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A market-based instrument for renewable energy

Modelling a dynamic price function for local areas

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Abstract

A market-based instrument for renewable energy – Modelling a dynamic price function for local areas

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This thesis describes the current situation of the electrical grid on a general level and contemporary support policies for residents who feed renewably produced electricity into the grid within a Swedish context. It shows which issues currently exists and suggests a new way to value overproduced renewable electricity which is not self-consumed. This way is called a dynamic price function (DPF), and this thesis models, simulates and analyzes the DPF in order to create an economic incentive to support the balance of the electrical grid – one of its most important parameters. The suggested DPF could potentially work with any renewable source in any area, but the focus in this thesis has been on solar power-systems for households in local areas. While the currently support policies, which uses static models to value overproduced renewable electricity, have created important incentives for the initial penetration of solar power among local residents they do not scale well as the share of renewable production on a local level increase. This might cause negative impacts on the electrical grid. The thesis' results show that by designing the DPF in certain ways it is possible to create an economic incentive for different behaviors. The most promising design incorporates three different incentives at the same time and they are: 1) to incentivize the initial penetration of solar power in local areas which do not have any production, 2) to incentivize a higher share of solar power, but not too high, and 3) to procure storage possibilities for overproduced electricity. These incentives do not only encourage a more even geographical distribution of solar power, but also allow for a higher share of solar power in the energy system without risking the balance of the grid.

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Populärvetenskaplig sammanfattning

Det senaste decenniet har andelen förnyelsebar elproduktion i det svenska elnätet blivit större, och allting tyder på att det kommer att fortsätta. Utvecklingen av förnyelsebara energikällor har lett till att traditionella sätt att producera elektricitet – både gällande teknik och geografisk placering – i ökande grad börjat ersättas av nya och mer flexibla lösningar. Ett exempel på detta är när traditionella el-konsumenter, exempelvis privatpersoner i villa, installerar en solcellsanläggning i anslutning till sitt eget boende och blir en s.k. ”prosument”: en producerande konsument. Prosumenter står i Sverige för den största andelen solcellsproducerad el i dagsläget, och de bor ofta i områden utanför stadskärnor där elnätet inte är lika utbyggt. Då det ständigt måste råda balans mellan konsumtion och produktion i elnätet, samtidigt som solcellsanläggningarnas produktion varierar, kan det uppstå problem med den lokala balansen i elnätet. Det är dessutom inte bara prosumenter som i ökande grad belastar elnätet, utan de senaste åren har det även tillkommit fler energitunga applikationer. Några exempel är elbilsladdare och värmepumpar hos privatpersoner samt utbyggnad av tillverkningsindustri. Detta har i Sverige lett till vad som kallats för en ”kapacitetsbrist”, för medan mängden el som produceras i Sverige sett över ett år är tillräcklig finns det en brist i kapaciteten att transportera elen dit den behövs under vissa tidpunkter. Ett sätt att hantera detta är att öka mängden decentraliserad och lokal elproduktion för att minska mängden el som behöver transporteras, och detta kan prosumenter hjälpa till med. Det behövs dock nya incitament skapas för *var* och *när* dessa matar ut el på nätet för att stödja balansen i det lokala elnätet.

I takt med att solcellsanläggningarna har blivit billigare och bättre kan prosumenter dimensionera sin anläggning för att bli självförsörjande under, i ökande grad, större delar av året. Detta medför också en större överproduktion vilken inte självkonsumeras utan som istället matas ut på elnätet. Det beror på att desto tidigare på våren samt senare på hösten en prosument vill vara självförsörjande, desto fler solceller behöver installeras. Resultatet blir en ökande mängd överproducerad el, och främst under sommaren. För överproducerad el utgår vanligtvis en ersättning som solcellsägaren har avtalat med sin elhandlare. Denna ersättning bygger dock ofta på ett fast pris som inte tar hänsyn till *var* och *när* denna el matas ut vilket inte skalar väl med nuvarande utbyggnad av solcellsanläggningar och elnätets struktur. Detta statiska tankesätt behöver förändras.

Många studier har analyserat hur elnätet kan regleras ”utifrån”, exempelvis genom frekvensreglering, men i denna uppsats studeras hur den el som prosumenter matar ut på elnätet kan värderas utifrån ett nytt tankesätt. Tanken är att skapa ett ekonomiskt incitament för att bidra till elnätets balans, snarare än att motverka den. Resultatet är en dynamisk prissättningsfunktion som gör att värdet på den överproducerade el som matas ut på nätet varierar med avseende på det lokala elnätets balans. Genom denna modell kan flera viktiga incitament skapas, bland annat att främja nya solcellsanläggningar i områden där de inte finns samtidigt som en en jämn geografisk spridning av lokal och förnyelsebar elproduktion uppmuntras. Men även till att öka andelen prosumenter samt att införskaffa lagringsmöjligheter för överproducerad el. Med en mindre andel prosumenter behövs generellt ingen lagring då de inte påverkar elnätets balans i någon större utsträckning, men i takt med att andelen växer ger lagringsmöjligheter flera positiva fördelar.

Den dynamiska prissättningsfunktionen är modellerad för att skala väl med en ökande andel prosumenter genom att vara tillräcklig komplex för att hantera de viktigaste systemparametrarna, men samtidigt simpel nog för att vara tydlig och inte behöva ändras i onödan. Tanken är att på så sätt uppmuntra till transparanta spelregler och framtida investeringar för att tillgodose det behov av en ökad mängd decentraliserad och förnyelsebar elproduktion som dagens utveckling visar på.

Abbreviations and synonyms

Abbreviation	Meaning	Swedish
CEER	Council of European Energy Regulators	Rådet för europeiska tillsynsmyndigheter inom energiområdet
DER	Distributed Energy Resources	Distribuerade energiresurser
DPF	Dynamic Price Function	Dynamisk prisfunktion
DSO	Distribution System Operator	Regionnätsoperatör
EU	European Union	Europeiska unionen
FiT	Feed-in Tariff	Inmatartariff
HVN	High Voltage Network	Distribution/regionnät
IEA	The International Energy Agency	Internationella energirådet
IRE	Intermittent Renewable Energy	Intermittent förnyelsebar energi
IT	Information Technology	Informationsteknologi
LVN	Low Voltage Network	Lågspänningsnät
MVN	Middle Voltage Network	Mellanspänningsnät
NM	Net-Meetering	Nettomätning
P2P	Peer-to-peer	Användare till användare
PV	PhotoVoltaic	Fotovoltaik/solceller
RES	Renewable Energy Sources	Förnyelsebara energikällor
SEA	The Swedish Energy Agency	Svenska Energimyndigheten
SEK	Swedish krona (currency)	Svensk krona
SEMI	Swedish Energy Market Inspectorate	Energimarknadsinspektionen
SVK	The TSO of Sweden	Svenska Kraftnät
TSO	Transmission System Operator	Stamnätsoperatör

Synonyms
PV, solar, solar power
electrical grid, electrical network, grid
electricity supplier, supplier
electrical behavior, electrical load, electrical profile, load profile, power usage
green electricity, renewable energy
fossil energy, gray energy, gray electricity
local production, decentralized production

Content

Introduction

To meet a worldwide growing demand for energy, while at the same time addressing environmental aspects, is a big challenge of the world today. Within the energy field there are many on-going projects on different scales which aim to reduce the dependency on fossil produced electricity by replacing it with renewable sources. One such source is solar power, also called photovoltaics (PV), and over the last decade local small-scale PV-systems for households have become increasingly feasible. As the penetration of such systems has increased, new incentives are however required in order to continuously support the development. This is the topic of this thesis.

The energy system in general, and the electrical grid in particular, is a crucial infrastructure of the modern society and it can be resembled with a living being's circulatory system where balance need to be kept at all times. Until a few years ago, residents and businesses in Sweden barely had to think about power availability – regardless of when all needed power were accessible. Recent years have however seen a development which increasingly risks disrupting the balance and availability. This has been mentioned as a "capacity problem", and has received attention from both Swedish media, Swedish companies and Svenska Kraftnät (SvK) which is the Transmission System Operator (TSO) of Sweden (Sveriges Television, 2019; Svenska Dagbladet, 2019; Uppsala Nya Tidning, 2018; Svenskt Näringsliv, 2018; Svenska Kraftnät, 2018).

On its *physical* side, the grid has not changed in a long time where a low number of power companies distributes electricity to a high number of consumers. But due to the capacity problem and increased share of intermittent renewable energy (IRE), such as PV-systems, a need to restructure and rebuild this side of the grid has risen (Svenska Kraftnät, 2017). The other, and increasingly important, side of the grid is the *virtual*. This side includes creating, analyzing and exchanging information about how electricity is consumed, produced, lost, bought, sold, stored, etc. This thesis will mainly focus on this side and how (over)production from local PV-system can be valued in a new way while at the same time consider the grid's most important parameter – its balance

Sweden does not have a production shortage, but the production is not geographically aligned with the consumption meaning long-distance transmission of electricity is necessary. This leads to many km of high voltage networks (HVN), requiring a lot of resources and subsequent transmission losses. To reduce this, distributed energy resources (DER) through IRE production such as PV can be utilized. Sweden is entering a new phase which partly will change how, where and when electricity is produced and the upcoming decades brings a potential need to replace around 100 TWh of production. The Swedish Energy Agency (SEA) predicts that IRE sources will contribute with a large part to this replacement. The use of electricity is also anticipated to change due to digitalization and growing cities, and SEA foresees a larger demand for flexibility and a more effective use of electricity where aspects from both the grid's physical and virtual side might be co-developed. (Energimyndigheten, 2019, p. 4). It is not evident when or how fast these changes will take place which creates both a challenge when it comes to planning the operation of the current grid but also an opportunity to consider how these changes could be structured and implemented.

One important actor in this development is the so-called "prosumer": a former traditional consumer who, by installing a PV-system for instance, can produce electricity themselves. While traditional consumers assume a passive behavior, the prosumer may increasingly adopt a proactive one. A proactive behavior is to act in advance to deal with expected change or difficulty, e.g. to become more self-sufficient by producing – and maybe storing – electricity. But it also brings challenges to the grid, especially in low-voltage areas when looking at balance and IRE production.

The problem that needs to be solved is how to handle an increased decentralization of electricity production since it poses challenges for the grid's physical side. Previously it could be difficult to get permission for local residents to feed electricity into the grid, then it became allowed in general but gave the prosumer little or no compensation (Andoni et al. 2019, p. 155). While todays policies in general encourage producing local and renewable electricity, they have one problem – they are static and do not consider *when* or *where* electricity is fed into the grid. With developing information technology (IT), especially of so-called "smart meters" which can record electricity data and share it almost in real time, new possibilities from the grid's virtual side are opening up.

This problem needs to be solved since there is a capacity problem and the traditional support policies and pricing of renewable electricity shows issues with the current development. The support policies do not seldom have short-term perspectives which can change quickly due to politics. IRE production, which does not have completely predictable way of producing, should be continuously incentivized but in a way which do not risk the balance of the grid. The goal is to become more sustainable while at the same time foster economic and social aspects. The Swedish electricity market became deregulated in 1996 which meant that electricity consumers freely could choose their provider. The deregulation was implemented in order to increase the freedom of choice and to create a sounder market environment where power companies had to compete on a higher level. The change did not affect the physical side of the grid however where the consumer's energy demand still was viewed as non-flexible and difficult to control. The penetration of IRE on a local level is changing this by making consumers more self-providing while at the same time empower dwellings to become collectively aware of their energy usage and to reduce their carbon footprint.

One way to solve the problem is to create a new way to value electricity using a Dynamic Price Function (DPF) to value (over)produced electricity instead of static one and, in the case of this thesis, apply it on prosumers in order to create incentives for certain behaviors. Through this communities of different sizes could potentially be created to gain a better overlook and improve energy management (Sousa et al. 2018). This could also lead to new possible types of markets, for example so-called peer-to-peer (P2P) market, where electricity is traded in a flexible way between bigger power companies, prosumers and other small scale DERs in a way that is not the case today (Long et al. 2017, p. 2228). Even though this is of relevance for this thesis, its main focus is to support the development of IRE in a transparent way for all stakeholders – from the producer to the consumers including the electricity utility companies – by testing a DPF. In a recent Swedish survey of 13 electrical utility companies, every company reviewed received criticism. The list included both smaller ones and the biggest, such as Eon and Fortum, and the critique was that comparing prices and finding a standard price per kWh were complex and unclear (TT, 2019).

One of the most interesting aspects with the development of DER is that, in principle, all consumers obtain the possibility to produce and sell electricity. The Royal Swedish Academy of Engineering Sciences (IVA), which is made up of decision-makers and experts from both business, industry and public administration in addition to the academy, has pointed out that while an increased user flexibility is not going to completely restructure the development of the grid, it may contribute to lower the transmission capacity requirements (IVA, 2016). This is what makes it interesting and relevant to conduct a study of the grids virtual side when it comes to dynamic compensation of prosumer's production. This is especially true in a Swedish context where such studies barely exist, although bigger national power companies have become increasingly aware of how new IT-applications has a potential to change their primary business at its core (Bloomberg, 2018). These developments and changes will likely not affect the operational responsibility of the grid, but rather manifest in new trading patterns which could affect normal operation.

Purpose

In this degree project the purpose is to analyze a new idea initially presented by Mihaylov et al. (2014) of how to value electricity. The aim is to model and simulate a Dynamic Price Function (DPF) for valuing locally produced renewable electricity and evaluate its effect on compensation for overproduced electricity, grid balance and overall incentives for a continued development of decentralized PV-systems.

Research questions

- How can a DPF for renewable electricity be designed in order to support the balance of the electrical grid?
- How can such a DPF impact the compensation for prosumers in a local area during local over- and underproduction within a Swedish context?
- How does storage possibilities impact the given compensation?
- What share of prosumers seems to give the highest mean compensation in this case?

Method and outlay

This thesis examines a mechanism to value electricity which has not yet been introduced anywhere in a real scenario. This includes modelling the main elements of a model described by Mihaylov et al. (2014), find relevant data to simulate the model, evaluate the results and discuss them in relation to the current system in, mainly, Sweden.

Chapter 1 covers four different sections with the aim to provide a frame of reference for the thesis as a whole. The four sections are:

1. PV-parameters and characteristics.
2. The electrical grid and its operators.
3. Rules, policies and incentives.
4. The electricity market.

Chapter 2 focuses on modelling, simulating and analyzing the DPF in a Swedish context. Finally, chapter 3 summarizes the result of chapter 2, discusses it in relation to chapter 1 and ends with a conclusion around the initially stated research questions.

Limitations and restrictions

There are several limitations and restrictions in this thesis since the DPF has the potential to incorporates several complex technological aspects while also relating to a wide market context. The most important of these are:

- While stochastic behavior of consumption and production is possible to simulate with the created MATLAB-script for the DPF, it is not used when evaluating the DPF in order to reduce the number of variables.
- Prediction algorithms are not modelled or simulated.
- No deeper physical analysis of power grid management is performed.
- The idea described by Mihaylov et al. (2014) connects to different aspects of virtual currencies, blockchain, certificates and trading patterns. These aspects will not be processed in this thesis to any depth, only briefly presented at the end of chapter 1 and discussed in chapter 3.

Chapter 1
Renewable electricity production: Technology and context

In this chapter the context for the implementation of the dynamic price function is set through four sections: 1) IRE production in terms of PV-systems and storage 2) The electrical grid, 3) Laws, regulations and current policies and 4) The electricity market.

1.1 PV-parameters and characteristics

PV is an IRE-technology that produces electricity by, in short, using semiconducting materials that can create freely moving electrons, i.e. electricity, by absorbing incoming light (photons). In Figure 1 important PV-parameters for understanding the production-pattern of PV-systems are shown:

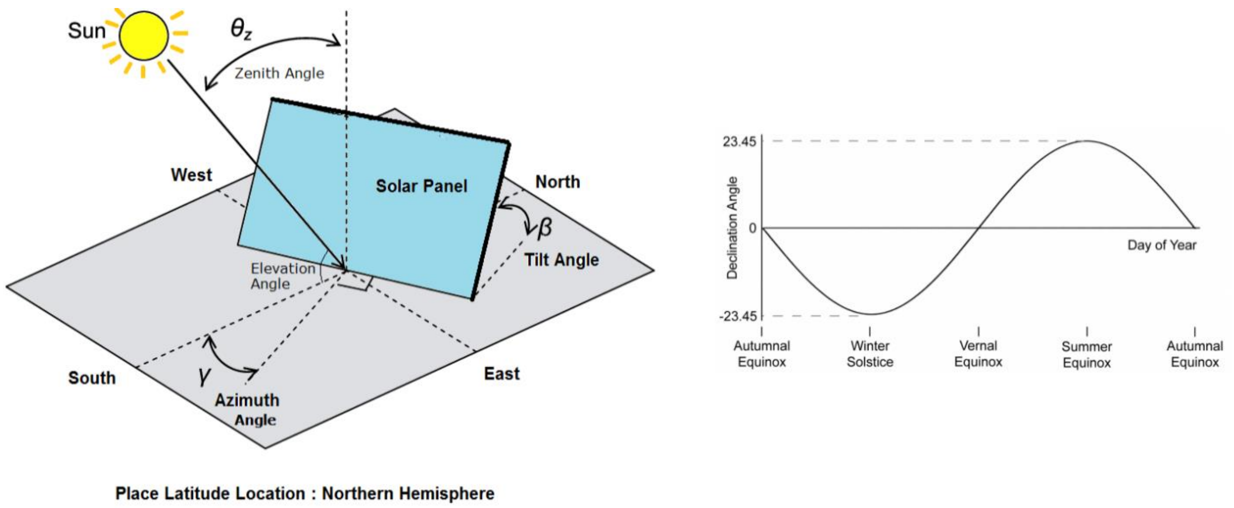

Figure 1 – Important PV-system parameters and declination angle of the sun over the year.

The azimuth and tilt angle can in general be decided but may depend on the position and direction of rooftops where prosumers usually install PV-systems. The zenith angle, on the other hand, depends entirely on location and is calculated from the declination angle, to the right in Figure 1, which stems from the Earth being tilted in relation to the sun. With θ_z and weather data the sun's resulting irradiance on the ground can be approximated which is the power source for PV-systems. The irradiance is a radiant flux measured with the units W/m^2. The declination angle itself is defined as the angle between the sun rays and the equatorial plane of the Earth, and together with the latitude and the time of the day the zenith angle θ_z can be calculated. On the Northern hemisphere a positive and larger declination angle means a more intense insolation, and thus PV-systems installed North of the equator have the largest production during summertime. A downside with PV-systems, especially in Sweden, is that the production has a slightly inverse correlation with the use of electricity. This comes from that during winter most electricity is needed in Sweden, but then the irradiance is at its lowest during the entire year and vice versa. Compared to wind power, PV-systems also needs more support in order to balance the grid and it is still more expensive per produced kWh (Energimyndigheten, 2019, p. 9). On the positive side PV-systems are easier for local residents to attain and to integrate on buildings within cities, thus creating more local production of electricity. The total irradiance in Sweden during a year is shown in Figure 2 where the production profile over a year clearly can be seen with most coming from spring and summer:

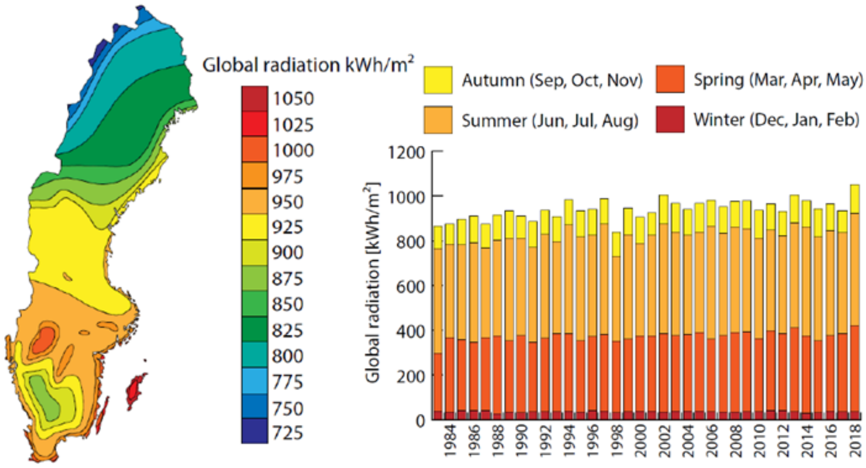

Figure 2 – Average geographical distribution of radiation in Sweden over the year and over the seasons.

