | 0.219583 | 0.0329167 | 0.1805 | -0.499333 |
| 2023-01-21 02:00:00 | 0.323917 | 0.384333 | -0.00883333 | 0.21575 | -0.516667 |
| 2023-01-21 03:00:00 | 0.189333 | 0.182917 | 0.0280833 | 0.382 | -0.610583 |
| 2023-01-21 04:00:00 | 0.263167 | 0.183333 | -0.00291667 | 0.31125 | -0.463667 |
| 2023-01-21 05:00:00 | 0.242833 | 0.316333 | 0.0909167 | 0.309 | -0.4845 |
| 2023-01-21 06:00:00 | 3.96442 | 4.1725 | 2.69617 | 5.31233 | 4.78417 |
| 2023-01-21 07:00:00 | 0.22875 | 0.606583 | 0.157333 | 0.2905 | -0.457333 |
| 2023-01-21 08:00:00 | 0.280583 | 0.529 | 0.278583 | 0.485167 | -0.261333 |
| 2023-01-21 09:00:00 | 0.564083 | 0.405583 | 0.129417 | 0.185917 | 0.402083 |

*Figure 10: power flow - 21/01/2023 - DP behavior*

A significant change in the dataframe is marked by Spyder with a different colour. This is clear in both dataframes during the cheapest hour of the night. It is clear that the power flow has significantly risen, as well as the value of the voltage angles. A negative voltage angle means that more power is consumed than generated, and that the bus's voltage angles become more and more different from the slack bus in a negative way (Von Meier, 2006). This is clear in the dataframes. In the power flow dataframe, a higher positive power flow from the power plant to each household can be noticed.

When running the tool with different significance factors, the following conclusions can be made. With a significance factor of 2, the tool outputs that all households have a significant voltage angle change. This means that the voltage angle at the cheapest hour, is twice the absolute value of the hour before, the hour after, and the unmanipulated voltage angle. Even with a significance factor of 5, all households show a significant voltage angle change. When changing the significance factor to 10, still two households appear to have a significant voltage angle change. This means that the new voltage angle is 10 times bigger than before. For the summer day (21/06/2023), findings were highly similar. As mentioned in section 4.2.1, the voltage angle, or phase angle, has meaning relative to the voltage angle of the slack bus, being 0. If the absolute value of the voltage angles at the households becomes bigger, the difference becomes bigger, and the threat of grid imbalance increases with the difference. A big difference leads to phase instability, which ultimately leads to frequency instability (Von Meier, 2006).

However, before making the conclusion that DP behavior indeed leads to grid instability, one nuance needs to be made. The phase angles are expressed in degrees. Thus, they can theoretically take a value from 0 to 360 degrees. This might mean that even though the value of the voltage angles becomes 10 times bigger, seeing that the angles in Fig. 9 are that small on a scale from 0-360, the factor 10 might still be an insignificant change for the grid. However, the analysis and conclusion of this matter must be performed by an electrical expert and falls out of the scope of this paper. What can be concluded however, is that the DP behavior that is pushed through smart metering devices clearly created a new peak in the power flow (Fig. 10), which was stated multiple times throughout this paper to cause grid imbalance and thus grid instability. Additionally, the sudden change in voltage angles, and implicit bigger difference in relation to the slack bus, demands great flexibility of the grid (e.g., immediate ramp-up of the central power plant) and may be cause for concern on its own.

These findings prove that the proposed mechanisms to solve the problems related to DERs, are not as straightforward as in literature might appear. They give rise to a whole new set of concerns and their combination must be considered extremely carefully.

### 4.6.2 ETL

Another finding that is derived from this work, is the complexity and effort that goes into ETL of data. The extraction of the household data through the REST-API, the transformation of this extracted data to a usable format, and the loading of this data in to the tool, requested a significant amount of time of the implementation of the tool. One can ask the question if just acquiring the needed data to be able to perform actual logic, should take that long. Even though a REST-API is promised to have a uniform interface, a clear architecture, and a clear executable code (IBM, n.d.), the process of obtaining data through a REST-API can be a complex process. Next, the transformation of the data, which happened in the CsvCreator and DataPreparers, accounted for a significant amount of time. The optimization of the ETL process falls out of the scope of this paper, it is however worth mentioning this complexity when encountering it.

