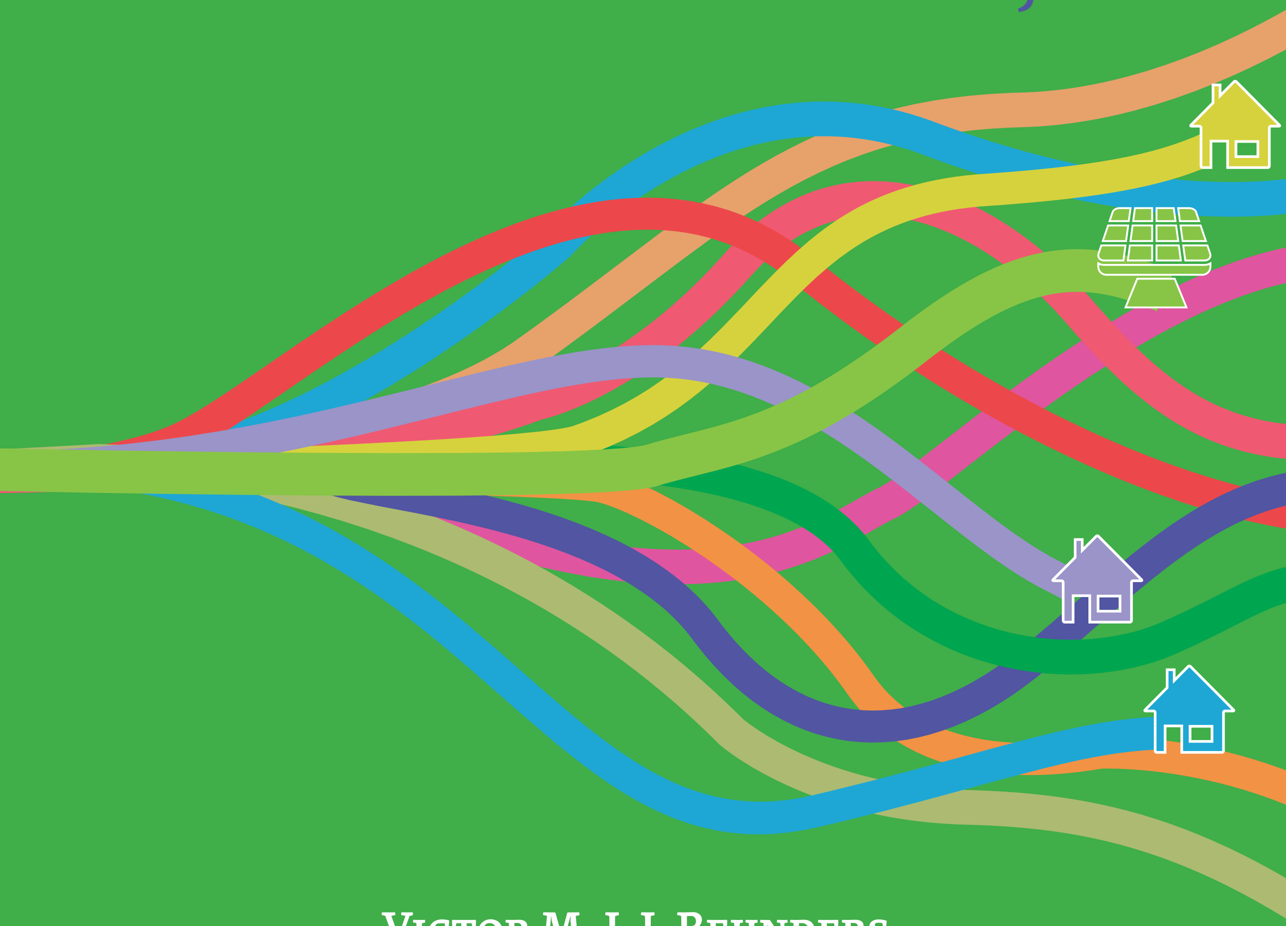
Pricing Mechanisms for Energy Communities

THE GRIDFLEX HEETEN PROJECT



Victor M. J. J. Reijnders

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Victor Maria Jacobus Johannes Reijnders

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Proefschrift

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ABSTRACT

One of the most challenging problems of the recent years is climate change. To decrease its effect, lowering CO2 emissions is crucial. One important step to take in this context, is the switch from using fossil fuels to using renewable energy sources. This switch also implies an electrification of appliances, e.g., electric vehicles, or heat pumps.

The resulting energy transition, however, causes problems in our electricity grid, as the electricity from renewable energy sources is often not produced at the same time (and location) as the electrical appliances need it. Moreover, this production, and the mentioned consumption, is highly synchronized. Next to a mismatch between supply and demand, this also causes huge peaks in the networks, leading to quicker degradation of assets, or even black outs.

At the low voltage level of the grid, this nowadays already causes issues. In certain neighbourhoods, solar panels need to be curtailed on sunny days, or at other times the simultaneous charging of electric vehicles may blow fuses. Fortunately, for these problems, solutions exists, amongst others, in the form of demand-side management, that aims, for example, match the consumption and production of renewable electricity to lower the stress on the grid. One way to apply demand-side management is with pricing. Pricing of electricity aims to activate people to use electricity at given moments. Furthermore, the usage of smart devices can be steered based on such prices.

As a single household does not provide enough flexibility, in this thesis, we focus on neighbourhoods, or energy communities, as a whole. This, e.g., supports households to capture the solar energy produced by neighbours. It is clear, however, that hereby not only technical aspects, but also a social component needs to be addressed.

The main motivation for the research of this thesis came from the GridFlex Heeten project, which focussed on implementing innovative pricing mechanisms in an energy community to lower the stress on the grid. The community considered in the project is located in Heeten, a village in the Netherlands, within a neighbourhood of 47 households.

The core focus of this thesis is on the design of pricing mechanisms for energy communities to help alleviate the stress on the electricity grid. Some of these pricing mechanisms were also used in the GridFlex Heeten project and corresponding field test. The specific contributions of this thesis are:

- *Pricing mechanisms based on losses using grid topology*: As the goal of the pricing mechanism is to reduce the stress on the grid, a logical choice is to have the pricing somehow reflect the costs that occur in the grid. Losses give a good indication of the stress on the assets in the grid and are used as basis of the pricing mechanism.

  The proposed pricing mechanism is based on the Shapley value and it distributes the costs based on the average marginal contribution of a household to the neighbourhood losses. This results in a pricing mechanism with the 'polluter pays' principle. Normally, calculating the Shapley value is computationally inefficient, but as losses scale quadratic with the power consumption, it can be calculated efficiently for this specific case.

  The disadvantage of this pricing is that the costs assigned to the households are highly dependent on the location of the household in the electricity grid. As this is not seen as a fair criterion by consumers, we introduce the concept of an *average location* of households in the grid. For this, we permute the location of the households and use the Shapley value based on the caused losses to assign the costs. These permutations of location are used in two ways: either by considering all possible permutations and taking the average over the resulting cost assignments (called the average location cost), or taking the average of the cost assignments using only the permutations where the location of a pair of households are exchanged (called the approximate average location cost). The latter can be calculated much faster, but keeps more locational bias.

  Calculating all the Shapley values for all these permutations (in case of the average location cost) normally would be computationally infeasible as the number of permutations scales factorial with the number of households in the general case. However, when considering radial grid structures, explicit expressions can describe the costs. For the approximate average location costs, the number of considered permutations scales only linearly with the number of households in the general case, so extensions to different grid structures can be done more easily. For radial grid structures, explicit expressions for the approximate average location cost can be found in a similar way as for the average location cost.

  For the resulting two cost assignments, larger consumers still have to pay higher costs, showing the possibility to address the locational bias that arises from the 'polluter pays' principle.

- *A hybrid pricing mechanism for joint system optimization and social acceptance*: As with the aforementioned pricing mechanism, social acceptance is crucial to take into account. Therefore, a framework for local electricity pricing mechanisms focussed on social acceptance is proposed. The goal of these mechanisms should be to flatten the overall electricity profile of the neighbourhood. In the proposed mechanisms, the price of electricity depends on the electricity load of the neighbourhood, and it is based on a linear price function, as this achieves the goal mentioned. However, these cost functions are deemed to be too complex, and consumers are generally unwilling to participate in systems offering these prices.

The problem with simpler pricing mechanisms that *are* accepted by consumers, is that they do not always help to achieve the intended goal, or might even worsen the situation. Therefore, the challenge is to bring together these conflicting aspects in a pricing mechanism: low complexity and flattening the neighbourhood load. For this, an electricity pricing is proposed that is a step-wise function that expresses the price per kWh for individual consumers based on the overall neighbourhood load. The resulting cost function is piecewise linear and approximates a quadratic cost function. These cost functions penalize periods with high neighbourhood peaks, and incentivize the neighbourhood to flatten their overall load.

Within the given framework the number of pieces and the prices per piece can be tailored to the neighbourhood. This way, the prices can be made fair, and the neighbourhood receives suitable incentives to lower or flatten their electricity load. A further advantage of this pricing is that the prices only change a couple of times a day, giving the consumer more certainty.

The performance of the presented pricing mechanisms is tested under various conditions and compared to other steering mechanisms. This hybrid pricing mechanism was implemented and tested in the GridFlex Heeten field test. Both the results from GridFlex Heeten as well as those from simulations are comparable to that of quadratic costs, while having low computational complexity. Furthermore, based on the feedback of participating consumers and criteria from literature, we conclude that the proposed mechanism is socially accepted. This shows the potential for these pricing mechanisms in practice.

» *An overview of the GridFlex Heeten field test and research project*: The aim of the GridFlex Heeten project was to test innovative pricing and steering mechanisms at a field test location with local electricity production and storage. This could result in a local energy market which should be scalable, and aim to improve the local matching of supply and demand. This thesis addresses the main project results, thereby providing a reference for future research projects.

These project results mainly comprise the pricing mechanisms created and tested in the project, namely the mentioned hybrid pricing mechanism, and a neighbourhood net-metering mechanism. In the latter, the consumers pay more for importing energy from outside the neighbourhood, and receive less for exporting it compared to using it within the neighbourhood. This stimulates self-consumption within the entire neighbourhood.

The information on the used prices was shared with the participants via an app. With this information they could adapt their electricity usage to save money. Furthermore, batteries were installed in the neighbourhood with a controller that responded to the given prices. This resulted in annual savings of €1 403.38 and €753.47 for the two considered pricing mechanisms, respectively.

Statistical tests showed that the participants did not structurally change their behaviour based on the pricing mechanisms. This was also confirmed by a neighbourhood team, which consisted of participants who were more involved in the project.

With the proposed pricing mechanisms, the potential for using pricing mechanisms to alleviate the stress on the grid, while taking into account the social acceptance was shown. However, before these pricing mechanisms can be applied outside of research projects, many challenges still need to be tackled. Some of such important aspects are the legal frameworks, the required infrastructure, and the necessary investments.

Samenvatting

Een van de meest uitdagende problemen van de afgelopen jaren is klimaatverandering. Om de effecten hiervan te verminderen, is het cruciaal om de CO2-uitstoot te verminderen. Een belangrijke stap hierin, is de overstap van het gebruik van fossiele brandstoffen naar het gebruik van hernieuwbare energiebronnen. Deze overstap houdt ook een elektrificatie van apparaten in, zoals elektrische voertuigen of warmtepompen.

De resulterende energietransitie zorgt echter ook voor problemen in ons elektriciteitsnet, omdat de elektriciteit uit hernieuwbare energiebronnen vaak niet op hetzelfde moment (en op dezelfde locatie) wordt geproduceerd als waar de elektrische apparaten het nodig hebben. Bovendien is deze productie sterk gesynchroniseerd, net als het genoemde verbruik. Naast een mismatch tussen vraag en aanbod zorgt dit ook voor enorme pieken in de netwerken, wat leidt tot snellere degradatie van netwerkcomponenten of zelfs stroomuitval.

Op het laagspanningsniveau van het netwerk veroorzaakt dit nu al problemen. In bepaalde buurten moeten zonnepanelen op zonnige dagen worden afgeschaald, of op andere momenten kan het gelijktijdig opladen van elektrische voertuigen zekeringen doen springen. Gelukkig bestaan er oplossingen voor deze problemen, onder andere in de vorm van slim beheer en afstemming van het verbruik en de productie van hernieuwbare elektriciteit om de druk op het net te verminderen. Een manier om dit toe te passen is via prijsmechanismen. Prijzen van elektriciteit kunnen mensen stimuleren om hun elektriciteitsgebruik aan te passen. Bovendien kunnen slimme apparaten worden gestuurd op basis van dergelijke prijzen.

Aangezien een enkel huishouden niet voldoende flexibiliteit biedt, richten we ons in dit proefschrift op wijken of energiegemeenschappen als geheel. Dit stelt huishoudens bijvoorbeeld in de gelegenheid om de zonne-energie te benutten die geproduceerd wordt door de buren. Het is echter duidelijk dat hierin niet alleen technische aspecten, maar ook sociale componenten moet worden meegenomen.

De belangrijkste motivatie voor het onderzoek van dit proefschrift kwam van het GridFlex Heeten project, dat zich richtte op de implementatie van innovatieve prijsmechanismen in een energiegemeenschap om de druk op het net te verminderen. De gemeenschap die in het project wordt beschouwd is een wijk genaamd De Veldegge met daarin 47 huishoudens, gelegen in Heeten, een dorp in Nederland.

De focus van dit proefschrift ligt op het ontwerpen van prijsmechanismen voor energiegemeenschappen om de druk op het elektriciteitsnet te verlichten. Sommige van deze prijsmechanismen werden ook gebruikt in het GridFlex Heeten project en bijbehorende veldtest. De specifieke bijdragen van dit proefschrift zijn:

» *Prijsmechanismen gebaseerd op verliezen en de topologie van het elektriciteitsnetwerk*: Aangezien het doel van het prijsmechanisme is om de druk op het net te verminderen, is het logisch dat de prijs op de een of andere manier de kosten weerspiegelt die veroorzaakt worden in het net. Verliezen geven een goede indicatie van de belasting van netwerkcomponenten en vormen de basis van het prijsmechanisme. Het voorgestelde prijsmechanisme is gebaseerd op de Shapley-waarde en verdeelt de kosten op basis van de gemiddelde marginale bijdrage van een huishouden aan de verliezen in de buurt. Dit resulteert in een prijsmechanisme waarin 'de vervuiler betaalt'. Normaal gesproken is het berekenen van de Shapley-waarde berekeningsintensief, maar omdat de verliezen kwadratisch schalen met het stroomverbruik, kan het efficiënt worden berekend voor dit specifieke geval.

  Het nadeel van dit prijsmechanisme is dat de toegewezen kosten aan de huishoudens sterk afhankelijk zijn van de locatie van het huishouden in het elektriciteitsnet. Aangezien dit niet als een eerlijk criterium wordt beschouwd door consumenten, introduceren we het concept van een 'gemiddelde locatie' van een huishouden in het net. Hiervoor permuteren we de locatie van de huishoudens en gebruiken we de Shapley-waarde, op basis van de veroorzaakte verliezen, om de kosten toe te wijzen. Deze locatiepermutaties worden op twee manieren gebruikt: ofwel door het gemiddelde te nemen over de kostenverdelingen van alle mogelijke permutaties (het gemiddelde locatiekosten), ofwel door het gemiddelde te nemen van de kostenverdelingen waarbij alleen de locatie van één paar huishoudens wordt gewisseld (de benaderende gemiddelde locatiekosten). Dit laatste kan veel sneller worden berekend, maar blijft meer afhankelijk van de locatie van het huishouden.

  Het berekenen van alle Shapley-waarden voor deze permutaties (in het geval van de gemiddelde locatiekosten) zou normaal gesproken niet haalbaar zijn, aangezien het aantal permutaties in het algemene geval groeit als de faculteit van het aantal huishoudens. Bij het overwegen van radiale netstructuren kunnen echter expliciete uitdrukkingen voor de kosten worden geformuleerd. Voor de benaderende gemiddelde locatiekosten neemt het aantal overwogen permutaties lineair toe met het aantal huishoudens, zodat uitbreidingen naar verschillende netstructuren gemakkelijker kunnen worden gedaan. Voor de benaderende gemiddelde locatiekosten kunnen ook expliciete uitdrukkingen worden gevonden voor radiale netstructuren op een vergelijkbare manier als voor de gemiddelde locatiekosten.

Voor de resulterende twee kostentoewijzingen moeten grotere verbruikers nog steeds wel de hogere kosten betalen, wat aantoont dat het mogelijk is de afhankelijkheid van de locatie te verminderen, maar wel vast te houden aan het 'de vervuiler betaalt'-principe.

» *Een hybride prijsmechanisme voor gelijktijdige systeemoptimalisatie en sociale acceptatie*: Zoals eerder genoemd is sociale acceptatie cruciaal voor de implementatie van prijsmechanismen. Daarom wordt in dit proefschrift een theoretisch kader voorgesteld voor lokale elektriciteitsprijsmechanismen gericht op deze sociale acceptatie. Het doel van deze prijsmechanismen is namelijk het afvlakken van het elektriciteitsprofiel van de hele buurt. Hierdoor hangt de energieprijs af van de belasting van het elektriciteitsnet van de buurt. Deze prijs is gebaseerd op een lineaire prijsfunctie, omdat die de piekbelasting het best afvlakken. De kostfuncties van dergelijke modellen worden echter als te complex beschouwd en consumenten zijn over het algemeen niet bereid om deel te nemen aan systemen die deze prijzen aanbieden.

Het probleem met eenvoudigere prijsmechanismen die *wel* geaccepteerd worden door consumenten, is dat ze niet altijd helpen om het beoogde doel te bereiken of de situatie zelfs kunnen verslechteren. De uitdaging ligt dus in het samenbrengen van deze conflicterende aspecten: lage complexiteit, en het afvlakken van het energieprofiel. In dit proefschrift wordt een prijsmechanisme met trapsgewijze waarden gepresenteerd waarin de prijs per kWh voor iedere consument gebaseerd wordt op de belasting van het energienetwerk van de buurt. De bijbehorende kostfunctie is stuksgewijs lineair en benadert een kwadratische functie, wat hoge pieken bestraft met hogere prijzen om zo de algehele belasting op het netwerk van de buurt af te vlakken.

Binnen dit theoretisch kader kunnen de hoeveelheid prijsniveaus en de prijs per niveau worden aangepast aan de buurt. Zo krijgt iedere consument een eerlijke energieprijs, en worden bewoners gestimuleerd om hun elektriciteitsverbruik af te vlakken. Daarnaast krijgt een consument zekerheid over de energieprijzen doordat deze slechts enkele keren per dag veranderen, wat bijdraagt aan de sociale acceptatie.

De prestaties van de gepresenteerde prijsmechanismen worden getest onder verschillende omstandigheden en vergeleken met andere sturingsmechanismen. Het voorgestelde hybride prijsmechanisme is geïmplementeerd en getest in het GridFlex Heeten project. Zowel de resultaten uit GridFlex Heeten als uit simulaties met het hybride prijsmechanisme zijn vergelijkbaar met resultaten die behaald zouden worden door kwadratische kosten, terwijl de hybride prijsmechanismen een lage computationele complexiteit hebben. Bovendien, op basis van de feedback van de deelnemende consumenten en criteria uit de literatuur, concluderen we dat het voorgestelde mechanisme sociaal geaccepteerd is. Dit toont de potentie van deze prijsmechanismen in de praktijk aan.

» *Een overzicht van de GridFlex Heeten veldtest en onderzoeksproject*: Het doel van het GridFlex Heeten project was het in de praktijk testen van innovatieve prijs- en sturingsmechanismen met lokale energieproductie en opslag. Hierdoor zou een lokale, schaalbare energiemarkt gerealiseerd kunnen worden, gericht op verbetering in de lokale afstemming van vraag en aanbod. Dit proefschrift behandelt de belangrijkste resultaten van het project en biedt daarmee een referentie voor toekomstige onderzoeksprojecten.

De resultaten beschrijven vooral de prijsmechanismen die zijn ontwikkeld en getest in het project, namelijk het eerder genoemde hybride prijsmechanisme en een wijksalderingsmechanisme. Bij laatstgenoemd mechanisme betalen de consumenten meer voor het importeren van energie van buiten de wijk en ontvangen ze minder voor de export buiten de wijk in vergelijking met binnen de wijk. Dit stimuleert zelfconsumptie binnen de gehele buurt.

De energietarieven werden steeds met de deelnemers gecommuniceerd middels een app. Zo konden zij hun energieverbruik aanpassen om geld te besparen. Daarnaast werden er batterijen in de buurt geplaatst met een controller die ook stuurde op de prijzen. Dit resulteerde in jaarlijkse besparingen voor de buurt van respectievelijk € 1.403,38 en € 753,47 voor de twee genoemde prijsmechanismen.

Ondanks deze besparingen toonden we middels statistische toetsen aan dat het gedrag van deelnemers niet structureel veranderde door deze prijsmechanismen. Deze bevinding werd ook bevestigd door het buurtteam, dat bestond uit deelnemers die nauw betrokken waren bij dit project.

Dit onderzoek toont de potentie aan van de inzet van prijsmechanismen om de druk op het net te verminderen, terwijl er wel rekening wordt gehouden met de sociale acceptatie ervan. Er zijn echter nog enkele uitdagingen die overkomen moeten worden voordat dergelijke prijsmechanismen buiten onderzoeksprojecten toegepast kunnen worden, zoals de juridische kaders en de vereiste infrastructuur.

Dankwoord

Het einde van mijn Ph.D., eindelijk daar. Jarenlang heb ik geploeterd om hier te komen, en dan komt het moment om ook eens terug te kijken, in plaats van alleen maar vooruit. Ik realiseer me maar al te goed dat ik deze reis natuurlijk niet alleen heb kunnen afleggen. Daarom zijn er een aantal personen en groepen die ik hier graag wil bedanken.

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Binnen de UT was ik onderdeel van de Energiegroep, een onofficiële groep die tussen de vakgroepen CAES en DMMP hangt. Dat zorgt soms voor onduidelijkheid ('Ik heb mijn werkplek bij CAES, maar mijn contract bij DMMP, bij wie moet ik nu aankloppen?'), maar ook voor wat voordeeltjes (dubbele kerstdiners en uitjes). Dank aan de CAES en DMMP collega's, plus de studenten die ik heb mogen begeleiden gedurende mijn tijd hier! Daarnaast had ik een heel team aan secretaresses bij wie ik terecht kon voor vragen: Marjo, Marlous, Nicole en Thyra, enorm bedankt voor alle hulp die jullie hebben geboden!

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ik hier heb gezeten is het van een compact clubje uitgegroeid tot een enorme energiegemeenschap, en puilde het energie-hok (de kamer waar mijn werkplek was) bijna uit. Iedereen enorm bedankt voor alle positieve energie die jullie hebben gegeven (ik ga me inhouden om alle namen te noemen, niet alleen omdat dat een enorme lijst is geworden over de jaren, maar ook omdat ik zo maar een naam onopzettelijk zou kunnen vergeten).

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Op naar het volgende avontuur!

Victor
Enschede, juni 2023

Contents

1

Introduction

Abstract – *This chapter serves as an introduction to the thesis. It introduces the ongoing change to renewable energy sources and the further electrification of devices called the energy transition. With this, also the basics of the electricity grid and the parties involved in the operation of the grid are explained. Moreover, several smart devices and the different types of control relevant in the context of this thesis are mentioned. Lastly, the research questions central to this thesis and the structure of the thesis are presented.*

1.1 Energy transition

Climate change is mentioned in the news almost every day. Especially the last years, the discussion regarding this has peaked. To combat this climate change, we need to limit the temperature increase of the Earth, as this increase leads to melting of the ice caps, higher sea levels, extreme weather, and many other negative consequences [90, 131, 161]. To limit the temperature increase to 2 degrees Celsius, parties (the European Union and 193 states) have joined the Paris Agreement, to, e.g., decrease the CO_2 emissions that cause the temperature rise [37]. Moreover, the United Nations hosts Climate Change Conferences to get world leaders together to create further plans to address and limit climate change [89].

A core element in this, is the change from fossil fuels to renewable energy sources (RES) for generating energy, as this change greatly reduce the CO_2 emissions. Possible ways are:

» *Wind turbines*. Using the wind, these turbines generate power. They are often grouped in big parks (wind parks), but also appear as single turbines, e.g. on farms. They are typically not placed near residential areas and work better, i.e. have a lower cost to power output ratio, at intermediate to large scales compared to small scale turbines [149]. The total potential for wind-generated electricity far exceeds the global energy needs [99]. However, wind also has a drawback, as we need to take into account that wind is very intermittent.

» *Photovoltaic (PV) systems.* These PV systems (also called solar panels) convert solar irradiation into electricity. These panels can be placed on top of residential or industrial buildings, or grouped together in large solar parks. The orientation of the panels is usually to the south to have maximum energy yields, but nowadays also more and more PV systems with both east and west orientations are installed. The former have their peak production during the start of the afternoon, but little production in the morning and late afternoon, and the latter spreads the energy production more over the day, but have a lower overall yield. The estimates for the global power potential for solar energy vary heavily, ranging from supplying around 10%, to far exceeding the global energy needs [25]. Also here, the energy is not consistently produced, raising challenges.

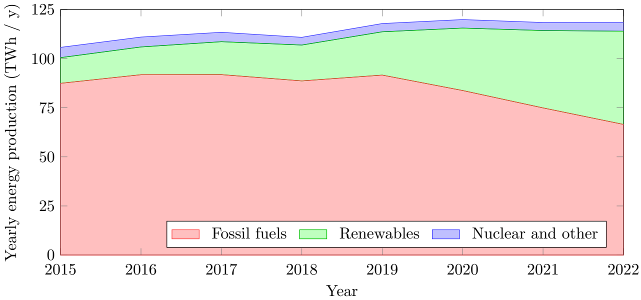
» *Other systems.* Next to the two mentioned system, there are also systems based on hydropower, geothermal energy, and wave power. These solutions are location specific, and are not considered further in this thesis.

For the Netherlands, this change is clearly visible in the yearly energy production per energy carrier (Figure 1.1). This transition to RES for generating energy is also motivated by other reasons, such as the impact of obtaining fossil fuel (e.g. earthquakes in Groningen due to gas extraction [168]) and (geo)political relations, such as the desire of countries to become more independent in terms of energy (e.g. no longer importing gas from Russia [57]).

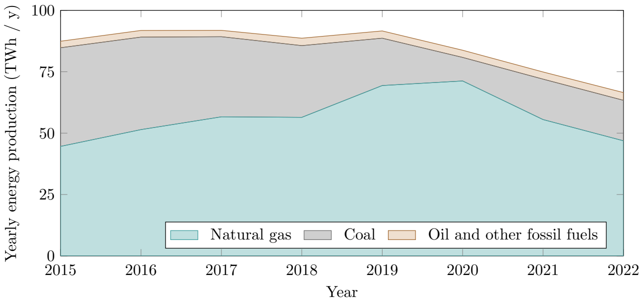
At the same time, we are electrifying a lot of devices to be able use these RES for powering them. Examples can be found in:

» *Electric vehicles (EVs).* These vehicles use electricity instead of petrol to drive. They can be charged at home, or at public chargers, either using slow or fast charging (ranging from 2.3 up to 150 kW). Many of these chargers allow the charging speed to be controlled [60]. The penetration of these cars is on the rise. In 2021, 6.6 million EVs were sold worldwide [73], and in December 2022 in the UK already more EVs were being sold compared to petrol cars citeAmes2023.

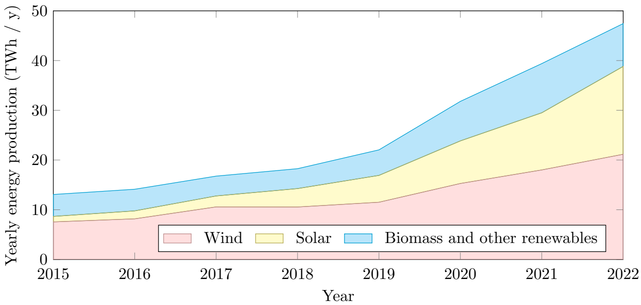
» *Heat pumps.* These devices heat households using electricity. They extract heat from the surrounding air or soil and use this heat for heating tap water or for directly heating the rooms in the building. Often, the heat pump control allows the indoor temperature to be in a specified (small) range, giving some freedom of how to operate the device. Heat pumps have high efficiencies [177]. Although they are getting more popular, they currently only meet around 10% of the global heating needs in buildings [74].