1.1.1 Uncertainty, variation and storage

All IRE sources have an intrinsic trait of not having a continuous and steady production pattern, but one that varies. This behavior is called having an "intermittent" character and makes detailed production predictions over longer time periods challenging. This differs from the typical on-demand characteristic which often are sought, and thus an increase of IRE sources may make it more difficult to balance the grid. Some sources state that reducing the day-ahead forecast errors of production with as little as 0.1 % could potentially save more than $2 million annually in the US state California only (Landelius, Andersson & Abrahamsson, 2019, p. 1). But the challenge lies not only in the physical side of the grid, but also in the virtual side. Since the marginal cost of electricity from intermittent sources in many cases are close to zero –they do not expend any fuel during production – the cost of electricity on a connected market might become unstable. During certain time intervals of high IRE production the cost of electricity may become significantly lower while becoming much higher during others, resulting in a more volatile price. Countries that have incorporated a large amount of IRE production, such as Germany and Denmark, have even had periods with a negative price of electricity. This stresses the impact IRE sources might inflict on a market due to their varying production pattern.

This intermittent character is however not entirely random as the behavior of different IRE sources covaries to some extent. PV-systems, for instance, has a larger variation in production within a short time scale whereas wind is more difficult to predict on a slightly longer timescale (Olauson, 2016, p. 95). There is also a weak negative correlation between the sun and the wind. This means that when it is sunny the wind speeds are in general lower and vice versa. Thus, by gathering data over time and performing statistical analyses an optimal combination of solar and wind power for different locations can be estimated.

Energy storage can also be used in addition to an adequate mix of different IRE sources to support the of the grid. As with the IRE source, there are also different storage technologies which functions on different timescales depending on type (Few, Schmidt & Gambhir, 2016). Traditional peak shifting has so far been driven by wholesale electricity prices however and not by using technology such as storage to improve local congestion management. But this latter part is increasingly becoming feasible where energy storage is used as a mean for increased flexibility to work with the associated inherent randomness of IRE sources, and it will likely become an increasingly important asset in order to maintain and operate the grid and its constraints.

In conclusion, challenges in managing the intrinsic character of IRE:s are mainly three-fold: 1) on shorter timescales it is difficult to predict the production in a detailed way, 2) the smaller the area of the analysis the more difficult it is to accurately predict the production, 3) the different frequency characteristics and fluctuations makes it difficult to balance the grid with a higher share of renewables. A storage solution that can handle many charging/discharging cycles while storing energy for at least a few days could, in theory, mitigate a large part of PV-systems uncertainty. The capacity to store energy will be used in this thesis, but storage characteristics will not be discussed in any depth. By looking at the intermittent character of PV most batteries are feasible, although more modern fly wheels could also potentially work and perhaps even better in some cases.

In a scenario with 100 % renewable energy system, SEA pictures a case with more wind than with solar power (Energimyndigheten, 2019). This might seem reasonable due to the geographical situation of Sweden, but during the summer half of the year Sweden has a considerable amount of sun light. Cloudiness and wind speeds are weakly inversely correlated, meaning that is the wind is usually stronger when there is cloudy weather with little sunlight and vice versa (Bett & Thornton, 2016). Thus, studies of how to coincide different types of IRE production with consumption of electricity becomes important in order to optimize the power system. Through digitalization and using energy storage both companies and residents could provide system services for the grid. As a summary, local production of electricity will become increasingly important due to foremost two reasons: 1) contribution of renewably produced electricity directly generated in the local system where it is needed and 2) it is the next step for both local residents and companies/industries who wants to optimize local energy systems (Energimyndigheten, 2019, p. 39).

1.1.2 PV-systems in Sweden today

The biggest market segment in Sweden currently for PV-systems is residential single-family households closely followed by commercial facilities. Of the total installed effect of 158 MW PV-generation capacity, the first segment made up 33 % and the second 32 % in 2018. Multi-family houses and other residentials made up 6 % each, while other types of commercial facilities made up 10 %. These segments combined made up a total of 87 % of all installed PV-capacity last year, meaning that industrial and centralized PV-parks still are a small market segment in Sweden. The reason behind PV-parks still being small segment is due to the lack of support schemes for bigger parks, making the production having to compete with the spot price plus revenues from electricity certificates in today's market. Policy changes are not unlikely though (Lindahl et al. 2018, p. 12f).

1.2 The electrical grid and its operators

In this section the electrical grid is briefly portrayed from an overall technological perspective. The electrical grid is divided into three overall parts in Sweden: "stamnät" (backbone grid), which is handled by the TSO, "regionnät" (distribution grid) and "lokalnät" (local grid) where the last two are operated by distribution system operators (DSOs). Electricity is mainly transmitted from big power plants throughout the backbone grid. As the power is transmitted to consumers it is transformed into lower voltages throughout the grid's regional and local transformers. An example of a high voltage network (HVN) is shown in Figure 3 on the next page where the general radial structure – that spreads outwards almost like the branches of a tree while becoming meshed – can be seen. This pattern becomes even more clear in networks where the voltage is lower.

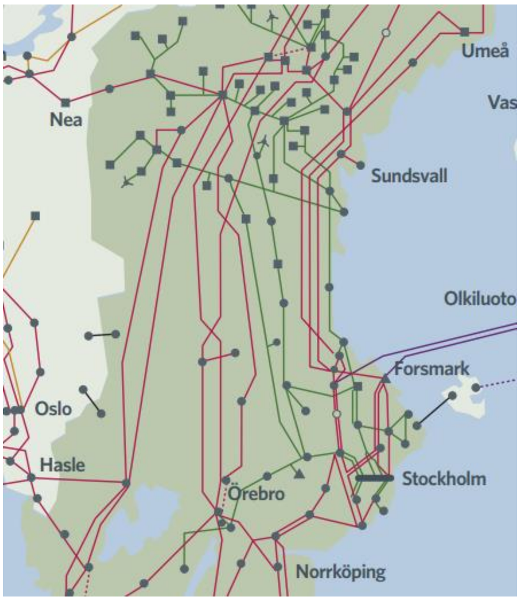

Figure 3 – The central part of the high voltage network of Sweden. Red lines are 400 kV and green 220 kV. Squares symbolizes hydro power plants, triangles heat power plants (including nuclear) and circles transformation stations. The circle with three lines is wind power parks.

Over hundred companies in total produces electricity with the four largest accounting for around 70 %. Most electricity is produced in the North and most is consumed in the South, and since Sweden has an oblong shape in the North to South direction many TWh of electricity is transmitted long distances which incurs losses. This is one driving force for more local production. This also related to the capacity problem described in the introduction which comes from how the production and consumption of electricity is not geographically aligned – sometimes the transmission capacity is not enough to satisfy demand. This has caused the power system to be divided into four regions since 2011 between which they price of electricity may vary. The general trend is higher price in the South (Energimarknadsbyrån, 2019a). This is yet another driving force for improving and developing the grid for better integration with DER such as PV to meet the electricity consumers expectations of capacity and availability (Energimarknadsbyrån, 2019b).

Sweden has around 15,000 km backbone grid from 220 to 400 kV with 160 transformers and 16 connections to nearby countries in total (Svenska Kraftnät, 2017). In addition, there is also around 31,000 km distribution network (40 to 130 kV) with 2,330 transformers (Energimarknadsbyrån, 2019c). The grid's distribution-to-transmission interface has no given standard from a technical point of view, but the separation is often related to different voltage levels as shown in Figure 4.

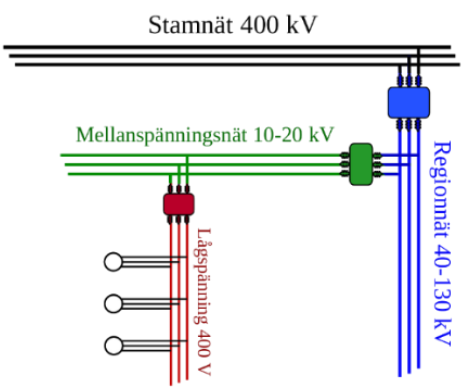

Figure 4 – Overview of the electrical grid in Sweden. The black lines are the backbone grid operated by the TSO and the rest is operated by DSOs. Blue represents distribution/regional grid, while green and red represents the local grid.

These voltage levels can also be related to the European Standards (EN 50160) shown in Table 1:

Table 1 – European voltage standard.

Voltage	EN 50160 standard
<1 kV	Low voltage network (LVN)
1-35 kV	Medium voltage network (MVN)
35> kV	High voltage network (HVN)

The Council of European Energy Regulators (CEER) was established in 2000 with the purpose of bringing independent energy regulators of Europe together and increase their cooperation in order to facilitate the creation of a (single), competitive, efficient and sustainable energy market within the European Union (EU). The DPF in focus of this thesis does not require, or necessarily lead to, a single market but could potentially work in such an environment. Since CEER focuses on the future roles of the DSOs who operates the LVN, which is where the DPF is thought to function within, this is of interest. An increase of DER, such as local IRE production from PV, will mainly impact the DSOs' part of the grid which might require increased maintenance and operational support in order to keep the balance. This will likely also impact future design. As mentioned in section 1.1.2, most of the installed capacity of PV today are in residential single-family households followed by commercial facilities, and these electricity users are all connected to the DSOs' grid (CEER, 2019, p. 12). Since the LVN in some sense have rather vague borders, a more rigid definition of an area to work with is adequate.

1.2.1 Definition of a "local" area and its relations

Households, which also could be called low voltage customers, are connected to the LVNs of DSOs. As pictured in the previous section, the electrical grid can be viewed as branches spreading out from a tree in a radial way and this can be used as starting point to visualize a local area which is a core aspect of the DPF due to its basis in local balance. A local area could be defined in a geographical sense by looking at a map, but a more reasonable definition in this context is as an area, or section, behind an LVN-transformer – the end of a branch in the grid structure. In Figure 5 below a local area, as defined in this thesis, is marked with a red border.

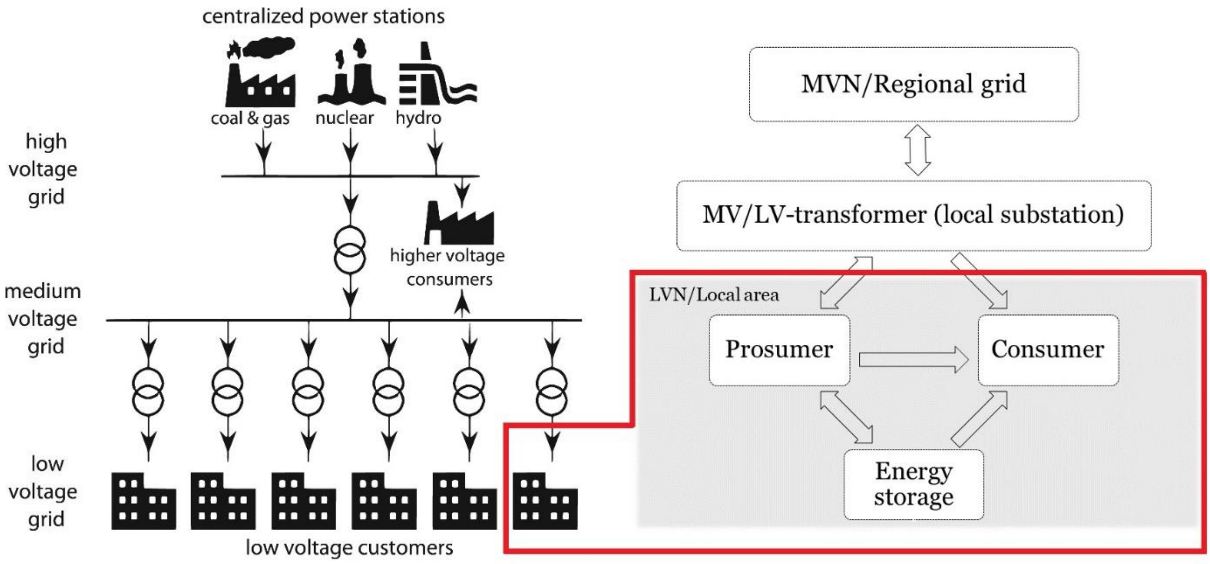

Figure 5 – Simple overview of a grid structure and the definition of a local area marked in red.

The implication is that every building to the down left in Figure 5 would be its own local area.

1.2.2 Distribution System Operators

DSOs are assigned one of the most important roles of the power system, namely being responsible for developing, designing, maintaining and operating the grid. This is their core activity and it is continuously monitored and controlled by energy regulators to prevent abuse. The DSOs traditionally offer services directly to consumers such as initial connection procedures, metering services and emergency actions. When it comes to other activities that are open for competition, the DSOs should not offer such without a formal permit and justification (CEER, 2019, p. 25). This is because the DSOs have a natural monopoly over the grid, meaning it would not be economically feasible and a waste of resources to build parallel systems, while they must remain a neutral market facilitator due to the fundamental part of electricity in the modern society. While it is not always clear where the line exactly should be drawn, both policymakers and regulators are continuously encouraged to provide more clarity. CEER has concluded, among other things, that:

- A market-centric approach is recommended for constructing the base for grid services wherever it is possible in order to minimize the risk of DSOs using their inherent advantage.
- The DSOs' core activity includes providing relevant network information to third parties to enable their services.
- As the energy sector progresses, policy makers and regulators should continue to develop their way of thinking around activities which may involve the DSOs (CEER, 2019, p. 5-9).

Why is this mentioned? It connects to the possible implementation and function of the DPF. In the next section the environment and information the DPF needs to function will be further discussed. The main idea is that competition is the most efficient way to meet requirements, and the challenge is to construct such a market environment within a natural monopoly. Naturally the DSOs, who usually are private companies, want to keep as much data as possible to themselves. But CEER have stated that it is a core service to electricity consumers to deliver detailed consumption data (CEER, 2019, p. 20). In an LVN, there are three main key stakeholders:

- Consumers (or prosumers if they also can produce).
- Electricity providers.
- Grid operators (DSOs).

Since the DSOs are not allowed to provide market services, such as selling electricity for instance, it would be the electricity providers who could use the DPF. As mentioned, consumers have the right to attain detailed consumption data. But this is only their own data, and not others or their local areas. As will be further discussed in the next chapter, the DPF requires both consumption and production data of a local area to function. The question is if, and how, such data from consumers and producers could become accessible to the electricity providers through the grid operators. These three stakeholders are in most cases in the center of the judicial discussion around the grid which will be the topic of the next section.

1.3 Rules, policies and incentives

In this section the intention is to process relevant aspects of the legal environment related to the purpose of this thesis. An initial, and important, distinction is that while a rule has to be obeyed and can be enforced a policy is a system of principles to guide decisions and achieve rational outcomes. A policy is a statement of intent and usually given by an organization or individual with a certain bias or goal in mind. The development of DER, e.g. through IRE as described, is by using IT moving the energy systems towards digitalization. This development relates to many different rules, policies and incentives and many of them connects to the EU's "Clean energy for all Europeans"-package which is an on-going policy framework. The idea is to make the rules more comparable between EU-countries and encourage changes for a larger share of IRE technologies within the electricity production, an increased number of prosumers and related information (EU, 2019a). This can for example be shown by the deployment of so-called "smart" meters.

Every consumer connected to the grid have a metering device which registers the transmission of electricity in both directions – if electricity is consumed it is withdrawn from the grid and if it is produced it is fed to the grid. Traditionally these meters could only measure the consumed electricity and had to be manually inspected on site, but the smart meters for consumers, prosumers, industries, storage unit etc. has bi-directional interface where electricity and information can go both ways while being remotely accessible. This allows to communicate data in almost real time. How such networks of consumers/prosumers, smart-meters, DSOs and electricity providers will work together has been pointed out by CEER as a field which will require further discussion among policy makers (CEER, 2019, p. 12). In UK alone, 53 million electricity and gas smart meters are planned to be installed by 2020 – one for every home and small business (Andoni et al. 2019, p. 1f). Such meters will very likely be required to be interoperable with different devices marketed by third parties as a consequence of the DSOs' role as a neutral market facilitator (CEER, 2019, p. 13f). This whole field has historically been a visionary concept and mainly a point of academic discussion but are now becoming a potential reality (Sousa et al. 2018).

1.3.1 Rules

As Sweden is a member of the EU, discussions about changes to EU laws are important since it will have a major impact on the future development the activities of the DSOs, the electricity market(s) and more. The "Clean energy for all Europeans"-package hold much information, and the most interesting section in this context focuses on electricity market design (EU, 2019b). The goal is to establish a modern design adapted to new realities where more flexibility, a market-orientated structure and an ability to accommodate a greater share of renewables are sought. The share of renewable electricity within the EU is expected to grow from 25 % to more than 50 % in the upcoming ten years, and it is highlighted that the rules needs to be updated in order to facilitate an increased integration of renewables. It is also emphasized that the market needs to be improved in order to meet this development and attract investment, both among producers and consumers:

> The market must also provide the right incentives for consumers to become more active and to contribute to keeping the electricity system stable (EU, 2019c).

On-going studies shows that the adoption of newer smart grid technologies provides possibilities to apply more flexibility reliability. Apart from the possibility to access consumption and production data, a large part of the discussions technology and policies are directed at how to reach a broader consensus over what unified set of rules should be used to value reliability. Researchers at Energy Institute at Haas has written (my underlining):

> As resources become more diverse, the challenge of forecasting their value for reliability months and years in advance greatly increases. This could necessitate an increased reliance on short-term performance measures, of which <u>energy prices are the most sophisticated</u> (Bushnell, Flagg & Mansur, 2017, p. 6).

SEA recommends that the planning of regulatory frame around the electrical grid is designed in a way that can incorporate possible changes within the grid (Energimyndigheten, 2019, p. 8). One such change is if it could be possible for a PV-system owner to directly transmit electricity between nearby buildings or consumers to optimize the use of roofs with good conditions. With current laws in Sweden this is not possible (Energimyndigheten, 2019, p. 41).

1.3.1.1 Access to consumption and production data in Sweden

While the previous section focused on current laws and how they might change, this section will scrutinize the perhaps most important aspect for this thesis – information sharing. The DPF that is the focus of the next chapter requires two main types of in-data that is not currently openly accessible: consumption and production of electricity linked to a local area. How such a local area could be defined was discussed in section 1.2.1, here the emphasis is on judicial aspects.

Data of transmitted electricity – both consumption and production – is to be measured both with respect to amount and time with an electricity meter in the part of the grid that falls under the concession duty according to the 3:rd chapter, § 10, of the Swedish electricity law (1997:857). Only internal grids are free from concession duty, and normal residential areas does not count as such. Latest in 2025, electricity meters in the LVN has to be equipped with an interface that allows users to see their own consumption and production in almost real time according to the Regulation (1997:716) on the measurement, calculation and reporting of transmitted electricity, § 23-31. The time interval is to be maximum 15 minutes according to § 26, and § 30 states that the measurement equipment shall make it possible for the grid concession owner to remotely access it.

The TSO of Sweden, SvK, and the Swedish Energy Market Inspectorate (SEMI), who is the supervisory authority of energy markets in Sweden, are running a project within this context together and are currently awaiting the Swedish government's law referral and propositions for the future judicial development (Energimarknadsinspektionen, 2019). The project's goal is to create an information hub where information transmitted between different actors on the Swedish electricity market is gathered (Svenska Kraftnät, 2019). Exactly what information that will be available, to whom and how is not clear yet; but the main goal is to create possibilities for new energy services which potentially could implicate access to such information that is needed for the DPF.

1.3.2 Two common currently used policies

With a larger share of DER in terms of IRE, several issues have started to arise when it comes to the grid (Mihaylov, Razo-Zapta & Nowé, 2018, p. 113 & Mihaylov et al. 2019, p. 691). While this development affects the whole grid, it is mainly the LVN that is relevant for local IRE production as described. In the thesis' introduction the current policies for local and renewable electricity production were criticized for not considering *when* or *where* electricity was fed into the grid. Previously, governments over the world have adopted several different policies to support renewable energy which undoubtedly have contributed to the development of renewable electricity production. Two of the most widely used policies are net metering (NM) and feed-in tariff (FiT).