### 4.6.3 Python programming

The need for a toolbox that could perform a PFA, led to the choice of Python as a programming language. However, studying in a software engineering department implies that significant attention of writing code goes to the design and architecture of it, to make sure it is well engineered and evolvable. Implementing code in Python while adhering to this. A specific remark to illustrate this, is the use of verb and noun classes. Functionality within a system should be separated into classes which only focus on one concern. In doing so, verb classes and noun classes should arise. A ‘noun’ and ‘verb’ object initialization should not occur by one class (Mannaert et al., 2016). However, in the code of the analytical tool, only verb classes were constructed. There was no noun class for household, or grid, or belpexPrice for example, which would be the case in a Java program. The reason for this is that the toolbox had a Network class implemented, or that Python makes use of a pandas dataframe to store household data in. A household object, was thus out of the question. This resulted in a suboptimal object-oriented programming structure in the tool. Here as well, the discussion of object-oriented programming in Python falls out of the scope of this paper. It is however, important to document any findings that cause concern or opportunity for future research.

# 5 Conclusion

In conclusion, this thesis addressed the design challenges associated with the integration of DERs into the electricity grid. It also presented potential technologies, theories and mechanisms for solving them. And, lastly, provided a code implementation to practically analyze these mechanisms. The objectives of this thesis were threefold. Firstly, by conducting interviews with practitioners and performing a subsequent literature review, the design challenges that are of utmost concern to grid participants were identified. The focus of this part was on the identification of design challenges that have a rippling impact through the electricity grid. These challenges were categorized into three main areas: physical structure, economics, and intelligence of the grid. Secondly, technologies, mechanisms, and theories were explored from the knowledge base to address these challenges. This involved examining technologies related to grid intelligence, where DTT and VPP were explored; researching economical balancing and pricing mechanisms; and applying Normalized Systems Theory on the physical structure of the grid as a general approach for addressing design challenges. By doing the latter, coupling modes where identified that cause the ripple effects of the design challenges mentioned in section 2. Additionally, the identification of cross-cutting concerns led to elaboration on encapsulating mechanisms or technologies to integrate these concerns and deplete the ripple effects. This way the evolvability and modularity of the electricity grid would be ensured. In a last section, an analytical tool for assessing the influence of DP paradigm on grid stability was designed and implemented. This tool contains a simulation of a microgrid using real data, a PFA on this data, the manipulation of said data according to DP induced consumer behavior, and lastly performed an evaluation of the PFA results after data manipulation. With its contents, it provided a way to tackle the following hypothesis: *What is* *the influence of DP induced consumer behavior on the stability of the electricity grid? Does exhibiting this similar behavior lead to a new set of peak demand moments?* The built program demonstrates the application of mechanisms identified to tackle the design challenges, and provides the possibility to critically analyze their integration into the grid. From this tool, it can indeed be concluded that DP induced behavior is a threat for new peak creation and has notions of leading to grid imbalance and grid instability.

By adhering to the design science research framework proposed by Hevner et al. (2004) and following the design guidelines and three-cycle view (hevner, 2007), a structured elaboration of this design science thesis was ensured. Adhering to the principles of the relevance cycle in this work ensured that the design challenges identified were in fact based on real-world needs. The rigor cycle involved exploring the knowledge base for potential solutions, which enabled me to apply NST on the electricity grid and develop a grounded, yet fresh perspective on the problem. The design cycle resulted in the design and implementation of the analytical tool.

In summary, this thesis has contributed to the understanding and resolution of the challenges associated with integrating renewable DERs into the electricity grid. By addressing the physical, economic, and intelligence-related design challenges of the grid, as well as possible mechanisms, it has laid the groundwork for a more sustainable and efficient energy future. Through the application of design science research, this work aims to guide the future practice and research considering renewable DER integration towards establishing a more modular and evolvable electricity grid.

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