(a) Total yearly energy production.



(b) Yearly energy production by fossil fuel energy carriers.



(c) Yearly energy production by renewable energy sources.

Figure 1.1: Yearly energy production in the Netherlands from 2015 up to and including 2022, split by energy carrier. Compiled using data from [21]. The data from 2021 and 2022 is preliminary at the time of writing.

- *Electric cooking*. There is an ongoing transition to use electricity for cooking instead of gas or other fuel types. This transition enables a decrease of CO_2 emissions and mitigates the negative health impacts of fuel-based cooking, such as, e.g., air pollution [24]. The World Health Organization (WHO) reports that in 2021 2.4 billion people are still using dirty fuels for cooking (households not relying on electricity, biogas, natural gas, liquefied petroleum gas (LPG), solar or alcohol fuels for cooking) [175], which illustrates the effect this transition will ultimately have. Nevertheless, in 2020, over 60% of homes in the United States were already using electricity to cook [160].

Changing from devices that use fossil fuels to electric versions is called electrification. These trends of switching to RES and electrifying the devices are the main aspects of the energy transition.

1.1.1 Distribution grid

However, the energy transition also introduces challenges, especially in the grid distributing the electricity as this has a limited capacity. The electricity grid can be divided mainly in three voltage levels (this overview is written based on the European grid, also see Figure 1.2):

- *High voltage (HV)*. This level transports electricity over long distances (hundreds of kilometres), with at least 60 kV, at 50 Hz. This is done either via underground or overhead lines. By using a high voltage, the current can be kept low to reduce the losses. At this level, already some issues are arising on a national level and across countries (e.g. the North-South connection in Germany [126]).
- *Medium voltage (MV)*. This level transports electricity to large industry and to the low voltage level, using voltages between 1 and 50 kV. At this level, also smaller RES are connected, such as solar parks. In the MV grid, regional issues are arising (e.g. insufficient capacity for new solar parks [104]).
- *Low voltage (LV)*. On this level, electricity is distributed to small industry and to households, with a voltage of 230 or 400 V (sometimes with exceptions for industry). Here, the problems, as described later in this chapter, are most prominent.

  These problems are caused by synchronisation in both the production and consumption of electricity. The PV peaks in a neighbourhood are synchronized, and highly intermittent, e.g. due to local clouds. Similarly, many of the EVs in a neighbourhood typically arrive and start charging around the same time, causing synchronised consumption peaks. Moreover, the timing of the generation peaks (for PV during the morning and afternoon) does not overlap with the consumption peaks (early morning and evening, see Figure 1.3). Adversing this with additional grid capacity

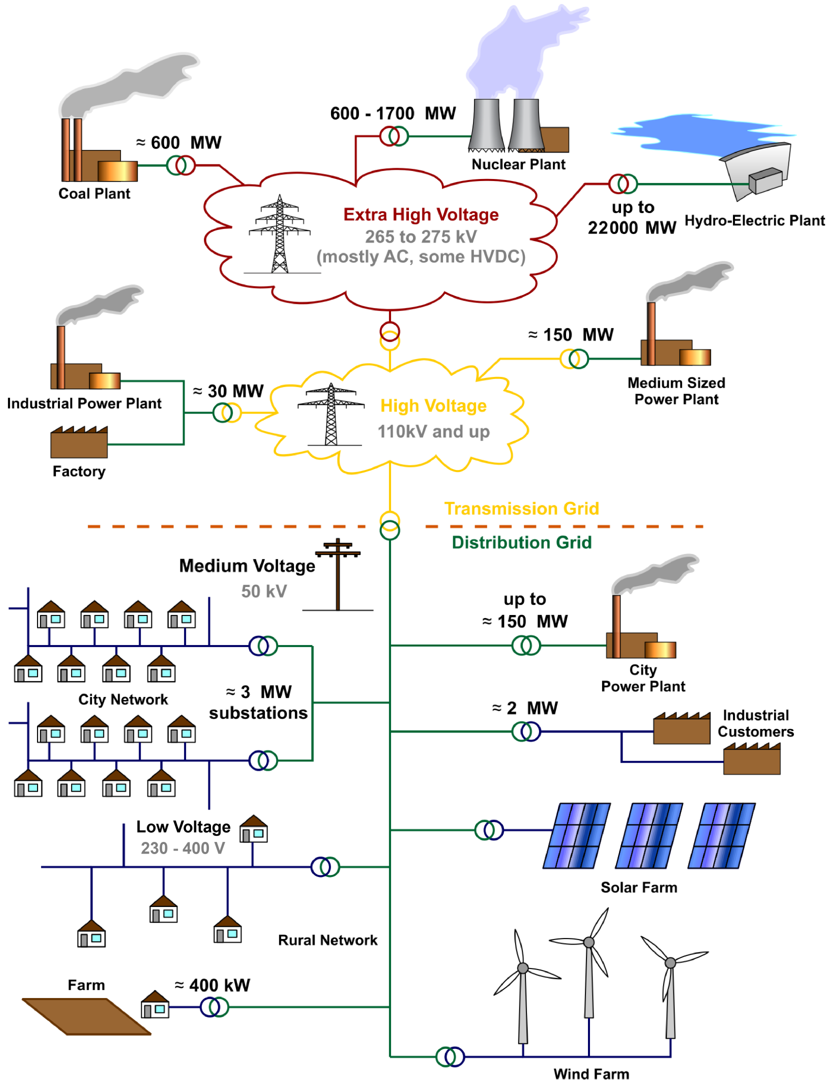


Figure 1.2: A layout of the electricity grid structure. Created based on the image provided in [101].

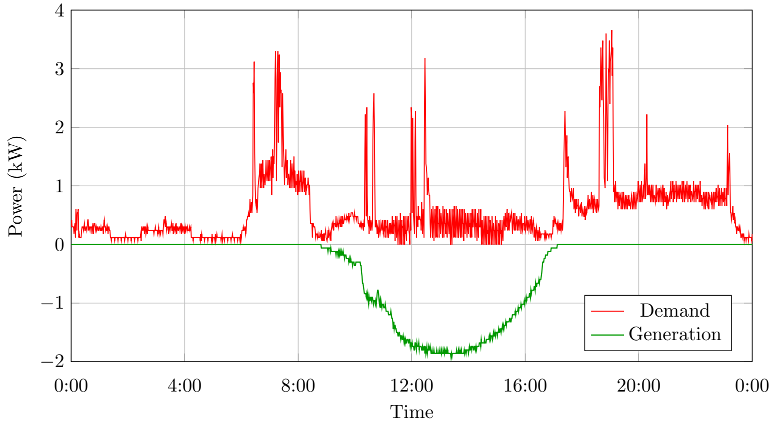


Figure 1.3: The mismatch of electricity demand and generation for a single household (on a minute base during a sunny day) from the GridFlex Heeten dataset on the 7th of February 2020 [VR:4]. The total electricity demand is 13.6 kWh and the total generation is 9.5 kWh.

would be too expensive and time-consuming, and on the short term, there is also not enough trained personnel available for this operation [3, 110].

The problems arising at the low voltage level will cascade to the higher levels. Currently, the problems mainly occur at the LV level, but also in MV and HV level they start to appear.

This thesis focuses on the LV level. Typically, the LV grids consist of the following assets:

» *Transformer (trafo)*. This asset converts electricity between the MV and LV level to supply power to a neighbourhood.

» *Network cables*. These cables transport the power from a transformer to the connection point of a household or utility (e.g. street lights), with voltages of either 230 or 400 V. These cables nowadays are three-phase, meaning they consist of three wires transporting electricity plus a neutral wire. More detailed information on this can be found in Chapter 18 of [11], or in [167] for Dutch grids. The households are then either connected to one or three of the phases, with a limiting connection size (e.g. 1 x 40 A, or 3 x 25 A). One branch of cables running from the transformer is called a feeder. Usually these feeders branch out to cover (part of) a neighbourhood. They are mostly underground and mostly use a radial topology, though ring or mesh topologies are also possible.

As previously mentioned, there are already problems in the grid nowadays, mostly appearing in the LV level, e.g.:

- *Technical losses*. The technical losses are the energy losses caused in the grid assets, as opposed to losses attributed to, e.g., meter tampering and faulty meters. These energy losses scale quadratic to the power transported. Due to this, large consumption and production peaks create very high losses. This, in turn, heats up the assets, leading to faster degradation and faults (see, i.e., [75] or [13]).
- *Voltage violations*. Especially during peaks, the supply or demand causes the voltage to rise or drop, respectively, especially at the ends of the feeders. The preferred voltage for households is 230 V, but a deviation of 10% is allowed for 10 minute average values in the Netherlands [116]. These voltage limits are in place for the grid to be stably operated. Operating outside these limits can be harmful for the devices connected to the grid, and can lead to failures [13].

When the grid becomes overloaded, these accompanying issues can lead to power failures, or even a black out. Preventing overloading and eventual black outs is especially relevant for the operators of the distribution grid as it prevents or defers expensive network upgrades that the operators would otherwise need to carry out.

1.1.2 Grid parties

There are two types of grid operators:

- The Transmission System Operator (TSO) operates the (national) HV grid. This is TenneT in the Netherlands.
- The Distribution System Operator (DSO) operates the regional MV and LV grids. Examples in the Netherlands are Enexis and Alliander.

Other important parties using the grid are electricity suppliers (e.g. Essent or Eneco in the Netherlands). Based on predictions of the usage of their customers, they buy the electricity from electricity producers. They can do this via long-term contracts, but also on the day-ahead market. Furthermore, if deviations occur between the demand of their customers and the bought electricity, the resulting deviations (resulting from forecast errors) have to be settled on the spot market, which is more volatile.

Before, the end users were simply considered to be passive and statistics could be used to predict their overall consumption. With the electrification of devices and volatile RES, this consumption can no longer simply be aggregated. As the consumption and production of individual households is difficult to predict, and prediction errors are expensive, the energy supplier benefits from having a stable and predictable electricity consumption that matches the forecast.

Nowadays, the electricity consumption can be influenced more and more, and it becomes interesting for energy suppliers to better match the actual electricity consumption to their forecast. This also opens the market to so-called aggregators. These aggregators build up a portfolio of households that offer flexibility to change their consumption such that the electricity supplier can achieve a reliable electricity usage prediction. Aggregators reward households for using this flexibility [76].

1.1.3 Smart devices and control

In the current and future energy system, the end users should no longer be passive, but can be activated by using, e.g., electricity prices. This can lead to changes in the behaviour of the consumers that affect their electricity consumption. Moreover, at a neighbourhood level, the previously applicable law of large numbers no longer holds as, e.g., PV panels synchronize their production, and EVs and heat pumps are charged simultaneous to some extend. As already mentioned, this may lead to issues in the grid. In general, we need to reduce the stress that we put on the network, as upgrading the network is very expensive and time consuming. Some ways of doing this are:

» *Demand-side management (DSM).* Includes everything that can be done on the demand side of an energy system to change the consumption and production [123]

» *Demand response (DR).* A subset of DSM where a signal is sent to consumers, either directly controlling their devices, or giving them information or incentives to (temporarily) change their energy consumption or production [12, 123].

Both DR and DSM aim to manage the electricity consumption and production behaviour of households. This thesis mainly focuses on DR, as we aim to either change the usage patterns of the inhabitants, or control smart devices. Examples of these devices are:

» *Smart washing machine, dryer, or dishwasher.* Users can postpone the activation by scheduling their starting times.

» *Batteries, or, more generally, energy storage devices (ESD).* These devices can be installed in households, or used as a neighbourhood energy storage. They can be controlled to (dis)charge energy, while respecting their maximum peak power, and capacity. There are many different types of batteries, each with their (dis)advantages.

» *Electric vehicles (EVs).* As mentioned already, these devices offer flexibility in both the time and the amounts they charge. In the near future, there may also be options to use vehicle-to-grid (V2G), where the car delivers back some of its energy to the house or the grid, and effectively is used as a battery.

» *Heat pumps.* They have a temperature bandwidth to operate in, but their main source of flexibility results from the heat buffer.

The mentioned devices give some flexibility in the electricity usage, while other devices in households cannot be controlled. This flexibility is a key concept, as it captures the amount, timings and other requirements of energy usage that could be influenced by DSM. The electricity usage of devices that cannot be controlled is called the baseload of a household, e.g. from lighting, fridge, TV, and other static appliances.

For setting up a concrete DSM system, access to data is important. Here, smart meters are essential to measure the total energy consumption or production of a household. Usually, this meter outputs the measurement data every ten seconds. On top of a smart meter, a household can also have a Home Energy Management System (HEMS). With a HEMS, a household may use the measurements of the smart meter to plan electricity usage accordingly, and send control signals to the smart devices or information to the consumer. One can differentiate two types of control:

- *Direct control*. Here an external party can directly turn off certain devices in the household, e.g. PV or air-conditioning systems.
- *Indirect control*. Here, the household receives information providing incentives to adapt their electricity usage. Examples of information that can be sent to households are
  - Steering signals indicating the time periods during which the electricity consumption should be decreased. This may be displayed, e.g., with a light that colours red.
  - Prices coming from pricing mechanisms.

With indirect control, the consumer can use the HEMS to automatically control their smart devices based on the prices or steering signals.

This thesis focusses on pricing mechanisms, which can be combined with other steering signals. When using a pricing mechanism, the prices for electricity usage or for grid usage are adapted such that smart devices can (automatically) respond to it, and create a schedule to save the households money. More on the different types of electricity pricing is explained in Chapter 3.

1.1.4 Different perspectives

Steering the consumption may be considered a technological fix, simply using automatization within households to respond to prices. However, for these problems there are many different perspectives that need to be taken into account when designing a solution. Other perspectives are, for example:

- *Economics*: rewards for responding to steering need to be determined, and the economic effects for the different parties should be analysed.
- *Social sciences*: a successful implementation requires involvement, and people would need to change their behaviour, so we need to know how to influence their choices and how to make sure they are willing to change.

» *Privacy*: all consumption data of households is collected.

These are all important perspectives to use, even if we try to solve a problem existing in a mainly technical domain. Especially the social sciences are essential to consider, as without the cooperation of the consumers, nothing will change.

One of the ways to address this, is by not just looking at the individual consumers, but by looking at communities of consumers together. With communities, we can treat the LV problems as a whole. These energy communities are further explained in Chapter 3.

An example of such an energy community is GridFlex Heeten. This community was central in the research project connected to this thesis, and is further explored in Chapter 2. For setting the up the energy community, different perspectives were integrated by, e.g., using a 'privacy by design' approach to ensure privacy protection from the start of the project [162].

1.2 Research questions and thesis outline

This thesis studies how pricing mechanisms and energy communities can aid the energy transition. The two research questions that are central to this work are:

» How can we fairly attribute the grid costs to the members of an energy community?

» How can monetary incentives be used to stimulate an energy community to achieve their goals concerning their interaction with the surrounding electricity grid?

To validate the suggested solutions to these questions, we apply them within a field test (GridFlex Heeten) that is central to this work. Therefore, in Chapter 2, we introduce the field test and its initial goals. As we need more information on both pricing mechanisms and energy communities to answer the research questions, Chapter 3 gives a background on these topics. After that, Chapter 4 addresses the first research question, presenting a pricing mechanism based on the caused electrical losses. The second research questions is answered in Chapter 5, where we present a hybrid pricing mechanism for both system optimization and social acceptance. These approaches are tested in a real-world field test. The results of this field test are presented in Chapter 6. Finally, in Chapter 7, the answers to the research questions are presented, along with an outlook for future research. Although GridFlex Heeten is central in all the results presented in this thesis, the obtained results can be applied broader.

2

GridFlex Heeten: Testing grid-based electricity prices and batteries in a field test

Abstract – *The research presented in this thesis was conducted within the context of the research project 'GridFlex Heeten'. In this chapter, this project is introduced, giving the initial plans and goals, along with some more general information. Most of the research plans were first proposed to project partners, and occasionally to (a small focus group of) the participants. Their input was then incorporated in the maturation of these ideas. While the research happened within the context of the project and the resulting energy community, the achieved results can be applied broader.*

2.1 Introduction

Historically, electricity production within the electricity grid was centralized in large power stations. However, nowadays, there is a shift towards renewable energy sources, and the corresponding energy production for a large part takes place on a local level. Furthermore, due to the dependence on weather conditions of most of this energy production, the produced output is to some extent uncontrollable, hard to predict, and also correlated. Parallel to this change in supply, also the energy demand rises due to an increased usage of, e.g., electric vehicles and heat pumps. The electricity consumption of these devices is also highly synchronized and typically a lot of the resulting consumption peaks do not coincide with peak production of renewable energy. This leads to problems,

This Chapter is mainly based on [VR:7].

especially at the distribution grid level, which was not designed to handle these extreme peaks in power. As a consequence, the grid may get overloaded if we do not use some form of smart control or offer incentives to shave the peaks [69].

Looking at the currently used pricing mechanisms for electricity, we observe that they do not provide customers an incentive to consume electricity at times when it is best for the overall energy system or to spread their consumption over the day. Upcoming Time-of-Use pricing or Critical Peak Pricing schemes tend to only shift peaks and may even increase the simultaneity of loads, e.g. for charging electric vehicles [102]. In general, more knowledge and insight about the effects of innovative pricing mechanisms is needed, especially when it comes to a real implementation. This could then provide input to fill the gap in regulations and create financial benefits for using these pricing mechanisms. In this work, we make a start in this direction by investigating these effects both conceptually and in a real world implementation.

The remainder of this chapter is structured as follows. In Section 2.2 we give some details on GridFlex Heeten, the project in which this research has been embedded. Section 2.3 describes the initial goals of the project, and Section 2.4 gives the proposed high-level approach of achieving these goals. After that, Section 2.5 introduces a model of the given network of the project neighbourhood. Section 2.6 and 2.7 introduce the specific way of reaching the goals set in the project, and the initial approach of dealing with the data obtained during the project, respectively. In Section 2.8, the implementation of the derived optimization model within the used software is explained. Finally, Section 2.9 provides a summary and an outlook of the project.

2.2 About the project

The work of this thesis is embedded in the research project GridFlex Heeten. This project was started in Heeten, a village in the Netherlands with approximately 3 600 inhabitants (see Figures 2.1 and 2.2 for the location and an impression of the village, respectively). Heeten is highly active in the energy transition, with multiple initiatives over the years. One of these initiatives was initiated by the energy cooperative 'Endona'. They have build a solar park of 2.2 MW, but they also obtained an exemption on the Dutch energy law for experimenting with pricing mechanisms ('Experimenten Decentrale Duurzame Elektriciteitsopwekking'). Based on this exemption, a research project and accompanying energy community were set up: GridFlex Heeten.

The aim of the GridFlex Heeten project is to realize a local energy market to test innovative pricing mechanisms, in combination with local electricity production and storage. This energy market should be scalable, and keep the energy and monetary streams local as much as possible. The envisioned pricing incentives have as a goal to improve the local match of supply and demand and to involve the end users, making them become aware of their energy needs.

Figure 2.1: Location of Heeten in the Netherlands. Created based on the image provided in [184].

Figure 2.2: An aerial view of Heeten.

The GridFlex Heeten project is carried out by a consortium of Enexis B.V. (project manager), Endona U.A., Escozon U.A., Enpuls B.V., Dr Ten B.V., ICT Group N.V. and the University of Twente [54]. As Endona U.A. has obtained an exemption on the Dutch energy law for experimenting with pricing mechanisms, this allows us to also validate developed concepts in a field test. The GridFlex Heeten project has started in January 2017 and ended in September 2020.

In the project, all 47 households behind a single transformer in a neighbourhood (De Veldegge) within Heeten participated. Some of the houses have PV installations and some of the houses were equipped with a 5 kWh sea salt battery, developed by Dr Ten [5]. The distribution of these assets over the houses was planned such that some houses have only a PV installation, some only a battery, some have both, and some have none. All involved households provide access to their smart meter data and their PV production, giving insight into their local energy streams. We may consider the households in this neighbourhood as an energy community, a topic we elaborate on in Chapter 3.

2.3 Goals

As mentioned in the previous section, the project aimed to design pricing mechanisms that provide an incentive to the consumers and their smart devices to keep the energy local. However, keeping the energy local can be done in many ways, e.g. by peak-shaving or maximizing self-consumption. Therefore, first, the fundamental goals of the project need to be defined in more detail. The different potential goals of the project are explored in the following sections.

2.3.1 Losses

One potential goal in local energy management is to reduce the technical losses in the energy system. Next to their direct costs, losses also cause assets in the network assets to heat up, leading to degradation. As losses scale quadratically with the current, minimizing the losses consequently also reduces the peaks in the energy profiles [47]. With lower peaks, the power lines have a lower risk to be overloaded and the probability of a blackout is reduced [5, 121, 181]. This saves the DSOs money, and protects the customers from disrupted electricity supply.

2.3.2 Degradation

Another important objective is to minimize the degradation of the LV-cables and the transformer. By minimizing the degradation, the expected lifetime of these assets is increased, and expensive upgrades and repairs can be postponed, or avoided completely. To quantify the degradation of these assets under certain energy consumption profiles, several models have been developed [56]. These models show that by using flexibility and energy storage, the peaks in energy usage within the grid can be reduced by 35 to 70% [170]. For Dutch DSOs this would results in total savings of around €32 million compared to business as usual [166].

2.3.3 CO_2 reduction

One of the reasons to switch to renewable sources for producing electricity is to reduce the negative influence of a high CO_2 output to the environment. Traditionally, electricity is generated at large power plants, often using fossil fuels to generate the electricity, resulting in a large CO_2 output. Switching to renewable energy sources helps to reduce this output [18]. However, as renewable energy sources do not have a controllable output, still demand peaks at low renewable production remain, which mostly have to be covered by more polluting sources, such as natural gas and oil [34, 153]. Therefore, by avoiding high peaks in the consumption profile and keeping as much locally produced energy within the neighbourhood, we can further reduce CO_2 output.

2.3.4 Consumer inclusion

Besides the above-mentioned goals to reduce the stress on the grid and reduce the CO_2 output, another goal of the project is to integrate the participants into the energy transformation process. By including them into the project, they become more energy aware, but they are also stimulated to adapt when and how they use their electricity. The project has to give insight in the flexibility provided by the participants in reaction to the used energy pricing schemes or other used incentives. Therefore, in the design of pricing mechanisms, we need to make sure that the needs of the participants are considered. One of the concerns of participants is in regards to their privacy. Therefore, to make sure the participants are willing to join, it is important to use the privacy-by-design method [20], in which the ways the private data of the consumers is handled is taken into account already when designing the energy system.

2.3.5 Project goals

The GridFlex Heeten project has some further goals that are mostly not related to the effects of pricing mechanisms. One of these is to investigate the consequences of regulations that follow from the introduction of the proposed pricing mechanisms, or from giving DSOs more options for different tariffs. Another goal is to create a viable business case for the DSO, the energy supplier and the consumers in the energy system when they use the developed pricing mechanism. Lastly, within the project also an investigation on the suitability of different battery topologies was planned.

2.4 Approach

The goals described in the previous section roughly belong to two categories: technical and social goals. The social goals are elaborated on further in Section 3.3, Chapter 5 and Chapter 6. For reaching the technical goals, a specific approach is used that is described in the remainder of this chapter.

As mentioned in Chapter 1, the electricity consumption and production behaviour of parts of the household can be managed to better match the stated goals. At the core of the used energy management approach is a central controller which sends signals to the inhabitants and the batteries. Note, that batteries are the only smart devices that can be influenced in the project. For the inhabitants, these signals should contain information to stimulate them to use their other energy flexibility to, e.g., relieve the stress on the network. We refer to these signals as *incentive signals*. The occupants of the household can decide to act based on the incentive signals, e.g. by delaying the start of their washing machine to a later time. Next to that, signals are sent to the batteries that are placed in the neighbourhood to control their consumption. These signals are called *control signals*. One important research question in the project is which type of signals should be sent to the households and batteries, and how these signals are calculated. An important requirement to keep in mind for answering this question is that the setup for computing and sending the signals should be scalable and that the computation effort needed is not too large. This would stimulate to copy this setup to other neighbourhoods.

As one of the aims is to decrease the stress on the network, a detailed model of the grid is needed that takes into account the spatial layout of the electricity network. Further input which can be connected to this model is the data from 47 households on a one minute base. The available data contains separate information on the baseload, the PV generation, and the battery load. Besides the data from the core houses within the project, also data from 26 other households located in Heeten is available. In these houses no battery is placed and no incentive signals are sent to these houses. These households can be used as a control group to compare the effect of the applied measures.

The derived model of the electricity network and the available measurement data will be integrated into a simulation tool (DEMKit, see Section 2.8.1). This tool also contains an approach to calculate the state of the entire underlying electricity network. This information is used as input by the tool to control the available flexibility following the following three steps [48, 108]:

1. Make a *forecast* of the expected electricity profile of the individual households for the upcoming time intervals.
2. *Plan the control signals* for the battery, and at the same time *determine incentive signals* for households based on the forecast.
3. *Control devices* to implement the planning based on the measurements.

Determining the control and incentive signals depends on the goals used for our optimization. This implies that depending on the considered goal, we get different signals. Existing starting points for deriving these signals could be the concepts used within profile steering [163] or auctions [109].

The core aspects of the approach sketched above are discussed in detail in the remainder of this chapter. We describe these aspects as they were settled at the start of the project. Note, that some of them have been adjusted during the project, as will be elaborated on in Chapter 6.

2.5 Modelling of the physical infrastructure of a neighbourhood

The starting point of the energy management is a model of the entire physical infrastructure neighbourhood, taking into account the houses, the underground cables, the transformer, and the geographical layout of all of these. This has to provide a realistic representation of the neighbourhood. We represent this model as a graph, where houses, cable joints, and the transformer are the nodes, and the cables are the edges. This representation makes it easy to analyse the network. The representation of the concrete electricity network of the project area is shown in Figure 2.3.

The network infrastructure introduced in the previous section is not the core of our work. We focus on the electricity flow over this network, which consists of the electricity profiles of the households in the network. These electricity profiles can be influenced by sending control signals to the involved batteries, and by sending incentive signals to the households. The occupants of the household can then decide to act based on the incentive signals. The network topology as shown in Figure 2.3 is hereby taken into account when deciding on the control and incentive signals.

2.6 Control and incentive signals

As mentioned, the only possibility to influence the energy consumption patterns of the participants is by providing them with certain signals. These signals can be coupled to a pricing scheme or to a global optimization approach. As for several of the considered goals, the (mathematically) optimal solution would be to flatten the overall load as much as possible over time (at the transformer, the cables as well as the houses; this is explained later in more detail), the used incentives should aim to reach this global optimum. However, next to this global objective, the aim is also to take into account to what extent people consider the used incentive scheme as fair [117].

In the following subsections, we elaborate on how the goals mentioned in Section 2.3 can be reached using signals, and specifically look at a way to determine these signals based on the Shapley value.

Figure 2.3: A layout of the electricity cables in De Veldegge in 2019. Created based on the image provided in [120].

2.6.1 Losses

As already indicated, energy losses are dependent on the occurring electricity flows in the network and have several undesirable effects. In the simulation tool, DEMKit, models are present to estimate the amount of losses dependent on the electricity flows in the grid.

Using these models, we can determine control signals for the batteries that aim to minimize the losses occurring in the grid. Moreover, we can determine incentive signals that aim to stimulate the households to shift their consumption such that the resulting losses in the grid are minimized. The control and incentive signals are determined jointly to take into account their expected effect on the electricity profile. Note that the estimation of losses is done within the simulation tool, but the incentive and control signals are sent to the actual participants and batteries, respectively.

As the losses scale quadratically with the current, the core goal becomes minimizing the peaks. As mentioned, the optimal profile, therefore, would be a completely flat profile. To obtain such a flat profile, a basic approach is to use a pricing mechanism that assigns higher prices to peaks. Examples of this are locational pricing mechanisms (given in Chapter 4), and the hybrid pricing mechanism described in Chapter 5 and in Section 6.4.1.