1.3.2.1 Net-Metering (NM)

With NM the electricity meter, counting the amount of electricity withdrawn and consumed from the grid, is allowed to count backwards when electricity is produced and fed into the grid. With this approach electricity is indirectly payed at the retail price while the grid is seen as a virtual storage. Usually the reading of the meter is not allowed be lower at the end of a year than at the beginning, thus becoming a net producer is not possible. (Mihaylov, Razo-Zapta & Nowé, 2018, p. 114).

1.3.2.2 Freed-in Tariff (FiT)

In contrast to NM, FiT gives a fixed rate (usually lower than the retail price) for a given time period but without an annual limit for feeding electricity into the grid. In addition to requiring a separate meter, much consideration needs to be put into the rate such that it becomes high enough to encourage investments without risk of overcompensation which can make the market unstable. Caution also needs to be exercised when it comes to changing the rate since frequent changes will send mixed signals to the market and investors and thereby undermine their will to invest (Mihaylov, Razo-Zapta & Nowé, 2018, p. 114). Becoming a net producer is also often not allowed in this case.

1.3.2.3 Problems with NM and FiT

Up until 2015, 52 countries had used NM while 110 jurisdictions at national or state/provincial level had used FiT (Mihaylov et al. 2019, p. 689). FiT is still the most widely adopted policy, but NM is still used in several countries with some examples being Belgium, Denmark, Italy and the Netherlands (Mihaylov et al. 2018). While these concepts work relatively well when the number of prosumers is few compared to the number of consumers, but several drawbacks start to arise when the number of prosumers increases. As Mihaylov et al. (2017) mentions, the main issue with these policies is that they do not create incentives for *when* and *where* electricity is fed to the grid. With this static view of rewarding production – without any considerations to the grid's stability in terms of loads or peaks – local IRE scale in a negative way. They also do not motivate as specific use of renewable electricity, just to feed it into the grid. Hence there is a need for phasing out these traditional schemes for mechanisms that scale better.

Concepts that see the grid as virtual storage, such as NM, also gives rise to situations that exert extra stress on the grid since it encourages prosumers to solely maximize their annual production. For local PV-system owners it might lead to a large overproduction during the middle of the day summertime – a time when electricity is needed the least. In local areas this might cause grid overloads as the share of prosumers increase, which the DSOs in the end must handle. Also, since NM is only counted towards own consumption, it might also create an incentive to increase the use of electricity during the winter when both the need and prices are higher. Both scenarios exert extra stress on the grid, increasing the risk for overload. CEER has also expressed that they want to avoid this situation (CEER, 2019, p. 14). FiT does not have the same issues as NM as it primarily motivates self-consumption due to almost always paying beneath the retail price of electricity. FiT, however, still does not give any incentives of *when* or *where* to fed electricity into the grid. Both these policies do not reward production in a way that considers actual energy demand. In a local area with potentially many prosumers, both policies will incentivize electricity being fed into the grid even though it is not needed by any nearby consumer. Finally, none of these policies gives any incentives to consume renewable electricity fed to the grid by other prosumers. NM and FiT have been the first policy mechanism to promote and contribute to the initial penetration of local renewable electricity production. They have functioned relatively well when the number of prosumers were low, but with an increasing share of prosumers new policy mechanisms are increasingly needed (Mihaylov et al. 2019, p. 692).

1.3.2.4 Comparing NM and FiT to newer concepts

An increase of DER in terms of IRE could intensify the problems as described in the previous section and, in the long run, affect all the LVN stakeholders in a negative way. Experts has thus advocated to replace these older policies with new incentives which can support development of an increasing share of prosumers, a more stable load on the grid while at the same time give possible benefits to all stakeholders (Mihaylov, Razo-Zapata & Nowé, 2018, p.116). Current incentives for active consumer participation have so far not proven sufficient, and according to a UK government report by the Competition and Market Authority poorly designed tariff prices and a lack of mobility in the market has caused electricity consumer to pay on average £1.4 billion in excessive prices per year in the UK between 2012-2015 (Andoni et al 2019, p. 144).

1.3.3 Market-based instruments

A market-based instrument (MBI) is a type of regulation based upon the idea to encourage market participants to behave in a certain way by using market signals to design incentives rather than forcing the participants with explicit directives. There is much to be said about MBIs, but only a basic overview can be done here. In an earlier study, one feature distinguishing an MBI was its ability to "harness market forces" – if well designed. This stems from its influence on companies and/or individuals to undertake policy goals out of their self-interest which, in the best case, pulls the entirety of the market towards the goal. As a contrast, more conventional policies created with the intent of regulating a market are often referred to as "command-and-control" as they generally include little flexibility in the means of achieving goals, leading to different actors of the market having to take on similar burdens regardless of their prerequisites. Command-and-control policies might be effective on reaching the goals in one sense, e.g. to limit pollutions, but the cost of the process can greatly vary between different actors without giving them any means of influence. It also could slow down the development and implementation of technology due to a lack of financial incentives to exceed the goal. Thus, MBIs could have the potential to provide a lower overall cost for energy efficiency while encouraging the market to iterate itself to the best solution. Command-and-control regulations could theoretically achieve the same but would require information of every actor on a detail level that is impossible for policy makers to obtain (Stavins, 2003, p. 358f). According to the International Energy Agency (IEA), MBIs can save energy for less than the cost of supply and are thus a form of energy efficiency measure. The most ambitious jurisdictions have achieved a cost-effective saving of 3 % of annual electricity consumption, reducing both the customers energy bill and the investments required on the supply side (IEA, 2017, p. 10f).

IEA was founded in 1974 and is an autonomous body within the Organization for Economic Cooperation and Development (OECD). IEA provides energy efficiency data, analysis and policy advice while carrying out energy cooperation between its 30 member countries where also the European commission participates. IEA also performs workshops, research collaborations and work with partners at a global level through e.g. the G7- and G20-meetings. The purpose is to support energy efficiency and give advice on implementing and measuring different policies (IEA, 2018). The organization has a clear goal of promoting renewable energy and energy efficiency, and in a report from 2017 IEA made their first overview of MBIs for energy efficiency introduced with:

> [...] many market failures are holding back the realization of the full potential that energy efficiency offers. For these reasons, there is growing interest in the role that markets can play in delivering cost-effective efficiency gains and reducing the need for direct government expenditure. MBIs offer the potential for policy makers to access more cost-effective efficiency gains (IEA, 2017, p. 9).

All policy instruments will interact with the market to some extent, e.g. by affecting the decisions of investors, the behavior of producers or consumption of energy. The difference with MBIs is that they provide the actors of the market with a higher degree of freedom. There has been an increased interest of MBIs in terms of delivering energy efficiency and their number within the EU has increased (IEA, 2017, p. 14f). The increase is also globally and between 2005-2015 MBIs nearly five-doubled. Even though MBIs are increasing, politicians have been slow to adopt their uses which some researches explained with the nature of political processes which takes time (Stavins, 2003, p. 422). The use and effects of MBIs may e.g. be seen in the USA where energy efficiency obligations have been one key factor behind the growth of energy service companies in addition to federal energy efficiency spending and increased interest from customers (IEA, 2017, p. 77).

1.3.3.1 Key policy design features

MBIs has several design aspects, and some important to considered are:

- MBIs can be designed to achieve specific policy goals.
- MBIs must work within existing policy frameworks since they will need support from technical standards and mix with other instruments to function well.
- The mechanism should be as simple as possible, but as complex as necessary.
- Including trading systems could have positive benefits but adds additional layers of complexity and sometimes extra costs which might exceed the benefits (IEA, 2017, p. 12f).

1.3.3.2 General design features

There are also several general questions that arises when designing an MBI. They are mainly around who (energy utilities, private customers, governmental organization etc.) should do what, how regulated it should be and how it should be funded (IEA, 2017, p. 26). Other important aspects worth to shortly mention is lifetime, cost saving calculations and how the MBI should be monitored, verified and evaluated (IEA, 2017, p. 39-55). These features decide an MBIs stability over time and how obliged entities will be able to monitor and react to market conditions and adjust their behavior.

1.4 The electricity market

As discussed in the section 1.3, many developments are on-going which will cause changes. While these still are in the future, what can be said about the electricity market in Sweden as of today?

1.4.1 Electricity subscription and the value of electricity

In Sweden there are three overall types of electricity subscription: standard, fixed and variable. Standard is used the least since it is the most expensive. It works as the default if an electricity consumer does not make any choice. Fixed gives a predetermined price per consumed kWh while the variable price is based around Nord Pool's spot prices. Nord Pool AS is the biggest power market in Northern Europe and offers both day-ahead and intraday trading. All prices are decided before its usage and is based upon expected supply and demand of the upcoming time interval.

A fixed price is usually higher than a variable price since the provider takes on a risk associated with the uncertainty of the market as the price development during the subscription period is unknown. In the last 15 years, a variable price has been more profitable 65 % of the time with one year-contracts and 57 % of the time with three year-contracts (Energimarknadsbyrån, 2019d).

1.4.1.1 Consumer's cost of buying electricity

Energimarknadsbyrån is a bureau run by a board appointed by three governmental institutions and two trade organizations in Sweden and aimed at giving individuals and small companies independent and free advice. According to the bureau, the average price of electricity was 1.45 SEK/kWh in Sweden 2018 for an average household with a yearly consumption of 20,000 kWh. Households connected to a district heating network had the same estimated yearly consumption of 20,000 kW, but with 5,000 kWh being electricity instead. This resulted in a slightly higher price per kWh due to a lower total consumption (Energimarknadsbyrån, 2019e).

1.4.1.2 Prosumer's value for selling electricity

To sell locally produced electricity, the prosumer has to sign a contract with an electricity provider. They will pay a static compensation per kWh according to the FiT mechanism. In addition to the selling price of electricity there are also other possible compensations, see Table 2:

Table 2 – Different compensations for selling renewable electricity in Sweden. All values are without tax.

Part	Compensation (SEK/kWh)	Note
Selling price (Prosument.se, 2019)	0.28-0.56	The lowest and highest compensation found for feeding renewable electricity into the grid in Sweden without temporary additions.
Grid benefit service (Ellevio, 2019)	0.02-0.06	The Swedish electricity law, 3:rd chapter § 15, obliges a DSO to pay a prosumer a certain amount per fed-in kWh since it (at least potentially) might contribute to reducing transmission losses.
Electricity certificate (Svensk Kraftmäkling, 2019)	0.05-0.20	A form of support for producers of renewable electricity. New PV-systems are guaranteed the right to such certificates for 15 years, longest until 2035 (Prosument.se, 2019). If the supplier does not give a fixed price it varies with the connected market where it can be sold. One (1) certificate is awarded for every MWh produced from a renewable source.
Guarantee of Origin (Prosument.se, 2019)	0.001-0.30	The market in Sweden is still too small for a distinct price. Some companies offer a relatively high price in order to sell solar certified electricity to their customers. One (1) "Guarantee of Origin" is awarded for each MWh produced from a renewable source.
Tax reduction (Skatteverket, 2019)	0.60	Used to reduce income tax. Maximum 18,000 SEK a year. Same connection for consuming and producing electricity is required among other things.
Total selling-value	0.96-1.72	

Figure 6 shows the total value of selling electricity with the low and high compensation-interval limits levels in Table 2 compared to the value of self-consumption:

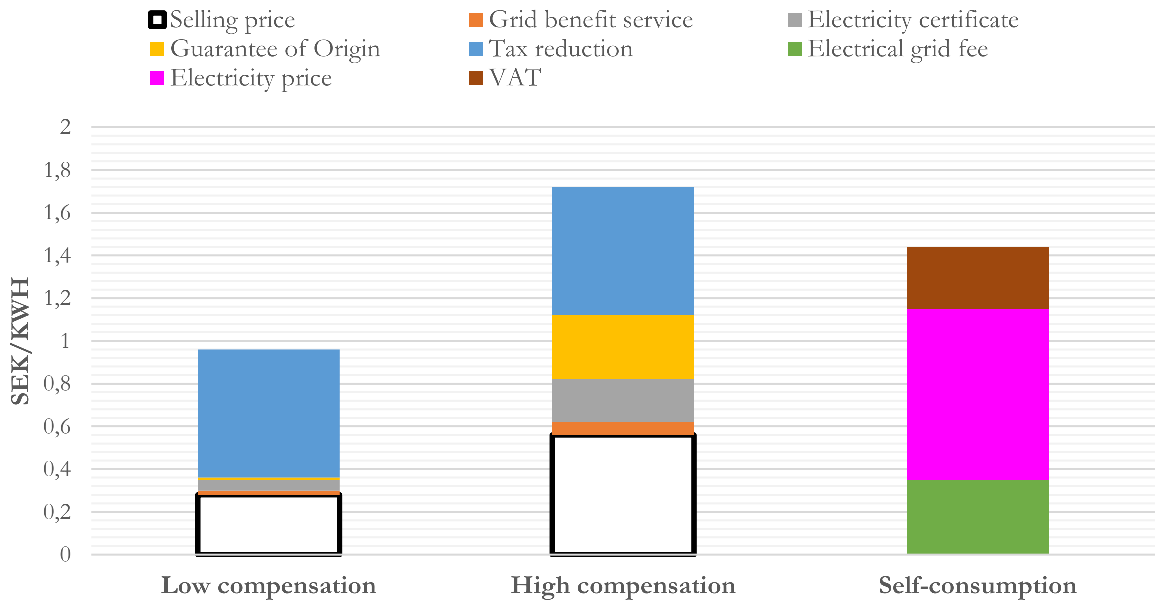

Figure 6 – Selling price compared self-consumption value of electricity.

Figure 6 shows that self-consumption has a high value, but that a high compensation could result in an even higher one. It is although unlikely that an electricity provider will offer the upper interval for all the compensations at the same time. This thesis will only focus on the white block called "Selling price" and compare the resulting DPF compensation in the next chapter to this.

1.4.2 A new structure for handling and valuing distributed production

This thesis' purpose of modelling, testing and discussing a DPF for renewable electricity is not the same as creating a new market, but rather a new way to value electricity. But it is still of interest to discuss how the DPF would position itself within a market. SEA has stated that the electricity market of the future will give more incentives for flexibility and a use of electricity which connects to grid balance. While they do not believe the market needs to be completely redesigned, they admit that there might be a need to modify it. (Energimyndigheten, 2019, p. 5). One way is by sending price signals to the actors of the market. As the share of prosumers grow and technology continue to develop, new market possibilities open up where produced electricity may be valued in different ways or where prosumers even could buy and sell directly to each other without involving a third party. No fully developed platform for such trade exists yet, but projects have started over recent years. Many of these stems from the idea of Peer-to-Peer (P2P) models in which electricity is traded between users in local areas, e.g. by using the concept of microgrids. A microgrid is a local grid that works as an extension to the traditional grid and operates in synchronization with it, and sometimes even autonomous in island-mode. The microgrid is made up of grid-users in a local and geographically defined area which is connected to the same transformer (Zhang et al. 2019, p. 3). IRE sources work well together with the concept of microgrids, and small community-based projects using microgrids are expected to become more important as the energy system develops (Andoni et al. 2019, p. 154). Figure 7 shows how different grid concepts may relate to each other:

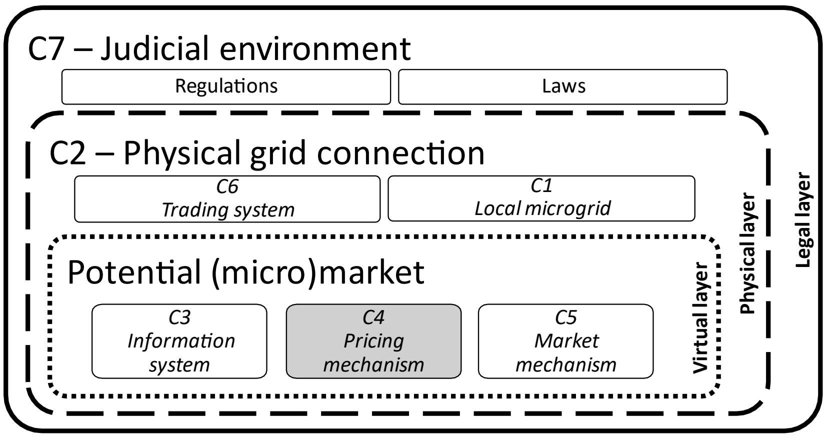

Figure 7 – A component-based overview of an electricity market.

In the structure of Figure 7 this thesis focuses on the component C4 – the pricing mechanism. The components written in italic does not exist in a conventional grid structure but are possible additions. A summarization of the components of Figure 7 is given in Table 3:

Table 3 – Components of Figure 7.

C1	C2	C3	C4	C5	C6	C7
Physical layer		Virtual layer				Judicial layer
		Creates a working, decentralized, energy market in its purest form and provides access			More external, provides a platform for C1-C5	
Local electrical grid (LVN)	D-NU interface	Information system	Price mechanism	Market mechanism	User interface	Laws and regulations
Constraints, consumption, production	Not needed with a traditional grid is not necessary	Enables market communication	Regulates buy and sell price	How trade would function	Could make processes automatic	Often overlooked but important

This idea of trading in this context connects with the P2P approach to markets which, in its simplest form, implies multi-bilateral agreements between participators. The development of microgrids and IT creates an infrastructure basis in the domains of monitoring, communication and control that are important enablers for P2P markets (Sousa et al. 2018). This development is not only complex in terms of technology, but when it comes to ethics and politics (Andoni et al. 2019, p. 156ff). Table 4 shows a SWOT analysis of P2P and energy markets:

Table 4 – SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis on P2P-markets.

Strengths	Weaknesses	Opportunities	Threats
Increased transparency and empowering consumers, e.g. better choice of supply selling energy	Sub-optimal price for energy	Increased democratization within the energy field	Legal and regulatory obstacles, but also potential market failure if poorly structured
Increased resilience and reliability of the system	Potentially difficult transition, e.g. in terms of negotiation and different mechanisms	Consumers might become more aware and cooperate better towards green energy	Potential grid congestions and difficulty in operating the grid
Make the potential market power more even amongst actors		Increased competition boosts the retailer market, might also postpone grid investments from system operators	Technology dependency, e.g. on blockchain, and security issues in relation to privacy data

P2P applications have existed for relatively long time – for instance did software as Napster emerge in the 1990s. Modern energy trading projects are however based on other solutions, and one of the most popular ones is blockchain which became known around the world with the arrival of Bitcoin in 2009. Previous studies have shown that blockchain potentially can provide a base for an energy market (Mengelkamp et al. 2018). According to a systematic review by Andoni et al. (2019) that studied 140 blockchain-project, the technology shows a transparent, tamper-proof and secure system that can enable novel business solutions. It is however important to realize that there is not one single blockchain architecture that fits all applications. In terms of energy matching using blockchain together with smart meters could potentially allow exact and safe real time tracking of producer or consumer use of the grid. There are many challenges though, and one key question is how an implementation would fit together with existing TSO and DSO operation. Ultimately, they control the grid and has the responsibility of power delivery (Andoni et al. 2019, p. 154f). Table 5 shows a brief discussion of blockchain as the basis of an information system, i.e. C3 in Figure 7:

Table 5 – Some of blockchain's potential benefits and challenges

Potential benefits	Future challenges
May reduce transaction costs	Scalability issues
Provide transparent data	Speed of transactions
Eliminate intermediaries/middlemen	Possible sensitive data open to everyone
Allow small-scale consumers/producers to participate at the energy market	Regulatory uncertainties, bad implementation might cause more problem than it solves
Increased flexibility	Lack of standardization and flexibility within the on-going projects

The overview presented in this chapter, and especially the last part with P2P markets and blockchain, relates to Mihaylov et al. (2014) and succeeding articles which inspired the DPF which will be the focus of the next chapter. It is of relevance to be aware of them since implementing a new policy mechanism in the rapidly changing environment of the electrical grid and connected markets is complex. But it is not impossible, CEER (2019) amongst others points at the possibility for normal grid consumers to generate power themselves and become a market participant.

Chapter 2
A new renewable electricity support mechanism

The previous chapter discussed aspects related to PV-systems, the electrical grid, the changing judicial landscape and how the development of IT has created new possibilities for markets and subsequently policy mechanisms. Governments worldwide have so far adopted many different approaches, which in general have contributed to at least an initial boost in renewable electricity production. But to coop with future scenarios where such production is decentralized and occurs in local LVN, new policies are needed. In this chapter, one such policy mechanism is presented. The idea which lies as the foundation for the DPF originally stems from a paper by Mihaylov et al. (2014) where a concept around what is called "NRGcoin" is portrayed. The idea has been continuously developed and was later also denoted as "NRG-X-Change" (Mihaylov et al. 2016). A recent article explained the concept as:

> NRGcoin is a residential support policy for renewable energy exchange. It is a decentralized mechanism based on smart contracts that reward prosumers for their injected green energy and makes green energy more economically attractive to consumers. In doing so, NRGcoin aims to offset the consumption of gray energy, i.e., energy from mixed sources, and helps increase the share of renewable energy sources (RES) in the overall energy mix (Mihaylov, Raza-Zapata & Nowé, 2018, p. 112).

From other researches the idea has been described as based on a consideration of a local grid's conditions when deciding the value of electricity fed into the grid by a prosumer. This consideration is then used to create an incentive to support the grid's balance (Liu et al. 2017). It has also been described as a project which aims to develop a virtual currency based on blockchain and smart contracts for small prosumers trading in P2P markets (Sousa et al. 2018, p. 5). The NRG-X-Change-concept is designed to work with a blockchain system, but such an implementation would lie at end stage and will, as mentioned, not be processed in this chapter (Mihaylov, Razo-Zapata & Nowé, 2018). The developers also stated in their first paper that:

> It should be noted that the NRGcoin currency is an added value to the energy trade mechanism and not designed to be an indivisible part of it. The trading of energy is also possible using fiat currency instead of NRGcoins [...] detailed investigations need to be carried out to determine to what extend standard currency can be used in the deployment phase (Mihaylov et al. 2014, p. 4).

The papers also mention that simulations and microeconomic theorizing is needed in order to tweak the concept and make it adequate. That is one focus of this chapter. Then, in a continued phase with more experience from administrating a concept like this, the virtual currency of NRGcoin could potentially be introduced and tested for additional possible benefits. Of course, there will be no single policy or instrument that is going to be adequate for all efficiency, or environmental, issues. But as CEER previously have stated it is important that the network users in the end are able to make their own decisions on how to provide flexibility services (CEER, 2019, p. 23). While previously discussed concepts as NM and FiT are examples of top-down focused incentives, the NRG-X-Change is a bottom-up incentive where the prosumer can affect their compensation while being encouraged to pursue certain goals. This could provide better adaption to local circumstances in terms while supporting an increased penetration of renewable energy.

2.1 The Dynamic Price Function

In this section the DPF's will be explained in steps starting with the main function and its so-called "design parameters" while ending with needed in-data and assumptions. If it has not been made clear yet, the main idea is to incentivize local electricity production to match supply with demand in order to decrease the load on the grid and consequently transmission loads between different regions. The function $g(\cdot)$ the DPF is based upon is written in Mihaylov et al. (2014) as:

$$g(x, t_p, t_c) = x \cdot q \cdot e^{-\frac{(t_p - t_c)^2}{a}} \tag{2.1}$$

where $\boldsymbol{x}$ is an amount of electrical energy, $\boldsymbol{t_p}$ corresponds to total local production, $\boldsymbol{t_c}$ to total local consumption while $\boldsymbol{q}$ and $\boldsymbol{a}$ are design parameters. In Figure 8 the function is visualized:

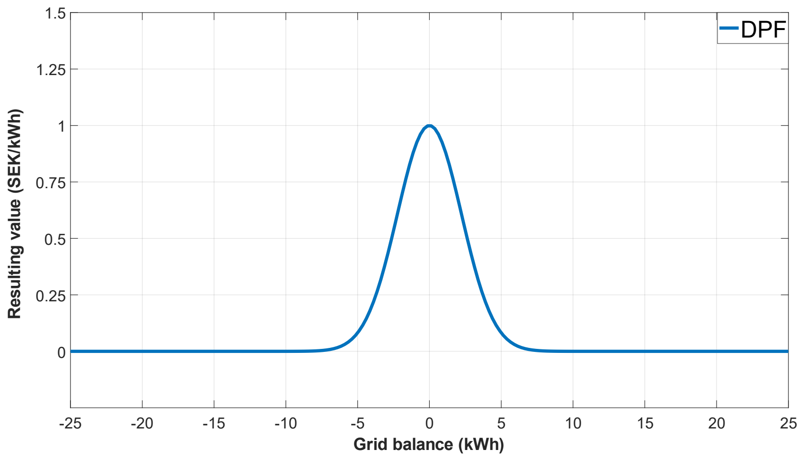

Figure 8 – Visualization of $g(x, t_p, t_c)$.

The x-axis represents a local grid's balance, and it simply equals t_p minus t_c. A positive value corresponds to an excess of electricity, that is overproduction, and a negative value corresponds to a deficiency of electricity, meaning it has to be received from outside the local area. When t_p and t_c equal each other the x-axis value is zero and the function simplifies to $g(\cdot) = x \cdot q$ which from Figure 8 show that q corresponds to the maximum value of electricity per kWh. In the figure both x and q is set to one meaning that in this case, at grid balance, every kWh is worth one Swedish krona (SEK). To incentivize balance the function $g(\cdot)$ approaches zero the less balanced the grid is, i.e. when local supply and demand deviates. If not all consumers and prosumers have smart meters that can communicate with a central unit, a local substation to which all consumers and prosumers in the local area are connected to could potentially measure the sum of t_p and t_c for each time interval by register the amount of electricity transmitted through it. Thus $g(\cdot)$ plays the role of a dynamic feed-in tariff to calculate the compensation for prosumers whom have produced renewable electricity and feed the amount x of it into the grid. Compared to the static policies of today, this creates an incentive mechanism that works closer to how the grid operates. To summarize, the function $g(\cdot)$ has three simple extreme points and they are shown in Table 6:

Table 6 – The highest and lowest possible values for the function $g(\cdot)$.

	$\boldsymbol{g(x, t_p, t_c)}$
$\boldsymbol{t_p = t_c}$	$x \cdot q$
$\boldsymbol{t_p \gg t_c}$	$\rightarrow 0$
$\boldsymbol{t_c \gg t_p}$	$\rightarrow 0$

2.1.1 The design parameters q and a

Apart from t_p and t_c, the most important parameters in Equation 2.1 are q and a. In Figure 9 the impact of the varying these design parameters is shown. The axes are the same for both (a) and (b) which makes it clear that $q$scales the height of the DPF, the maximum possible value, whereas a scales the width of the DPF – how the balance of the grid affect the resulting value per kWh.

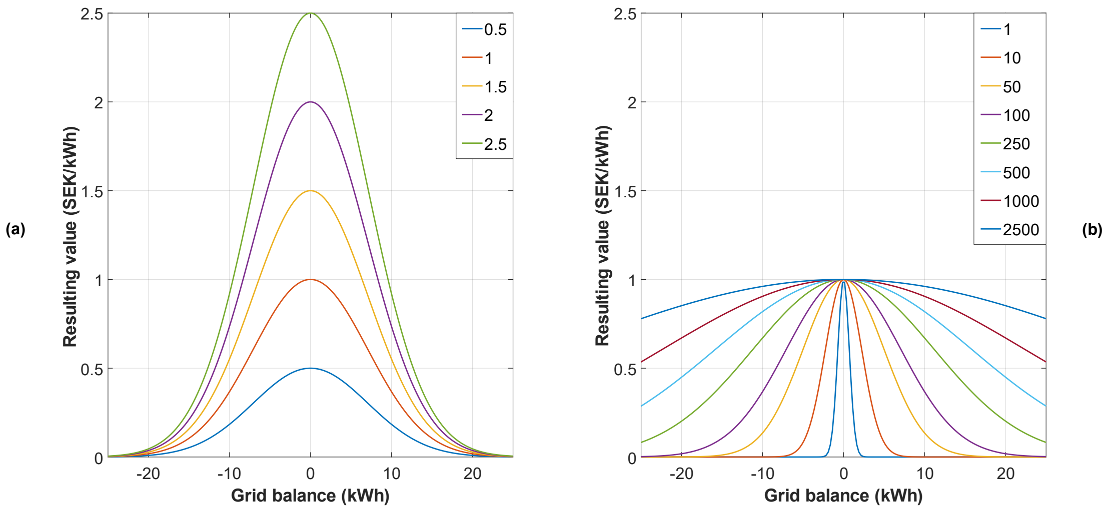

Figure 9 – How alternating the design parameters affect the behavior of $g(x, t_p, t_c)$: (a) Altering q with fixed a at 100 and (b) Altering a with a fixed q at 1.

In Figure 9 (a) the design parameter q is shown to scale the DPF linearly – that is if q doubles so do the resulting value. In Mihaylov et al. (2014) q is said to need carefulness when being configured in order to ensure that the profit for the relevant stakeholders is reasonable and covers the cost of transmission. In this thesis q has been set to equal the spot price. While the DPF needs to be dynamic in its character, it is reasonable to anchored it to something that is relevant and stable in order to decrease the risk for the DPF to become the subject of pure speculative activities. By letting the DPF follow the spot market – in essence letting it vary around the spot markets own variations – the first design parameter q gives the DPF an adequate mix of stability while still providing possibilities for dynamics and flexibility. A fixed value would not be able to do this.

The other design parameter, a, instead increasingly smoothens the function as its value becomes higher which is visualized in Figure 9 (b). This is very interesting since it shows that a connects the function to the grid's balance – which is the most important aspect to consider in this thesis, and thus a will be the main focus. As can be seen, when a is small it is a must to be at, or very close to, grid balance for electricity that is fed into the grid to have any value at all. As the value of a increases, grid imbalance is punished less and less meaning a prosumer can feed electricity into the grid further and further away from balance and still receive a compensation for it. The function's shape is symmetrical, which implies that this is equally true both for underproduction and overproduction. In Mihaylov et al. (2014), a is mentioned as a scaling factor for when $t_p \neq t_c$. Otherwise there are no deeper or more detailed discussions on these parameters – not in the original or in succeeding papers. Thus, it is open for interpretation, and in modelling and testing the DPF, the approach is to make these parameters dependent on other data in order to reduce the number of variables. Above, q was linked to the spot price. In the next section a is discussed.

2.1.1.1 Three ways of designing the a-parameter

While the original paper by Mihaylov et al. (2014) pictures the function as plotted in Figure 8 as symmetrical, a later paper states that "any over-produced energy that exceeds the local demand is not paid" (Mihaylov et al 2018, p. 117). This suggests that the value of a would go towards zero during overproduction, and thus be different for under- and overproduction. To remind, the main idea for the DPF is to provide a mechanism that incentivize balance. Since a is connected to the balance of the grid and affects how the DPF value fed-in electricity – what is the most reasonable way to design it? While a small value might be reasonable for a local area with a lower number of consumers where a single prosumer would have a greater impact on the grid during overproduction, a large value could be seen as more reasonable for a higher number of consumers since a single prosumer will not be able to affect the grid in the same way in such a scenario. To extend the last example a little: if there are few prosumers in an area with many consumers, then they will likely never be able to get close to local grid balance by themselves – five single-family households with average sized PV-systems will never provide enough electricity for 45 other households; not even during the middle of the day during peak production. For these prosumers to get any compensation at all for electricity they feed into the grid, a needs to have a large value since the local grid balance will be in a state of large underproduction; i.e. far to the left of the x-axis of Figure 8 and 9. At the same time, the higher the number of consumers – and prosumers – the more challenging and complex it will be to keep the local grid precisely at balance since the difference between production and consumption creates a larger grid balance interval. In these cases, it could be reasoned that there should be higher requirements to stay within balance, indicating a smaller a.

This point at that a should not be a fixed value, but rather be dependent on situational factors and be able to vary – but how? If a only becomes larger with system size, as the number of consumers or prosumers increase that is, the incentive to keep balance will become weaker and weaker. To handle this when designing a, the parameter should somehow connect to the *share* of prosumers in relation to the number of consumers in a local area. One way could to make the value of a initially large in order to create an incentive for a few households become prosumers in the first place. Then, as share of prosumers increase, the value of a should decrease in order to increase the incentive for the prosumers to support and stay close to the balance of the grid when feeding electricity into it to minimize the risk for imbalance and unwanted disruptions.

From this discussion, three different ways of designing the value of a is formulated in order to test how it scales with system size and share of prosumers. For the first and second way one case is created for each, and for the third way four different cases are created. All in all, they are:

1. In the first way, a is set to equal the maximum consumption effect value in a local area:

$$a = P_{cons,\ peak} \tag{2.2}$$

2. In the second way, a is calculated as a parameter z divided by the quote of the maximum production effect value and the maximum consumption effect squared of a local area:

$$a = \frac{z}{\left[\frac{P_{prod,\ peak}}{P_{cons,\ peak}{}^{2}}\right]} = z \cdot \left[\frac{P_{cons,\ peak}{}^{2}}{P_{prod,\ peak}}\right]^{-1} \tag{2.3}$$

3. In the third way, a is calculated similar to Equation (2.3), but by placing an exponent c over the entire denominator:

$$a = \frac{z}{\left[\frac{P_{prod,\ peak}}{P_{cons,\ peak}}\right]^{c}} = z \cdot \left[\frac{P_{cons,\ peak}}{P_{prod,\ peak}}\right]^{-c} \qquad \text{where } c = \{1,2,3,4\} \qquad (2.4)$$

The reasoning behind each equation has been explained, but since this a central aspect of the DPF it is of importance to understand it and a short summary follows below:

- In Equation (2.2) the idea is to keep the value of a rather small to strongly incentivize local balance. But for a to vary and make it more reasonable for prosumers to receive a compensation in an area with many consumers a is set to linearly scale with the area's maximum consumption effect. Otherwise, if a is consistently small, a slight misalignment between local consumption and production would result no compensation at all for electricity fed into the grid.
- In Equation (2.3) the idea is to make a initially large and then slowly make it decrease. In an area with a low share of prosumers, $P_{prod,\ peak}$ is much smaller than $P_{cons,\ peak}$ which will result in the whole denominator becoming small giving a large a. As the share of prosumers increase so will $P_{prod,\ peak}$ which will result in a smaller and smaller a and making the requirements for staying closer to local grid balance higher.
- In Equation (2.4) the idea is similar to the one behind Equation (2.3), but now the entire denominator has the same exponent instead and takes a value from 1 to 4.

In Figure 10 the three ways are visualized where z in Equation (2.3) and (2.4) has been set to equal 1. The first way corresponds to case 1 which scales with the number of consumers since it only is dependent on the maximum consumption effect. The second way corresponds to case 2 and scales with both the number of consumers and prosumers, thus the x-axis shows the share of prosumers in percentage. The third way corresponds to case 3 to 6 and have the same x-axis as case 2.

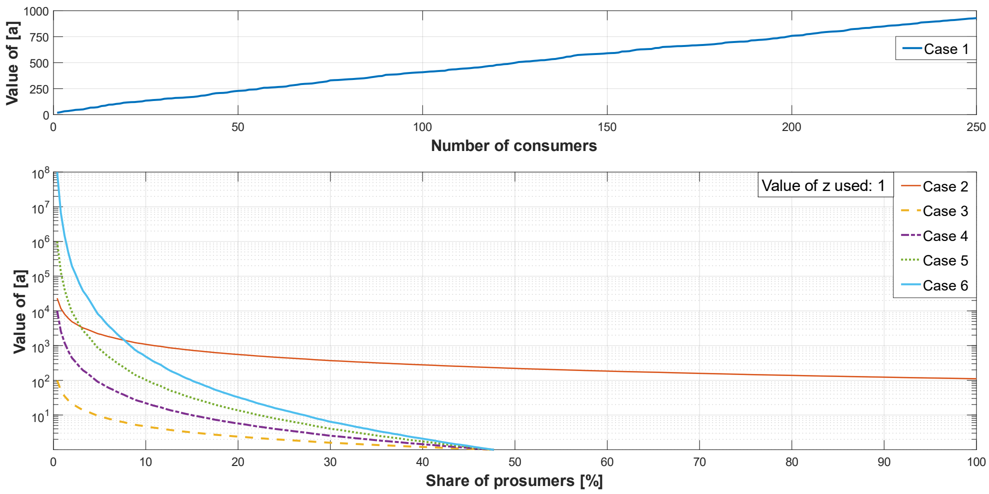

Figure 10 – Six cases of designing the a-parameter and how they scale. Case 1 is shown in the upper half of the figure and case 2 to 6 in the lower half. In the lower half the number of consumers is consistently 250.

In case 1, the value of a increases linearly and becomes around 1000 with 250 consumers. Case 2 initially has a value slightly over 20,000 which then slowly decreases towards around 100. Case 3-6 has an initial value between around 100 to over 100,000,000, but it then decreases more quickly than case 2 until the value equals one at around 47.6 % prosumers. Why does this happen? It is because at 47.6 % the consumption maximum effect and the production maximum effect are equally large in the data used to create this figure, thus the quote becomes one. After a share of

47.7 % prosumers it becomes less than one since the maximum production effect becomes larger than the maximum consumption effect. This would lead to unreasonably high requirements for the prosumers since with a value of a less than one, all prosumers need to collectively contribute to an almost perfect local grid balance for receiving any compensation at all for electricity they fed into the grid (see Figure 9 (b) for a reminder). Hence another z value is tested, this time 100. The result is a shape that prima facie seems more reasonable, and the result is shown in Figure 11:

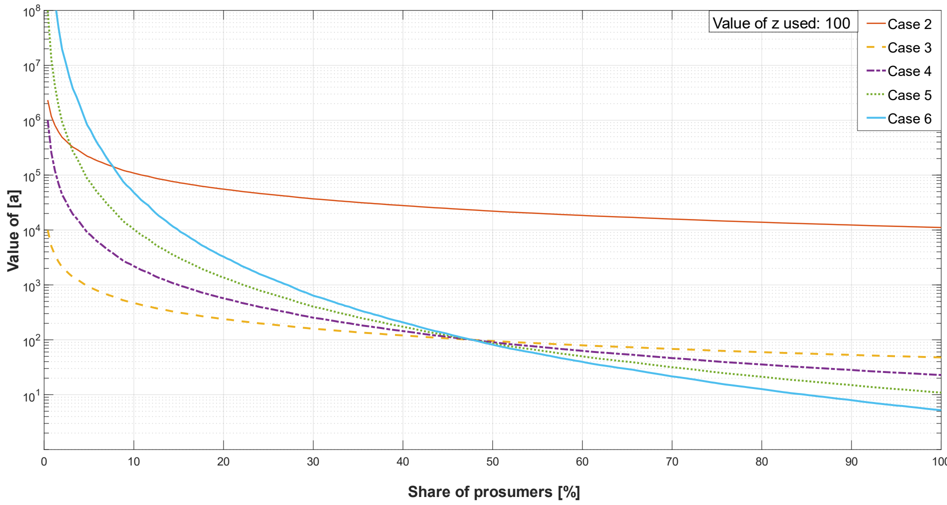

Figure 11 – the same cases as the lower half as in Figure 10 but with a value of z set to 100 instead.

Of the cases in the third way, case 6 seems perhaps most interesting against the background of the discussion in this section since it initially has a higher value of a which then decreases faster than case 3 to 5. How the different cases affect the compensation is simulated in section 2.2.2 and 2.2.3.

One final aspect is relevant to mention before the next section. The quote between the maximum production effect and maximum consumption effect in the above cases is taken as the maximum values over an entire year. Another way to approach these values is to retrieve them from shorter intervals, e.g. let the quote depend on the values from the previous week only. Figure 12 shows the different between taking the values from an entire year against from the previous week:

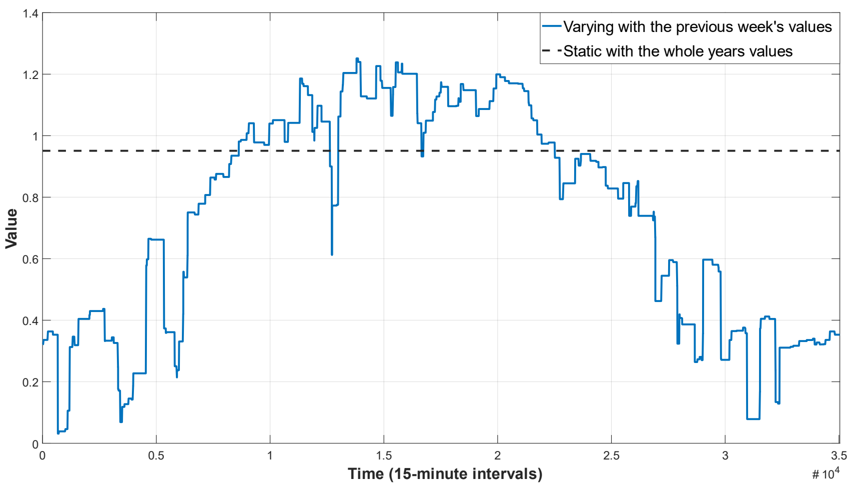

Figure 12 – Fixed vs varying quote between $P_{prod,\ peak}$ and $P_{cons,\ peak}$.