2.6.2 Degradation

Next to the losses, also the impact of the operation of the assets on their degradation has to be considered for an economic operation of the overall system. For this, we use degradation models of the assets, which are already incorporated into the used simulation tool. Our aim is to derive the control signals for the batteries in a way that they adapt their usage such that the degradation is minimized. Furthermore, we also determine incentive signals for the participants to inform them how to shift their consumption to minimize degradation of grid assets. As peaks and overloading assets are the main reasons for faster degradation, these signals should stimulate minimizing the peaks. Note that this is identical to the solution of the previous subsection.

2.6.3 CO_2 reduction

To reduce the CO_2 footprint of a neighbourhood, a first step is usually to keep renewable energy produced in the neighbourhood behind the transformer. This implies that the neighbourhood should aim for maximizing the self-consumption. However, this does not necessarily coincide with reducing the stress on the network, as now the task of the batteries is only to charge all energy from PV panels which is not consumed directly. Hereby, no timing of this charging is enforced, and therefore, this might still leave high peaks in the energy consumption patterns.

However, note that the peaks of the electricity demand are mostly captured by CO_2 emitting generators, e.g. gas generators, keeping the peaks to a minimum also contributes to reduce the CO_2 output. As such, having a flat profile with high self-consumption can be considered as the aim of the neighbourhood. This also implies that the pricing mechanisms in Chapter 4 and Chapter 5 are beneficial for this goal.

2.6.4 Capacity

Currently, Dutch households just pay for their annual electricity per kWh, in addition to taxes and network costs. However, for large (industrial) consumers capacity tariffs are used already. The advantage of such a capacity tariff is that customers are directly stimulated to keep the peaks in their energy usage to a minimum. A possible disadvantage of capacity tariffs is that they do not take into account the possible (lack of) peaks caused by other users in the network.

To address this shortcoming, a possible solution can be to introduce capacity tariff at the transformer instead of having it at the household level. This implies that the tariff for the households depends on the overall load of all households behind the transformer at any given time. An issue here can be that this approach only considers the overall load and does not circumvent that relatively high peaks occur at some specific locations within the low-voltage network behind the transformer. This approach is further explored in Chapter 5.

2.6.5 Shapley value

The challenge with losses and peak loads in the grid is that they do not depend on the behaviour of an individual household but on the behaviour of a group of households. Therefore, an alternative approach may be to base the costs associated with a household on the added cost which this individual household adds to the total costs of the group. This is precisely what is considered in certain concepts from game theory and is expressed by the Shapley value [146]. This value also has some other attractive properties such as efficiency (the total gain is distributed), symmetry (if two individuals add the same amount to the overall group, then their Shapley value is also the same), linearity (forming coalitions between the individuals does not change the Shapley value) and zero player (an individual that adds nothing, has a Shapley value of zero). A formal definition of the Shapley value is given in Section 4.3.1.

Considering the energy profiles for each household as their contribution, we can use the Shapley value to indicate how much a household has contributed to the incurred cost (losses/degradation/CO_2 increase) of the network. To make this concrete, we first have to specify a way to calculate the costs that a group of households generates. For this, different costs functions may be used, dependent on the used optimization criteria.

The downside of using the Shapley value in combination with cost functions based on losses or degradation is that it is heavily influenced by the location of the customer in the network, which may be perceived as unfair. This is due to the fact that electricity used by households at the end of a cable need to travel a longer distance, therefore incurring more losses. However, this shortcoming may be overcome by making some additional assumptions on how the occurring losses in the overall system are distributed over households. This approach is further explored in Chapter 4.

2.7 Data flow

To compute control and incentive signals for energy management in a neighbourhood, data of the households in the neighbourhood is needed. Here, we have to take into account the aforementioned privacy-by-design method [162]. The used flow of data for the considered setting within the field test is given in Figure 2.4. Each of the 47 houses has a smart meter, which is connected to a home energy

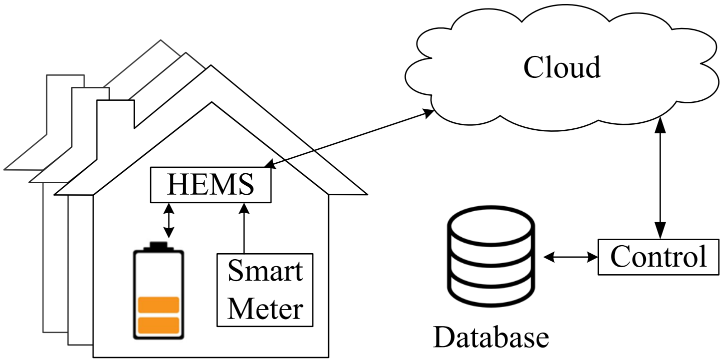


Figure 2.4: Dataflow in the field test.

management system (HEMS). If PV panels or a battery are present in a house, the HEMS gathers the data of these devices separately. The HEMS collects the local data and sends it to a cloud service on a minute base.

Using the cloud service, the households can have real-time access to their own data. Also the used simulation tool has direct access to this data, receiving it with a minute time resolution and storing it in a central database. This database acts as a source of information for our simulations, but also for the real-time control signals of the batteries and the real-time incentive signals sent to the households. Concretely, the data is used as an input for calculating specifications or properties of households, but also for making predictions on, e.g., the baseload profiles of households or the generation profiles of PV installations. This data, together with the used optimization criteria, form the input for calculating the control and incentive signals. These signals are then sent to the batteries and households. More information on how the participants access the data, as well as how the incentive signals are sent, can be found in Section 3.3.2.

2.7.1 Dataset

The data of the households, both in De Veldegge and in the control group, has also been stored and published as an open access database for future research [VR:4]. The data was collected between August 2018 and August 2020 in 77 households and consists of the electricity consumption and gas usage per minute per household. The electricity consumption is split in PV production (if PV panels were present), battery usage (if a battery was present), and the remainder.

2.8 Implementation

In this section basic information on the used simulation tool and the modelling of this batteries is given. The entire electricity network is modelled in the already mentioned simulation tool DEMKit [66, 67]. In this simulation tool, general models of different assets commonly found in electricity network are implemented and can be used to create a realistic representation of the network, but also of the involved assets, specifically also the used battery. Next to that, several optimization algorithms are available to determine control signals and incentive signals. A benefit of using DEMKit is that it can be used to easily create, implement and tweak devices or algorithms to test these elements and the effect they have on the network.

2.8.1 DEMKit

The Decentralized Energy Management toolKit, or DEMKit for short, is a smart grid optimization and simulation tool developed at the University of Twente. DEMKit uses as base for the control and optimization the TRIANA concept [108]. This simulation tool follows a cyber-physical systems approach, in which the effects of steering algorithms on assets in the grid can be tested [66]. For our case this implies that the batteries directly get their control signals from DEMKit. More information on the use of DEMKit in GridFlex Heeten is given in Chapter 5 and Chapter 6.

2.8.2 Battery model DiBu

To compute a planning for the use of the batteries and to predict the behaviour of the batteries as a response to a given planning, a detailed model for batteries is used in DEMKit. This DiBu-model (short for Diffusion Buffer) predicts the State of Charge of batteries quite accurately based on the internal battery voltage. The voltage of the battery at a given time is determined based on its previous voltage by using specific update steps, depending on the usage of the battery (charging or discharging) [5].

2.9 Summary and outlook

In this chapter, we have presented the basic ideas and goals as they were given at the start of the GridFlex Heeten project. The goal in this project was to test the influence of different control or incentive signals within a neighbourhood of 47 houses aiming to relieve the stress on the electricity network. For this, control signals for batteries, and incentive signals for the households, are calculated, dependent on the used optimization criteria. Possible optimization criteria in this context are: minimizing degradation, losses, and CO_2 output, while taking into account (the wishes of) the participants. For this, the electricity network of this neighbourhood is modelled, incorporating the concrete geographical layout.

The obtained model is implemented in the simulation tool DEMKit. At a later stage in the project, innovative pricing mechanisms have been implemented to investigate their effect on the behaviour of the participants, as well as on the steering of the batteries.

A broader introduction on energy communities in general and GridFlex Heeten specifically is given in Section 3.3.1. Different pricing mechanisms are investigated in Section 3.3.2, Chapter 4, Chapter 5, and Section 6.4. The overall results of the GridFlex Heeten project are discussed in Chapter 6.

3
Background

Abstract – *This chapter provides some background on the most relevant topics discussed in this thesis, namely pricing mechanisms and energy communities. The goal is to introduce the readers to the used definitions of commonly used terminology and to give elaborate reference materials for readers from a different background.*

In the previous chapters, it was already mentioned that by using pricing mechanisms some pressure can be alleviated from the grid. As pricing mechanisms come in a multitude of types, in Section 3.2, we discuss the most common mechanisms, and the ones that are most relevant to this thesis. We also present some of the effects these pricing mechanisms have (had) in practice.

As most of the research presented in this thesis revolves around energy communities, in Section 3.3, we describe the most common forms of energy communities, their benefits, and apply those to the situation of GridFlex Heeten. Moreover, we discuss some issues for extending these energy community concepts and present some results indicating what impact project like GridFlex Heeten can have. This section thereby gives a proper overview for the different terms related to energy communities, as well as their possible benefits, and can be used as a basis for other projects.

3.1 Introduction

In this thesis, two core topics within the energy domain are treated, namely pricing mechanisms and energy communities. In the previous chapter, it was already mentioned that the aim is to use pricing mechanisms to steer the electricity usage of the participants of the energy community in the GridFlex Heeten project.

Parts of this Chapter are based on [VR:3].

As there are many definitions around for energy communities and for different pricing mechanisms, this chapter treats the most important and commonly used ones to bring all readers on the same page.

This chapter is structured as follows:

» Section 3.2 discusses the most common pricing mechanisms, and the ones that are most relevant to this thesis;

» Section 3.3 introduces energy communities;

» Section 3.3.1 considers different types of energy communities and their benefits;

» Section 3.3.2 gives more details on the GridFlex Heeten project;

» Section 3.3.3 analyses the difficulties to further roll out energy community concepts;

» Section 3.4 presents some results of the case study in Heeten, followed by the conclusions of the chapter.

3.2 Pricing mechanisms

In the previous two chapters, we have already mentioned pricing mechanisms and the need for them. In this section, we elaborate further on this subject. In Section 3.2.1, the use and necessity of pricing mechanisms is discussed, and in Section 3.2.2 the most prominent and relevant types of pricing mechanisms used for electricity are presented.

3.2.1 Use and necessity

As already mentioned, electricity profiles of consumers have to be influenced to alleviate stress on the network or to reach other sustainability goals. In [30], the potential for carbon emission reductions within 10 years by altered adoption and use of available technologies (e.g. lowering the thermostat and water heater temperature, or changing to more energy-efficient appliances) in homes and non-business travel in the United States was investigated and it was estimated that the implementation of these interventions could save an estimated 20% of household direct emissions or 7.4% of US national emissions, with little or no reduction in household well-being. This shows the existing potential of energy management, as an energy management system can take over some of these actions (e.g., lowering the thermostat) and have more (smart) devices to steer, and it is envisioned that this potential will only grow. To alleviate the stress on the electricity grid, flexible devices present in households, as described in Section 1.1.3, can be enabled. This can either be done manually by the consumers that schedule their devices for a later time, or it can be done automatically via HEMSs.

For the former option, consumers need information on how to (re)schedule their devices, but they should also get some incentives to do so. For this, one can consider changing the price of electricity in some way to better reflect the cost of producing it and to better reflect the stress on the network. These financial incentives are called pricing mechanisms, as the price of electricity or of the used capacity is modified to relieve stress on the grid (or any of the other chosen goals). In [154], the main findings demonstrate that consumers react positively to such feedback and dynamic prices.

For the latter option of enabling flexible devices, a HEMS can be used to automatically steer the smart devices based on the information the HEMS receives. In case of dynamic prices, the HEMS can steer the devices in such a way that the consumers benefit the most. However, for this, the consumer first needs to hand over the control of devices to the HEMS. In [31], it has been indicated that automated response is also preferred over manual response by consumers, as they do not need to change their daily routine or lower their comfort.

Even though saving money seems to be the biggest factor to consider dynamic tariffs, in [31] it was shown that it needs to be a significant amount to achieve response by users. However, the incentives could and should transcend a solely monetary status, as it seems that the possible savings are still low. Therefore, being 'green' and doing the right thing (plus signalling this to your local environment) can be considered crucial as well [139]. Consumers indicated that if they were to provide such a thing as 'flexibility', they would have to feel that they contribute to the collective benefit of society, and that their actions help society reach environmental or climatic targets, instead of only responding to price signals [157].

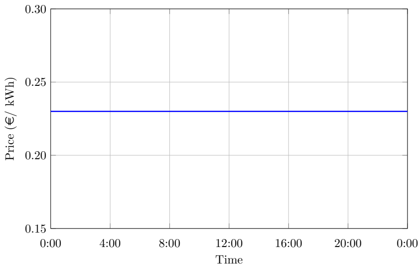
The type of steering sketched above is often called indirect control, as the consumer still have the choice whether or not they adapt their energy usage based on the prices. This is in contrast to direct control, where a DSO, aggregator, or other party can directly control smart devices (e.g. AC units) in households to avoid peaks.

3.2.2 Types of pricing mechanisms

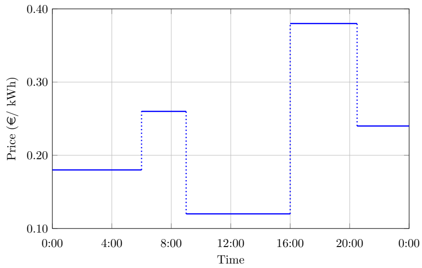
A pricing mechanism describes how the price of a commodity (in our case electricity) is influenced by the supply and demand of that commodity throughout time. There are many different types of pricing mechanisms. In the following subsections, we describe the most prominent ones and the ones most relevant to this research. Thereby, also the fundamental definitions of regularly used terms are given.

3.2.2.1 Flat rate

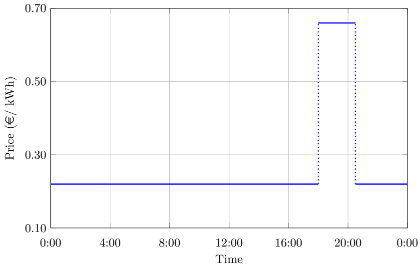
A flat rate pricing mechanism is the simplest form of pricing. Here, the price per unit (normally, the price per kWh) is set per billing period, often even for



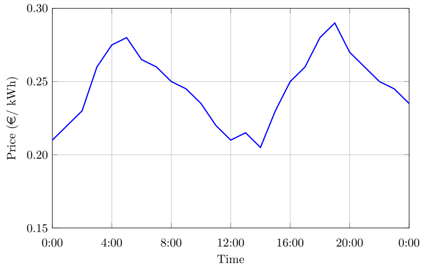
(a) Flat rate pricing mechanism.



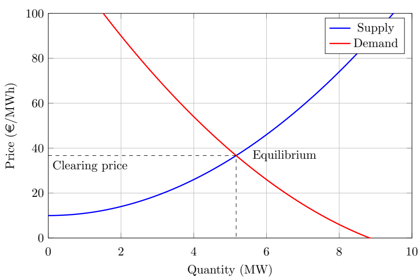
(b) Time of use pricing curve.



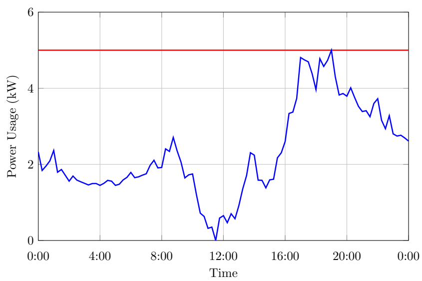
(c) Critical peak pricing example.



(d) Real-time pricing curve.



(e) Setting the electricity price based on supply (in blue) and demand curve (in red).



(f) Capacity tariff based on maximum power (in red) with household power usage (in blue).

Figure 3.1: Examples of different pricing mechanisms.

one or multiple years. An example flat rate is shown in Figure 3.1a. In the Netherlands, but also in many other countries, this is one of the most common pricing mechanisms for electricity.

While this form of pricing makes it is easy for the consumers to identify how much they have to pay for their electricity usage, the downside is that it does not activate the consumers to change their energy usage in any way, except for lowering their total usage. Also, for all utilities (e.g. water or electricity), using a fixed price per unit is ineffective, as it would burden some consumers with a cost that is out of proportion to what their consumption actually costs [23].

3.2.2.2 Time of Use pricing

With Time of Use (ToU) pricing, the price of electricity changes throughout a given period (typically a day). Often, this period is divided into multiple blocks of a few hours each. During each block, a different price per kWh is set. These prices are normally set per billing period, and each day offers the same blocks and corresponding prices. A simple example of this is day-night pricing, where during the night, the price of electricity is slightly lower than during the day. The different prices for ToU schemes are usually determined depending on the expected supply and demand, e.g. lower prices during the afternoon when solar energy is expected, but higher prices in the evening when a higher consumption is present. An example of a typical ToU pricing curve is shown in Figure 3.1b.

ToU pricing already is used as a pricing mechanism for consumers in multiple countries, such as Malaysia [155], Italy [158] and Canada [138]. ToU pricing also leads to a reduction of the peaks by about 8%, even though the effects range greatly between different test sites (between 0.1 and 21%) [154, 183]. As indicated in [41, 154], for ToU pricing, the price difference between peak and off-peak usage is the primary factor that determines the degree of customer response. Furthermore, consumers are relatively enthusiastic about using this type of pricing [42].

The downside of using ToU pricing is that the prices do not reflect the actual state of the grid. So even though on average during the afternoon there is a surplus of energy due to the PV influx, on a cloudy day there is no surplus but the price is still low. Flexible devices would still be scheduled during the afternoon, which may cause problems in the grid. Moreover, when using ToU prices with automated systems and flexible devices, the peaks may even increase [128]. This is due to the synchronisation of all smart devices in houses being scheduled during the least expensive periods of the day.

3.2.2.3 (Critical) Peak Pricing

Another common form of pricing is peak pricing, or Critical Peak Pricing (CPP). With CPP, the basic price of electricity follows a flat rate or in some cases a ToU price, except for a few moments when the grid is (expected to be) overloaded.

During these moments, the price of electricity if raised by a considerable amount (up to 30 times, but usually around 3 times [16, 40]) to discourage customers from consuming electricity on that moment. These moments typically last for a few hours and are usually communicated a day ahead. The maximum number of times per year the price can be raised is also set, typically up to 50 or 100 hours a year [16]. An example of a CPP price raise is given in Figure 3.1c.

Similar as with the ToU pricing, also CPP is used already in practice, for example in the United States [71]. The reduction induced by CPP on the peaks averages at around 18% [41, 154, 183], although the ranges reported for different pilots and implementations are huge (between 13 and 20%, and with enabling technologies even to 27 to 44% [41], 11 to 28% according to [154], and between 1.9 and 50% in [183]). Note, that with CPP only during the few moments when it is activated this reduction is achieved, while with ToU pricing, the reduction is throughout the whole year.

Similar to CPP, there is Peak Time Rebate (PTR) pricing, where customers are compensated for the amount of energy they shift away from a peak period, instead of being penalised for the amount they still consume during a peak. While the incentive is in principle the same in both cases, research has shown that customers find a loss of X dollars more aversive than a gain of X dollars is attractive [81]. This may indicate that CPP could have a larger effect than PTR, although [154] reports only a 12% reduction in peaks for pilots using this type of pricing.

3.2.2.4 Real-Time Pricing

With Real-Time Pricing (RTP), the price of electricity can change throughout the day, similar to ToU pricing. The difference here is that with RTP, prices are not communicated long in advance, and are not set for multiple days. Instead, the prices are only known a day, or even a shorter period, in advance. This way, the prices can more accurately reflect the situation in the given energy system. With RTP, prices might be coupled to a energy market, such as the spot market EPEX, or, more often, directly coupled to the production costs of the electricity for the utility/energy supplier/DSO. An example of RTP is given in Figure 3.1d.

Also RTP is already used in practice, for example in the Netherlands with the energy supplier NieuweStroom, that have their prices for industrial customers directly coupled to the EPEX prices [118]. From several pilot programs, it was gathered that RTP leads to the highest daily reduction in peaks (around 10%), compared to other used pricing mechanism [154, 183]. Note, that CPP had higher reductions, but only during the peak days. However, even though the daily reduction is higher, customers themselves seem to prefer TOU over RTP [31]. This could be due to the high uncertainty in costs for the consumers, which is also the reason why several companies are offering RTP in combination with bounds on the price range.

3.2.2.5 Auction-based pricing

Instead of setting the price beforehand, the price can also be set by comparing the prices the producers and the consumers of electricity are willing to get or pay. Here, different amounts of electricity can be sold to different consumers for different prices using a form of auctioning. A simple way of doing so, is by comparing the supply and demand curves of the involved parties and setting the price of electricity accordingly (see Figure 3.1e). In a supply curve, the consumer sets the amount of electricity they want to buy for a range of prices. Similarly for a demand curve, the producer sets the amount of electricity they are willing to sell for a range of prices. At this point, this mechanism is mostly used for clearing the larger energy markets.

An example of a system that uses auction-based pricing to control the flexibility of smart devices is the PowerMatcher [87]. The PowerMatcher is a multi-agent based distributed software system for near-real-time coordination in smart electricity grids. One agent per cluster in this system handles the price forming by searching for an equilibrium price, while each device has an agent bidding in an economically optimal way [88].This system managed to reduce the peak load by about 15%.

An advantage of using auction-based pricing approaches is that the price is set based on the current state of the system. This means that, for instance, with enough flexibility, the consumption is adjusted to the production. This also means that prices can be influenced by consumers such that they do not pay too much for electricity. However, as their flexibility is limited, these consumers eventually need to buy electricity, regardless of the price, leading to a potential overpay. The eventual costs for the consumers are therefore very difficult to predict. Also, defining the demand curve for consumers could be very challenging and time-consuming. Finally, not all auction-based pricing mechanisms include planning ahead. This then makes it almost impossible for consumers or for a HEMS to plan their flexible devices during a day.

3.2.2.6 Capacity tariff

Besides the pricing mechanisms that ask a certain price per kWh of electricity usage, there are also other ways of coupling a price to the usage. One frequently used way of doing so is with capacity tariffs. Here, the price is not dependent on the energy usage, but on the power usage. Consumers either buy a certain capacity to use for the billing period, or get billed afterwards based on their (peak) power usage. In many countries, variations of the capacity tariff are used for network costs by DSOs. A consumer pays for the capacity they can use, which is usually coupled to the physical connection a household has to the grid. In that case, exceeding the capacity limit simply results in a broken fuse, so there is also a physical limitation to the capacity. An example of a capacity tariff is given in Figure 3.1f.

When billing afterwards, the costs are then usually dependent on the highest power peaks the consumer realized in that billing period, where high peaks are billed considerably higher compared to low ones. In the Netherlands, for larger consumers, a similar system is already in place. There, next to the energy usage fee, these consumers are also billed on their highest peaks in, e.g., a month. In this way, the consumers are incentivised to keep their peaks low, which in general relieves the grid (see Section 2.6). However, once the consumer caused a peak early in their billing period, the incentive to keep the peaks low is lost.

3.3 Local energy communities

All around the world, local energy communities are popping up that aim to organize their energy production and consumption. Many of these communities do not want to be dependent on large, faceless energy companies. Instead, they believe that the best way to become more environmental-friendly is to get, to some extent, independent of the overall energy system by organizing a local energy system where energy is locally produced, consumed, stored and shared. In 2021, around 676 energy communities were active in the Netherlands alone. Similarly, in other parts of Europe, the number of energy communities has been steadily growing over the years [152]. In many cases, these communities consist of proactive prosumers (consumers that both produce and consume energy) which want to be part of a decentralized, decarbonized, and digitalized energy system and aim to push the energy transition forward. These communities are therefore crucial for the transition towards renewable energy systems [176].

Parallel to this, the increasing environmental awareness leads to a yearly increase in the share of electric vehicles, PV systems, and batteries owned by households. However, the increase of these assets also introduces problems to the local energy infrastructure, mainly to the electricity system [86]. These problems include voltage and frequency issues, which are often due to the highly synchronized electrical loads and demands. Energy communities, on the one hand, may contribute to these problems, but, on the other hand, they can also be part of the solution to overcome these problems. If the individual consumers in a community coordinate their energy-related behaviour in some way, this can be the starting point for the decentralized optimization of their combined energy profile.

In literature, a growing interest in decentralized energy management solutions can be found [7, 82, 156]. An advantage of such decentralized solutions is that they are often still computationally tractable, solve the problems at the place where they occur, retain economic benefits locally and support the inhabitants in changing their behaviour [86, 98]. In general, the concepts that arise in a specific decentralized context may only be created to solve the concrete problem at hand. However, these concepts can be copied to other locations. This is in contrast to centralized solutions, which may, in theory, be able to solve the energy management problem to optimality, but which are not scalable, especially taking into account the growing number of steerable devices in the electrification at hand.

As mentioned above, one approach to realize decentralized energy solutions is through citizen energy communities, which aim to provide environmental, economic or social benefits to the community or the local area [125]. Hereby, the community members may control the actions of the community themselves or may outsource this control to a third party, for example, an aggregator.

An example of a beneficial decentralized solution is to lower the load on the grid coupling point of an energy community. Lowering this load does not only reduce the transport losses but also unburdens the remainder of the grid. From this reduction, several players in the system would benefit. The network operator could give a discount on the network tariff since the peak load on the coupling point is lower, and therefore, the stress on his network decreases. A lowered stress, in turn, would increase the lifespan of most assets and lower the need to replace (underground) cables in the (near) future [56]. For the energy supplier, the energy consumption of the neighbourhood becomes more predictable or even shapable, and the supplier can purchase energy at a lower cost. The supplier may therefore also give the community a discount on their electricity price. These discounts together could stimulate the energy community to reduce its peak loads.

A core task for an energy community is to find a way to share the savings they achieve as a community amongst its members. Next to just compensating the individual members based on their contribution, an alternative way may be to use the savings for the community, e.g. by buying community-owned solar panels, or setting up a community playground.

Focusing on the shared connection of a community and not on individual households takes a different approach than most other methods to reduce the stress on the grid. In the case of a shared connection, the network operator and energy supplier are only concerned with the energy flow on the common connection point, and not with what is happening behind this point. So instead of managing everything behind the meter of single households, the overall neighbourhood can be aggregated and managed with appropriate methods, such as innovative pricing mechanisms or an energy management system.

The remainder of this section considers a concrete real-world project, GridFlex Heeten as described in Chapter 2, where such a control strategy for a neighbourhood is applied, which aims to influence the energy flow at the common connection point of this neighbourhood.

3.3.1 Energy communities

To describe energy communities, several interchangeable terms with minor differences are used, of which the usage mainly depends on the geographical origin of the publication. The most frequently used terms include the following:

- *Citizen Energy Community*. According to the European Commission, a Citizen Energy Community means a legal entity that: '(a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises; (b) has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and (c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;' (Article 2 of the Electricity Directive [125]).
- *Renewable Energy Community*. In the same directive, the European Commission also speaks about Renewable Energy Communities. These can generally be seen as a subset of citizen energy communities, as the members of renewable energy communities need to be located in the proximity of renewable energy projects owned and developed by the community [137]. This indicates that there are more stringent requirements to become a renewable energy community.
- *Advanced Energy Communities*. The term Advanced Energy Community is mostly used in the USA [113]. Although being very similar to the European Commission definition, the advanced energy communities focus more on the technologies being used within the community.
- *Smart Community*. In Japan, the term Smart Community is used [2]. Also here, a Smart Community does not need to be locally operated or owned at all.
- *Community Energy*. In Australia, the term Community Energy is defined by the Australian Renewable Energy Agency (ARENA) [4]. ARENA takes the definition a bit broader, thereby including any community renewable energy project.
- *Local Energy Community*. A Local Energy Community (LEC) does not have a strict definition according to the European Commission, but is commonly used in research. Local Energy Communities can be seen as a subset of Citizen or Renewable Energy Communities, where the members, as well as the assets of the community are all geographically close, preferably even all connected to the same part of the distribution network [43, 49, 94].