The result shows that a fixed quote is higher during winter, early spring and late fall than the varying quote. This could be a reasonable implementation in order to punish imbalance during the summer to a higher extent, but in the following sections a fixed value will be used for this quote in order to make it easier to analyze how different values of a affect the DPF. But before that, where did the data used in this section come from? And which additional data is required for the DPF? That is the topic for the next section.

2.1.2 Assumptions and input data for the simulations

In addition to the previous section, there are also other variables that will affect the DPF. While t_p in Equation (2.1) refers to the total amount of fed-in electricity to the grid, it depends on the number of prosumers, the PV-systems peak effect and how they are installed in terms of angels (see Figure 1) and more. Another important aspect is that the simulations are using 15-minute intervals. Even if available technology can handle shorter time intervals, laws and regulations in Sweden are currently pointing at using 15-minute intervals as previously described. While the insolation data used for the production are real collected data, the simulation approximates what a PV-system's resulting output could be making it synthetic in its character. The consumption data is purely synthetic. How the simulated consumption and production work more in detail are presented the next two sections in addition to the use of storage and Nordpool's spot price.

When modeling, simulating and analyzing the DPF, the same consumption and production of 250 households are used consistently as static in-data. That means that when different combinations of consumers and prosumers are tested the same data is used repeatedly. For example, when 10 % prosumers are simulated it is assumed that consumer 1 to 25 becomes a prosumer and when 20 % prosumers are simulated it is assumed that consumer 1 to 50 becomes a prosumer and so on. This means that the stochastic effect that would take place if new consumption and production data were simulated for every case is not included. It would be possible to do this, but the simulations are simplified in certain aspects in order to focus the analysis on the DPF's a parameter. Also, if the DPF would be implemented in a real scenario, it could potentially alter the behavior of consumers and prosumers and how they affect the grid. No attempts are made to account for such change in behavior.

2.1.2.1 Consumption

To get an estimate of the electricity consumption of single-family households, a MATLAB-script simulating a stochastic load model is used. An example of five days is shown in Figure 13.

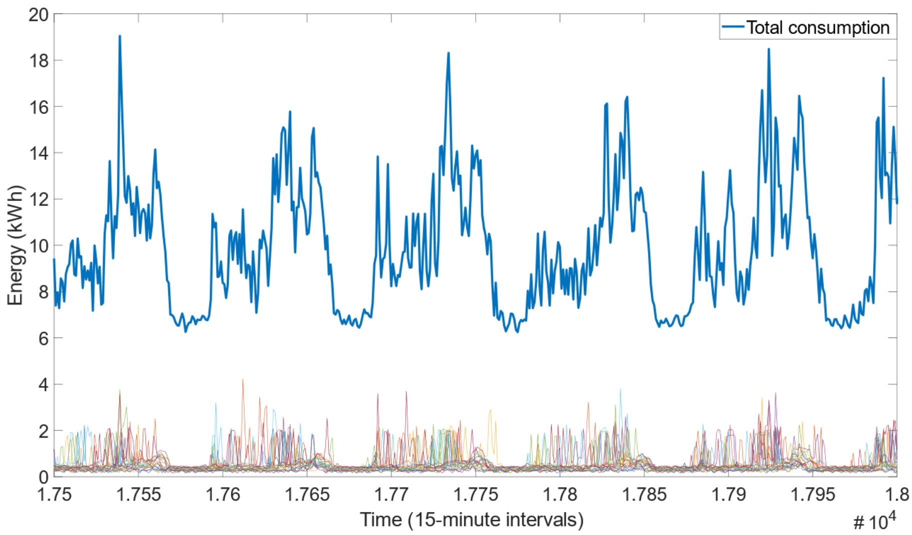

Figure 13 – Simulated consumption of electricity from 20 households during the summer. The separated consumption for the households is shown the lower half of the figure while the thick blue line is the aggregated consumption. Here the typical shape can be seen with a smaller peak in the morning and a larger in the evening.

The script uses self-reported use of electrical appliances implemented through a Markov-chain model. It is based upon a chain of probabilities where one action is linked to others over time and the details are described in two articles by Widén et al. (2009) and Widén & Wäckelgård (2010). The script simulates the electricity consumption of one household on a minute basis over an entire year, and in the implementation for the DPF a for-loop is used where any number of households can be chosen where their separate and total consumption is aggregated into 15-minutes segments.

2.1.2.2 Production

The simulated production of electricity from PV-systems uses irradiance data from Lövstalöt (latitude 59.9598, longitude 17.5720) North of the city Uppsala in Sweden. The data is processed through three MATLAB-scripts to approximate the amount of sun light received by a surface and the resulting electrical effect:

- The first script uses the irradiance data, an albedo value (set to 0.2) and angles in terms of azimuth and tilt (see Figure 1 for how the angles are defined) to simulate the light received by a surface. The angles are randomized separately for every prosumer's PV-system: the tilt between 15° to 45° and the azimuth between –90° (East) to 90° (West).
- The second script perform a simplified DC-effect calculation using the first scripts output together with an ambient temperature, PV-system efficiency and peak effect. The script uses average ambient temperature of per month in Sweden from 2018 (SMHI, 2019).
- The third script converts the DC-effect from the second script into AC by scaling the values to account for various losses. The output data is given per hour which is approximated on 15-minute segments. This assumes that the production of one hour can be equally spread out over four quarters.

An example of the resulting production of five days is shown in Figure 14:

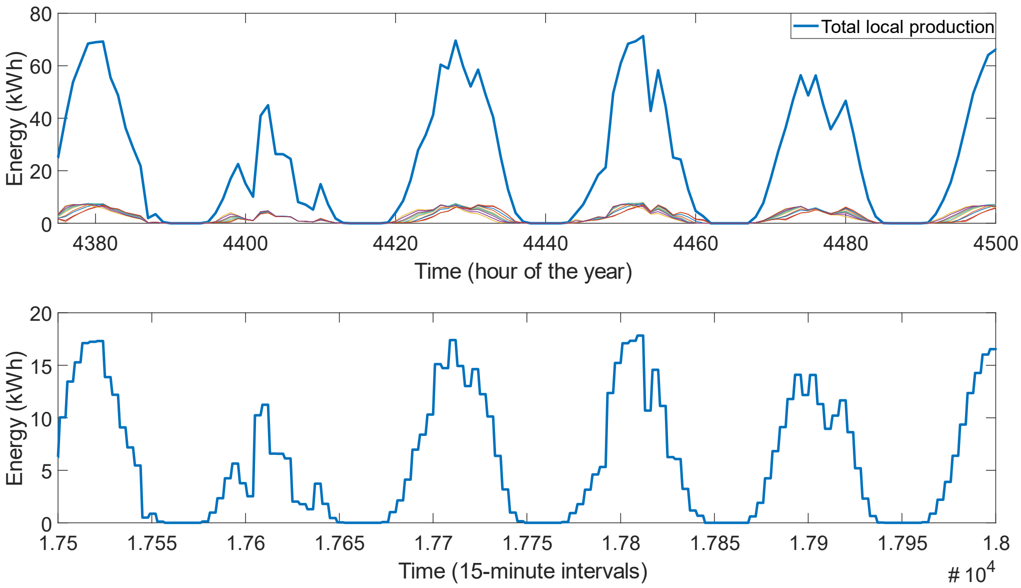

Figure 14 – Simulated production of electricity from 10 prosumer's PV-systems with 10 kW peak-effect during the summer. Notice the different y-axes between the two graphs due to the hour to 15-minute interval approximation.

As a default it is assumed that the prosumers self-consume as much as possible of their produced electricity. This is also the main business model for the market in Sweden today (Lindahl et al. 2018, p. 43). Only produced electricity that cannot be self-consumed is counted as excess electricity, that is overproduction, which is fed into the grid by the prosumer.

2.1.2.3 The storage algorithm

Storage is used to store electricity that is fed into the grid but not needed in the local area at that time, meaning the local production is greater than the local consumption. When the local production at a later time drop below the local consumption, the stored electricity is used to fill in the difference. Thus, storage increase the amount of time local balance can be maintained. Overall, the storage has three limits:

- The size (kWh) of the storage. The simulations run two parallel tracks, in the first the prosumers have no storage capacity and in the second the prosumers have a specified, average, storage.
- The charge effect (kW) of the storage. The storage has a physical limit of how fast it can charge electricity, and any overproduced local electricity above this limit has to be fed into the grid and transmitted out of the local area.
- The discharge effect (kW) of the storage. Works in the same way as the previous point, but when it comes to receive electricity from outside the local area instead.

It is assumed that prosumer's storage units can be aggregated into one, big, storage unit for the whole local area. Figure 15 shows an overview of the storage's function in the different situations:

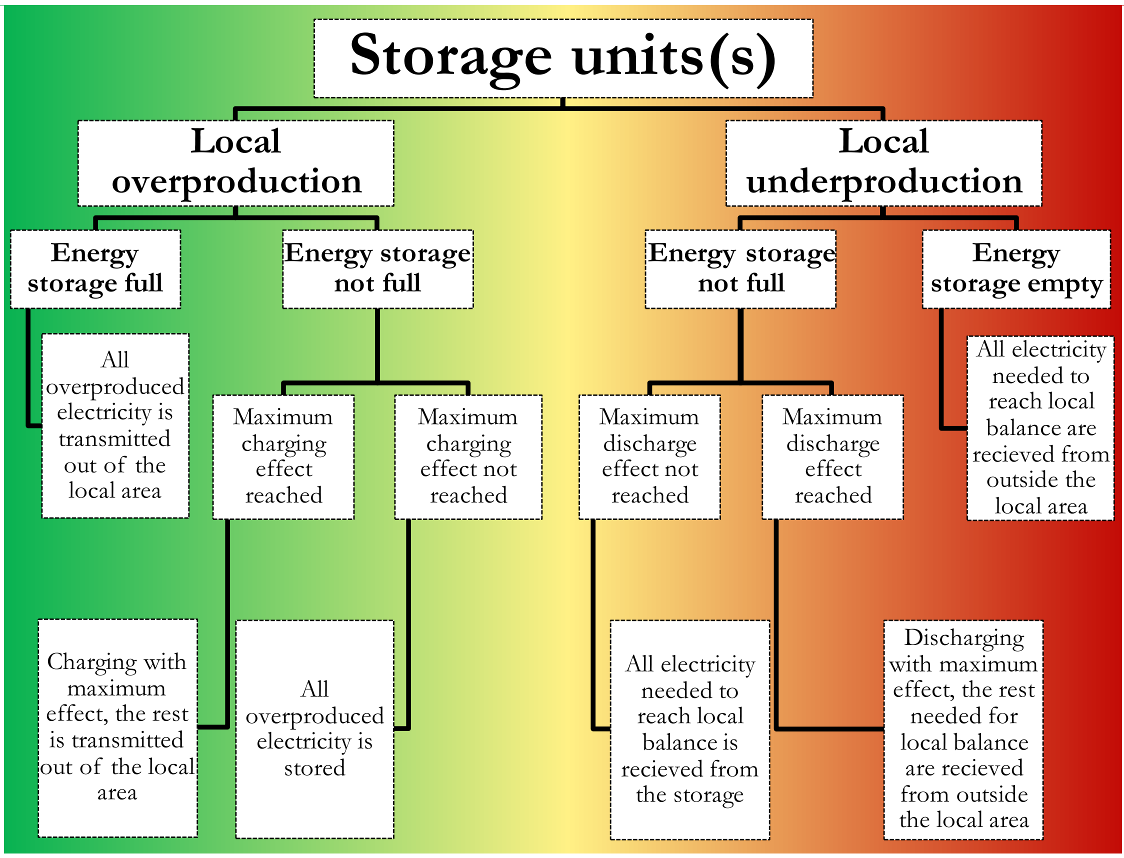

Figure 15 – The storage algorithm.

2.1.2.4 Spot market data

Nord Pool is the biggest electricity market in Northern Europe. The market does not have a monopoly, but almost all trade takes place through it. Nord Pool's spot price makes up the basis for many electricity provider's own profit and what they are willing to pay prosumers to buy their electricity. In Figure 16 the spot price is shown from 2010, except 2012.

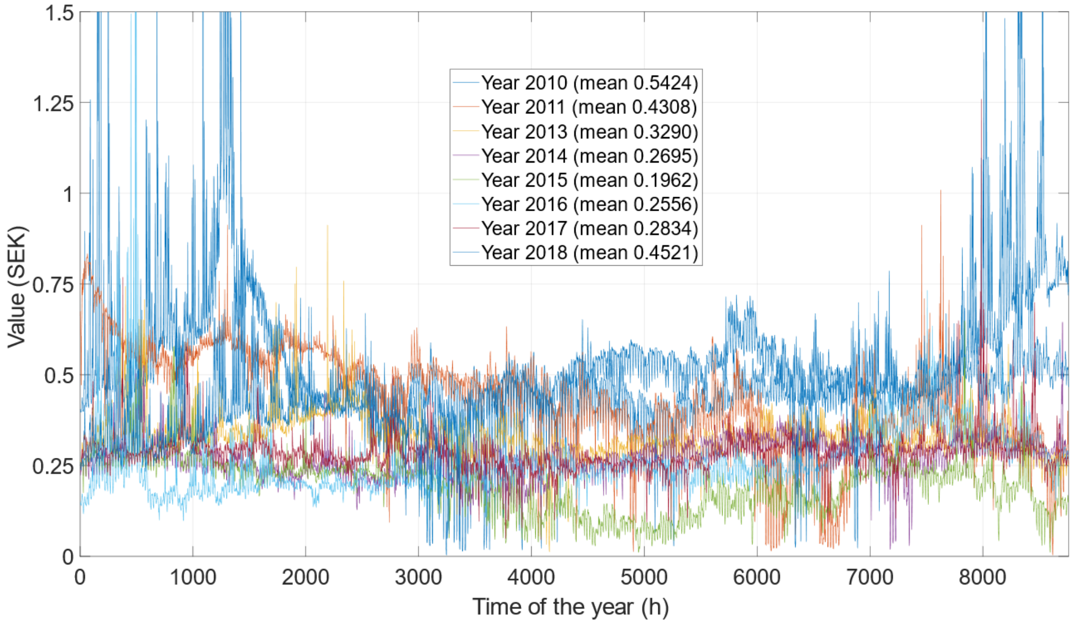

Figure 16 – Spot market prices over the years 2010-2018 except 2012.

2.1.3 Summary of all DPF parameters

In Table 7 below all the DPF parameters are summarized. It also shows the values the user can change when simulating the script, and what the default values are. All in all, there are 10 parameters that can be changed and this the main reason behind the assumptions and decisions made in order to simplify the simulations and the analysis of the DPF.

Table 7 – DPF parameters and their default values

Parameters or variable	Range	Default value	Explanation	Dependent on	Unit
x	-	-	Fed-in electricity per prosumer	1. The prosumer's PV-system 2. Storage capabilities	kWh
t_p	-	-	Total local production	1. Number of prosumers and their (over)production 2. Average PV-peak effect 3. Weather/insolation	kWh
t_c	-	-	Total local consumption	1. Number of consumers and their need of energy	kWh
q	Any	1·Spot price	Maximum compensation rate	User	SEK/kWh
a	Any	-	Scaling factor	User	kWh[2]
Number of consumers	Any	-	Consumption to simulate	User	households
Number of prosumers	Up to the number of consumers	-	Production to simulate	User	households
Simulation interval	Any	One year	Time period	User	15-minute intervals[1]
Storage size	Any	10[2]	Average storage size per prosumer	User	kWh/prosumer

[1] Same as in the original NRGcoin-paper (Mihaylov et al. 2014).
[2] According to Mihaylov et al. (2016) typical retail commercial batteries for local storage ranges between 4-13.2 kWh.

Storage maximum charge/discharge effect	Any	5[3]	How fast the storage can charge/discharge	User	kW/storage unit
Average rated PV-peak effect	Any	10[4]	Affects maximum production effect	User	kW/prosumer
Spot price	2010-2018 (not 2012)	2018	The raw cost of electricity	Nord pool	SEK/kWh
Low and high static compensation	Any	0.28 and, 0.565[5]	Comparison value	User	SEK/kWh

The next section 0 is dedicated to simulating the DPF. In the first part a demonstration simulation is shown in order to visualize and explain the DPF before focusing on the design of the α-parameter as presented in section 2.1.1.1.

2.2 Analyzing the dynamic price function

The first part of this section shows a demonstration simulation of the DPF and explains all the possible out-data and what will be used to further analyze the α-parameter in the following sections.

2.2.1 Demonstration of the dynamic price function

In this simulation 100 consumers with a share of 50 % prosumers is chosen where α has been set to 1000. All default parameters from Table 7 are used except for the storage where the average size per prosumer is set to 7 kWh and the maximum effect limits to 2.5 kW to visualize how the storage functions more clearly. This part consists of five figures where Figure 17 show how the consumption and production align over one year together with the resulting overproduction per prosumer. Figure 18 and Figure 19 show the DPF without and with storage. Figure 20 show the storage utilization and Figure 21 the compensation from the DPF compared to the static methods.

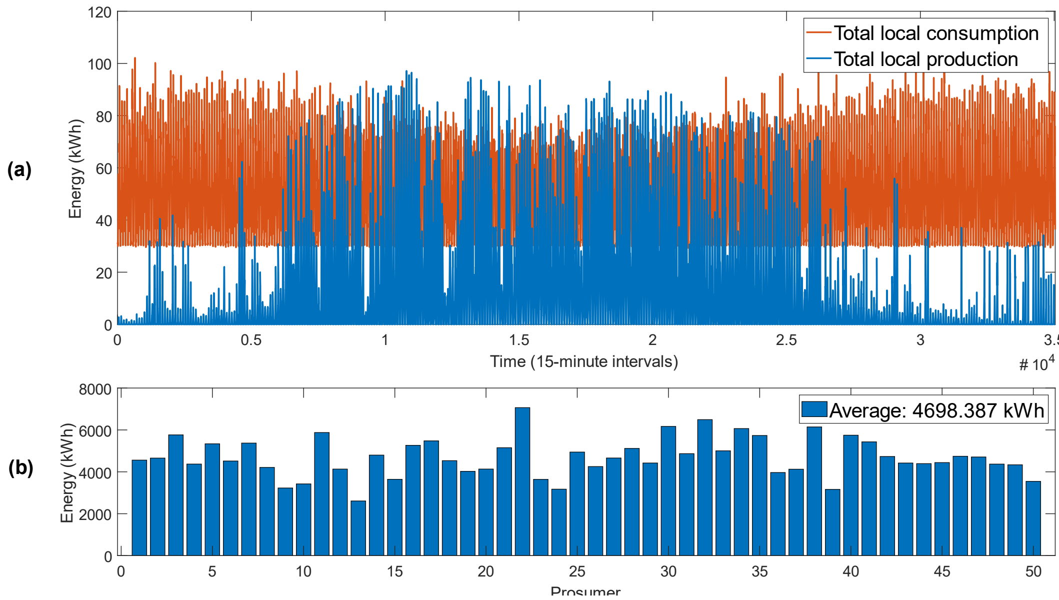

Figure 17 – (a) PV-production of 50 prosumers with average 10 kW peak compared to the consumption from 100 consumers. (b) Aggregated annual overproduction per prosumer and overall average.

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[3] Local voltage is 400 V in Sweden and a typical fuse size 16-25 A (Vattenfall, 2019). This gives a maximum effect flow of 11-17 kW. Here half of the lower limit is assumed to make it likely that there is a margin to the grid's limit.
[4] In Sweden approximately 2,209 systems with 5-10 kW_p and 1,623 system with 10-20 kW_p were installed among single-family households in 2018 (Lindahl et al. 2018, p. 23). From this 10 kW_p is picked as a reasonable average.
[5] As described in section 1.4.1.2.