Even though a community focuses on local benefits, we see that in most definitions it does not mean that all members are situated in that same area. Areas and communities are not synonymous—there can rather be multiple overlapping communities in one area [171]. A citizen energy community is simply a community where citizens own and participate in renewable energy or energy efficiency projects (according to REScoop). Limits on the physical distance between members are only present in LECs.

In the context of energy communities, several other concepts are often used. Although these concepts are closely related, they are used in slightly different contexts.

» *Energy Cell.* Energy cells consist of generators, converters, storage systems, consumers and connections to electricity, gas, and heat distribution grids on various scales (size of a house, neighbourhood, city) [58].
» *Microgrid.* Microgrids are typically defined as 'electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded' [100]. Here, the focus is more on the controlled operation and on being able to operate in islanded mode. In most cases, there is also a focus on financial benefits.
» *Virtual Power Plant.* A Virtual Power Plant (VPP) 'aggregates the capacity of many diverse DERs, it creates a single operating profile from a composite of the parameters characterizing each DERs and can incorporate the impact of the network on aggregate DERs output. A VPP is a flexible representation of a portfolio of DERs that can be used to make contracts in the wholesale market and to offer services to the system operator' [132], where DERs are distributed energy resources. A VPP hereby transcends the microgrid definition by not being bound to the same physical grid, as further described in [91].

This thesis mainly focuses on local energy communities, but also extends to citizen energy communities as further described in the recently adopted Clean Energy Package of the European Union [36]. This new energy rulebook gives an obligation to the EU countries to adapt their legislation to allow for citizen energy communities. Due to this, these communities turn into official legal entities having corresponding rights. With the Clean Energy Package, citizen energy communities obtain rights to:

» Generate, consume and sell their own renewable energy,
» share energy within the community, and
» engage in individual and 'jointly acting' self-consumption.

The latter, however, is restricted to joint self-consumption in the same building or apartment block. According to the EU legislation, consumers have to be provided entry to all electricity markets to trade their flexibility and self-generated electricity, and consumers should have the possibility to participate in all forms of demand response. The EU directive has been put into force in June 2019; member states had until June 2021 to implement the directive in their national legislation. However, not all countries managed to implement the directive, e.g. in the Netherlands, only proposals for a new energy law have been made, and the early versions disregarded energy communities as drivers for the energy transition [29], much to the dismay of energy cooperations and communities.

As mentioned before, the definition of citizen energy communities does not imply proximity. As long as there is a legal entity that is owned and controlled by the members, they can be considered to belong to the same community. Together they can aim to control their energy flows to be, e.g., energy-neutral over a specific period (e.g. a year) or even energy-independent. However, since these members are not necessarily located on the same part of the grid, the benefits of being energy-independent are not visible when looking at the actual energy flows in the corresponding grids. The transportation losses and the stress on the network could even increase as being an energy-independent community might imply that large amounts of energy are exchanged between different members of the community. As such, these communities have an advantage if the members of a community are also physically in one area and connected to the same network. This is also the reason why we focus on local energy communities.

On the European scale, there are over 8 400 energy initiatives, of which 7 700 are energy communities [35, 141], and a total of over 1 250 000 citizens are involved [135]. The organization REScoop.eu is the European federation for renewable energy cooperatives and has a growing network of 3 300 European energy cooperatives [134] and over 1 900 communities [135]. Most of them are active in energy production; some examples are:

» ODE decentraal in the Netherlands [122], and

» DGRV in Germany [28].

Others organize the energy supply for their members, such as:

» Energie VanOns in the Netherlands [169],

» COCITER in Belgium [143], and

» Ènostra in Italy [186].

Furthermore, there are also some organisations active in distribution, such as EWS in Germany [142]. More information on EWS and their peer-to-peer energy trading community can be found in [96]. Additionally, an interesting example of an energy community, which is similar to the project considered in this thesis, can be found in [150].

As mentioned before, this thesis is focusing on local energy communities. In particular, these communities should have a common coupling point to the electricity grid by, e.g., being connected to the same LV/MV transformer (Figure 3.2). In this sense, achieving lower peaks as a community actually also lowers the stress on the grid.

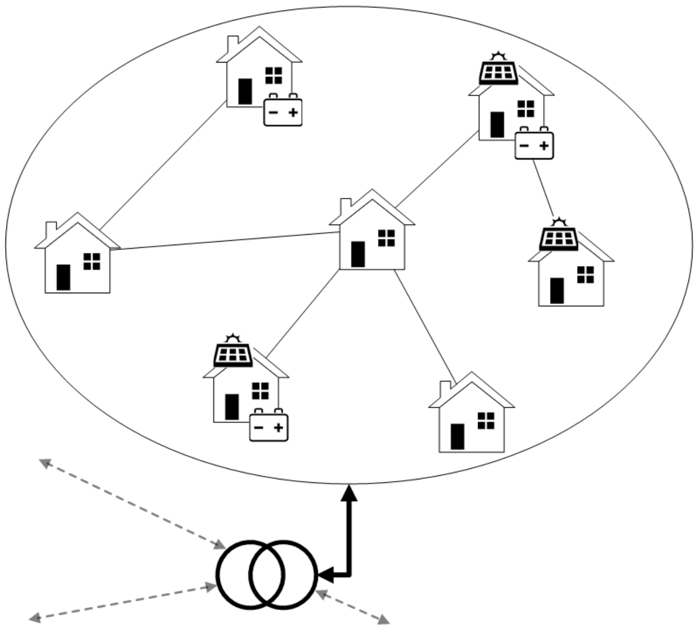


Figure 3.2: An energy community located on the same part of the grid with a transformer as a common point of coupling.

The concept of energy communities used in this chapter is closest to the microgrids mentioned above. In literature, much attention is paid to microgrids (see, e.g., [62, 185]), whereby a clear distinction is made between islanded, and non-islanded microgrids. Islanded microgrids are not relying on the main electricity grid (or only very seldom) [8, 82]. All energy generation and load balancing has to be done within the microgrid, making it independent and resilient to disturbances in the main grid. The difference to non-islanded microgrids is that non-islanded microgrids still regularly use their connection to the main grid, although they often limit the corresponding power exchange. Becoming an islanded microgrid is not that common since the investment and operating costs are very high. Besides that, there are not many benefits in becoming islanded yet and legislation around it is a challenge [165]. Energy communities which consist of physically close entities could best be compared to a non-islanded microgrid, although in a community, the members themselves control the community and are less focused on financial benefits.

Like non-islanded microgrids, energy communities may aim to become more independent from the main grid. However, there are also benefits to gain by staying connected to the grid, e.g. for offering certain flexibility services to the grid an energy community can create extra income. An overview of such energy services and flexibility services for communities is given in [85] and further

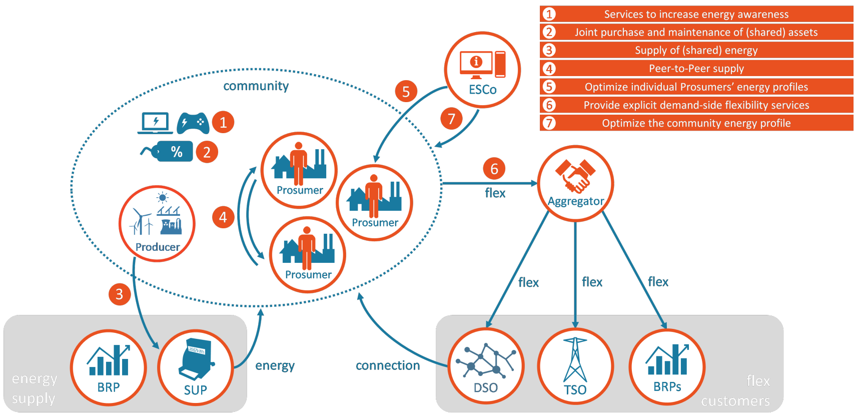


Figure 3.3: Seven value propositions for citizens energy communities. Source: USEF Foundation.

explained in the remainder of this section. In total, seven different energy and flexibility services are distinguished in USEF (Figure 3.3).

USEF is the Universal Smart Energy Framework, the integral market design for the trading of flexible energy use [26]. USEF provides a common standard for other energy devices and services to build on, and makes flexibility in energy use a tradeable commodity. It introduces market roles, models for their interaction and a market coordination mechanism. These mechanisms fit on top of most existing energy market models and are designed to offer a fair market for all stakeholders [26].

These seven services form the main benefits for setting up an energy community, and some of these propositions can be found back in existing projects. The seven energy and flexibility services for communities are:

- *Services to increase energy awareness*. Mostly this includes training and information sharing, but also the use of smart meter data to better understand individual consumption patterns and the impact of renewable generation on the energy balance. In the case consumers have rooftop PV installed, they get insight in the challenge to reach day-night balance and summer/winter balance.
- *Joint purchase and maintenance of (shared) assets*. Most communities start via shared investments in renewable generation resources like wind turbines or solar farms. Typically, the energy generated by their resources is sold to an energy wholesale market party via a so-called Power Purchase Agreement (PPA).
- *Supply of (shared) energy*. Once generation capacity is available, communities can further evolve by organizing self-supply from their resources.

To this end, the community should take the Electricity Supplier role, including the responsibilities related to this (regulated) role, or associate with an existing supplier. Furthermore, the community, as a legal entity, must respect the freedom of individual consumers to choose their supplier without being expelled from the community.

» *Peer-to-Peer supply*. A logical extension to self-supply is to facilitate peer-to-peer transactions between the participants. Here, an infrastructure must be in place for keeping track of all transactions and setting the prices for electricity.

» *Optimize individual prosumers' energy profiles*. In case the participants have a certain flexibility in their consumption and generation, i.e. can shape their energy profiles, this flexibility can be used to create added value. The flexibility can be used to optimize the individual profiles towards increased self-consumption, reduced peak load, or in response to dynamic tariffs. This is sometimes referred to as implicit demand response.

» *Provide explicit demand-side flexibility services*. The flexibility of the participants can be used to deliver flexibility services to stakeholders in the electricity market. For example, a community can bundle the individual pieces of flexibility into a larger volume and offer balancing services to transmission system operators, congestion management services to grid operators, or trade on the electricity markets. This is sometimes referred to as explicit demand response. Typically the flexibility is offered via a market bid, acquired by the counterparty, activated, and settled afterwards. Hereby, the community takes the so-called aggregator or demand-response operator role and takes (risk) positions in the various markets.

» *Optimize the community energy profile*. Instead of optimizing individual profiles, one can also optimize the joint profile. It must be noted, however, that there is not always an economic benefit for this, as it depends on local pricing structures, taxes, and other legislation.

A community may take several roles in the traditional energy field. Taking a supplier or aggregator role, as needed in some of the services listed above, requires a certain level of organization and professionalism of the community as these roles impose a lot of risks and responsibilities. This maturity is also required for taking over some responsibilities of a DSO, in case the community wants to operate as a microgrid.

Often, a community initiative starts with an enthusiastic group of people. However, it seems that it is challenging to ensure continuity. The reasons for this may be that the risks are hard to bear and difficult to share amongst the community members or that the community faces some competition of traditional suppliers who have certain competitive advantages due to their larger size [145, 176].

Location	Number of communities	Number of citizens	Community solar power (MWp)	Community wind power (MW)
Netherlands	∼676	∼112 000	217	296

Table 3.1: Details of Dutch energy communities in 2021 [152].

An example of such an advantage occurs in case of balance responsibility of a portfolio. This task is typically easier with increased portfolio size. Thus, in the long run, energy communities may need to structure their organization and grow to a critical mass to survive.

Despite all the drawbacks mentioned above, energy communities are emerging and also recently got a dominant position in the European legislation. The underlying motivations for participating in energy communities are the fact that they can take the lead in the energy transition, be in full control, and re-invest all benefits into the community.

In 2021, around 676 energy communities were identified within the Netherlands [152]. This was a 15% growth compared to 2019. Further details can be found in Table 3.1. A concrete example of a Dutch energy community is investigated in depth in the following section.

3.3.2 Case study of GridFlex Heeten

An example of a citizen energy community is given in the village of Heeten, The Netherlands. Here, 47 households are organized in a local community. All the households are situated behind a single transformer and are working together to reduce the stress on the local distribution network (see Figure 3.4 for a picture of the neighbourhood). Their primary focus is on the reduction of the peaks at the transformer. More information on this community and the related project was already given in Chapter 2.

To reach their goals, the energy community has initiated the GridFlex Heeten project [54], where a consortium of Enexis B.V. (project manager), Endona U.A., Escozon U.A., Enpuls B.V., Dr Ten B.V., ICT Group N.V., and the University of Twente are working together, as already mentioned in the previous chapter. The partners have the goal of using the flexibility of batteries and the flexibility of the inhabitants of the energy community in combination with novel pricing mechanisms to reduce the overall stress on the network.

Lowering this stress would result in deferring or avoiding grid reinforcement, as well as reducing grid losses. This again would save costs for the network operator, and indirectly, for the participants as well. Endona U.A. has obtained an exemption on the Dutch energy law for experimenting with different electricity tariffs so that these pricing mechanisms can be validated in this field test.

Figure 3.4: An aerial view of the GridFlex Heeten energy community and the neighbouring solar park. Source: Enexis Netbeheer B.V.

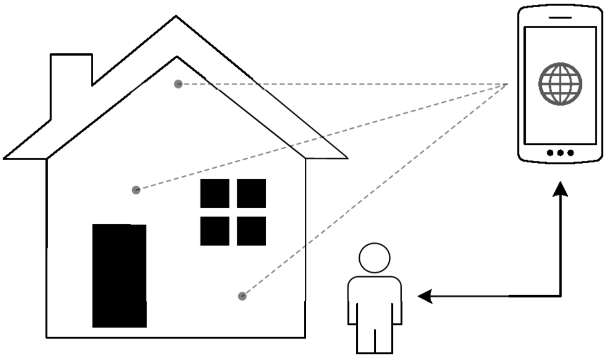


Figure 3.5: The inhabitant gets feedback on its consumption via an app.

In the community of Heeten, some of the households have rooftop PV installations and some are equipped with a 5 kWh battery behind the meter. All households provide access to their smart meter data and their PV production, giving insight into their local energy streams. They also receive information about their energy consumption via an app on their phones (Figure 3.5).

This information consists of their current and past energy usage, split into their gas and electricity consumption, as well as their PV production, standby usage, and self-consumption rate (Figure 3.6, right panel). The app allows the inhabitants to get a clear view of their energy profiles and peak usage. The batteries are shown as well, so the inhabitants can get a good impression of the battery's behaviour (Figure 3.6, left panel). These households also get a price forecast for the coming 24 hours via the app (Figure 3.6, middle panel). In this way, the

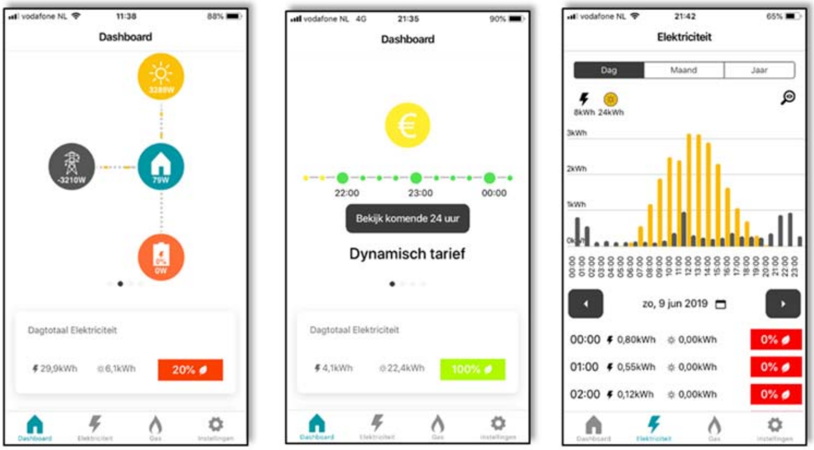


Figure 3.6: Overview of the app the inhabitants used. Source: ICT Group N.V.

inhabitants can shift their energy usage to cheaper time periods. The used prices are calculated in such a way that cheaper slots coincide with the periods with expected low energy traffic on the transformer.

Next to the actively-involved participants, another 28 households in the remaining part of Heeten are only monitored and do not get price forecasts. In this way, it can be investigated if there is a change in the behaviour of the community compared to this reference group.

For the pilot, the households are not seen as separate entities, but as a community located behind one transformer. This is one of the key concepts in this project. All inhabitants behind the transformer are participating and are part of this energy community. This way, there is one common coupling point over which the connection costs can be calculated.

Traditionally, in the Netherlands, a consumer pays the network operator for his connection (usually a three-phase 25 ampere connection) and the transport of energy. Network operators calculate their tariffs using an average amount of energy, namely 3 500 kWh a year, for every consumer with a 3 x 25 A connection. Based on this amount, the total network costs are spread out equally over all customers. Using the average amount of energy implies that for a community of 47 households, network operators calculate with an energy usage of 164 500 kWh a year.

In this pilot, the connection cost is decoupled from the cost of transport of energy. The consumers pay for their connections as usual. However, for the cost of transport, the community is seen as if they have only one common connection. This means that the energy that is transported is measured and calculated based on the level at the transformer. In other words, for the transport

Level of demand	Power (kW/15 min)	Price (€/kWh)
Low	0 - 15	0.01
Medium	15 - 25	0.05
High	25 and above	0.25

Table 3.2: Levels of power demand on the transformer with the corresponding prices for the transport of energy used in the GridFlex Heeten pilot.

cost, the energy that stays within the community is not charged, since it is not transported over the transformer. This promotes self-consumption within the whole neighbourhood. A similar idea is also mentioned in the ETHZ project in [150].

The transport costs for the energy consumed by the community are not calculated in the usual way. Each household still pays for the transport of their energy; only the price is different than usual. In the pilot, the price of the transport per kWh depends on the total power used by the community. This price increases with the power demand at the transformer. Therefore, every inhabitant of the neighbourhood pays the same price per kWh, but the price depends on their behaviour as a group.

For the price scheme, three different levels of demand with a corresponding power range on the transformer are defined. This leads to three different prices used (see Table 3.2). Since the measurements at the transformer take place every 15 minutes, the level of demand is determined by the average power supplied on the transformer in these 15 minutes. Consequently, the costs of transport of energy for a household is calculated by multiplying the energy consumption of the house with the price corresponding to the level of demand on the transformer. Since each household has a different energy usage in these 15 minutes, their total costs for that period are different as well.

When switching to a higher level of demand, the price per kWh increases. For the increase between two consecutive levels, the same factor is used. This implies that the result is approximately a quadratic price function which is known to support the reduction of peaks [106].

In the case of GridFlex Heeten, the factor between the levels is chosen to be five. This factor, as well as the values at which the levels change, were selected by analysing past energy usage and making sure the prices to be paid by the inhabitants still are reasonable. More specifically, in the initial model, for a community power consumption below 15 kW, the price for transport is €0.01 per kWh, from 15 kW until 25 kW the price is €0.05 and above 25 kW the price is €0.25 for every kWh that has been transported (see also Table 3.2). More information on this type of pricing is given in Chapter 5 and for the definitive pricing used in GridFlex Heeten and the obtained results, see Chapter 6.

By using batteries and by shifting the energy consumption of the inhabitants, the community can reduce the costs of transport. The batteries are operated using a control algorithm which takes into account weather forecasts, past energy consumption, and information about the neighbourhood. This means that the only influence of the inhabitants of the neighbourhood is on their electricity consumption. As mentioned above, the inhabitants are supported by an app, so they know the expected level of demand on the transformer level (Figure 3.2, central dashboard). If the inhabitants manage to decrease their energy usage in high demand periods, they may drop to only having a medium level of demand. This would amount to paying a factor five less for the transport of energy in that period.

The idea behind this pricing scheme is to reduce the transport losses of energy and to reduce the congestion on the grid (with the consequence of reduced investments in the grid). The cost reduction is highest if the community succeeds to reduce the transport of energy to zero, meaning that no transport over the transformer takes place. In this case, the community would even become an islanded microgrid.

In terms of the seven value propositions of USEF (Figure 3.3), the community in Heeten is an example of a community with collective generation and flexibility from batteries. The flexibility is used in an implicit demand-response scheme on a community level to minimize the joint peak load. This would correspond to the seventh type of energy and flexibility service for communities, as introduced in Section 3.3.1. Typically, as a side result also the joint self-consumption rate will increase since people want to reduce peaks and keep as much energy as possible behind the meter, and therefore also behind the transformer.

By reducing the peaks, the network operator has some benefits as well. The assets in the electricity grid do not age as quickly as they would otherwise, and the costs for maintenance or even replacement can be lowered. Also, there may be fewer voltage problems in the neighbourhood, and there might be no need (yet) to upgrade to a more expensive transformer [56]. Therefore, the network operator can offer some remuneration to the inhabitants, as is done now with the variable transport cost.

In the pilot, a further focus was on the added value of the batteries in this setting. For this, the impact of the batteries on the sketched pricing scheme has been extensively evaluated. The results of this effort are presented in Section 3.4 and Chapter 6. Also the inhabitants' willingness to shift their energy consumption has been investigated (see Chapter 6).

3.3.3 Extending the concept

In the previous sections, potential benefits for setting up an energy community were given, next to the way these were handled in the GridFlex Heeten community. As mentioned, the concept used in GridFlex Heeten may be interesting to

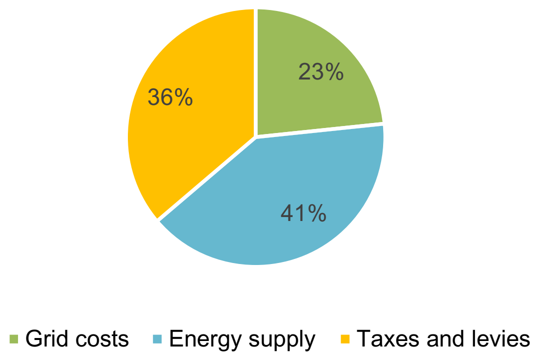


Figure 3.7: Composition of the energy price in the Netherlands in 2019 based on a household with an annual usage of 3 500 kWh.

extend to other communities. However, several issues arise when putting this into practice. In this section, the fundamental difficulties for extending the GridFlex Heeten concept, and other concepts for energy communities, are addressed. This includes an analysis of the possibilities present in current legislation and some suggestions on how to change this legislation to overcome the problems faced by energy communities nowadays.

The potential to extend the Heeten setup to a general concept for energy communities is mainly dependent on legislation. As per today, the Dutch legislation hampers some of the seven value propositions mentioned in USEF. To a certain extent, this is due to the composition of energy prices in the Netherlands. They consists of a grid tariff based on the capacity of the connection, the supply costs (which is typically a price per day and a price per kWh), and taxes and levies (see Figure 3.7). Based on an annual usage of 3 500 kWh in 2019, this adds up to 0.23 €/kWh.

There is only very little bandwidth to influence this electricity price. The grid costs, as well as the taxes, are regulated, so the only price differences can come from the energy supply costs. However, the current system allows no incentives which can be given to customers to change their energy consumption pattern. Up to now, such approaches can only be tested in pilot projects.

Looking at the seven energy and flexibility services mentioned in Section 3.3.1, energy communities today have difficulties to participate in some of these services as under the current Dutch law, these services are restricted to specific parties or are not adequately valued. Other services can be very difficult to set up. Below, an analysis for each of the seven services in the current legislation is given:

- » *Services to increase energy awareness.* Such services are in principle possible. Many pilot projects aim to accomplish more energy awareness. Since customers can opt to read out their smart meter data, individual consumption patterns and information on the energy balance can be extracted, and corresponding information can be passed to the inhabitants. This may lead to increased awareness and therefore often also to higher self-consumption rates. Additionally, it often leads to a lower energy consumption due to more efficient energy usage.
- » *Joint purchase and maintenance of (shared) assets.* For many energy communities, the purchase of solar or wind installations was the main reason for being initiated. The advantage for the participants is that they do not have to pay tax on the annual energy they consume from their common generation source ('postcoderoosregeling' in Dutch). However, this scheme does not encourage the direct physical joint self-consumption since the calculations are made only on an annual basis.
- » *Supply of (shared) energy.* In principle, a community may take the role of an electricity supplier, including the responsibilities related to this (regulated) role. Note that for the latter, it may also cooperate with an existing supplier. However, being an electricity supplier results in considerable responsibilities for a community, and it is questionable if any benefits would arise, compared to the larger scale of traditional suppliers in which more efficient purchasing and selling of electricity is possible.
- » *Peer-to-Peer supply.* This form of supply is almost impossible in current legislation. To make it possible, all participants would have to obtain permits to sell electricity and would have to take some balancing responsibility. However, prosumers, in general, do not have the proper scale of production, flexibility, and automation needed for the latter task. Although some suppliers offer a peer-to-peer proposition to their clients, for a community, this would imply that all members must switch to this particular supplier to make it work.
- » *Optimize individual prosumers' energy profiles.* Grid costs are depending on the capacity of the given grid connection and by that are fixed. Hence, there is no incentive to reduce grid usage at peak times. Energy prices are typically determined by fixed tariff or day-night tariff. In the latter case, the differences are rather low, and therefore there is no significant reason to optimize the profile. Note, that legislation does not prohibit optimization of energy profiles. Furthermore, consumers can claim a tax refund for their annual self-consumption. This implies that all consumption up to the level of the production surplus is not taxed ('salderingsregeling' in Dutch). Therefore, a net-zero energy building would not pay any taxes on its consumption even though they might cause frequent and/or large peaks in the network. Note that this scheme does not encourage consumers to optimize direct self-consumption and also ruins the business case for home batteries. Summarizing, due to the low price variation in

combination with the tax refund scheme, there is no financial advantage to store self-generated energy in a battery for later consumption. At this point, people can use the grid as a 'battery' without even paying for losses caused by this 'battery'. Nowadays, only in some particular cases where the battery is used to reduce the grid connection capacity, a beneficial business case is possible. Note, however, that the current regulation of the tax refund scheme will most likely be faded out in the coming years, meaning that the market for batteries might grow. An alternative version of this net-metering is described in Section 6.4.2.

» *Provide explicit demand-side flexibility services.* Communities who want to participate in explicit demand response schemes are facing high minimum production sizes and need consent from their supplier. This makes it nearly impossible for smaller energy communities to participate in any explicit demand response unless they participate via some larger body.

» *Optimize the community energy profile.* Since currently there are no possibilities within the law to negotiate a specific energy tariff for a community, and the current legislation also does not allow a community to disconnect from the main grid, there is currently no benefit for influencing the energy profile of a community. It may be that when microgrids can go completely islanded, operators would offer them to only pay for their local part of the grid. However, this would be extremely difficult to organize and execute.

Summarizing, the current tax schemes for both individuals and communities are very advantageous to invest in renewable generation, whereas the added value of exploiting the flexibility of energy is almost none.

For the pilot in Heeten, however, an exempt from the law was approved, which allows the community to offer dynamic grid tariffs. Instead of a fixed tariff of 0.52 €/day, which results in around 0.05 €/kWh based on annual usage of 3 500 kWh, the community members are offered a varying scheme, as will be explained in Section 3.3.2. Without the exempt in the law and the fact that the GridFlex Heeten project is a pilot project, these dynamic tariffs would not have been possible. Some indications on the achieved savings by the energy community can be found in Section 3.4.

From the perspective of a network operator, giving possible discounts to a community only makes sense if it can be shown that the community reduces the stress on the grid. However, this is only possible if there is some common connection point to the grid by the community. Therefore, one of the hurdles of setting up a grid tariff for an energy community similar to the one introduced in this chapter is that the whole neighbourhood behind a transformer (or another common connection point) needs to become part of the community. Setting up such a community in an existing neighbourhood is therefore very challenging. Most probably, some customers do not want to be included [10]. However, for newly-build neighbourhoods, this could be an interesting opportunity. By making the energy community an integral part of the neighbourhood, it becomes natural to have the whole neighbourhood working together. This approach has been chosen for a project of 3 000 households which is built by Sonnen in Arizona and which uses a VPP approach. More information on this project can be found in [150].