In Figure 17 (a) the production shows the typical bell shape over the year with the highest values during the summer half of the year and the lowest during the winter half. The consumption instead shows a typical slightly inversed shape compared to the production with lower values during the summer half of the year and higher during the winter half. In (b) the overproduction per prosumer clearly varies which is reasonable since every prosumer have slightly different consumption patterns in addition to their PV-systems being simulated with different angles.

Figure 18 is dense with information and it is difficult to see any details about the DPF. It does however show an overview and some important insights, and a zoomed-in figure follows next. In (a) the overproduction is shown to only take place from late spring to early fall. The maximum local production effect is 55.9 % of the maximum consumption effect in this simulation which is something the local grid should be able to manage (a somewhat more thorough discussion can be found in section 2.2.1.2). In (b) the DPF displays a dynamic and varying character which goes up and down frequently over the simulated year. Note however that it never goes above the upper, blue, line which represents the spot price. As q in this case is set to equal the spot price, the corresponding spot price decides the maximum possible compensation for every time interval.

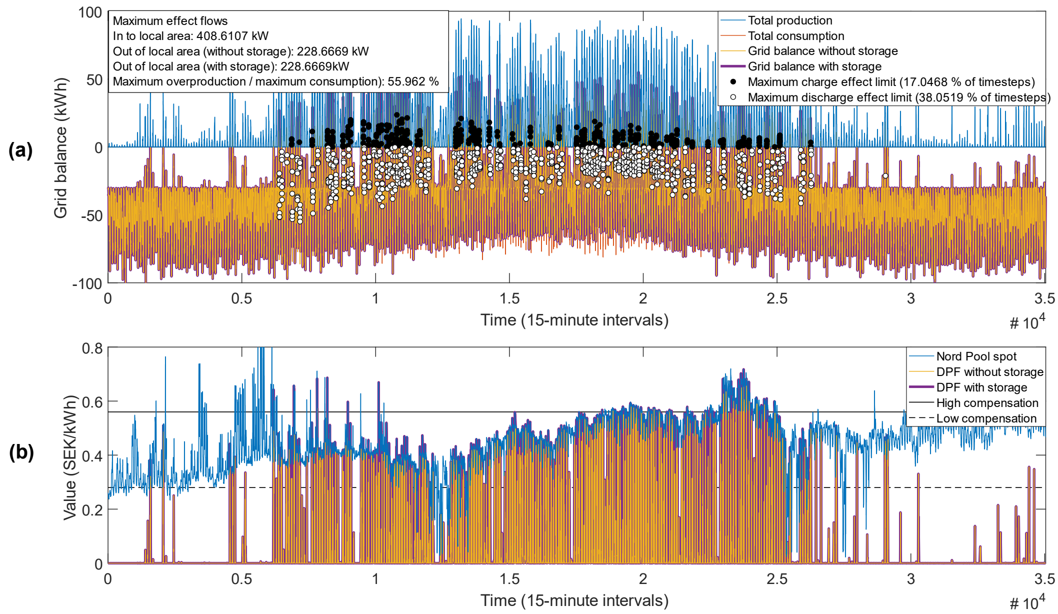

Figure 18 – The DPF when simulating an entire year. (a) Difference is consumption and production in the local area. (b) The resulting DPF compared to spot price, high and low compensation.

Figure 19 on the next page shows the details of the DPF and how it works. As the yellow line in (a) varies, which corresponds to the actual local grid balance when storage is not used, the corresponding compensation, the yellow line in (b), varies with it. It is only when yellow line in (a) is close to the black horizontal line, which represents perfect local grid balance, the resulting compensation in (b) becomes greater than zero. This is connected to design parameter a, which here is set to a static value of 1000. It could be a good idea to look at Figure 9 again to be reminded of how this parameter works. The purple line in (a) corresponds to the actual local grid balance when storage is used, and as can be seen it buffers the overproduction and underproduction and is closer to the grid balanced for more time intervals than the yellow line. The corresponding compensation, the purple line in (b), shows more time steps with a higher compensation as a result. The black and white dots in (a) visualizes the effect limits of the storage when it is unable to charge or discharge electricity fast enough, meaning some electricity fed into the grid is transmitted out of the local area instead of being stored. When the purple line coincides with the yellow line again after being separated from it in (a), it means that the storage is full (above the black line) or empty (below the black line). Finally, the solid and dashed lines in (b) corresponds to the static compensation as discussed in 1.4.1.2.

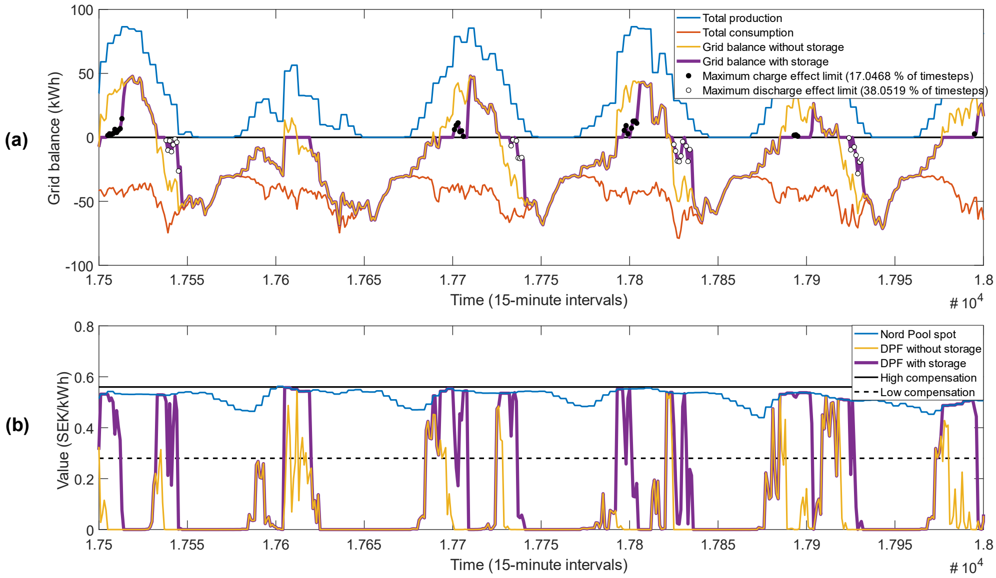

Figure 19 – A zoom in on Figure 18 to show the grid balance variations and resulting value of fed-in electricity.

Figure 20 shows the utilization of the storage during course of a year:

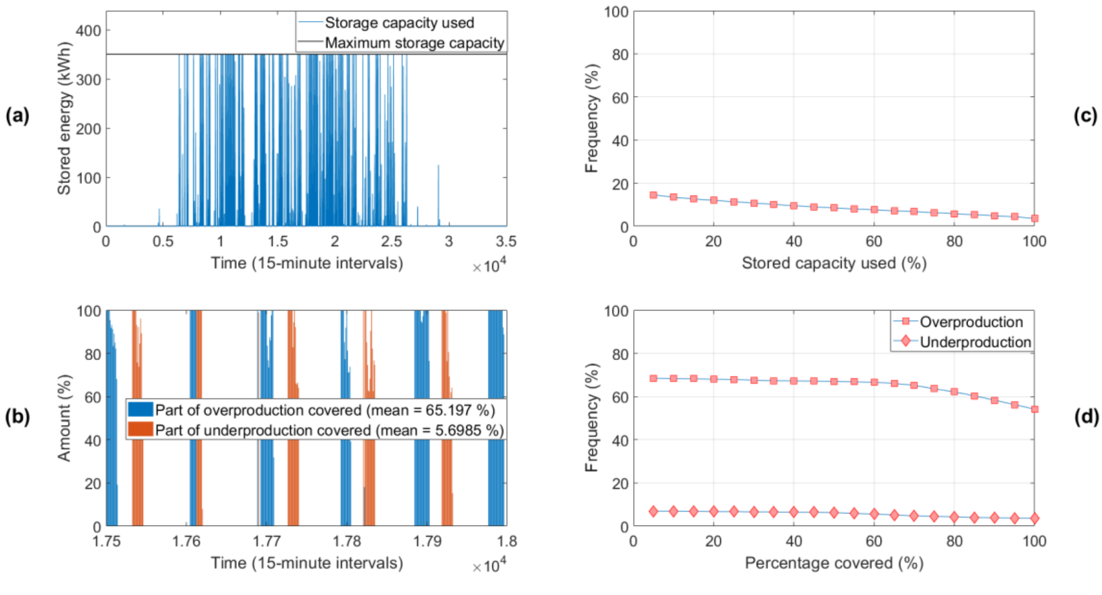

Figure 20 – Storage utilization. (a) Storage usage over one year, 7 kWh average per prosumer with an effect limit of 2.5 kW resulted in a total size of 350 kWh which could charge/discharge 31.25 kWh per 15 minute-interval. (b) The over- and underproduction coverage of the storage. (c) Time steps at or above a certain % of maximum storage capacity. (d) The frequency of how big shares of local over- and underproduction the storage could cover

From (a) in Figure 20 it is evident that the storage is only used when overproduction occurs and that usually a full charge/discharge cycle takes place for every day during the summer. The x-axis in (b) is zoomed-in to visualize how the storage covers over- and underproduction over five days. The graph in (c) shows that during the simulation the storage is charged at least 5 % during 14.6 % of the time steps while being fully charged during 3.67 % of the time steps. Note that this also includes the winter half of the year when the storage is barely used. The last part (d) shows that during this simulation the storage could store all the electricity fed into the grid during 54.1 % of the time steps with overproduction, and slightly more when partially covering overproduction. In this simulation the storage size was the primary limiting factor which affected how much of the overproduction that could be stored. The storage could provide all the electricity to reach balance during 3.6 % of the time steps with underproduction, and since it quickly discharges it did not provide parts of the electricity consumption for any significant increased amount of time steps.

The last figure of this section, Figure 21, shows the resulting compensation for every prosumer.

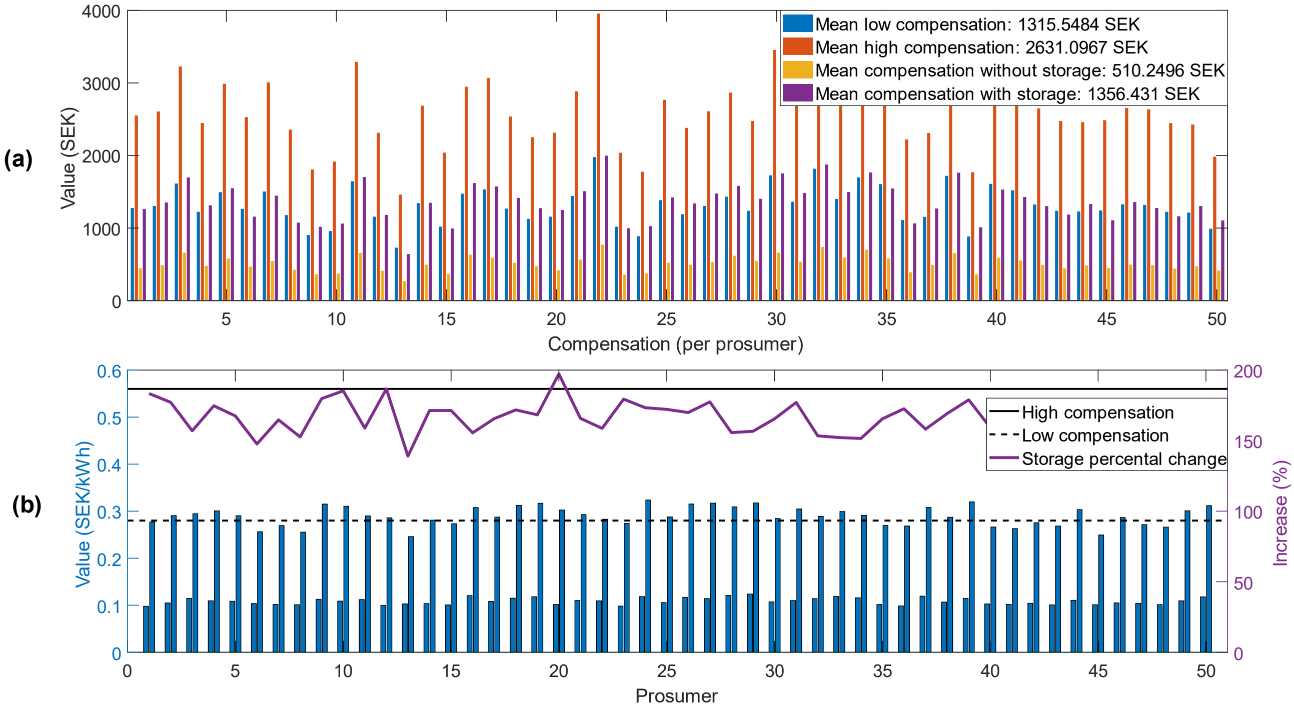

Figure 21 – Compensation per prosumer without and with storage and compared to static compensations. (a) Total compensations. (b) Average value per fed-in kWh and how much it increases with using storage.

While the other figures in this section might be more interesting out of a technical perspective, Figure 21 provides the basis for the following sections where analyzing the optimal share of prosumers and different cases of designing the α-paramter is done by using the resulting average compensation per prosumer as a measurement (top right corner in (a)). In (a) the compensation varies between the prosumers as expected showing that the resulting mean compensation barely becomes higher than the corresponding lower static compensation – if storage is used. Without storage the compensation is only about 37 % of the lower static compensation. The high static compensation gives almost twice the total mean compensation as the DPF when using storage. In (b) a similar image is portrayed, but with average compensation received per kWh instead. This truly shows the effect of using the DPF since the compensation per kWh fed into the grid between the prosumers differs. It also shows that procuring storages possibilities increases the value per fed-in kWh by around 175 %.

As this demonstration simulation shows, when 50 % of 100 consumers become prosumers it results in several occasions of overproduction in an imagined local area. Before proceeding to simulate the optimal share of prosumers together with different cases of the α-parameter, a short analysis of how the overproduction changes with different shares of prosumers and a power flow analysis is performed in the next section.

2.2.1.1 *Overproduction*

As mentioned, it is assumed that the prosumers self-consume as much of their produced electricity as possible before feeding any excess into the grid. Simulating an increasing share of prosumers with 250 consumers initially show an overproduction between 4400 to 5000 kWh per prosumer. When the share of prosumers increases the value stabilizes around 4,870 kWh, see Figure 22:

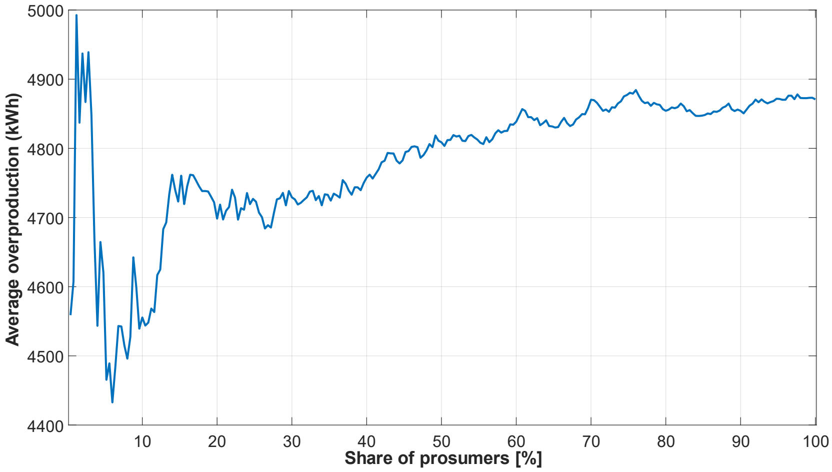

Figure 22 – Mean overproduction per prosumer with an increasing share of prosumers-

This correlates well with a national survey of PV-systems in Sweden where the average production fed into the grid by local PV-systems was 4,632 kWh in 2018 (Lindahl et al. 2018, p. 44).

2.2.1.2 *Power flow analysis*

The balance criterion of a local grid is based upon an assumption that since the electrical grid is dimensioned to manage the peak consumption effects of all consumers in a local area, that peak effect can be used as a reference value for the peak production effect. For a deeper analysis more factors would need to be accounted for, e.g. the balance's rate of change, but here the criterion is if the grid is dimensioned to manage a certain effect transmitted into a local area, it should also be able to handle the same effect transmitted out of the local area. If also assuming that the grid has a safety margin, it should tolerate a slightly higher effect than the peak consumption effect. By this reasoning the maximum tolerable overproduction effect in the local area is considered to be 10 % higher than the consumption peak effect. The quote between the overproduction peak and the consumption peak from an entire year is shown in Figure 23 with an increasing share of prosumers:

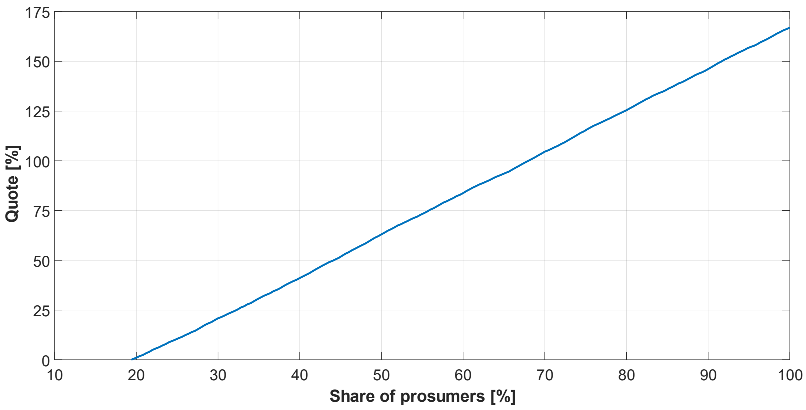

Figure 23 – Local area overproduction peak effect divided by consumption peak effect in an imagined local area with 250 consumers and an increasing share of prosumers. The PV-systems have a peak effect of 10 kW and self-consumption s primarily used.

Note that in this case no storage is being used, meaning that except self-consumption all excess electricity is fed into the grid. This simple analysis points out three things: 1) before a share of 19.5 % prosumers no overproduction on a local area scale occurs, 2) at a share of 68 % prosumers the yearly overproduction peak effect is as large as the consumption peak effect, 3) at a share of 72.8 % prosumers the yearly overproduction peak effect is 10 % higher which was set as the upper limit before risking severe imbalances. The result indicates that a maximum share of around 70 % prosumers are what the grid likely could handle given the assumptions and simplifications made.

2.2.2 Optimal share of prosumers

In this section the three different ways presented in 2.1.1.1 are analyzed in an imaged local area with 250 consumers and an increasing share of prosumers. The "optimal share" is defined as the share of prosumers which yields the highest mean compensation for every prosumer. Note that with 250 consumers the percentage-resolution of the x-axis is 100/250 = 0.4 %. In section 0 the value of the a-parameter was set to 1000, in this section a will be allowed to vary as:

- In Equation (2.2) a varies with the maximum consumption effect, and since the number of consumers consistently is 250 the value of a is the same for all share of prosumers.
- In Equation (2.3) and (2.4) the value of a will vary as $P_{prod,\ peak}$ increase with the share of prosumers. The value of z will also be varied in order to analyze its impact.

In the figures below the optimal share of prosumers occurs at a low percentage in some cases which then only slowly decreases. This is because in these situations the value of a is initially very large, and thus the mean compensation quickly changes up and down in a spike-wise manner since the amount of electricity fed into the grid – that is used to calculate the mean compensation per prosumer – is the same as in Figure 22. What also is interesting is the cases with a second peak and at what percentage that occurs. In all simulations 250 consumers, 10 kWh storage per prosumer, 5 kW as maximum storage charge/discharge effect and spot price data from 2018 are used. One figure from each of the three ways is shown here, and since the third way have four cases only case 6, where c equals 4, is shown to save space. The other figures can be found in Appendix 1.