Whether or not the used concept of GridFlex Heeten is transferable to other communities is mainly dependent on the upcoming legislation in response to the EU directive. However, the outcome of pilot projects like GridFlex Heeten may steer the legislation in the right direction. More concretely, based on the experience gained in the pilot project in Heeten, the current legislation should be changed to make the following aspects possible:

» A clearly defined legal position of citizen energy communities with the possibility to generate, store, and consume electricity, to have access to all markets, and to have a level playing field with traditional market players.

» A grid tariff scheme where higher community self-consumption and lower peak loads can be compensated.

» An energy pricing scheme where energy transfers within the community have a lower price than energy exchanges across the 'borders' of the community.

» A taxation scheme where individual self-consumption and community self-consumption is encouraged. This scheme should be based on real-time self-consumption instead of annual averages.

If these aspects are integrated into future legislation, better business cases for energy communities can be made.

3.4 Preliminary results of the case study

Even though the results, obtained after using the proposed pricing mechanism for some time, that are presented in this section are not final results (see Chapter 6), these results give a good indication of the potential impact energy communities may have if legislation would be changed.

One of the crucial questions of the GridFlex Heeten project is to test if household batteries have a significant effect on the total energy profiles of the neighbourhood. For this, a scenario with virtual batteries of 5 kWh at 24 locations in the local grid was simulated using a smart steering algorithm to control the batteries. For this, the neighbourhood was modelled in the open-source Decentralized Energy Management toolKit DEMKit [66, 67]. DEMKit is a software tool designed for decentralized management of energy systems using a model predictive control approach. For GridFlex Heeten, a model of the neighbourhood including the grid structure was set up, and data from the households was used as input,

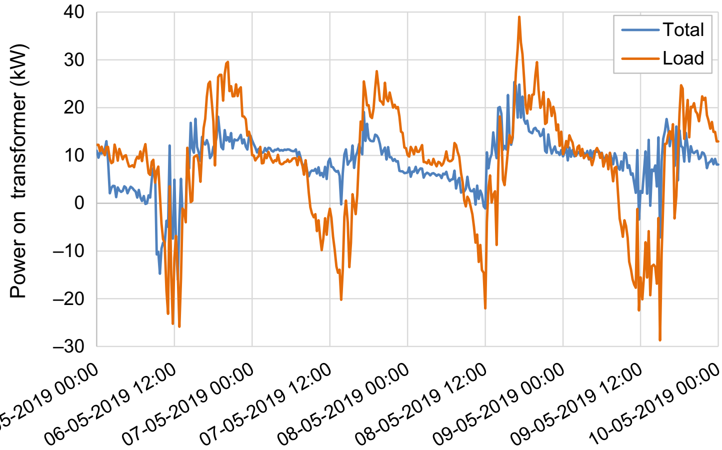


Figure 3.8: The effect that batteries have on the peaks, showing transformer load with batteries ('Total', in blue) and without batteries ('Load', in orange).

as already mentioned in Chapter 2. Furthermore, virtual batteries were then added to this model of the given situation in Heeten.

To analyse the situation in Heeten, load flows were simulated and predicted. In addition, an ADMM type of control [136], was used to send steering signals to the virtual batteries. In this control, the batteries iteratively send adjusted schedules to lower the expected peaks of the transformer for the coming 24 hours. When an acceptable solution is achieved, the coming period (15 minutes) from the resulting schedule is executed. After that, the process is repeated meaning that updated predictions and load flows are simulated, and the control process is iterated.

One of the lessons learned from the case study is that the batteries can have a tremendous effect. Figure 3.8 shows the resulting peaks of the neighbourhood with and without batteries. It can be seen that the peaks have been reduced by up to 36% (from 39 to 25 kW). Using the new payment scheme as introduced in Section 3.3.2, the inhabitants together would save €1 500 per year (about 14% of the total connection and transport costs). Note, that this money is devoted to the entire neighbourhood and not to individual households. More information on this specific type of pricing mechanism can be found in Chapter 5.

In a further phase of the project, information was given to the inhabitants to support them to decrease their energy consumption, as well as to shift their consumption away from peak moments. More information on the effects of providing this information can be found in Chapter 6.

Level of demand	Energy per level without batteries (% of total energy)	Energy per level with batteries (% of total energy)
Low	66.3%	81.6%
Medium	25.0%	17.4%
High	8.6%	1.0%

Table 3.3: Usage of each level of demand without and with batteries.

For the network operator, the introduced measures also improved the situation as the neighbourhood only exceeded the 15 kW mark 18% of the time, compared to 34% without using batteries (Table 3.3). While the current peaks do not pose a problem for the present cables and transformer, the results give a good indication of what impact batteries may have.

The achieved results for the battery are considerable, however, they form only part of the aim of the project, as already indicated in Chapter 2. In a second step, we analysed how much the inhabitants are willing and able to change their behaviour and shift their energy consumption. More information on this subject is presented in Chapter 6.

3.5 Conclusions

Energy communities are on the rise in Europe. A reason for the growth in the number of energy communities can be found in the motivation of prosumers to take the lead in the energy transition and to be in full control, and the fact that benefits generated by the community may be re-invested into the community. Furthermore, the seven energy and flexibility services for energy communities listed in this chapter may allow for additional benefits to be achieved for the inhabitants of the community.

However, many barriers are still to be overcome for energy communities to achieve these benefits. Next to the need for a structured organization and a sufficient scale to withstand the competition of more prominent players, energy communities are still very uncommon and up to now have hardly any options to attain savings. The latter problem stems from the main barrier for energy communities, the current legislation. However, the new EU directive makes citizen energy communities an official legal entity, implying that energy communities are getting a position in legislation. Nevertheless, their exact rights and duties are still to be determined. With proper price schemes from suppliers or network operators and the legal options to apply them, significant savings may be acquired when the community is controlled in a smart way, as is demonstrated in the case study of this chapter, and in the forthcoming Chapter 5, and Chapter 6.

Within the presented case study, a dynamic community grid tariff is applied as implicit demand response, in combination with batteries, to research the effect these elements have on the electricity peaks of the community. This approach has specifically been created for energy communities that have one common coupling point to the distribution grid. Simulations for the given case study identified several key benefits, including lowering the peaks at the transformer by 36% and potential savings of €1 500 per year in grid costs for the inhabitants of Heeten.

It is still to be seen if the upcoming legislation in response to the new EU directive will allow using concepts like the ones researched within GridFlex Heeten in other neighbourhoods as well. We hope that the outcome of pilot projects like GridFlex Heeten will steer the legislation in this direction.

To conclude, based on the experiences and results achieved within the GridFlex Heeten project, energy communities may have a severe impact on the energy transition in the coming years.

4 Pricing mechanism based on losses using grid topology

Abstract – *As mentioned in the previous chapters, we aim to fairly distribute costs that are made in a neighbourhood. This chapter introduces a pricing mechanism that distributes the electricity costs of a neighbourhood based on the losses caused by all households, as the losses can be considered as a good indication of overloading and degradation of assets in the grid. This mechanism is based on the Shapley value, which is a concept to fairly distribute costs based on the average marginal contributions of the participants. The Shapley value is normally computationally expensive to calculate, but in case of losses in a radial network it can be efficiently determined. As the resulting costs for each household are highly dependent on the location in the electricity grid, two variants of the pricing mechanism are proposed that works with households on 'average locations' to distribute the costs more fairly.*

The proposed pricing mechanisms were designed to be used in the GridFlex Heeten pilots. However, also outside the scope of this project the mechanisms are useful to share costs as they are following a 'polluter pays' strategy. Moreover, the results from this chapter show that specific network topologies can lead to structures in the Shapley value that make it computationally feasible. Furthermore, the 'polluter pays' mechanisms based on losses show to be heavily influenced by the location in the grid, which, however, can be decreased by using 'average locations'.

This Chapter is mainly based on [VR:6].

4.1 Introduction

Currently, pricing mechanisms for electricity in the domestic sector provide no incentives to customers to adapt their behaviour to, e.g., consume electricity at times when it is better for the grid or to spread their consumption evenly over the day. Even the more advanced mechanisms like time-of-use pricing, peak pricing or real-time pricing, already mentioned in the previous chapter, have their disadvantages as they tend to only shift peaks and may even increase the synchronisation of loads, e.g. with the charging of electric vehicles [102, 105]. Furthermore, the broadly used time-of-use pricing or peak pricing mechanisms do not reflect the actual costs incurred by the consumption or production of energy [93, 179]. This would again mean the incentives provides by these mechanisms do not relieve the grid.

Several new pricing mechanisms have already been proposed in recent years. In [107] the authors have looked at demand response as a game with a monotone price function, in particular with a quadratic price function. Similar to this, in [27] a game was defined for determining prices whereby no specific properties were assumed for the price function, implying that pricing mechanisms proposed in our work could be integrated into this game. In [105] an optimization framework was developed for real-time pricing environments, where some adjustments to the prices to compensate for load synchronisation were added. Locational marginal prices have also received some attention (see [52], as well as some pilot and commercials projects [32]). Here, prices depend on both the location as well as the extra cost incurred from raising the consumption. In [127] the authors take the total load in the grid as a variable input for a quadratic price function. Finally, in [80], determining transportation prices for medium voltage networks using the Aumann-Shapley value has been explored.

In this chapter, we present a novel pricing mechanism based on the losses caused by the transport of energy in the low voltage (LV) grid. The mechanism is based on the Shapley value. Normally, the calculation of this value is computationally expensive, however, in our setting an efficient structure can be used to reduce this complexity [45]. As the resulting energy prices are highly dependent on the location in the network, these prices possibly do not lead to a fair mechanism. Therefore, we propose two variants based on permutations of the locations within the network. This way, a pricing mechanism is obtained that fully distributes all costs based on the individual consumption, assuming that everyone is at an "average location" in the grid.

This chapter is organised as follows. In Section 4.2 we introduce the considered model. After that, we introduce the new pricing mechanisms using a small example and in Section 4.4, we generalize the description to general instances. We demonstrate our mechanisms on a few small cases in Section 4.5 and discuss some possible obstacles for putting the mechanisms into practice in Section 4.6. We finish this chapter with some conclusions.

4.2 Model

The proposed approach is based on a model of a neighbourhood, incorporating the houses, the underground cables, the transformer, and their geographical layout. This model can be represented as a graph, where houses, cable joints, and the transformer are the nodes, and the cables are the edges. This representation forms the base for analysing the network. To present the concept, we focus on a single feeder without any branches and do not take into account the losses in the cable connecting a household to the feeder, as these are almost negligible and make the modelling unnecessarily difficult. Instead, we assume that the house is directly connected at the joint, implying that the considered graph is a chain.

The starting point for determining the costs are the losses in the cables, which scale quadratically with the power. We denote the set of households by $H = \{h_1, \dots, h_n\}$, and represent the set of locations for the households in the network by vertices $L = \{1, \dots, n\}$. We assume the locations are numbered consecutively from furthest to closest to the feeder and we introduce a mapping $p : L \rightarrow H$ that gives for each location which household is connected to that location. Furthermore, the transformer T in the grid is connected to location n via cable segment (n, T). Finally, we assume that for each cable segment $(i, i+1)$ a function $F_i^p(f_i^p)$ is given that specifies the costs of a power flow f_i^p on this cable segment (i.e. losses). As losses are assumed to be quadratic in the power flow, we model F_i^p as

$$F_i^p\left(f_i^p\right) = e_i\left(f_i^p\right)^2, \tag{4.1}$$

where e_i is a parameter depending on length, age, condition, etc., of the segment $(i, i+1)$. Note that the flows f_i^p depend on the location of the households, so on the function p.

To calculate the overall costs of a given flow in the network, we introduce a function $F^p := \sum_i F_i^p(f_i^p)$. The involved power flows on an edge in this expression are based on the power consumptions of the households. Let X_{h_j} denote this power consumption for household h_j. Then adding up the power of all households using cable segment $(i, i+1)$ gives us f_i^p. More formally:

$$f_i^p = \sum_{j=1}^{i} X_{p(j)}. \tag{4.2}$$

As, in our analysis, we may need to consider the power flow of a subset $S \subseteq H$ of households, we denote by $f_i^p(S)$ the power flow on cable segment $(i, i+1)$ induced by the subset S. This flow is given by

$$f_i^p(S) = \sum_{\substack{j=1 \\ p(j)\in S}}^{i} X_{p(j)}. \tag{4.3}$$

Note that $f_i^p = f_i^p(H)$. Similarly, we denote the overall costs induced by the households in S by $F^p(S) = \sum_i F_i^p(f_i^p(S))$.

The presented model is based on the following considerations:

» We address the network costs and the electricity costs in one pricing mechanism. Both of them scale quadratically [93], so we can use the same structure for both. Constant and linear terms of the network and electricity cost (e.g. overhead costs) can be added to the developed pricing mechanism as linear and constant terms without changing the overall structure of the analysis.

» We only consider active power, meaning we do not explicitly take into account reactive power. This may be included by introducing imaginary numbers, however, this would complicate the analysis and distract attention from the main issue considered in this chapter.

» We assume a single-phase cable. However, note, that an extension to three-phase cables can be done by simply splitting a three-phase cable into three separate single-phase cables.

» To ease the explanation, we assume that all energy flows are in the same direction (so either all from or towards the transformer). Note that this has no further effect on the remaining analysis.

4.3 SMALL EXAMPLE

To get some intuition for the considered problem, we start with a small example of three houses h_1, h_2, h_3 and one transformer T as shown in Figure 4.1. In the example we have $p(1) = h_1$, $p(2) = h_2$ and $p(3) = h_3$. Using (4.1) for this model leads to the following costs for the cable segments:

$$F_1^p\left(f_1^p\right) = e_1\left(f_1^p\right)^2 = e_1 X_{h_1}^2$$
$$F_2^p\left(f_2^p\right) = e_2\left(f_2^p\right)^2 = e_2\left(X_{h_1} + X_{h_2}\right)^2$$
$$F_3^p\left(f_3^p\right) = e_3\left(f_3^p\right)^2 = e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)^2.$$

Taking the costs for all cable segments together, this gives

$$F^p = e_1 X_{h_1}^2 + e_2\left(X_{h_1} + X_{h_2}\right)^2 + e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)^2. \qquad (4.4)$$

If we look at the individual costs each household creates (so assuming the other households are not there), we would get $(e_1 + e_2 + e_3)X_{h_1}^2$, $(e_2 + e_3)X_{h_2}^2$ and $e_3 X_{h_3}^2$ for households h_1, h_2 and h_3 respectively. Note that these costs do not add up to the actual total costs as calculated in (4.4). This means that using only these individual costs is not sufficient to divide the total costs among the households, implying that we need a different approach.

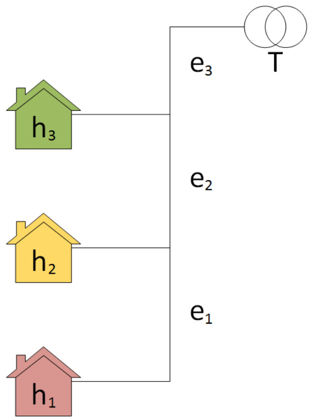


Figure 4.1: Motivating example with three households.

4.3.1 Shapley value

One way of dividing the costs among a group of participants used in literature is the Shapley value [146]. In game theory, the Shapley value is used to divide the costs based on how much a player adds to the total costs of each possible coalition in a game. In our case a coalition corresponds to a (sub)set of households. For such a coalition we only take into account the power of those households when calculating the costs. Based on this, the Shapley value ϕ_{h_i} of household h_i is given as (similar to [146])

$$\phi_{h_i} = \sum_{S \subseteq H \setminus \{h_i\}} \frac{|S|!(|H| - |S| - 1)!}{|H|!} (F^p(S \cup \{h_i\}) - F^p(S)). \tag{4.5}$$

The Shapley value has a few important properties:

- *Efficiency*: $\sum_{h_i \in H} \phi_{h_i} = F^p$. This implies that the Shapley value of all households together covers precisely the total costs.
- *Symmetry*: if $F^p(S \cup \{h_i\}) = F^p(S \cup \{h_j\})$ for all $S \subseteq H \setminus \{h_i, h_j\}$ then $\phi_{h_i} = \phi_{h_j}$. This means that is two different households add the same costs to all relevant other subsets of households, they also have the same Shapley value.
- *Linearity*: $(\phi + \Phi)_{h_i} = \phi_{h_i} + \Phi_{h_i}$, where Φ is of the same structure as ϕ except that the function F^p is replaced by some other cost function. This states that if we have the Shapley values of a household based on two different cost functions, adding these values together would be identical to adding the cost functions together and calculating the Shapley value based on the combined cost function.

» *Zero player*: if $F^p(S \cup \{h_i\}) = F^p(S)$ for all $S \subseteq H \setminus \{h_i\}$, then $\phi_{h_i} = 0$. This implies that if a household adds no costs to any possible subset of households, this household should have a Shapley value of zero.

It is well known from literature that the Shapley value is the only possible division of costs that has these four properties (see, e.g., [146]).

If we apply (4.5) to the small example introduced in Figure 4.1, the Shapley value of household h_1 becomes

$$\begin{aligned}
\phi_{h_1} = & \frac{0!\,2!}{3!}(F^p(\{h_1\}) - F^p(\emptyset)) \\
& + \frac{1!\,1!}{3!}(F^p(\{h_1,h_3\}) - F^p(\{h_3\})) \\
& + \frac{1!\,1!}{3!}(F^p(\{h_1,h_2\}) - F^p(\{h_2\})) \\
& + \frac{2!\,0!}{3!}(F^p(\{h_1,h_2,h_3\}) - F^p(\{h_2,h_3\})) \\
= & \tfrac{1}{3}(e_1+e_2+e_3)X_{h_1}^2 \\
& + \tfrac{1}{6}\left(e_1X_{h_1}^2 + e_2X_{h_1}^2 e_3\left(X_{h_1}+X_{h_3}\right)^2 - e_3X_{h_3}^2\right) \\
& + \tfrac{1}{6}\left(e_1X_{h_1}^2 + (e_2+e_3)\left(X_{h_1}+X_{h_3}\right)^2 - (e_2+e_3)X_{h_2}^2\right) \\
& + \tfrac{1}{3}\left(e_1X_{h_1}^2 + e_2\left(X_{h_1}+X_{h_2}\right)^2\right. \\
& \left. + e_3\left(X_{h_1}+X_{h_2}+X_{h_3}\right)^2 - e_2X_{h_2}^2 - e_3\left(X_{h_2}+X_{h_3}\right)^2\right) \\
= & e_1X_{h_1}^2 + e_2X_{h_1}\left(X_{h_1}+X_{h_2}\right) \\
& + e_3X_{h_1}\left(X_{h_1}+X_{h_2}+X_{h_3}\right).
\end{aligned}$$

Similarly, we get the following Shapley values for households h_2 and h_3:

$$\begin{aligned}
\phi_{h_2} &= e_2X_{h_2}\left(X_{h_1}+X_{h_2}\right) + e_3X_{h_2}\left(X_{h_1}+X_{h_2}+X_{h_3}\right), \\
\phi_{h_3} &= e_3X_{h_3}\left(X_{h_1}+X_{h_2}+X_{h_3}\right).
\end{aligned}$$

For the three households, this can be summarized as follows:

$$\phi_{h_i} = X_{h_i}\sum_{j=i}^{3} e_j \left(\sum_{k=1}^{j} X_{h_k}\right). \tag{4.6}$$

As $\phi := \phi_{h_1} + \phi_{h_2} + \phi_{h_3} = F^p$, the sum of all Shapley values is equal to the total costs in the network. Therefore, if we choose to allocate costs to households based on their Shapley value, the total costs F^p are distributed among the households.

However, when comparing ϕ_{h_1} with ϕ_{h_3}, it can be seen that in case of identical power usage, household h_1 has to pay much more than household h_3. This is due to the greater distance to the transformer and the fact that only the losses are used for calculating the costs. This in principle also makes sense, as household h_1 is responsible for more losses. In this way the Shapley value preserves a sense of fairness. However, from a user perspective, this may be seen as unfair as your payment is strongly location dependent and not only usage-dependent. Thus, implementing such a locationally biased pricing mechanism is most likely not going to be accepted, as people do not see their location in the grid as a righteous criterion justifying these price differences. As such, the mechanism would be judged as not treating everyone (formally) equal [117].

Therefore, to be able to integrate the Shapley value in a pricing scheme, we need to get locational independence to some extent. This is what is considered in the following sections.

4.3.2 Average location

In the above example, household h_i was considered to be on location i, i.e., $p(i) = h_i$. However, if we want locational independence, we need to get rid of this dependency on a specific location.

Note that if we switch locations of households, the contribution to the losses of each household changes. Therefore, we consider all possible permutations p of the households and calculate the corresponding contribution to the losses according to the Shapley value. If we then take the average over all possible permutations p (in the example there are 3! possible permutations, see Figure 4.2 for an overview), we get the contributions of a household if it would be on an 'average location' in the grid, as well as all other households being on 'average locations'. The average contribution μ_{h_1} of household h_1 over all possible permutations, using (4.6) and the permutations as shown in Figure 4.2, now is given by

$$\begin{aligned}\mu_{h_1} = X_{h_1}\Big(&\tfrac{1}{3}e_1X_{h_1} + \tfrac{1}{3}e_2\left(2X_{h_1} + X_{h_2} + X_{h_3}\right)\\ &+e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)\Big).\end{aligned}$$

Similarly, for h_2 and h_3 we get

$$\begin{aligned}\mu_{h_2} = X_{h_2}\Big(&\tfrac{1}{3}e_1X_{h_2} + \tfrac{1}{3}e_2\left(X_{h_1} + 2X_{h_2} + X_{h_3}\right)\\ &+e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)\Big),\\ \mu_{h_3} = X_{h_3}\Big(&\tfrac{1}{3}e_1X_{h_3} + \tfrac{1}{3}e_2\left(X_{h_1} + X_{h_2} + 2X_{h_3}\right)\\ &+e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)\Big).\end{aligned}$$

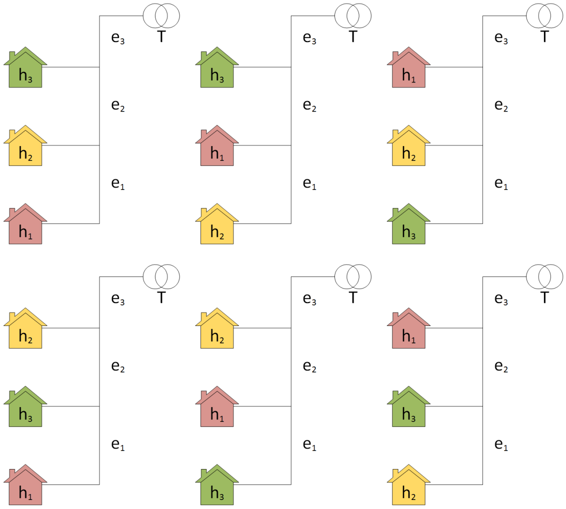


Figure 4.2: All permutations in the given example with three households.

As with the Shapley values, we then assign the average location values as costs to the households. Adding up these costs gives us the total average costs:

$$\begin{aligned}\mu := {} & \mu_{h_1} + \mu_{h_2} + \mu_{h_3} \\ = {} & \tfrac{1}{3} e_1 \left(X_{h_1}^2 + X_{h_2}^2 + X_{h_3}^2 \right) + \tfrac{2}{3} e_2 \left(X_{h_1}^2 + X_{h_2}^2 \right. \\ & \left. + X_{h_3}^2 + X_{h_1} X_{h_2} + X_{h_1} X_{h_3} + X_{h_2} X_{h_3} \right) \\ & + e_3 \left(X_{h_1} + X_{h_2} + X_{h_3} \right)^2 .\end{aligned}$$

Note that, as to be expected, these total average costs are not equal to the total actual costs F^p in (4.4). So in order to divide the actual overall cost over the households, we use the average location costs μ_{h_i} as a proportion of the actual costs attributed to each household in the average case:

$$\tilde{\mu}_{h_i} = \frac{\mu_{h_i}}{\mu} \phi. \tag{4.7}$$

We call $\tilde{\mu}_{h_i}$ the scaled average location costs to be paid by the household in this average location pricing mechanism. Comparing the properties of these costs with the properties of the Shapley value, we see that we had to give up one property to achieve this locational independence. To see this, we take the case where all households have an identical power usage. Then, household h_1 adds more in terms of the cost function F^p when added to any other subset of households than household h_3 adds, because of its location in the grid. However, for both

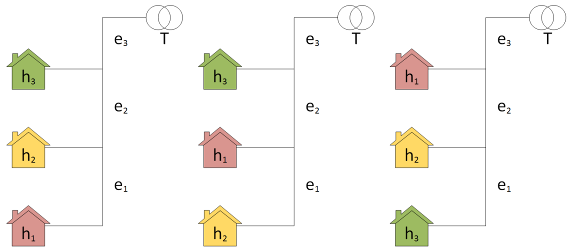


Figure 4.3: All permutations used in the approximate average location for household h_1 of the given example with three households.

these households their scaled average location costs $\tilde{\mu}_{h_i}$ are the same. This means the cost division based on scaled average location is no longer symmetric.

Another observation for the case where the power usage of households is identical, is that the price per unit of electricity (i.e., $\tilde{\mu}_{h_i}/X_{h_i}$) is equal for all households. As such, all locational dependency is averaged out in this pricing. Even though we aimed achieve less locational dependency, offering the same marginal prices to all households might not sufficiently reflect the cause of the costs and therefore, not give the incentive to lower the costs where they are created. So, we present an alternative in the next section.

4.3.3 Approximate average location

In the previous subsection, we used the average location, defined by all possible permutations of all households, to determine the costs allocated to a household. In addition to the drawbacks mentioned above, we also note that as the number of permutations grows exponentially with the number of houses, the calculation may become quite inefficient or even infeasible (although, for the special case of chain networks, the formulas presented in the previous section grow only quadratically in the number of households (see Section 4.4.2)). Therefore, we aim to have a more efficient alternative which can also be used when extending to non-chain networks. For this, we propose the following alternative as an approximation of the average location. For the approximate average contributions of household h_i, we consider only the permutations p_i^j for $j = 1,\ldots,n$, which differ from the identity permutation by exchanging household h_i with household h_j. More formally, the permutations p_i^j are defined by

$$p_i^j(k) = \begin{cases} h_j, & \text{if } k = i, \\ h_i, & \text{if } k = j, \\ h_k, & \text{otherwise.} \end{cases} \tag{4.8}$$

Now, to determine the approximate average contribution of household h_i to the losses, we do not take the average of the Shapley value over all $n!$ permutations, but only over the n permutations $p_i^1, \ldots, p_i^n$. The resulting approximate average location value is denoted by ρ_{h_i}, which again we use to assign costs to the household. Note that using only these permutations scales down the considered cases from $n!$ to n, which also reduces the computational complexity of calculating ρ_{h_i}. If we work this out for h_1 and $n = 3$ (see Figure 4.3 and using (4.6)), we get

$$\rho_{h_1} = X_{h_1}\left(\tfrac{1}{3}e_1 X_{h_1} + \tfrac{2}{3}e_2\left(X_{h_1} + X_{h_2}\right) + e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)\right).$$

Similarly for h_2 and h_3 we get

$$\rho_{h_2} = X_{h_2}\left(\tfrac{1}{3}e_1 X_{h_2} + \tfrac{2}{3}e_2\left(X_{h_1} + X_{h_2}\right) + e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)\right),$$
$$\rho_{h_3} = X_{h_3}\left(\tfrac{1}{3}e_1 X_{h_3} + \tfrac{1}{3}e_2\left(X_{h_1} + X_{h_2} + 2X_{h_3}\right) + e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)\right).$$

We observe that for ρ_{h_3} the term following e_2 looks structurally different than for ρ_{h_1} and ρ_{h_2}. This is because household h_3 does not have an effect on e_2 in the identity permutation, while h_1 and h_2 do. Note that for the case $n = 3$, coincidentally ρ_{h_3} is equal to μ_{h_3}. Furthermore, if the power usage of two households is identical, the costs assigned to these households are also identical.

For the total approximate average location costs we get

$$\begin{aligned}\rho &:= \rho_{h_1} + \rho_{h_2} + \rho_{h_3} \\ &= \tfrac{1}{3}e_1\left(X_{h_1}^2 + X_{h_2}^2 + X_{h_3}^2\right) + \tfrac{1}{3}e_2\left(2X_{h_1}^2 + 2X_{h_2}^2 + 2X_{h_3}^2 + 4X_{h_1}X_{h_2} + X_{h_1}X_{h_3} + X_{h_2}X_{h_3}\right) \\ &\quad + e_3\left(X_{h_1} + X_{h_2} + X_{h_3}\right)^2.\end{aligned}$$

Again, these total costs are not equal to the total actual costs as calculated in (4.4). Thus, to determine the costs to be paid by the households when using this pricing mechanism, we have to scale ρ_{h_i} to get the scaled approximate average location cost $\tilde{\rho}_{h_i}$:

$$\tilde{\rho}_{h_i} = \frac{\rho_{h_i}}{\rho}\phi. \tag{4.9}$$

If we have identical power usage for all households, i.e., $X_{h_i} = X$ for all $h_i \in H$, again we get identical costs for all households:

$$\rho_{h_i} = \left(\tfrac{1}{3}e_1 + \tfrac{4}{3}e_2 + 3e_3\right)X^2.$$

This then also holds for the scaled approximate average location costs. Moreover, following the same argumentation as for the average location costs, we do not have that the approximate average location cost function is symmetric.

4.4 General case

In the previous section, we introduced three different pricing mechanisms and applied them to the case of three households, namely the Shapley value, the average location costs, and the approximate average location costs. In this section we generalize the derivation to the case of n households, $h_1, \dots, h_n$.

4.4.1 Shapley value

With a simple generalization of the reasoning in Section 4.3.1 which led to (4.6), we get the following explicit expression for the Shapley value of household h_i if we base the costs on the incurred losses:

$$\phi_{h_i} = X_{h_i} \left(\sum_{j=i}^{n} e_j \left(\sum_{k=1}^{j} X_{h_k} \right) \right).$$

This means that for each cable segment $(j, j+1)$ between household h_i and the transformer (i.e. $j \geq i$), we take the summed power usage of all households using this segment (households h_1 to h_j) and multiply this by the power usage of household h_i. The total cost then becomes:

$$\begin{aligned} \phi &= \sum_{i=1}^{n} \phi_{h_i} \\ &= \sum_{i=1}^{n} X_{h_i} \left(\sum_{j=i}^{n} e_j \left(\sum_{k=1}^{j} X_{h_k} \right) \right) \\ &= \sum_{j=1}^{n} e_j \left(\sum_{k=1}^{j} X_{h_k} \right)^2 . \end{aligned} \tag{4.10}$$

4.4.2 Average location

To derive an expression for the average location cost μ_{h_i}, we need to get some intuition of how the expression is constructed. First of all, note that as we average over all possible permutations p, it does not matter which household we take to calculate the costs, meaning that we end up with the same structural expression for each house. Secondly, as we have n households, we have a total of $n!$ possible permutations. In the previous sections, we have seen that the expression for μ_{h_i} always is of the form

$$\mu_{h_i} = X_{h_i}\left(\sum_{j=1}^{n} e_j y_{i,j}\right), \tag{4.11}$$

where $y_{i,j}$ expresses the contribution of cable segment $(j, j+1)$ to the average costs of household h_i. It remains to find these terms $y_{i,j}$ for each cable segment. Note that only the permutations where household h_i is on a location k with $k \leq j$ contribute to the power usage and therefore to the costs created in cable segment $(j, j+1)$ by household h_i. Thus, only permutations p for which $p(k) = h_i$ with $k \leq j$ have to be considered. For the first cable segment $(1,2)$, this means that only the permutations where $p(1) = h_i$ contribute to $y_{i,1}$. This occurs $(n-1)!$ times out of the $n!$ permutations and each time the power usage on the cable segment is given by X_{h_i}. As we average over all $n!$ permutations, we obtain

$$y_{i,1} = \frac{(n-1)!}{n!} X_{h_i} = \tfrac{1}{n} X_{h_i}. \tag{4.12}$$

For the second segment, we only have to take into account the permutation where $p(1) = h_i$ or $p(2) = h_i$. Each of these options occurs $(n-1)!$ out of the $n!$ permutations. If $p(1) = h_i$, any of the $n-1$ other households h_k with $k \neq i$, appear equally frequent on location 2. This then means that each combination of h_i and h_k on the first two positions occurs in $(n-2)!$ of the overall $n!$ permutations. A similar argument holds for $p(2) = h_i$. This means the contribution in the second cable segment by household h_i to the costs is

$$\begin{aligned} y_{i,2} &= 2\left(\frac{(n-2)!}{n!} \sum_{k=1, k\neq i}^{n} (X_{h_i} + X_{h_k})\right) \\ &= 2\left(\frac{(n-1)!}{n!} X_{h_i} + \frac{(n-2)!}{n!}\left(\sum_{j=1, j\neq i}^{n} X_{h_j}\right)\right) \\ &= \frac{2}{n} X_{h_i} + \frac{2}{n(n-1)} \sum_{j=1, j\neq i}^{n} X_{h_j}. \end{aligned} \tag{4.13}$$

To derive an expression for $y_{i,j}$, note that we only need to take into account permutations where h_i is on location 1 to j. Each option occurs $(n-1)!$ times. If $p(j) = h_i$, any of the $n-1$ other households h_k with $k \neq i$, all appear equally frequent on locations 1 to $j-1$. So, for each h_k, it appears on one of the first $j-1$ positions in $(j-1) \cdot (n-2)!$ of the $n!$ permutations. Similar arguments hold for $p(1) = h_i$ up to $p(j-1) = h_i$. This means the contribution in the j-th cable segment by household h_i to the costs is

$$\begin{aligned} y_{i,j} &= j\Bigg(\frac{(n-1)!}{n!}X_{h_i} \\ &\quad + \frac{(j-1)\cdot(n-2)!}{n!}\Bigg(\sum_{k=1,k\neq i}^{n} X_{h_k}\Bigg)\Bigg) \\ &= \frac{j}{n}X_{h_i} + \frac{j(j-1)}{n(n-1)}\sum_{k=1,k\neq i}^{n} X_{h_k}. \end{aligned} \tag{4.14}$$

Note that (4.14) for $j \in \{1,2\}$ leads to the expressions we derived in (4.12) and (4.13). Combining the contributions of all segments into the costs expression of (4.11), we obtain

$$\mu_{h_i} = X_{h_i}\sum_{j=1}^{n} e_j\left(\frac{j}{n}X_{h_i} + \frac{j(j-1)}{n(n-1)}\sum_{k=1,k\neq i}^{n} X_{h_k}\right). \tag{4.15}$$

This leads to the following total average location costs:

$$\mu = \sum_{j=1}^{n} e_j \frac{j}{n}\left(\frac{j-1}{n-1}\left(\sum_{i=1}^{n} X_{h_i}\right)^2 + \frac{n-j}{n-1}\sum_{i=1}^{n} X_{h_i}^2\right).$$

Similar to the case with three households, we need to scale the average location costs to distribute the actual costs given by (4.7). These scaled average location costs are then the costs as assigned by this pricing mechanism.

4.4.3 Approximate average location

To derive an expression for the approximate average location cost, similar to the average location cost, we need to get some intuition on how it is constructed. Opposed to the average location cost, we now do not take the average over all possible permutations, but for household h_i only the n permutations $p_i^1, \ldots, p_i^n$, as defined in (4.8), are considered. In contrast to (4.15), two households which have the same power consumption X_{h_i} no longer will have identical costs here (although with identical power consumption for *all* households, the costs are the same for all households).

As in the previous section, we use the same structure in the cost function meaning that for each cable segment $(j, j+1)$, we need to find the term $y_{i,j}$ that specifies the contribution of segment $(j, j+1)$ to the approximate average costs of household h_i. Note that only permutations with $p(k) = h_i$ with $k \leq j$ contribute to the power usage and therefore to the costs created in cable segment $(j, j+1)$

by household h_i. For the first cable segment $(1,2)$, this means that only permutations where $p(1) = h_i$ contribute to $y_{i,1}$. This happens exactly once, so the contribution of the first cable segment to the approximate average location costs of h_i is

$$y_{i,1} = \tfrac{1}{n} X_{h_i}.$$

For the second segment, we have to take into account the permutations where h_i is on location 1 or 2. For this, we consider two cases based on the original position i of the household h_i. If $i \in \{1,2\}$, meaning that in its original position the household already contributes to the power usage on the second cable segment, only the identity permutation with $p(i) = h_i$ for all i and the permutation exchanging the first two positions have to be considered. In both of these permutations the contribution to the costs is $X_{h_1} + X_{h_2}$. If $i \geq 3$, meaning the original position of the household is after the second cable segment and does not influence the power usage, only the permutations p_i^1 and p_i^2 lead to a contribution of h_i to the power usage on the second cable segment with values $X_{h_2} + X_{h_i}$ and $X_{h_1} + X_{h_i}$, respectively. The total contribution to the second cable segment of these permutations is $X_{h_1} + X_{h_2} + 2X_{h_i}$. As we take the average over the n possible permutations $p_i^1, \ldots, p_i^n$, this means that the contribution of the second cable segment to the approximate average location costs of h_i is

$$y_{i,2} = \begin{cases} \frac{2}{n}\left(X_{h_1} + X_{h_2}\right), & \text{if } i \in \{1,2\}, \\ \frac{1}{n}\left(X_{h_1} + X_{h_2} + 2X_{h_i}\right), & \text{if } i \in \{3,\ldots,n\}. \end{cases}$$

To derive the expression for $y_{i,j}$, note that we again need to take into account only permutations p_i^k with $k \leq j$. These are the permutations where h_i is on one of the locations 1 to j. Each of these locations is occupied by h_i exactly once. If $i \leq j$, meaning that in its original position the household already contributes to the power usage on the j-th cable segment, then all permutations $p_i^1, \ldots, p_i^j$ lead to a contribution on the power usage of segment $(j, j+1)$ with a value of $\sum_{k=1}^{j} X_{h_k}$. If $i > j$, then for each permutations $p_i^\ell \in \{p_i^1, \ldots, p_i^j\}$, it leads to a contribution on the power usage of cable segment $(j, j+1)$ with value $X_{h_i} + \sum_{k=1, k\neq \ell}^{j} X_{h_k}$. This means that the contribution of the j-th cable segment to the approximate average location costs of h_i is

$$y_{i,j} = \begin{cases} \frac{j}{n} \sum_{k=1}^{j} X_{h_k}, & \text{if } i \in \{1,\ldots,j\}, \\ \frac{j}{n} X_{h_i} + \frac{j-1}{n} \sum_{k=1}^{j} X_{h_k}, & \text{if } i \in \{j+1,\ldots,n\}. \end{cases}$$

	X_{h_1}	X_{h_2}	X_{h_3}	Total costs
Case 1	3	3	3	126
Case 2	3	-9	0	81
Case 3	3	6	9	414

Table 4.1: Power consumption X_{h_i} of each household and resulting total costs for three cases.

Combining the contributions of all cable segments into the costs expression similar to (4.11) leads to

$$\rho_{h_i} = X_{h_i} \left(\sum_{j=1}^{i-1} e_j \left(\tfrac{j}{n} X_{h_i} + \tfrac{j-1}{n} \sum_{k=1}^{j} X_{h_k} \right) + \sum_{j=i}^{n} e_j \left(\tfrac{j}{n} \sum_{k=1}^{j} X_{h_k} \right) \right).$$

Note, that this expression depends on the original location of household h_i, as the summation splits in two different parts depending on the location i. However, if the power consumptions is the same for all households, i.e., $X_{h_i} = X$ for all $h_i \in H$, this dependency disappears:

$$\rho_{h_i} = X^2 \left(\sum_{j=1}^{n} e_j \tfrac{j^2}{n} \right).$$

Summing up the ρ_{h_i} for all $h_i \in H$ gives a total approximate average location cost of

$$\rho = \sum_{j=1}^{n-1} \tfrac{e_j}{n} \left(j \left(\sum_{i=1}^{j} X_{h_i} \right)^2 + j \sum_{i=1}^{n} X_{h_i}^2 + (j-1) \left(\sum_{i=1}^{j} X_{h_i} \right) \left(\sum_{k=j+1}^{n} X_{h_k} \right) \right) + e_n \left(\sum_{i=1}^{n} X_{h_i} \right)^2 .$$

As with the average location costs in the previous section, we need to scale the approximate average location costs to distribute the actual costs by (4.9). These scaled approximate average location costs are then the costs as assigned by this pricing mechanism.

	Case 1						Case 2						Case 3					
	Unscaled costs			Scaled costs			Unscaled costs			Scaled costs			Unscaled costs			Scaled costs		
	h_1	h_2	h_3	h_1	h_2	h_3	h_1	h_2	h_3	h_1	h_2	h_3	h_1	h_2	h_3	h_1	h_2	h_3
Linear	3	3	3	42	42	42	3	-9	0	-40.5	121.5	0	3	6	9	69.0	138.0	207.0
Quadratic	9	9	9	42	42	42	9	81	0	8.1	72.9	0	9	36	82	29.3	117.4	267.3
Shapley	54	45	27	54	45	27	-27	108	0	-27.0	108.0	0	90	162	162	90.0	162.0	162.0
Average	42	42	42	42	42	42	-18	99	0	-18.0	99.0	0	78	168	270	62.6	134.8	216.6
Approx. Av.	42	42	42	42	42	42	-27	117	0	-24.3	105.3	0	75	156	243	65.5	136.3	212.2

Table 4.2: Unscaled and scaled costs for each household in the cases presented in Table 4.1 for different pricing mechanisms.

4.5 Numerical comparison

To get some insight in the differences between the newly introduced pricing mechanisms and some of the well-known mechanisms such as linear and quadratic costs, we provide a numerical comparison of these pricing mechanisms. For this, we use the small example presented in Figure 4.1, and consider three different cases which correspond to a possible morning, afternoon, and evening situation, respectively. In Table 4.1 the power consumption X_{h_i} and the total costs based on (4.4) are given for these three cases. As the focus of this section is on the pricing mechanisms and not on modelling the cables, for simplicity, we assume the cable parameter are $e_1 = e_2 = e_3 = 1$, thereby representing a situation with three identical cables.

The costs for households h_1, h_2 and h_3 calculated with the different pricing mechanisms in the three cases are presented in Table 4.2. The given values are the scaled and unscaled costs for linear costs, quadratic costs, Shapley value costs, average location costs, and approximate average location costs. For the linear costs, which indicates constant prices, we use X_{h_i} to calculate the unscaled costs. For the quadratic pricing, indicating linear prices, we use $X_{h_i}^2$ to calculate the unscaled costs. For each of the pricing mechanisms we then divide the total costs over households according to their ratios (similar to (4.7) and (4.9)) to get the scaled costs.

The results for Case 1, which represent a situation with identical usage, show that the costs are identical for all households for all pricing mechanisms except for the Shapley value. This at least shows a degree of fairness in the (approximate) average location pricing mechanism, and it clearly shows the locational dependency of the Shapley value as we mentioned in Section 4.3.1. In Case 2, household h_1 gets rewarded for its consumption, while household h_2 pays for its production when using the newly presented pricing mechanisms. It is interesting to see that in Cases 1 and 3 household h_3 has to pay more than its Shapley value in all four remaining pricing mechanisms. This is because h_3 causes relatively little losses due to its location close to the transformer, but as it has a high consumption, in an average location it causes a high amount of losses. These observations show clearly that the Shapley value penalizes households further from the transformer, and favours households close to it. For all three cases, the differences between the average and approximate average location pricing mechanism are relatively small. The largest deviation occurs in Case 2, where the difference between the cost according to the average location for household h_1 and h_2 is the largest as well.

Overall, we can state that with the average and approximate average pricing mechanism, we support the strategy that the polluter pays and the ones helping to solve the congestion get rewarded. Also, we see that the costs are hardly locationally biased (especially compared to the Shapley value in Case 3).

4.6 Practical issues

As already mentioned in Chapter 2, within the GridFlex Heeten project innovative pricing mechanisms were developed and tested in a setting with local electricity production and storage. The pricing mechanisms from this chapter were initially planned to be implemented in the field test. However, during the project, different design choices were made and other mechanisms were tested (as described in Section 3.3.2, Chapter 5, and Chapter 6).

Furthermore, during the process, another aspect of the considered pricing mechanism became clear. It was difficult to explain the workings of the mechanism to the project partners and the participants, as the costs for each household might change rapidly, and the emerging costs were perceived as if coming from a black box. Therefore, in the following chapter, pricing mechanisms are designed which explicitly take these aspects into account.

Nevertheless, the pricing mechanisms from this chapter are still useful for other purposes. In case the difficulty of explaining how the prices are set are not important, i.e., with fully automated decision making for smart devices, these mechanisms offer a way to share the costs in a 'polluter pays' fashion based on the losses. These costs normally are heavily influenced by the location in the grid, but we have shown that this influence can be decreased using different notions of an average location in the grid. Moreover, the results from this chapter show that specific network structures and price functions can make the use of the Shapley value computationally feasible.

4.7 Conclusions

In this chapter, we have presented a novel pricing mechanism based on the losses caused by the transport of energy in the LV grid. The mechanism is based on the Shapley value, and supports the 'polluter pays' principle.

As the costs resulting from the mechanism are highly dependent on the location of households in the grid, we presented two alternatives for using average locations of a household in the grid. We have shown that the corresponding prices can be determined efficiently in the case of specific electricity grid structures.

We conclude this chapter with some possible extensions to the presented pricing mechanisms. As we only focused on networks that are represented by a chain, it is of interest to consider also arbitrary radial networks. Although this would require to adapt part of the approach used in this chapter, an efficient approximation should still be possible.

Another interesting question is how households respond to the presented prices in an optimization context, especially considering automatically steerable smart devices, e.g., electric vehicles or heat pumps. Furthermore, it is of interest to investigate the influence of the cable parameters e_j on the resulting prices.

Lastly, as mentioned in Section 4.6, there are still some barriers to implement these mechanisms in existing neighbourhoods. Therefore, it would be crucial to investigate how to overcome these barriers. Chapter 5 further investigates this question.

5

A hybrid pricing mechanism for joint system optimization and social acceptance

Abstract – *This chapter presents a framework for local electricity pricing mechanisms for households designed for social acceptance. The optimization goal of the mechanisms in this framework is to flatten the neighbourhood electricity profile. The motivation and need for such mechanisms result from the expectation that the energy transition leading to high peaks in the distribution grid, both in electricity consumption and renewable generation, posing a significant challenge to the grid. Although quadratic cost functions have the potential to achieve the envisioned system optimization, their drawback is that consumers find the resulting pricing mechanisms too complicated and are generally not willing to participate in systems offering such prices. In contrast, the simpler pricing mechanisms currently used in practice are socially accepted, but these mechanisms lack sufficient incentive to reduce electricity peaks in the distribution grids.*

Our approach is to combine these two concepts in a hybrid pricing mechanism for local energy communities, using a piecewise linear cost function, that approximates a quadratic function. The resulting pricing mechanism is evaluated in the GridFlex Heeten project. Based on the feedback of participating consumers and other criteria defined in literature, we conclude that the proposed mechanism is socially accepted. The performance of the hybrid pricing mechanism can be improved such that it obtains results comparable to those of quadratic cost functions. A detailed numerical evaluation and the results from the field test indicate that the presented pricing mechanism has the potential for being used in practice.

This Chapter is mainly based on [VR:1] and [VR:2].

5.1 Introduction

Traditionally, the electricity grid was built to distribute electricity from centralized power generation to households and other consumers. However, nowadays, more and more renewable energy is injected into this grid at a decentralized level. This renewable generation has a highly intermittent character and creates enormous peaks in the supply of electricity. Furthermore, due to the current electrification, electricity loads will also increase drastically in the near future and place an additional burden on the distribution grids. In particular, the charging of electric vehicles (EVs) may lead to immense peaks in the local part of the electricity grid due to their synchronous occurrence. However, the distribution networks are not well prepared for such increased peak demands and intermittent generation. Therefore, we need to either invest heavily in upgrading the network, or reduce the expected peaks by spreading the loads responsible for these peaks more evenly, using, e.g., demand-side management or demand response [148].

One demand response method for reducing peaks in electricity consumption is to use dynamic electricity prices. The resulting price variations may encourage (residential) consumers to modify (the timing of) their electricity usage, thereby unburdening the grid. In addition, smart appliances may automatically react to such prices without reducing the comfort of the consumer (see, e.g., [47]).

At a single household level, the available smart appliances generally do not provide sufficient flexibility for completely flattening the consumption profile of that household. Therefore, we focus on flattening the profile of a group of households in a specific part of the grid: a neighbourhood or local energy community. The advantage is that now the system can support the households in flattening their *combined* peaks.

A further reason to focus on the neighbourhood level is that people are in general more eager to participate in initiatives when there is a local incentive together with social cohesion [115]. In addition, to achieve the required amount of flexibility, consumers have to be convinced to enable this flexibility for the overall neighbourhood goals [53]. Thus, to ensure consumer participation in a pricing mechanism, social acceptance needs to be considered as well. However, this important aspect is often ignored in research [151].

Literature in this direction distinguishes two branches of research. Firstly, some studies focus on simple mechanisms for single households where the consumer is only a price taker (see, e.g., [61], [22], [174]). These mechanisms may not lead to a sufficient change in the energy profiles to solve the problems in the local grid, and they may even worsen them (see, e.g., [105]). Secondly, some studies focus on more complex mechanisms incorporating multiple households, where consumers are both price takers and makers. However, these mechanisms make it quite complicated for consumers to determine the prices and to determine how to adapt their behaviour (see, e.g., [178], [172], or [1]). As for our envisioned mechanisms, the participation of the consumers is a crucial element and our proposed approach takes the viewpoints of consumers on such mechanisms as a starting point.

Based on the aspects mentioned above, our aim is to present a hybrid pricing mechanism for a neighbourhood behind one medium-to-low-voltage (MV/LV) transformer, combining unburdening the grid by lowering the electricity peaks, and social acceptance. To achieve this, we aim to ensure that the consumers understand and accept the underlying concept of the pricing mechanism.

In this chapter, we present a framework consisting of multiple similar neighbourhood pricing mechanisms all supporting this two-fold aim. The used electricity prices for the households depend on the total load at the transformer. This implies that all neighbourhood inhabitants pay the same price per unit of electricity and these prices can differ throughout the day.

Summarizing, the main contributions of this chapter are:

» An analysis of current pricing mechanisms for both system optimization and social acceptance, discussing their advantages and disadvantages.

» A framework for creating hybrid pricing mechanisms for a neighbourhood or energy community that perform well on both system optimization and social acceptance, based on a piecewise linear approximation of a quadratic cost function.

» A technique to speed up the convergence of the proposed mechanisms when used in optimization algorithms.

» An extensive numerical evaluation of the proposed hybrid pricing mechanism, including a comparison to other pricing mechanisms, based on simulations and a field test within an energy community.

The remainder of this chapter is organized as follows. First, in Sections 5.2 and 5.3, we discuss existing concepts of system-based pricing mechanisms and socially acceptable pricing mechanisms, respectively. This is followed by the introduction of our hybrid pricing mechanism in Section 5.4 and a description of the implementation of the pricing mechanism in an optimization algorithm in Section 5.5. Then, in Section 5.6, we evaluate and compare the performance of the resulting hybrid pricing mechanism. This chapter is concluded in Section 5.7, where also recommendations for further research are given.

5.2 System-based pricing mechanisms

In this section, we describe the formal setting and the considered pricing mechanisms. Given are a set $\mathscr{H} = \{1,\ldots,H\}$ of households in a neighbourhood (a group of households connected to the same part of the grid) and a time horizon divided into a set $\mathscr{T} = \{1,\ldots,T\}$ of consecutive time intervals. Let

$E_t = \left(e_t^1, \ldots, e_t^H\right)$ denote the electricity demand of the households in time interval t, where e_t^h is the electricity consumption of household h in time interval t in kWh.

The general model for the costs is given by a price function $p_t^h(E_t)$ that specifies the price per kWh depending on the consumption vector E_t for each time interval $t \in \mathcal{T}$ and each household $h \in \mathcal{H}$. This allows for the modelling of a variety of different price functions, such as, e.g., a constant price, a time-dependent price, but also a price that depends on the electricity consumption e_t^h of household h, or on the sum $S_t = \sum_h e_t^h$ of the electricity consumption of all households in interval t. Based on this price function, the cost function for a household results from multiplying the consumption of a household with the price function:

$$c_t^h(E_t) = p_t^h(E_t) e_t^h.$$

The total costs of all households in time interval t then can be expressed as $C_t(E_t) = \sum_h c_t^h(E_t) = \sum_h p_t^h(E_t) e_t^h$. As these costs heavily depend on the price function $p_t^h(E_t)$, we discuss some possible design choices for this function in more detail.

Under static Time of Use (ToU) pricing (see Section 3.2.2.2), all prices are set beforehand, so $p_t^h(E_t) = p_t$. This type of pricing gives consumers certainty about the price they have to pay, but this does not incentivize them to avoid higher peaks caused by synchronized loads [105]. An alternative is to have dynamic prices, where these prices are not set up front but depend on the electricity consumption. There are multiple choices for such dynamic pricing strategies. For example, they may depend on the electricity consumption of the individual household ($p_t^h(E_t) = p_t^h(e_t^h)$), or on the consumption of the neighbourhood ($p_t^h(E_t) = p_t(S_t)$). An important reason to use dynamic prices is that they may provide incentives to alleviate congestion on the grid [79].

These dynamic prices $p_t^h(E_t)$ may be set beforehand (a certain amount of hours ahead of time), making the resulting cost more predictable and, therefore, more socially accepted by the consumers. Alternatively, the price could be set in real-time, taking into account more actual information, e.g., on the congestion. However, this makes it more difficult for consumers to determine the price they need to pay in advance.

If pricing mechanisms aim to support a system-based perspective, the goal of the system has to be defined first. In this chapter, we already mentioned that we want to flatten the electricity profile, so the system goal is peak minimization.

Minimizing the peaks improves the power quality, and minimizes the energy transport losses [148]. As the losses cause depreciation of the assets in the grid (e.g., the cables and the transformer), lowering these losses can result in a prolonged lifetime of these assets [56]. Similarly, with lower peaks, investments needed to upgrade the assets can be deferred [148]. Furthermore, peak demands are covered mainly by more polluting energy sources, such as natural gas and oil [34, 153]. Therefore, by avoiding high peaks, we reduce the CO_2 output.

With the total neighbourhood electricity consumption S_t, this goal can be expressed, similar as done in [47], by

$$\begin{aligned} \min_{e_t^h} \quad & \sum_t (S_t)^2, && (5.1)\\ \text{s.t.} \quad & S_t = \sum_{h \in \mathscr{H}} e_t^h, && \forall t \in \mathscr{T} \\ & e_t^{h,min} \leq e_t^h \leq e_t^{h,max}, && \forall t \in \mathscr{T}, \forall h \in \mathscr{H} \end{aligned}$$

where $e_t^{h,min}$ and $e_t^{h,max}$ are the permitted range for the energy consumption that each household h can attain, given their flexible loads. As the focus of this chapter is not to create a mathematical model of the flexibility in a household, the values of $e_t^{h,min}$ and $e_t^{h,max}$ are considered to be known.

Note that by squaring electricity consumption, the highest peaks get penalized the most. Optimizing over this goal results in the flattest electricity profile.

To reach the objective (5.1), a natural choice is to have the costs related to the square of the consumption, i.e., to have $C_t(E_t) \approx (S_t)^2$. Besides corresponding to the objective, this choice is also motivated by the marginal costs of electricity in peak hours scaling quadratically with respect to the consumption [159]. If we furthermore assume that the price functions are independent of the households, meaning that each household is given the same price of electricity, we get $c_t^h(E_t) = p_t(E_t)e_t^h$. This results in a total cost of:

$$\begin{aligned} C_t(E_t) &= \sum_h c_t^h(E_t) \\ &= \sum_h p_t(E_t)e_t^h \\ &= p_t(E_t)S_t. \end{aligned}$$

Since we aim for $C_t(E_t) \approx (S_t)^2$, the price function has to fulfil $p_t(E_t) \approx S_t$. This leads to costs for an individual household that are quadratic with respect to their consumption:

$$c_t^h(E_t) = p_t(E_t)e_t^h \approx S_t e_t^h = \left(e_t^h\right)^2 + e_t^h \left(\sum_{i \in H \setminus \{h\}} e_t^i \right).$$

Note that this may lead to costs for delivering electricity back to the grid. However, from a network perspective, this makes sense, especially when the pricing mechanism aims to lower the peaks, also those arising from energy production.