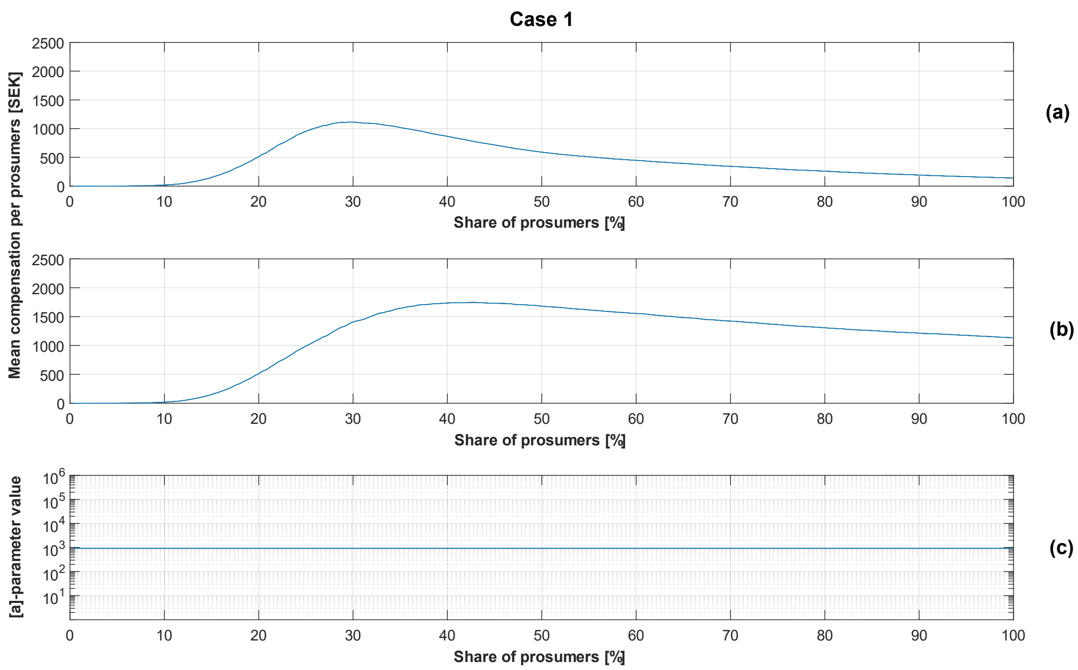

Figure 24 – Increasing the share of prosumer with case 1 to find the optimal share of prosumers. (a) Without storage it is at 29.6 %. (b) With storage it is at 42.8 %. (c) The value of a over the range of different shares of prosumers.

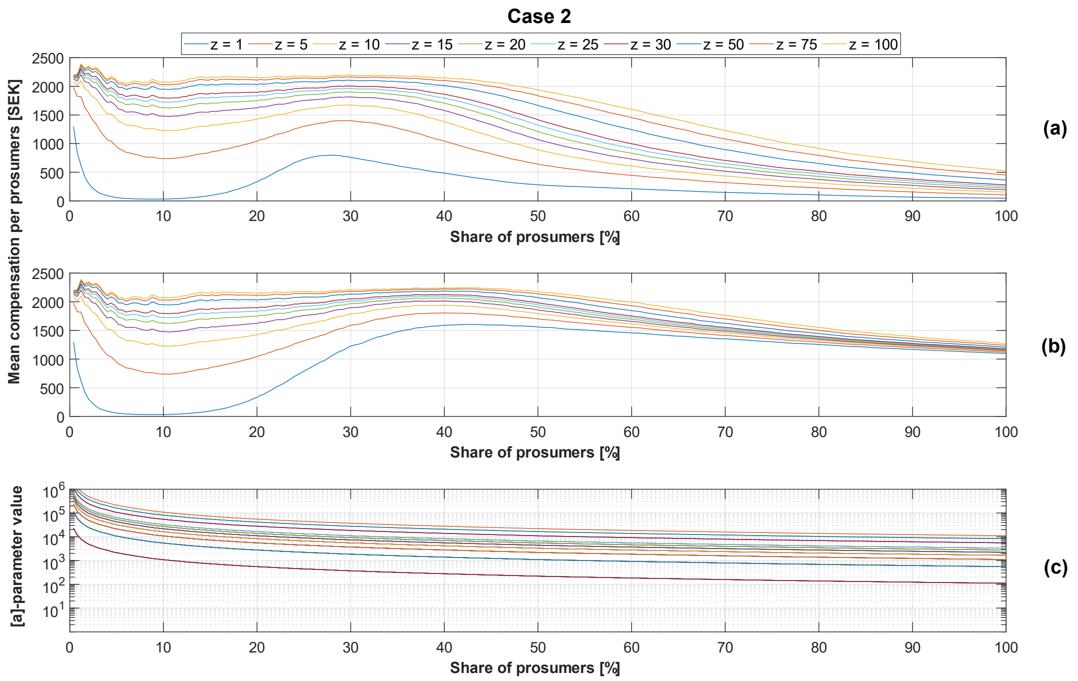

Figure 25 – Increasing the share of prosumer with case 2 to find the optimal share of prosumers. (a) Without storage it is between 28.0-29.6 %. (b) With storage it is between 39.6-42.8 %. (c) Value of a for different simulations.

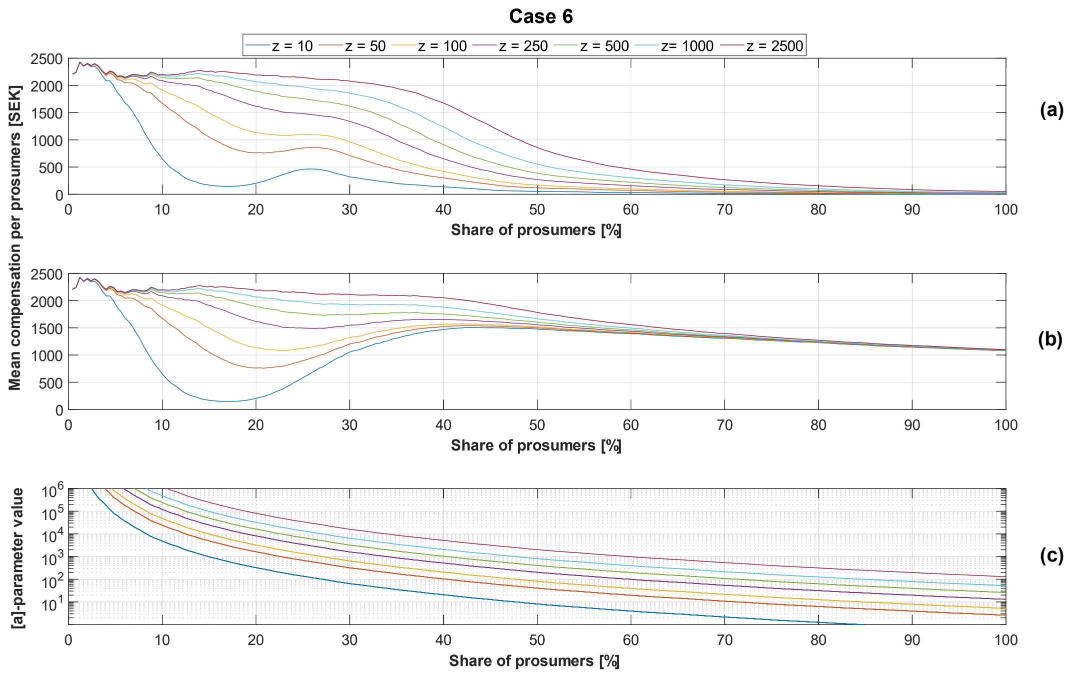

Figure 26 – Increasing the share of prosumer with case 3 to find the optimal share of prosumers. (a) Without storage it is around 25.6 % with lower values of a. (b) With storage it is between 36.8-42.4 % with lower values of a. (c) Value of a for different simulations.

Case 1 show that before a share of 10 % prosumers no compensation is given at all for their overproduction. The value of a is too small for the prosumer's combined overproduction to get close enough to local balance. As Figure 23 in the previous section showed, a share of almost 20 % prosumer were required before they could balance the grid by themselves even once. Otherwise case 1 has a clear peak for the DPF both without and with storage. Case 2 show a completely different behavior with an initially high compensation that quickly decreases for small values of z, but slow for larger values – especially with using storage. Case 6 shows a similar behavior to case 2. While the mean compensation does not decrease as quickly with a lower share of prosumers, it decreases quicker with a higher share. Note that the values of z is larger here than in case 2.

The share of prosumers that gives the highest mean compensation is around 26-30 % when not using storage and 37-43 % for when using storage in all cases. The biggest difference is how the cases behaves before and after these peaks. In the next section these cases will be simulated with the spot price from 2010 to 2018 in order to analyze how the compensation differs over the years.

2.2.3 Testing the different cases for spot prices between 2010-2018

In this section the spot prices throughout 2010-2018 are simulated and compared with the low and high static compensation. Data from 2012 could not be found or retrieved from Nord Pool's website. These simulations also use 250 consumers with an increasing share of prosumers as the previous section but are simulated through bins to visualize the difference of using storage in another way. In all simulations the value of z is set to 100, hence by looking at the line in Figure 25 and Figure 26 corresponding to $z = 100$ and at the year 2018 in the figures below the same mean compensation values can be seen. All values for the used parameters are in footnote 6.[6] As previously, case 1, 2 and 6 are shown here while case 3-5 can be found in Appendix 2.

The figures for all cases have the same axes, and for every year 20 bins are plotted. The first layer consists of the blue bins which represents using storage. On top of them the bins for when not using storage is plotted; these are thinner and in red in order to visualize the difference. All of these values are compared to what the compensation would have been with a static low and high compensation (cf. Figure 19 (b)) and if the average spot price had been received for every overproduced kWh fed into the grid by the prosumers. Below the different cases are shown.

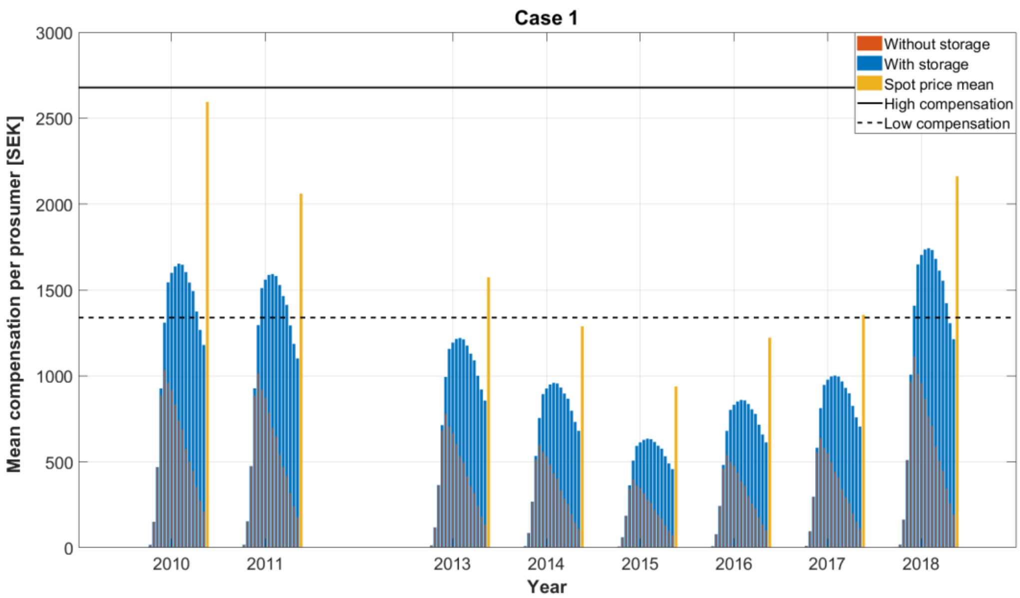

Figure 27 – Mean compensation per prosumer using spot prices 2010-2018 and case 1.

[6] The bins are in percentage (and number) of prosumers: 1.2 % (3), 2.0 % (5), 5.2 % (13), 7.2 % (18), 10.0 % (25), 15.2 % (38), 20.0 % (50), 25.2 % (63), 30.0 % (75), 35.2 % (88), 37.2 % (93), 40.0 % (100), 43.2 % (108), 45.2 % (113), 50.0 % (125), 55.2 % (138), 60.0 % (150), 70.0 % (175), 80.0 % (200) and 90.0 % (225). Otherwise same default parameters are used as presented in Table 7.

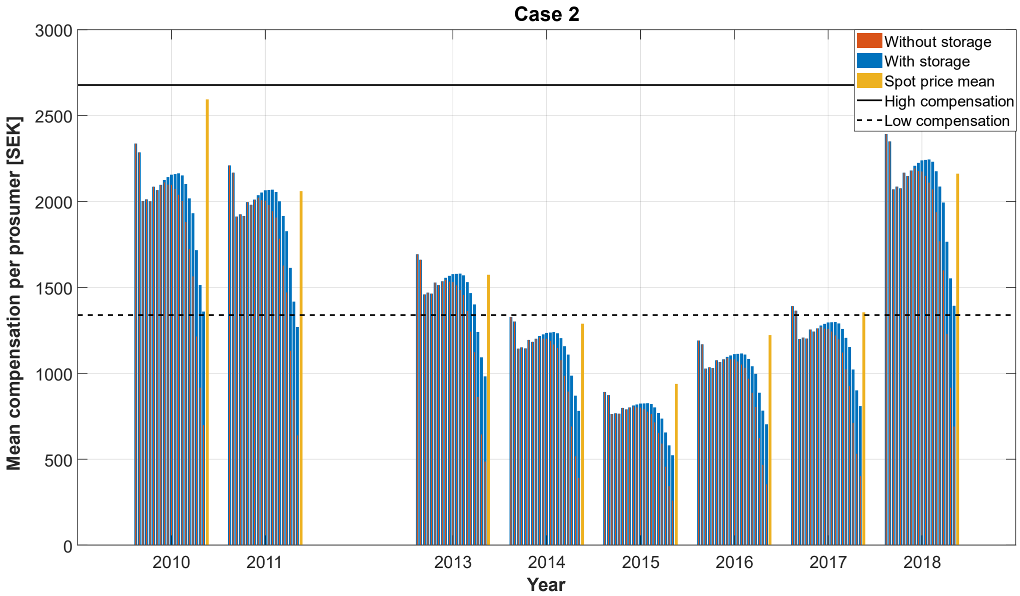

Figure 29 – Mean compensation per prosumer using spot prices 2010-2018 and case 2.

Figure 28 – Mean compensation per prosumer using spot prices 2010-2018 and case 6.

Here the dynamic character of the three different ways appears more clearly than in the previous section. In case 1 the compensation is almost zero until the share of prosumers becomes over 10 %. The compensation is same for using storage or not until about 25 % where the compensation for when not using storage starts to decrease while the compensation for when using storage has a peak at 43.2 %. In case 2 the compensation is instead initially high, decreases slightly until its second peak. The big difference here is that the compensation for when not using storage is very close to for when using storage with almost all shares of prosumers. In case 6 the compensation with a low share of prosumers is initially as large as for case 2 but then quickly decreasing until its second peak. This peak is almost as large as in case 1, but smaller than in case 2. The difference between case 6 and case 3-5 in Appendix 2 is that as the function's exponent increases the compensation decreases less before the second peak. All the cases have one thing in common, and that is the optimal share of prosumers which occurs at 43.2 % with the given resolution. Next, the last chapter follows which will discuss the results of this chapter against the background of chapter 1.

Chapter 3
Discussion and conclusions

In order to value electricity in a more dynamic way than the mechanisms used today, this thesis modelled, simulated and analyzed a DPF based upon an idea presented by Mihaylov et al. (2014). Of the DPF's two design parameters q and a, the parameter a was chosen to be in focus since it is connected to the balance of the grid which is one of the most important parameters of the whole electrical system. A value also had to be chosen for parameter q, and it was suggested to be linked with Nord Pool's spot market price. The idea was to anchor the DPF with an existing market by following its price development. This would strengthen the DPF's dynamic character and lower the potential need for changing the function as time passes. As pointed out in chapter 1, if policies, laws and regulations change too often the will to invest in that market decreases.

The concept of MBIs was presented in chapter 1, and one of its key policy design features is to be as simple as possible, but as complex as necessary. With this in mind, different ways to design the DPF's parameter a was modelled as described by Equation (2.1)-(2.4) through six different cases. Even though these equations are simple, they show a potential to affect more complex grid qualities such as balance, regulation, and prediction of the power flows. Even though the impact of separate prosumers on the grid on a system scale level is small, it might become much greater on the scale of a local grid. Since the prosumers cannot be required to have a deep insight in these qualities due to their complexity, the DPF is designed to support these by providing an economic incentive for prosumers actively want to balance the local grid. This is based upon looking at the prosumers as rational actors on a market where profit decides the outcomes. Section 2.2.2 tested different values of a in order to find the optimal share of prosumers, and the result showed that the optimal share was similar regardless of the case and value of z used. What primarily changed was the magnitude of the mean compensation and its behavior as the share of prosumers increased. This is an interesting result. The DPF is built to incentivize grid balance, and from its design it seems that the best average local balance occurs around a share of 25-28 % prosumers when not using storage and around 37-43 % when using storage. Here it is important to consider all the parameter values used, such as the average PV-system peak effect and the storage size. In the simulations these parameters were kept at the same values and changing them would alter the results. There are many parameters that could be varied in the DPF simulations, and the number of simulations required to vary them all in a meaningful way would be far greater than the scope of this thesis. Thus, all stochastic behavior from simulating the consumption and production was removed while the other parameters was locked at a default value according to Table 7.

In section 2.2.3 the different cases from section 2.1.1.1 together with the spot prices between 2010-2018, except 2012, were simulated. While case 1 gave an economic incentive to reach a share of around 40 % prosumers while promoting storage, it gave no incentive to initially become a prosumer. In case 2 there was an economical incentive to become a prosumer since the compensation was initially large, but there was no incentive to procure storage since the compensation was not much smaller without using storage. The reason is that the parameter a in case 2 is large for all shares of prosumers and thus do not punish off balance to any greater extent. The reason to procure storage is to be able to keep the local area's grid closer to balance for a longer period of time, hence a smaller value of a is needed. This was tested in case 6 where a is initially large but then quickly decreases as the share of prosumers increases leading to higher requirements for the prosumers to stay closer to grid balance in order to receive any compensation for their overproduced electricity Compared to case 3 to 5, the value of a in case 6 is initially larger decreases faster when the share of prosumers increase which seems to be a good design because it makes case 6 provide three different, but important, incentives:

1. To become a prosumer to start with (initial high compensation).
2. To incentivize more consumers to become prosumers, but not too many (the second compensation peak).
3. To procure storage (otherwise compensation decreases as the share of prosumers increases).

One aspect that could be further developed is the transition to the second peak in case 6 for instance. It could be done with a different exponent of the third design way of a in Equation (2.4), or with a completely different design of a. One final and important notice about the simulations is that in order to be able to reach a higher, and perhaps more competitive, compensation from the DPF the q-parameter would likely need to be altered to some kind of multiple of the spot price larger than 1. When using storage, the mean compensation given by the DPF were in the highest cases slightly above the low static compensation but still far away from the high static compensation. But just by giving the parameter q a multiple of two times the spot price for instance, the mean compensation would be around the higher static compensation instead. As a short summary of the DPF it can be said to reflect, or concretize, what could be called a "temporal" value of locally produced renewable electricity. With increasingly shorter time intervals, the resolution, or granularity, of the function will also increasingly get closer to the real behavior of the grid's balance which functions on the scale of seconds.

Going back to a broader context, most electricity markets have a pricing based on the traditional hierarchical top-down approach where customers, including prosumers, are seen as passive receivers (Sousa et al. 2018, p. 2). The DPF does not only encourage a more proactive behavior, it does so through a transparent mechanism which in the best case also could create a gain for all the grid's different stakeholders. Some examples of this could be:

- Prosumers can affect their compensation for excess electricity.
- The electricity suppliers could simplify their revenue models.
- The DSOs could operate the grid with less effort.

The fact that there is a mandatory separation between distribution and supply activities in Sweden creates an important restriction to think careful about the design of an MBI within this environment. The DSOs will become the gatekeepers in a consumer-centered market as they are the single point of contact for the grid users who, only through their DSO, may access services provided by others. The question becomes how others, e.g. electricity suppliers, will interact with the DSOs. The reason rules, policies, MBIs and new markets were discussed in chapter 1 was to provide a fundamental insight of how wide and complex the context of an energy market can be. Instead of modelling an equally complex market mechanism for locally produced electricity, the ambition was to design an MBI which rewards markets participants to always try a little harder to align with the mechanism of the MBI since every small step in the wanted direction is compensated if designed correctly. The current development points towards more DER, especially in the form of IRE sources, at the same time as there is an increased flow of information within the energy market. Local distributed control and management techniques are by several researched pointed out as necessary to accommodate more decentralized and digitalized systems (Andoni et al. 2019, p. 2). The DPF could be a step towards such a development, and while it might not be enough by itself to create a new market, it could potentially function in most already existing ones. The reason the prosumers, in this case single-family households, are put at the center of it is because they currently are the biggest market segment for PV-systems in Sweden. They are also located in the LVN, grouped in local areas, which means incentives for balancing the grid at this system level are one of the most important factors when it comes to the continued penetration of PV-system.