Quadratic costs have already shown their effectiveness in the literature:

» In [84] a linear wholesale price is used, which gives a quadratic cost for the consumers, that they can use to optimize over.

» In [133] quadratic costs are assigned to the "transformer"-aggregator, which transfers the costs to the consumers.

» In [111] losses are minimized as the central objective, which is quadratic in the consumption. The consumers then have approximately linear costs, and the resulting problem is solved using ADMM.

» In [112] quadratic costs are assumed for an aggregator, and these costs are minimized while charging EVs.

» In [182] a quadratic cost function is used to maximize the welfare of customers in a peer-to-peer trading model.

Next to the above, other pricing mechanisms supporting different system objectives have been used in literature:

» In [147] the Shapley value is used to attribute the losses.

» In Chapter 4, we proposed a mechanism where the prices are created based on the Shapley value to minimize losses based on households getting an average location in the grid.

» In [92] real-time pricing is used such that individual best responses coincide with the system objective.

» In [72] a congestion game is presented to come to dynamic prices for the grid.

» In [38] different locational marginal prices based on carbon-related costs are used to lower the carbon emissions.

Pricing mechanisms, such as those mentioned above, aim to steer an electricity profile of a household or neighbourhood to a best possible solution for a given goal in an iterative way. The reason that this best solution is achieved in an iterative fashion and cannot be achieved in one step is that the individual households do not know beforehand what the values of the neighbourhood electricity consumption E_t or the total neighbourhood consumption S_t are, as it is unknown to the individual households how the other households respond to the prices. Based on an initial prediction of the electricity profile S_t of the neighbourhood, individual households get price information and utilize their flexibility accordingly. However, this may lead to an overshoot or undershoot in some time intervals. Therefore, updated prices based on the planned electricity profiles are sent to the households. This is iteratively done until no, or only minor, changes in the profiles are made (see Figure 5.1 for a schematic overview), meaning that the process has converged. This convergence process typically takes seconds, or at most a few minutes. Only then, the definitive prices for the coming time interval(s) are set. Depending on the chosen method and the pricing mechanisms, the electricity profile may come close to or precisely be the optimal profile.

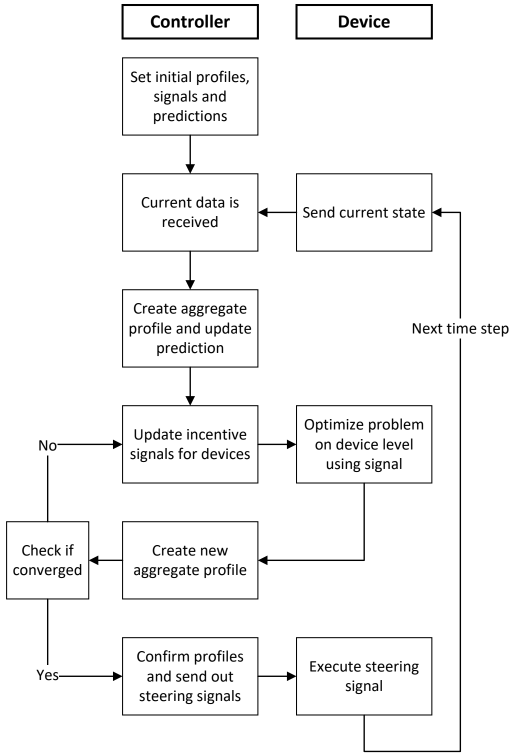


Figure 5.1: Flow of iterative energy management algorithms.

Although the introduced linear prices, and thus the quadratic costs, have advantages from a system-based perspective, there are issues with these prices on a social level. For example, it is difficult to convince people to participate in these pricing mechanisms due to their unpredictable and complex nature. When only focusing on technocratic aspects of mechanisms (i.e., technological experts deciding on bureaucracy), consumers likely will not accept a change towards such new pricing mechanisms, especially when these changes are mandatory. Examples of rejections of forced technological solutions can be found, e.g., in the roll-out of smart meters in the Netherlands, which only considered technical and commercial aspects. As a result, a lot of resistance still exists [63]. Another example can be found in the forced smart metering and Time of Use prices in Australia, where people heavily resisted this change [51].

A further aspect that makes people hesitant to use linear prices, is that the prices continually change over time, and even minor differences in the electricity consumption may lead to substantial differences in the costs. In [117], the unpredictability of the prices for consumers was seen as a significant point for people judging these prices as unfair. However, the fairness of prices as perceived by the consumers is seen as an essential criterion for regulators [78]. Therefore, there is a need for pricing mechanisms that take fairness into account as well as acceptance by consumers.

5.3 Socially-acceptable pricing mechanisms

As concluded in the previous section, it is crucial to consider how consumers perceive pricing mechanisms. When the mechanism is too complicated, or it is unclear to the consumers how much they have to pay, it will be difficult to convince them to use these mechanisms [31, 117]. Furthermore, oversimplifying the explanation to consumers alienates them, thereby preventing to unlock their full potential [9]. Examples can be seen in the difficulties for energy research projects to get participants. Within the e-Balance project, it was noted that the difficulty in understanding both the energy system and usage of smart appliances led to reduced cooperation of users [129]. Furthermore, the final document of JEM 2.0 [77] reports that it was challenging to have consumers participating in the project when the financial aspects were not directly apparent (in their case, the prices were dynamically updated via the Dutch spot market prices).

Looking at current practice, the implemented models used for electricity pricing are often simple. The price of electricity is offered as a constant price (or perhaps as a static Time of Use price). For the Netherlands, even the network costs are constant [6]. Consumers rate these constant prices fairer than a price that is more complex [117]. However, these 'simple' prices do not reflect the actual costs occurring in the system. Additionally, the resulting network costs will increase drastically with the expected increase in loads, showing that the current pricing mechanisms are not future-proof.

Nevertheless, there are already examples of socially acceptable pricing mechanisms that provide some incentive to unburden the grid, e.g., time-dependent constant prices (Time of Use prices). Furthermore, an often-used example is peak pricing, where a grid operator can raise the price of electricity a few times a month or year when the grid is extremely congested. Practice shows that these schemes can reduce peaks [154]. However, these mechanisms also have their disadvantages, as they may even increase the synchronization of loads, e.g., for charging electric vehicles, thereby creating large peaks in the grid [102, 105].

Introducing thresholds that require either no action from the consumer, or require a lot of flexibility, such as those resulting from peak pricing, can lead to undesirable behaviour for the network. This behaviour was observed in a previously proposed price model from the Distribution System Operators (DSOs) in the Netherlands and Belgium. Here, the consumer can choose a specific contractual capacity (lower than the maximum physical capacity) in advance. If the consumer exceeds this contractual limit, they pay a fee proportional to the energy (in kWh) exceeding the limit [59]. Even though this model encourages consumers to stay within their contractual capacity, it does not support the previously-mentioned goal of unburdening the grid, as it may still be possible that all consumers are just below their maximum contracted capacity but jointly congest the network. Moreover, the scheme does not support neighbours who 'cancel out' their joint peaks, e.g., when one of the neighbours has a large PV installation and the other has a large load during the daytime. A solution for this is to consider a neighbourhood as a whole.

A further disadvantage of the model mentioned above is that a consumer with an electricity profile, where the load exceeds the contractual limit by an amount $\bar{e}$ in two intervals, is penalized by the same amount as a consumer who exceeds the limit during one interval by $2\bar{e}$. This is because the fee is proportional to the energy and not to the maximum power. However, the latter consumer has a higher probability of causing a larger peak, implying that the model does not discourage having one large peak instead of multiple smaller peaks.

Based on the considerations in this section, we present a hybrid pricing mechanism in the next section that addresses the stated issues.

5.4 Hybrid pricing mechanism

This section present a framework for creating the hybrid pricing mechanisms, along with a few possible economic implications, results from the implementation of such a pricing mechanism in a field, and an observation on the optimal electricity profile resulting from the mechanisms.

5.4.1 Definition

The hybrid pricing mechanism we propose in this work combines the system-oriented and the socially-acceptable regimes. It is based on prices that grow linearly with the neighbourhood electricity consumption S_t, implying quadratic costs. More concrete, the price for each additionally consumed or produced kWh is chosen as a staircase function (see the blue solid line in Figure 5.2), which represents a piecewise linear cost function.

Mathematically, this is expressed as

$$p_t(S_t) = \begin{cases} a_1, & \text{for } S_t \leq b_1, \\ a_2, & \text{for } b_1 < S_t \leq b_2, \\ \vdots & \vdots \\ a_{m-1}, & \text{for } b_{m-2} < S_t \leq b_{m-1}, \\ a_m, & \text{for } b_{m-1} < S_t, \end{cases} \tag{5.2}$$

where m is the number of pieces of the price function, $b_1, \ldots, b_{m-1}$ represent the breakpoints at which the electricity price changes, and $a_1, \ldots, a_m$ are the corresponding prices per kWh for the additional consumed or produced electricity in that piece. Here, we assume that $a_1 \leq \cdots \leq a_m$ to ensure the cost function

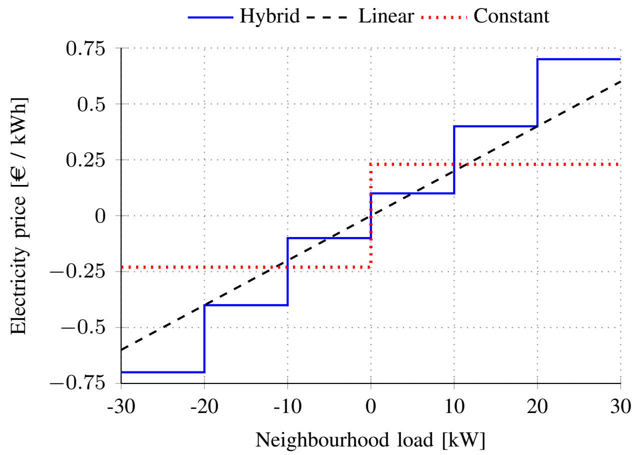


Figure 5.2: An example of the proposed hybrid price function p_t compared to a linear and a constant price function.

is convex. W.l.o.g., we assume that one of the breakpoints $b_1, \ldots, b_{m-1}$ is at 0 and we let b_i be this breakpoint, i.e., $b_i = 0$. Then, for a positive electricity consumption $\bar{S}_t$, given that $b_{j-1} < \bar{S}_t \leq b_j$, the cost is calculated as

$$c_t(\bar{S}_t) = \sum_{k=i+1}^{j-1} a_k(b_k - b_{k-1}) + a_j(\bar{S}_t - b_{j-1}). \tag{5.3}$$

For a negative electricity consumption, a corresponding formulation can be given. This pricing mechanism can be compared to tax brackets in which higher incomes are taxed progressively higher [130]. By choosing the price functions in this way, we get a pricing mechanism that provides an incentive to reduce the peaks. From a system perspective, optimization based on this function still leads to an approximation of the profile we would get with the quadratic cost function, albeit with slower convergence (i.e., more iterations in Figure 5.1) as it only approximates the quadratic function (see Figure 5.3). Note that transforming a pricing mechanism into a piecewise linear price is not a new principle and has been shown to work well (see, e.g., [39] or [124]). Also, in other fields, similar mechanisms that use such piecewise linear functions are in place, like, e.g., the aforementioned progressive tax schemes [14].

From a social perspective, this mechanism has advantages, as this mechanism can be seen as a combination of a transport tariff with peak pricing, which consumers assess as more fair than a flat rate or a complex pricing mechanism [117]. On the other hand, a study carried out in Great Britain indicates that consumers are still somewhat hesitant to accept Time of Use tariffs, especially when these tariffs are dynamic [42].

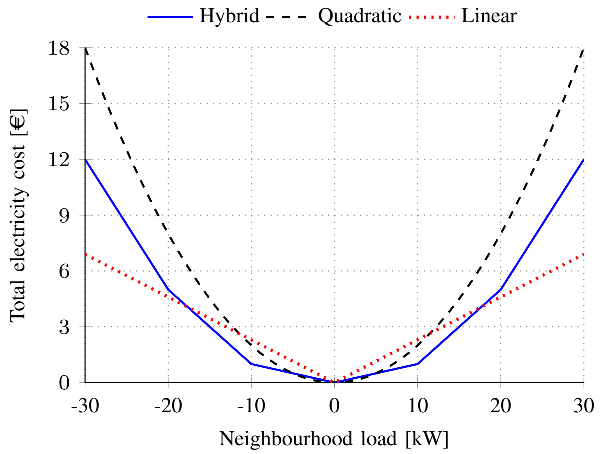


Figure 5.3: An example of the proposed hybrid cost function c_t compared to a quadratic and a linear cost function.

Moreover, Naus et al. [115] report that people are more attracted to local solutions where social cohesion plays a role. They also found that the financial schemes need to make sense to the consumers and, therefore, preferably have only a few different tariff blocks per day. The pricing mechanism proposed in this chapter stems from the spatial proximity of the involved consumers, as the mechanism depends on the collective consumption of the set of households in a neighbourhood. Furthermore, there are only a few different tariffs per day because, even though the neighbourhood electricity consumption S_t changes continuously over time, only when S_t crosses a boundary b_j, the consumers experience a different price. This indicates that the proposed pricing mechanism represents a desired financial scheme such as characterized in [115].

Note that in this chapter, we mainly propose a framework for setting up a pricing mechanism. To implement the mechanism in a community, it needs to be tailored to the neighbourhood, as can be seen in the specific case of GridFlex Heeten (see Section 3.3.2 and Section 6.4.1 of this thesis).

5.4.2 Economic effects

One of the goals of the pricing mechanisms proposed in this chapter is to give the community the possibility to obtain savings on their electricity bills by using their flexibility. To implement such a mechanism, the energy community can take the role of an aggregator (or contract an existing aggregator) to supply their energy. The aggregator could then negotiate for compensation by the DSO when the community is using the network to a lesser extent and creating fewer peaks. This results in prolonging the lifetime of the assets, which is beneficial for the DSO. Furthermore, the aggregator also could get lower rates for supplying energy, as the electrical load of the community is more predictable and flatter. As already mentioned in Section 5.2, a flatter profile is better for a supplier, as the cost of generators rises quadratically with the load.

Another option for the aggregator is to set the prices a_i depending on the electricity market. This may be done by changing the prices within a billing period, or even daily, to better reflect the supply and demand of electricity. However, this could also lead to lower acceptance of the pricing mechanism due to the uncertainty in the costs [117].

While the pricing mechanism proposed in this chapter is developed for residential users, including commercial and industrial users is also a possibility. However, when communities consist of different types of consumers, the prices must be set carefully to ensure that these tariffs are fair for all consumers. An alternative in such a situation would be to split up these different types of consumers in terms of pricing, while they still jointly try to flatten the peaks of their network.

The obtained savings of the energy community can either be used for a communal goal (e.g., acquiring communal PV panels or improving a neighbourhood playground) or can be settled directly with the inhabitants (e.g., pro rata, or equally shared) as a deposit for the next billing period. It is important to engage the members of the energy community in all phases of creating the energy community to get local support for the ideas and the pricing mechanism, so also for deciding how to distribute the savings [86]. An example of how a community could deal with this can be found in Chapter 6, where the participants of the GridFlex Heeten project chose to use their savings to buy a defibrillator for their neighbourhood and train several inhabitants in using it. More information on this project is given in the next section.

5.4.3 Field test results

The pricing mechanism proposed in this chapter was implemented within the GridFlex Heeten project. In this project, the partners aim to reduce peaks and better match supply and demand by innovative pricing mechanisms in combination with local energy production and storage (see Chapter 2). All households behind one transformer in a neighbourhood in Heeten, the Netherlands, were outfitted with a home energy management system (HEMS). Additionally, batteries were installed in some of the households. The goal of this neighbourhood was to keep the load on the neighbourhood transformer low. The used incentive for this was the hybrid pricing mechanism, where their savings were used for a communal goal [55]. This goal was chosen by the participants during co-creation sessions.

In the used implementation of the hybrid pricing mechanism, five different pieces were used in the cost function (so $m = 5$ in (5.2)). The participants of the project received this price information on a mobile app. Flyers explaining the mechanism were distributed to the participants, and information meetings were held to clarify the concepts. To test the understanding of consumers concerning the proposed pricing mechanism, interactive workshops with several consumers participating in the project were conducted. During these workshops, the participants indicated that they understood the idea behind the mechanism and found it suitable. These co-creation sessions were also used to tailor the mechanism and goal to the community, determine the way to inform them of the prices, and to increase the acceptance and effectiveness of the pricing mechanism.

5.4.4 Limit behaviour

If sufficient flexibility is available, ideally, a pricing mechanism would stimulate consumers to create a perfectly flat electricity profile. If all customers do this, the resulting flat profile coincides with the global optimal solution of (5.1). In the case of the proposed pricing mechanism, it is optimal to keep the neighbourhood electricity consumption in that piece of the price function where $|a_i|$ is the smallest. In the example from Figure 5.3, this is between -10 and 10 kW. When the neighbourhood electricity consumption is at this global optimum, individual consumers have no incentive to change their electricity profile, as changing the consumption such that it would no longer be in the same piece would increase the price and, as a result, the costs for the consumer. Therefore, the only price-neutral change of the consumption would be within its piece. With sufficient flexibility, all time intervals have the same price, so there is no incentive to shift loads between intervals. This means there is no incentive for any individual consumer to change their electricity profile, i.e., this solution is a Nash equilibrium [114]. So with this hybrid pricing mechanism, if sufficient flexibility is present for all customers, the global optimum coincides with an optimal solution for the individual consumers, and a flat profile is obtained.

5.5 Implementation

The pricing mechanism specified in the previous section performs well on both social acceptance and peak shaving. To use such a pricing mechanism in a neighbourhood, the inhabitants have to enable their flexibility and either activate their devices manually, or give a home energy management system (HEMS) the possibility to automatically steer their devices. For the latter case, the pricing mechanism needs to be integrated into an algorithm. This algorithm can then, in an iterative way, determine the optimal electricity profile as already illustrated in Figure 5.1. As mentioned in the previous section, a naive implementation of the hybrid pricing mechanism converges slower to the optimal electricity profile than when using a quadratic cost function.

However, to speed up the convergence and have it on par with that of a quadratic cost function, we can use a result from [140]. For this, we add a small quadratic term to the cost function for the computation of the optimal solution. Note that this term only improves the convergence speed, but the solution of the optimization and, therefore, the actual costs for the consumers remain the same.

The motivation for adding this term is based on Section 5.2 of [140]. This article shows that the operation of storage devices in energy systems is an instance of a specific class of optimization problems, as long as the cost function is convex. The results in our chapter apply to that class of optimization problems, as our cost function c_t from (5.3) is convex by design. The other restrictions on the objective, constraints, and variables in [140] also align with the optimization problem discussed in our chapter.

Adding a fixed quadratic part to each linear piece of the hybrid cost function c_t makes it strictly convex and even strongly convex, which we use later. Formally, for the strictly convex cost function c_t^* we get $c_t^*(\bar{S}_t) = c_t(\bar{S}_t) + \epsilon \bar{S}_t^{\,2}$, with $0 < \epsilon \ll 1$. Corollary 3 of [140] states that for the given problem, the optimal solution of the strictly convex cost function c_t^* is also optimal for the convex cost function c_t. Thus we can replace c_t by c_t^* during the optimization process to obtain the optimal solution with fast convergence. Fast convergence here means we can get a guaranteed linear convergence, which we will discuss further in the next section. With the added term, we now have a pricing mechanism that performs well in optimization, both in convergence speed and solution quality, and also in social acceptance.

5.6 Numerical evaluation

In the previous sections, we presented a hybrid pricing mechanism aimed at social acceptance, which also performs well in optimization. To analyse its potential compared to other types of pricing mechanisms and steering methods, we use a numerical evaluation, where we simulate a neighbourhood with a HEMS and a battery in each house. Furthermore, we present an analysis of the performance of the hybrid pricing mechanism in the GridFlex Heeten project. In both cases, the goal of the households is to minimize the total electricity cost of the neighbourhood with respect to a given cost function. This means that the households do not optimize their individual costs.

The choice to optimize on a neighbourhood level was made for several reasons. Firstly, as mentioned before, by having social cohesion on a local level and working towards a common goal, consumers are more eager to participate [115]. Secondly, the energy management system is easier to implement on a neighbourhood level, also resulting in faster convergence. Thirdly, as mentioned in Section 5.4.4, with sufficient flexibility, the neighbourhood optimum coincides with the optimal solution for the individual consumers (a Nash equilibrium).

Our aim is to investigate if minimizing the costs also leads to minimizing the system-objective, namely minimizing the peaks (see (5.1)). In the evaluation, we compare the effects of four types of steering methods:

» Using no steering (NO)

» Minimization of a quadratic cost function (QC)

» Minimization of the hybrid pricing mechanism (HPM)

» Using profile steering (PS)

When no steering signals (NO) are given, the batteries in the households are simply not used, and the resulting profiles are the electricity consumption profiles of the households without the use of a battery (reference case). The second option uses the quadratic cost function (QC) and is expected to achieve the global system optimum (as described in Section 5.2). The hybrid pricing mechanism (HPM) is the third option and uses the speed-up described in Section 5.5, while optimizing on a neighbourhood level. Lastly, profile steering (PS) is a decentralized control strategy sending desired power profiles as steering signals to the households that, in turn, flatten their load based on these signals [47]. In context of Figure 5.1, when creating a new aggregate profile, PS only selects the device that contributes most towards decreasing the global objective value to update its profile and then updates the desired power profile accordingly.

To implement the steering methods based on QC and HPM, we used an adapted version of the Alternating Direction Method of Multipliers (ADMM) algorithm from [136]. ADMM is an iterative optimization method in which a large optimization problem (in our case: flattening the electricity profile of the neighbourhood according to a cost function) is subdivided into many smaller optimization problems (flattening the electricity profile of each household according to a separate cost function) that can be solved more efficiently, while jointly solving the overall problem [17]. In context of Figure 5.1, with QC and HPM all devices simultaneously are updated in each iteration, in contrast to PS.

5.6.1 Simulation setup

The simulations were executed using DEMKit [66], the Decentralized Energy Management toolKit. As input, we used real data from the GridFlex Heeten project [VR:4]. This dataset consists of 70 Dutch households, with minute-granularity data on a household level. For our base case, we use data from 45 households on the 21st of September 2019, each with a virtual battery having a capacity of 5.4 kWh and a maximum (dis)charging power of 2.7 kW. Furthermore, we assume to have perfect predictions of the neighbourhood electricity consumption for the next 48 hours.

In each of the following subsections, we focus on one specific aspect of the base case and vary it to determine its influence on the performance of HPM by comparing it to NO, QC, and PS. First, in Section 5.6.2, the effect of PV production is investigated by selecting different input days. Then, in Section 5.6.3, we include EVs in the simulations to demonstrate the difference between charging the EVs controlled or uncontrolled. Varying the battery capacity and maximum power

Method	Parameter	Value
ADMM (QC and HPM)	Maximum iteration count	90
	δ	1
	μ	10
	ϵ^{pri}	4.6
	ϵ^{dual}	2.5
	τ^{incr}	2
	τ^{decr}	2
PS	Maximum iteration count	90
	Multiple commits	False
	Minimum improvement	10^{-6}

Table 5.1: Parameters of the steering methods as used for the simulations.

is considered in Section 5.6.4. The effects of changing the used prediction and planning procedure are discussed in Section 5.6.5. Furthermore, the performance of the methods when scaling up the simulations is studied in Section 5.6.6.

To quantify the performance of the steering methods described above, they are compared on two performance indicators: the objective value according to (5.1) and the total computation time. These values are calculated as averages over 25 runs with the same parameters to get a representative range of behaviours of the algorithms in DEMKit. These runs simulate a single day and only differ in the random seeds used to vary the input.

The base simulation without any steering (NO) takes some time to execute, therefore, we focus mainly on the added computation time of the steering methods, which is the difference between the total computation time of NO and the total computation time of the steering method. Although these computation times depend heavily on the implementation, they still provide a good impression of the performance of the different methods.

The simulations were conducted on a Dell Precision 3510 with a quad-core Intel Core i7-6700HQ and 16 GB RAM. For all steering methods, we set a maximum on the iteration count (the number of convergence checks in Figure 5.1 after which it is forced to 'Yes') to limit the computation times. For the ADMM algorithms of QC and HPM, we used the parameters following [136]. For PS, we used the default values and model structure as mentioned in [70]. The overview of the chosen values for the parameters is in Table 5.1.

5.6.2 Influence of PV production

As the PV generation profile of a household can be capricious, we first check how our method deals with different levels of volatile PV production.

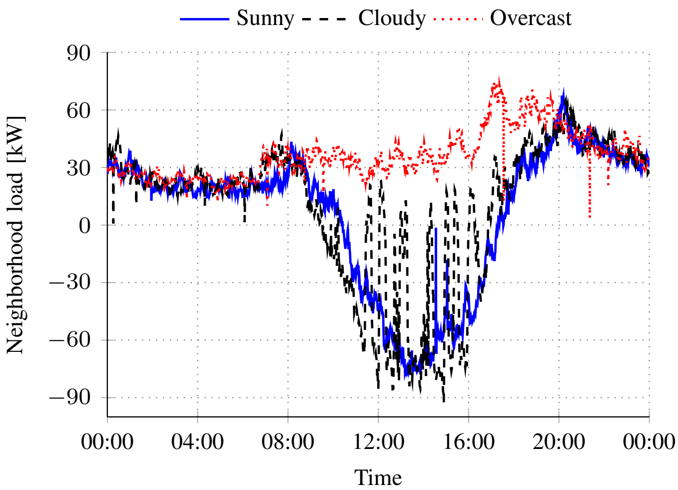


Figure 5.4: Total power profiles of all households for a sunny, cloudy, and overcast day.

To test this, we use PV profiles based on different weather types (i.e., different input days) for the simulations. The question then becomes how the other methods perform given various PV productions. We used three weather types: sunny, cloudy, and overcast. For the sunny day, we used data from the 21st of September 2019. The cloudy day was on the 2nd of October 2019, and, lastly, the overcast data is from the 18th of November 2019. The total energy profiles of all households on these days are given in Figure 5.4.

As mentioned, we take the base simulation and vary only the weather type to compare the performance of the steering methods on the performance indicators. For all three weather types (sunny, cloudy, and overcast), QC, HPM, and PS perform identically in terms of the objective value (with a slight deviation for cloudy weather between PS and the others). All lead to significant improvements compared to NO, achieving a decrease of between 50.1% and 94.4% of the objective value of NO (see Table 5.2). With overcast weather, there is hardly any PV energy to store and later use to flatten out peaks. Consequently, these objective values are the highest.

For the computation times, the results of the different weather types are comparable to each other. For all weather types, with NO, the total computation time averages around 44 seconds, where HPM takes around 82 seconds and QC approximately 92 seconds. PS performs the worst, ranging between 194 and 312 seconds. Again, see Table 5.2 for the complete table with all results.

Weather type	Method	Objective value	Computation time (s)
Sunny	QC	20 841	93.6
	HPM	20 841	86.0
	PS	20 841	312.7
	NO	375 022	44.3
Cloudy	QC	52 663	92.2
	HPM	52 663	81.4
	PS	52 722	276.4
	NO	409 032	44.7
Overcast	QC	277 711	91.0
	HPM	277 711	81.5
	PS	277 711	194.1
	NO	556 162	42.8

Table 5.2: Objective value according to (5.1) and the total computation time for the profiles resulting from QC, HPM, PS, and NO under different PV production conditions.

5.6.3 Influence of EVs

The energy consumption of households is significantly influenced by the presence of EVs that need to charge. As the market share for EVs is quickly rising, the effects of EV charging need to be considered [173]. Already when 20% of the households have an EV, issues in the grid arise [119]. This stresses the importance of simulating such a case and demonstrating the effect of the steering methods on the charging of EVs.