Another wanted consequence of using the DPF is to geographically spread the installation of IRE, thus affecting the grid and providing local production in an even way. As economic compensation is seen as the main driving force, tweaking the a-parameter in the right way can incentivize an even spread of PV-systems without the need to create specifically addressed installation contributions from the state or other institutions. How is shown by case 6 which provides an economical incentive to be among the first prosumers in a local area. In a long-term perspective and to utilize the grid in a more effective manner, cheaper and more sustainable storage is likely going to be needed in addition to more advanced control mechanisms. But these cannot be created in an instant, and the development needs many small steps. The DPF is one possible such step where the objective of always matching supply and demand at all times is in focus, thus creating an incentive for flattening peaks and large variations. Some might think it is unfair to receive different compensation for the same amount of electricity depending on where and when it is produced, but this is not different from how the retail market of electricity works. What needs more consideration is the possible stigma from consumers who would be among the first to become prosumers in a local area if an implementation such as case 6 is used. Initially their compensation is large, but if the share of prosumers increases the mean compensation will go down for all prosumers in the local area until eventually reaching the second peak. This peak however still has a smaller magnitude than the initial compensation the first prosumers received. How, and if, this could lead to other design concepts for the DPF is something that needs consideration.

There are also several other aspects tied to the DPF that requires more analysis, discussion and research. In terms of technology not everyone might have the knowledge or the will to participate. When it comes to storage, such solution exists and works but are still in many cases expensive. Batteries are common, but the improvement of other technologies – e.g. flywheels – could possibly work well with the intermittent character of PV-systems. Maybe converting excess electricity into hydrogen gas which can be stored and later used to produce electricity or heat could be used. In terms of economy the design of q and a will be of crucial importance and their fine-tuning needs more testing. If looking at social aspects, promoting the continued development of PV-systems have a public support which can be seen in the increasing share of prosumers. New ways to value their overproduction and to incentivize certain behaviors was inspiration of this thesis, taking it one step further to introduce and test a digital currency as presented in Mihaylov et al. (2014) could also be evaluated. In terms of judicial aspects, all the information needed for the DPF is not available as of today and it is unknown if it will become so. The laws and regulations in this context are currently undergoing changes, and in the outlook made in section 1.3.1 about the work of different policy-organizations such as CEER, IEA and SEA a possible path can be seen towards more openly accessible information. Policy organizations always works for a certain goal, and while that goal should be critically scrutinized; the same is true for the EU and different national legislative authorities. No one of these are working in a vacuum but are impacted by each other.

If policy development, which affect how laws and regulations changes, within Sweden and the EU continue to point towards more openly accessible data then the DPF could .in theory be implemented. How this would work together with privacy protection regulations and other legal aspects, as pictured by C7 in Figure 7, will be of uttermost importance and something that will decide if and when this could happen. The technology is already more or less available and the flexibility services will be increasingly important as DER becomes a larger part of the electrical grid.

To support this, DSOs will likely share more information as it is in the interest of all grid stakeholders. New flexibility services have the potential to provide value for how to handle an increased dynamic character of the electrical grid in terms of more IRE sources and intensive power applications and it could come from price-based time-of-use tariffs to contractual-based direct load control instructions e.g. (CEER, 2019, p. 22). To spread among consumers, these kinds of services needs to become automated as soon as possible. And while the DSOs are not to offer these services directly, due to their role of as a neutral facilitator, they should allocate resources for them. This means that the DSOs mainly will act as the facilitators of flexibility services by providing the relevant information to markets actors, and as a buyer of such services from them.

Finally, is more solar power realistic in Sweden? In section 2.2.1.2 a simple power flow analysis was performed, and the results pointed at a technically maximum share of prosumers of around 70 %. This is around 30 percentage units higher than the optimal share of prosumers from simulating case 1 to 6, making these cases seem technically possible. According to SEA the upcoming decades unambiguously points at a larger share of PV-production than today, and one of their recent futuristic scenarios includes 25 TWh of electricity coming from PV-systems compared to 0.19 TWh in 2017. The driving forces is lower prices coupled with an interest among people to support local and small-scale electricity production among other things. PV-systems on residential roofs that mainly cover the prosumers own demand is today seen as the most profitable and is expected to be the most growing form of PV-systems the upcoming years (Energimyndigheten, 2019, p. 37-40). This development is however tightly connected to subsidies and policies, and they might change which contributes to the environment of uncertainty the DPF is intended to counteract.

3.1 Future studies

As mentioned in the previous section, one of the most important aspects around the DPF is how to the design parameters q and a. But there also needs to be an incentive for someone to administer the system using the DPF. The exact details of this could be the focus for another study. In Mihaylov et al. (2014) a more bidding based system through a virtual currency-approach is discussed. It was not used in this thesis since an implementation with a virtual currency would be more complicated while being further away from how the system works today, but it could be analyzed and tested. Being able to sell directly to other consumers without a middle hand, perhaps by using a decentralized market and protocols like blockchain, is something that is technologically possible. But no such fully developed or commercialized system exists yet. The first reference proposing P2P for power systems is from 2007, and today there are real examples of testing P2P to share energy in local areas in New York for instance (Sousa et al. 2018, p. 3). There are also other virtual currency suggestions than NRGcoin, for example "Picle" in Great Britain, "Vandebron" in the Netherlands and "SonnenCommunity" in Germany which explores different possible business models with energy throughout P2P solutions (Zhang et al. 2018, p. 1-12).

The paper by Mihaylov et al. (2014) also discusses a buying function, as opposed to the idea that inspired the DPF which is for selling electricity. Thinking around and designing such a function for locally produced IRE could also be an interesting topic to explore. The following papers Mihaylov and others about the NRG-X-Change-concept also bring up topics such as "green" certificates and more which is relevant since the current market structures for certificates are fragmented and complex. Small actors on the market may in many cases have a hard time participating in the system, and much of it is performed manually which causes concern for errors and even fraud (Andoni et al. 2019, p. 163). The legal environment could likewise be studied in more detail. The technology to gather and share the needed data for the DPF exists, but how this is going to work in conjunction with privacy regulations such as the GDPR is not clear. Reliable forecasting algorithms also needs to be developed that works with the smart meters to make the system even more dynamic and efficient. Studies has shown that when customers can affect their spending in a more open way, they tend to make more rational choices and try to lower their costs, but how should this be modelled? Future research could target consumers by focusing on the human dimension which may drift towards social sciences in order to find the optimal implementation (Sousa et al. 2018, p. 25).

3.2 Conclusion

If more decentralized IRE production, such as PV-systems, will become a reality then using a method to value the (over)produced electricity depending on the condition of the electrical grid will be of importance. Since many PV-system owners are local residents, who are assumed to be rational and acting in their self-interest, economic incentives will likely work well – if designed in an adequate way. The DPF modelled, simulated and analyzed in this thesis is one such incentive. With a connection to one of the grid's most important parameters – the balance – it shows a way of valuing electricity depending on *when* and *where* it is fed into the grid which is especially important for local areas where the grid is weaker. The following conclusions are drawn based upon the research questions initially posed:

- How can a DPF for renewable electricity be designed in order to support the balance of the electrical grid?

It can be designed to economically incentivize the balance of a grid in a local area by using its consumption and production data together with two design parameters: one linked to Nord Pool's spot market price and another connected to the balance in the local grid which punishes imbalance.

- How can such a DPF impact the compensation for prosumers in a local area during local over- and underproduction within a Swedish context?

As the imbalance between local consumption and production decreases, the compensation of feeding overproduced electricity into the local grid increases. The most fruitful case in the thesis was deemed to be case 6 where three important incentives were given:

1. To become a prosumer to start with.
2. To push the local area to a higher share of prosumers, but not too high.
3. To procure storage possibilities.

The compensation over the range of different shares of prosumers can be impacted in many ways.

- How does storage possibilities impact the given compensation?

Procuring storage has two main benefits:

1. During overproduction, instead of feeding electricity into the grid it can be stored.
2. During underproduction, instead of receiving electricity from outside the local area the storage can discharge stored electricity.

In both of these cases the entire local area can maintain local balance for a longer period of time which leads to more time intervals with higher compensation from the DPF.

- What share of prosumers seems to give the highest mean compensation in this case?

The share slightly differs throughout the different cases, but without storage the optimal share of prosumers was around 26-30 % and with storage around 37-43 %.

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Figures

Figure 1 (left half) – Metro Train Simulation: Solar Power System Calculator. Accessed at: http://www.metrotrainsimulation.com/solarload.html [2019-11-24]

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Tables

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Table 4 – Sousa et al. 2018, p. 17.

Table 5 – Sousa et al. 2018, p. 17.

Appendix

Appendix I

Optimal share of prosumers case 3-5

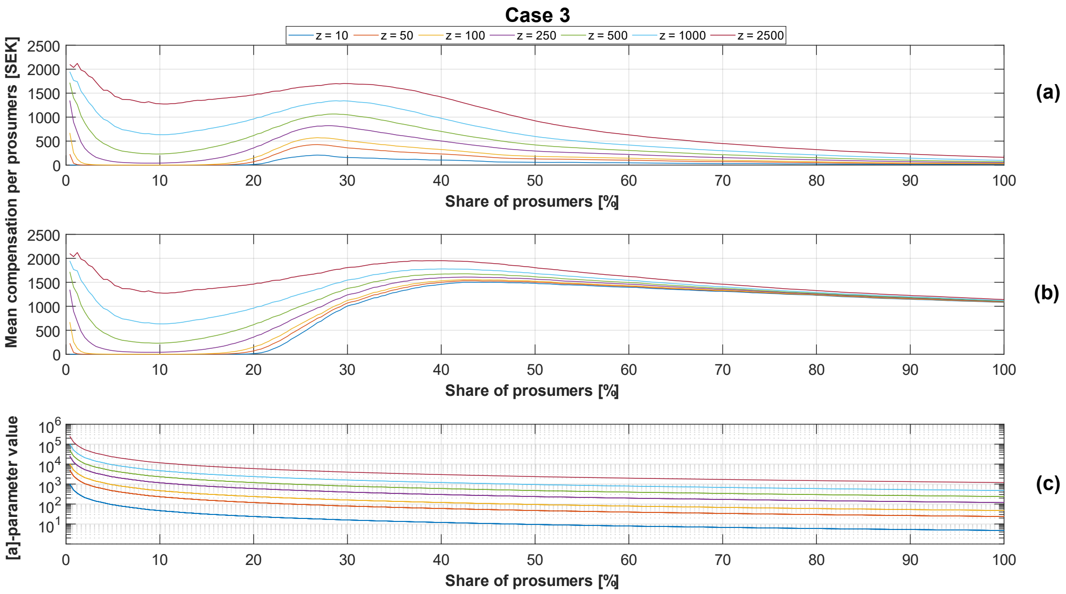

Figure 30 – Varying the a-parameter and the share of prosumer according to case 3 to analyze the mean compensation and to find the optimum share of prosumers. (a) Without storage between 26.8-29.6 %. (b) With storage between 39.6-42.4 %. (c) Value of a for different simulations.

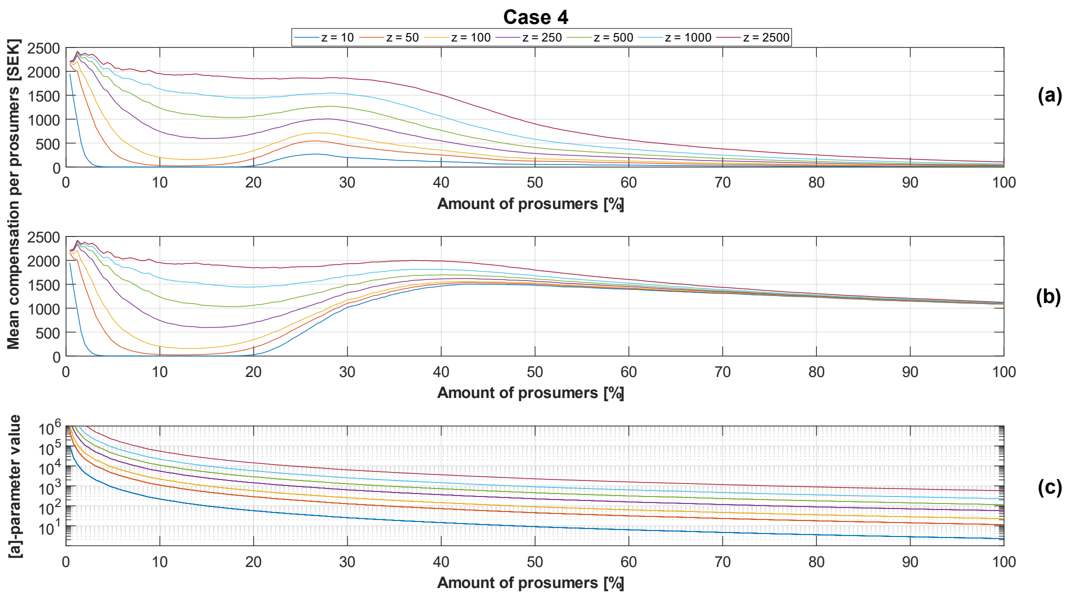

Figure 31 – Varying the a-parameter and the share of prosumer according to case 4 to analyze the mean compensation and to find the optimum share of prosumers. (a) Without storage between 26.8-28.0 %. (b) With storage between 36.8-42.4 %. (c) Value of a for different simulations.

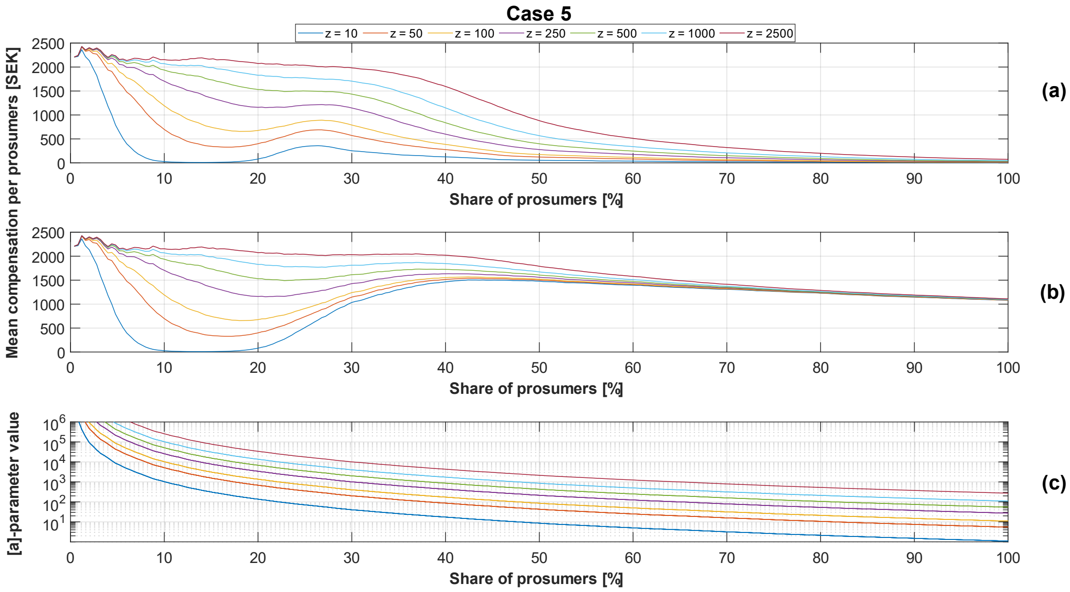

Figure 32 – Varying the a-parameter and the share of prosumer according to case 5 to analyze the mean compensation and to find the optimum share of prosumers. (a) Without storage between 26.4-26.8%. (b) With storage between 36.8-42.4 %. (c) Value of a for different simulations.

Appendix 2

Testing the different cases for spot price 2010-2018 case 3-5

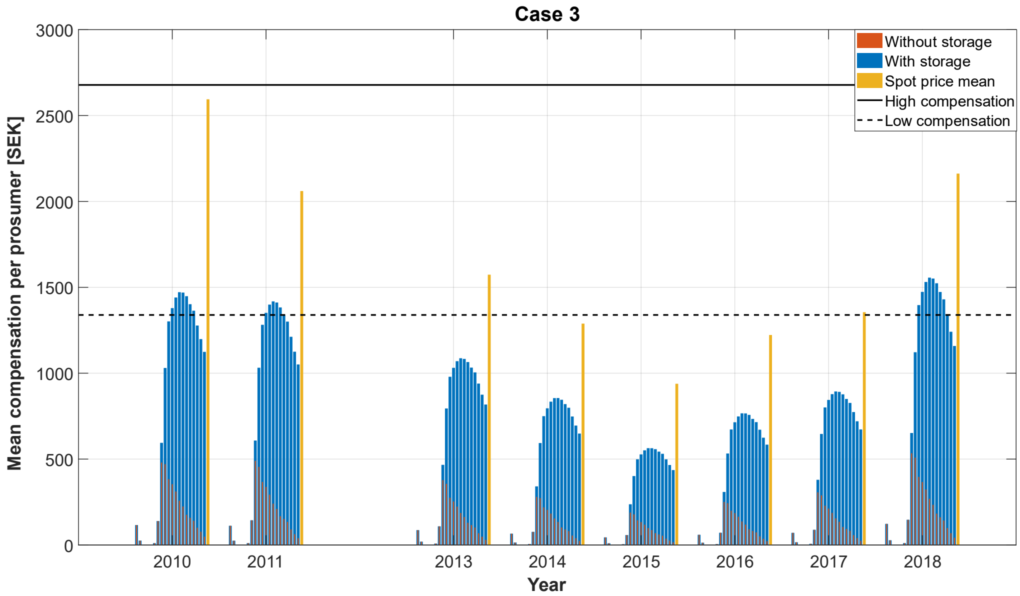

Figure 33 – Mean compensation per prosumer using spot prices 2010-2018 and case 3.

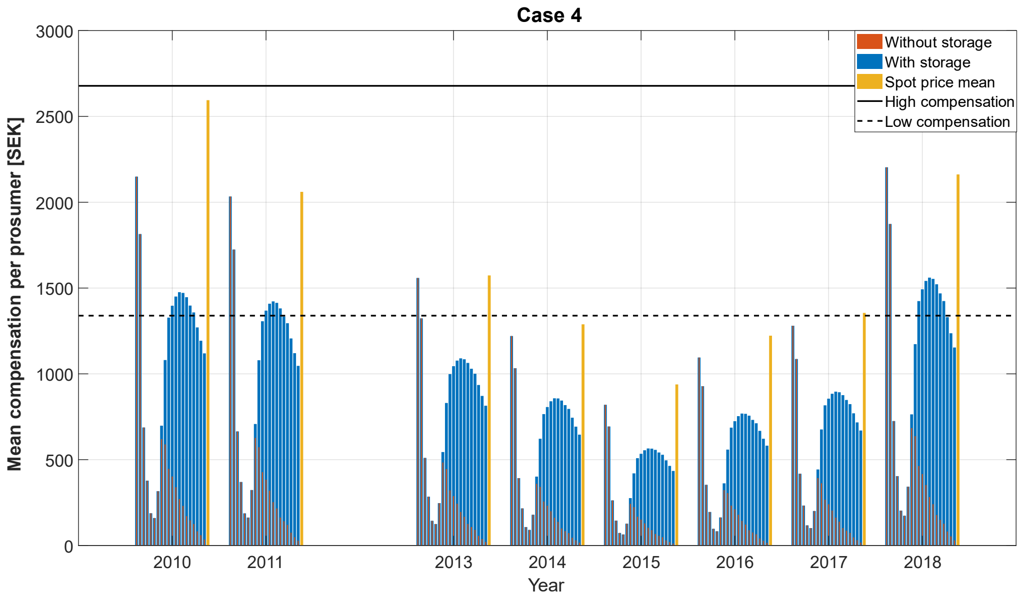

Figure 34 – Mean compensation per prosumer using spot prices 2010-2018 and case 4.

Figure 35 – Mean compensation per prosumer using spot prices 2010-2018 and case 5.