For this, we include nine EVs in the simulation of the base case, corresponding to a penetration of 20%. All EVs are assumed to have a total capacity of 60 kWh and a charging and discharging power limit of 7.4 kW, corresponding to 32A single phase charging with the option to use vehicle-to-grid (V2G). The EVs arrive at the households between 16:00 and 19:00, at which point the battery has between 15 and 45 kWh left and needs to be fully charged when leaving at a given time between 6:00 and 9:00 the next day. For each EV, we pick an arrival time, leftover charge, and departure time uniformly at random, independent of the other EVs.

As we want to demonstrate the effect of charging the EVs overnight, we extend the base case by one day and compare the following cases: the base case extended to two days without EVs, uncontrolled charging (charging at maximum power directly when plugged in, without batteries), and controlled charging with QC, HPM, and PS (all with batteries). Figure 5.5 shows the difference between uncontrolled and controlled charging, resulting in reduced peaks of over 80%.

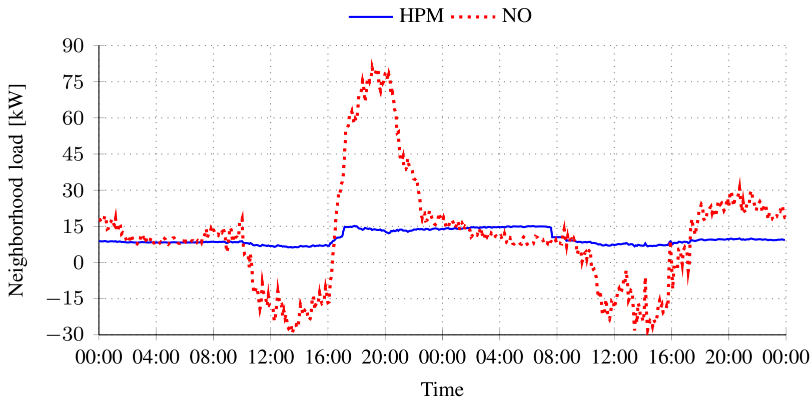


Figure 5.5: Total power profiles of the simulated households with EVs using uncontrolled charging (NO) and controlled charging (HPM).

EV	Method	Objective value	Computation time (s)
Controlled charging	QC	315 102	151.7
	HPM	316 878	133.4
	PS	315 102	2 736.1
Uncontrolled charging	NO	1 898 972	41.6
None	NO	763 555	42.2

Table 5.3: Objective value according to (5.1) and the total computation time for the profiles resulting from QC, HPM, PS, and NO with different EV setups.

When adding EVs to the base case, the objective value according to (5.1) increases by 149%. All steering methods obtain an objective value that is immensely lower, although HPM performs slightly worse than QC and PS. For the computation times, PS is about 20 times slower than HPM and QC. This might be due to the low minimum improvement parameter of PS that causes the profile to be updated unnecessarily. The other results can be found in Table 5.3. Although we allowed the EVs to use V2G for all simulated cases, none of the EVs made use of this possibility. This is probably due to the available batteries discharging to charge the EV and minimizing the household peaks simultaneously.

5.6.4 Influence of available flexibility

One of the other aspects we can influence in the simulation is the amount of flexibility the optimization methods can utilize. As the only steerable devices in the base case of the simulation are the batteries, we provide a sensitivity analysis by varying their capacity and power. The total capacity and power

Flexibility	Method	Objective value	Computation time (s)
Oversized	QC	3 911	92.1
	HPM	3 911	84.2
	PS	3 911	203.7
Fitted	QC	20 841	93.6
	HPM	20 841	86.0
	PS	20 841	312.7
Undersized	QC	159 316	100.0
	HPM	159 316	90.9
	PS	159 316	205.0
None	NO	375 022	44.3

Table 5.4: Objective value according to (5.1) and the total computation time for the profiles resulting from QC, HPM, PS, and NO with different amounts of flexibility.

of the batteries can significantly influence the time the optimization methods need to converge. Therefore, we simulated three cases: oversized, fitted, and undersized batteries within each household.

For the fitted batteries, we first needed to determine the minimal amount of flexibility required to reasonably flatten the energy consumption profile. In our case, we ended up using a 5.4 kWh / 2.7 kW battery in each household. For over- and undersized batteries, we simulated a 10 kWh / 5 kW and 1 kWh / 0.5 kW battery in each household, respectively.

The simulations were done using the input data of the sunny day. The results here are in line with those of different PV production. The objective value is the same for all methods (QC, HPM, and PS) but, as expected, differs with the amount of flexibility. The undersized batteries obtained a decrease in the objective value of 57.5% compared to NO. In contrast, the fitted and oversized batteries reached a reduction of 94.4% and 99.0%, respectively (see Table 5.4).

The total computation times for QC and HPM are similar to those of the different weather types, with HPM having a computation time of 87 seconds on average, about 8 seconds faster than QC. Both outperformed PS, which had a computation time of about 204 seconds with the over- or undersized batteries, and 313 seconds with the fitted batteries. For the complete table with all results, again see Table 5.4.

We note that by using undersized the batteries, insufficient flexibility is available, and therefore it can no longer be guaranteed that the global optimum coincides with a Nash equilibrium. This makes comparing HPM and QC to PS slightly unfair, as PS also optimizes the electricity profiles of the individual households.

Predictions	Method	Objective value	Computation time (s)
Perfect	QC	20 841	93.6
	HPM	20 841	86.0
	PS	20 841	312.7
Replanning	QC	140 456	861.0
	HPM	141 028	715.5
	PS	140 456	902.0
Event-based	PS	141 665	188.1
None	NO	375 022	44.3

Table 5.5: Objective value according to (5.1) and the total computation time for the profiles resulting from QC, HPM, PS, and NO with different prediction and planning methods.

5.6.5 Prediction error resilience

Up to this point, we assumed perfect predictions for testing these methods. However, in a real-world setting, this would not be the case. To solve this, the predictions can be made in a rolling horizon fashion, where once per specified time interval, an updated prediction for the next time intervals is made, based on the most recently acquired information. In our case, we updated the prediction for the next 24 hours every simulated hour. More information on how these predictions are made can be found in [108] and [46]. We evaluated the performance of the QC, HPM, and PS using this form of replanning.

For the profile steering method in DEMKit, another way of replanning is available [68]. Here, the prediction is only updated when an event is triggered. These events are triggered when, for instance, the original prediction and the recently acquired information differ too much or when a energy storage device is almost full or empty. This way, a replanning is only made when needed.

The results of the different methods when using the prediction procedures described above can be found in Table 5.5. Clearly, the objective value when using a rolling horizon with replanning is significantly higher than in the case of perfect predictions. Nonetheless, the objective values when replanning are still considerably lower than without optimization. Interestingly, the objective value of HPM when replanning is slightly higher than for the other methods.

A drawback of replanning is that the computation times are substantially higher when compared to perfect predictions. This difference is explained by the fact that with perfect information, only one planning is made, while the replanning procedure makes one for each simulated hour. Interestingly, the event-based procedure for PS does not show an increase in computation time but even outperforms the perfect information procedure. This is because, in the event-based procedure, a swift but approximate planning is made by limiting the maximum number of iterations to convergence. The planning is then only updated when needed. However, the prize for this speed-up is an increase in the objective value, but this increase is minimal. Similar methods for QC and HPM may lead to comparable results.

5.6.6 Scalability

Another critical factor when using optimization methods is scalability, i.e., the change in performance when the input grows. This input growth may be either in the number of planned time intervals or in the number of households. As the compared methods operate in a rolling horizon fashion, extending the number of the simulated time intervals leads approximately to a linear growth of the objective value and the computation time.

To see how the number of households influences the performance, we compared the methods when running the simulations for 1, 5, 10, 25, 45, and 70 households. The results for the total computation time can be found in Figure 5.6. The computation time for NO increases linearly with time, as is expected with DEMKit. Another observation is that QC and HPM grow similarly in computation time. Except for an increment at five households, the computation time shows quadratic growth. For PS, a trend is hard to identify.

For the objective value, little valuable information is found from scaling up the number of households. The objective values attained by QC, HPM, and PS are identical for each number of households and are all significantly lower than for NO.

If we look at the scalability from a computational complexity viewpoint, the added term for the HPM, as described in Section 5.5, has its advantages. It is known that the convergence rate for strongly convex functions is linear when using ADMM. This holds for QC but also for our implementation of HPM. This gives our implementation of HPM a linear convergence rate [95].

For each iteration of ADMM, the optimization problems in the individual households need to be solved. This is done in DEMKit with the continuous battery charging algorithm [164]. The computational complexity of this algorithm is $O(T^2)$ per battery, with T the amount of planned time intervals [164]. Furthermore, as ADMM converges linearly and is observed to have a computation time linear in the number of households H [136], both HPM and QC have a computational complexity of $O(H^2T^2)$, which is in agreement with the results of Figure 5.6. The computation time per iteration of PS typically scales linearly in the number of households. However, PS has no guaranteed convergence speed, although, in practice, the number of iterations is constant or at least bounded by $O(H)$ [70]. As PS uses the same buffer optimization algorithm, its total computational complexity can also be approximated by $O(H^2T^2)$.

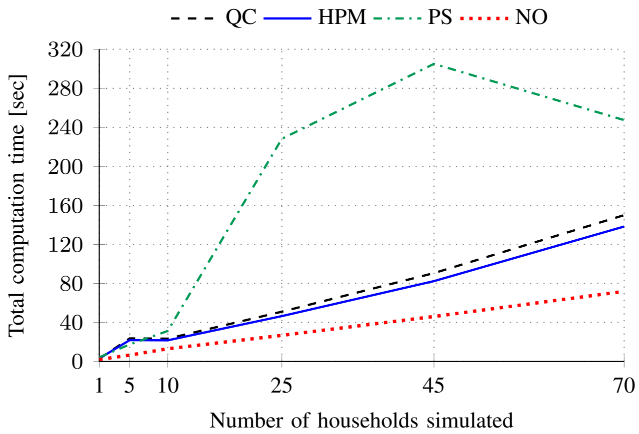


Figure 5.6: Computation times for QC, HPM, PS, and NO when changing the number of households.

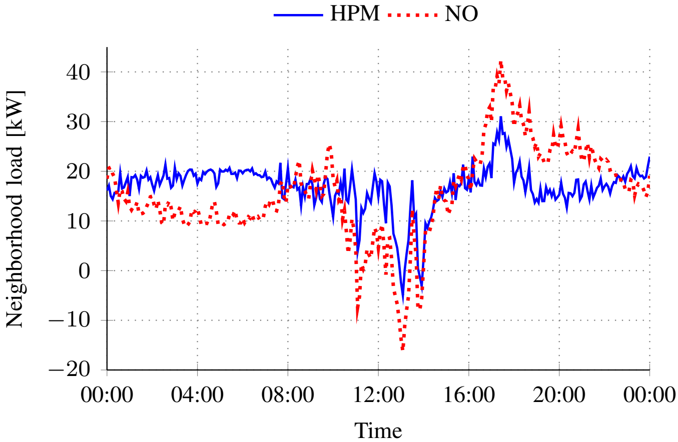
5.6.7 Real data

As mentioned in Section 5.4.3, the hybrid pricing mechanism was used in the GridFlex Heeten field test. The pricing mechanism used the added quadratic term from Section 5.5 and was implemented using the ADMM algorithm in DEMKit. The algorithm ran in real-time to directly steer the eight batteries present in the neighbourhood. As the project initially intended to have more batteries placed there, the capacity and power outputs of the real batteries were doubled in DEMKit to get a realistic impression of what could have been achieved in the extended setting.

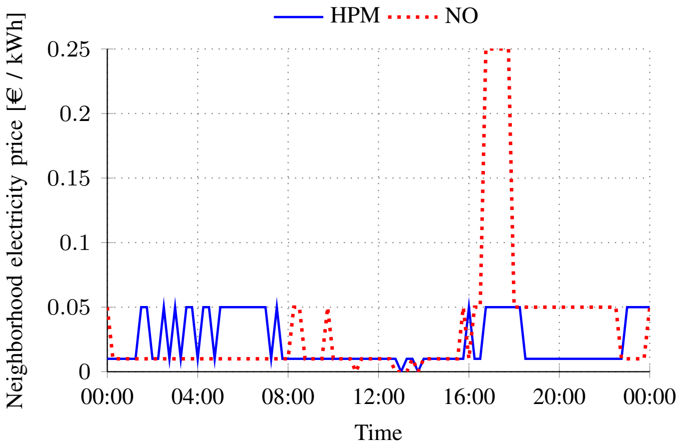
Within DEMKit, a rolling horizon of 48 hours was used, and the predictions were updated every 15 minutes. Figure 5.7 shows the electricity profile of the neighbourhood on the 30th of December 2020 with the hybrid pricing mechanism and without any control (corresponding to HPM and NO). It shows that the overall profile of HPM is much more flat compared to NO, and that the maximum peak was reduced from 42.4 kW to 31.1 kW. The algorithm was fast enough to keep up with steering the batteries online. The results obtained in GridFlex Heeten show the potential of using the hybrid pricing mechanism in practice. Chapter 6 provides some more results of this pricing mechanism in the GridFlex Heeten field test.

5.7 Conclusions

This chapter presented a framework for pricing mechanisms that are suitable for system optimization but at the same time are socially acceptable. The underlying system goal is to flatten the neighbourhood electricity profile. To achieve this, we



(a) Total power profile of the GridFlex Heeten neighbourhood.



(b) Electricity prices for the GridFlex Heeten neighbourhood.

Figure 5.7: The effects on the electricity profile of the GridFlex Heeten neighbourhood using HPM and NO.

proposed a hybrid pricing mechanism that uses a piecewise linear approximation of a quadratic cost function.

The presented hybrid pricing mechanism has been implemented and evaluated in a field test with an energy community, where it was observed that the consumers understood the mechanism and considered it suitable. Furthermore, the described mechanism meets several requirements from literature for social acceptance. For the implementation of this pricing mechanism in optimization algorithms, an additional term can be added to the hybrid pricing mechanism to speed up the convergence without an impact on the quality of the solution. Our numerical evaluation shows that with this speed-up, the results of the proposed hybrid pricing mechanism are comparable with steering methods specifically designed for system optimization. Moreover, the mechanism can keep up with the online steering of batteries in terms of computation time and solution quality. This indicates that our pricing mechanism has the potential to be used in practice.

In this chapter only the effect on peak reduction is assessed. Therefore, in future research it should be explored if similar mechanisms exist for different system goals. Especially using the results from [140], that show that different instances within similar classes of optimization problems have the same optimal solution, we may be able to link other system goals to the proposed mechanism. As the hybrid pricing mechanism needs to be tailored to each neighbourhood or local energy community, future work should entail developing a method that supports the decision on specific parameters of the mechanism, i.e., deciding on the needed number of pieces m, the prices a_i and the boundaries b_j for specific communities, given their wishes and characteristics. Also, designing an event-based prediction method for the hybrid pricing mechanism could drastically reduce the computation times for realistic implementations, as was demonstrated in the numerical evaluation of profile steering. Moreover, the framework presented here could be further tailored to cases with industrial users, especially when they are in the same neighbourhood as residential users. Finally, more research is needed to fully explore the effect of such mechanisms on the behaviour of consumers and the social acceptance of these pricing mechanisms.

6

GridFlex Heeten: Project results

Abstract – *In the previous chapters, the GridFlex Heeten project has been introduced and used as a motivation and test case for the developed pricing mechanisms. To provide additional context, this chapter presents the corresponding project overview, the relevant project research questions, and the achieved results.*

The research questions of the project focussed on three themes. The first theme encompassed pricing mechanisms and their effect on certain key performance indicators. The two used pricing mechanisms within the project led to peak reductions of approximately 25% and annual savings of €1 403.38 and €753.47, respectively.

The second theme deals with the consumer participation within the project. By setting up a neighbourhood representative team, the communication with and connection to the neighbourhood participants greatly improved. However, consistent and regular communication proved to be essential for keeping the involvement of the participants in the project, even if at times there is little to present.

The third and last theme concerned different battery sizings and types. Different types of batteries were installed in the neighbourhood, and were controlled based on the pricing mechanism. Furthermore, performance indicators were used to decide on ideal battery specifications using simulations.

The answers to the research questions of the project provide a useful reference for similar projects.

6.1 Introduction

Throughout this thesis, the GridFlex Heeten project was the main motivation for the research and results from the project are presented. The project was introduced in Chapter 2 alongside its initial plans and goals. This chapter deals with the project research questions relevant to this thesis and presents corresponding results. These results provide a reference for similar projects to learn from.

First, in Section 6.2, a timeline of the project is presented to place these results into perspective. Here, important phases of the project are indicated, alongside the periods in which the different pricing mechanisms were tested in the neighbourhood, and when the different batteries were installed. Next, in Section 6.3, we discuss the relevant research questions formulated and treated during the project. These questions address the pricing mechanisms in the project and the analysis of the behaviour of the participants (Section 6.4), the participation of the inhabitants in the project (Section 6.5), and the different types of batteries, their suitability and ideal sizing (Section 6.6). We finish by presenting some concluding remarks regarding the project.

6.2 Project timeline

To give a more clear view on the course of the project, Figure 6.1 presents some of the key moments in the project. Furthermore, on the left, it also shows the periods used for the data analysis. The data was collected between August 2018 and August 2020, as also indicated in Section 2.7.1.

6.3 Project research questions

During the project, concrete research questions were formulated to ensure a focus and priority of research activities for the different involved parties. These questions also helped to track what aspects remained to be researched during the project. As shown in the previous section, these research questions were formulated relatively late in the project. Before that, the project plan and the accompanying use case document were used to provide a direction to the project activities.

However, as these documents were not very specific and also mixed the different personal goals of the involved parties with the project goals, this led to some misunderstandings and some conflicting expectations. The developed research questions improved the focus. The responsibility for answering the specific questions was assigned to the parties that considered them important. This was a great help during the remainder of the project.

This section treats the project research questions relevant to the research of the University of Twente. Note, that these are different from the research questions stated in Section 1.2. The relevant questions were gathered from the project plan, use case documents, research questions brainstorm, white paper, and the goals as stated in Chapter 2.

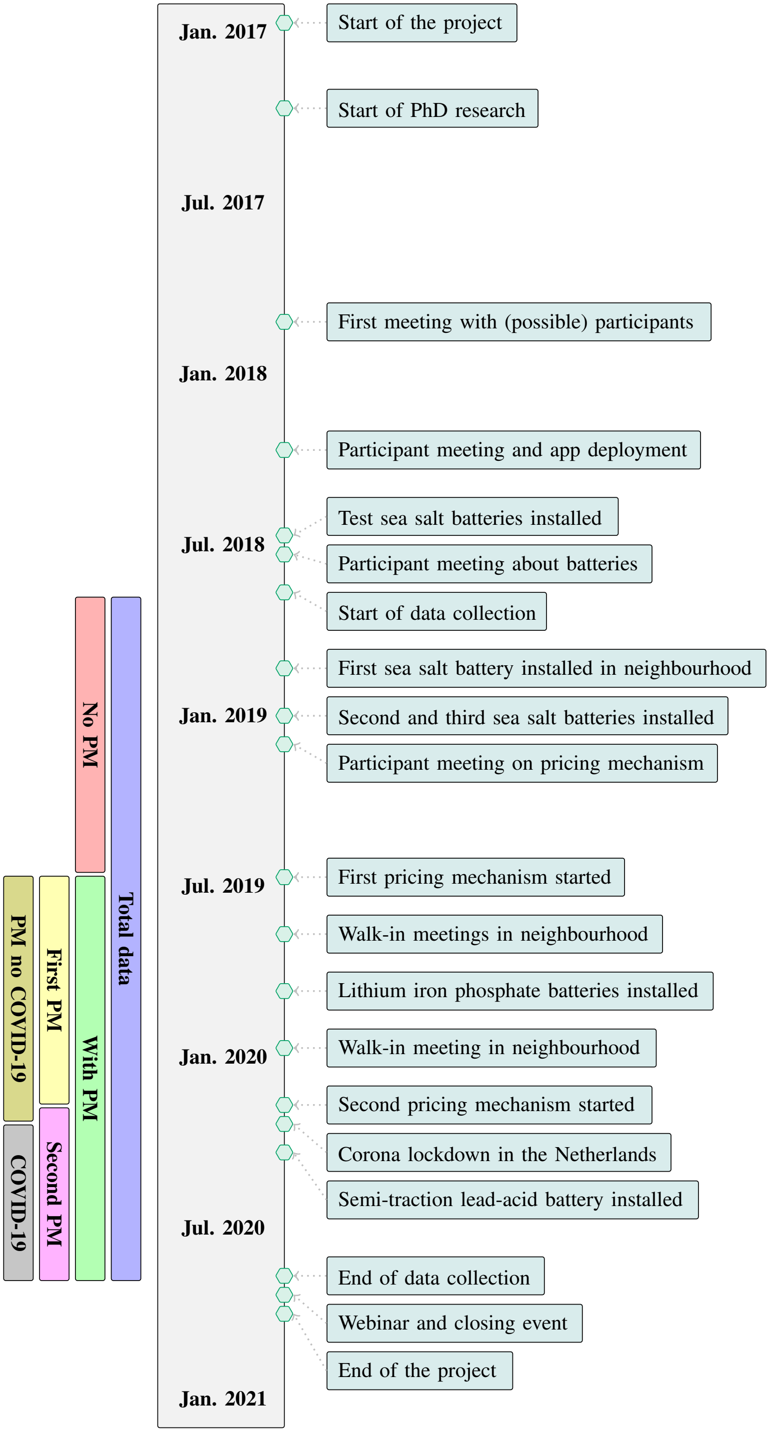


Figure 6.1: Timeline of the GridFlex Heeten project including the most relevant events on the right and the periods used for data analysis on the left.

To provide some context, the main research question of the project was:

How can we create a socially ideal local energy system based on local energy storage and local settlement mechanisms?

The specific research questions relevant to the research presented in this thesis can be categorized in three themes:

» Pricing mechanisms and their effect on certain key performance indicators (KPIs, see Chapter 2),
» Consumer participation,
» Battery sizing and type.

These themes are treated in the remainder of this chapter, however, we do not go into detail answering the separate questions. Note, that some of these themes were already (partially) treated in the previous chapters. For a broader overview of the research questions treated during the project, and the lessons learned, we refer to [55].

6.4 Pricing mechanisms

Several of the research questions of the project were related to pricing mechanisms. These questions are:

» How can we compare the effects of monetary and non-monetary KPIs?
» How are these KPIs influenced?
» What effect do specific pricing mechanisms have on these KPIs?
» What type of steering and (communication) infrastructure is needed to achieve the intended effects on the KPIs?
» How should we reward participants for collaborating?

These questions are jointly treated in this section.

In the following, we discuss the two pricing mechanisms used in the GridFlex Heeten project, and present their results from the perspective of the project. These mechanisms are the hybrid pricing mechanism, as presented in Section 3.3 and Chapter 5, and the neighbourhood net metering mechanism. These pricing mechanisms were thoroughly discussed within the project team, and with the participants. As already mentioned in Section 4.6, we did not use the average location pricing mechanism. Finally, in Section 6.4.3, the behaviour of the participants in regards to the pricing mechanisms is analysed.

6.4.1 Hybrid pricing mechanism

This section treats the first pricing mechanism tested in GridFlex Heeten, the hybrid pricing mechanism. This pricing mechanism was explained in Section 3.3

and used in the general framework presented in Chapter 5. As mentioned there, the base for this pricing mechanism is a capacity tariff with multiple price levels, but on a neighbourhood level. The participants pay based on the electricity transport on the transformer. Depending on the level of demand on the transformer, an energy price is set for all inhabitants. This means they all receive the same price, but their total costs are subject to their own consumption during that period. By this, the inhabitants can also influence the price for electricity by using their flexibility.

The motivation for operating on a neighbourhood level is that capacity tariffs for individual households have some drawbacks, as already indicated in Chapter 5. Firstly, individual households often do not have the flexibility to stay within the specified limits. Secondly, households are penalized for helping each other, and, lastly, if all households consume the maximum allowed power within their limits simultaneously they can still overload the transformer. Therefore, a neighbourhood approach is beneficial.

To apply the hybrid pricing mechanism framework of Chapter 5 in GridFlex Heeten, we set the parameters of the mechanism in the following way. We used six price regions, with breakpoints at -43.75, -25, 0, 18.75, and 31.25 kW and prices of -25, -5, 0, 1, 5, and 25 euro cent per kWh in each piece for the final payment of the participants, meaning that $m = 6$ according to the definition in Section 5.4.1. This is in contrast to the evaluation in Chapter 5, where it is mentioned that the optimization used five regions. The extra region for the payment was created in a later phase of the project by splitting the middle price region and adding a breakpoint at 0 kW. The region just below 0 kW was given a price of 0 euro cent per kWh as a lenience towards the participants to stimulate small amounts of PV production. However, the optimization on the neighbourhood level still used the 5 regions as described in Chapter 5.

The inhabitants received the prices via an app that displayed their current and historical electricity usage, and predictions of the prices for the coming 24 hours. An impression of the app was given in Figure 3.6 in Section 3.3.2. Prices were updated every five minutes, whereby the prices for the coming three hours were fixed. The latter was decided on after a co-creation session with the participants, where the participants indicated they wanted some certainty to base their planned energy consumption on. The pricing mechanism was communicated using colours that correspond to the prices. To keep it simple for the participants, the project team decided to only use three colours (red, yellow, and green) instead of six (which was the number of price regions used). The colour red corresponds to a high price (indicating the participants should reduce their consumption), yellow to a medium price (indicating the participants should reduce their consumption if possible, or at least not increase it), and green to a low price (indicating there would be no limitations).

The hybrid pricing mechanism was evaluated for 14 months, from July 2019 to August 2020. During the months of July 2020 and August 2020, the pricing mechanism was only active to study the effects of the algorithms steering the batteries, and no longer for the participants to adjust their behaviour, or to create possible monetary savings.

Furthermore, from March 2020, the hybrid pricing mechanism was combined with the neighbourhood net metering mechanism, which is described in Section 6.4.2. During those last months, the information sent to the inhabitants slightly changed. Green intervals now indicated the expected transformer load would be below 5 kW, replacing the meaning of 'no limitations in consumption' to then indicate that the participants should shift some of their consumption to these intervals. Yellow intervals then indicated a transformer load between 5 and 25 kW, and red intervals correspond to a transformer load above 25 kW.

The COVID-19 pandemic in the Netherlands from March 2020 complicated the test phase of this pricing mechanism. As people worked from home during the lockdown, this led to changes of the electricity consumption in this period. Therefore, it became difficult to assess what changes in the electricity profile stem from the lockdown or from the pricing mechanisms.

We already mentioned in Section 3.3 that the first results indicated a peak reduction of about 30%. Taking the entire period in which only the hybrid pricing mechanism was in place, the batteries achieved a peak reduction of about 25%. In Figure 6.2, the peak demand with and without batteries is presented for the months in which the participants were requested to adjust their behaviour based on the pricing mechanisms (July 2019 to June 2020).

Furthermore, savings achieved by the batteries and possible changes in behaviour, and the number of time intervals (of 15 minutes) that were in each price region are displayed (NegRed, NegYellow, NegGreen, PosGreen, PosYellow, and PosRed, corresponding to the prices mentioned above) in Figure 6.4. The total savings achieved by this pricing mechanism in 12 months amounted to €1 403.38 for the neighbourhood (see Figure 6.3).

The results in Figure 6.3 indicate that there is a large difference between the summer and winter months. In November, December, and January, this pricing mechanism actually led to higher costs compared to the conventional pricing. This can be explained by the higher energy consumption during the winter months, which is also noticeable in the number of red intervals (see Figure 6.4). During the summer months, the production peaks are, as expected, getting more dominant, as can be seen in the increase of the number of NegRed intervals in May and June.

Another observation is that the batteries are clearly capable of flattening the energy consumption profile. The energy in the red intervals is transferred to yellow, and the energy of the yellow intervals towards green. This effect occurs both for the production and the consumptions peaks. Also for the months with a lower peak reduction, i.e., for January and May, the shift towards the green intervals is still clearly present, indicating lower overall peaks.

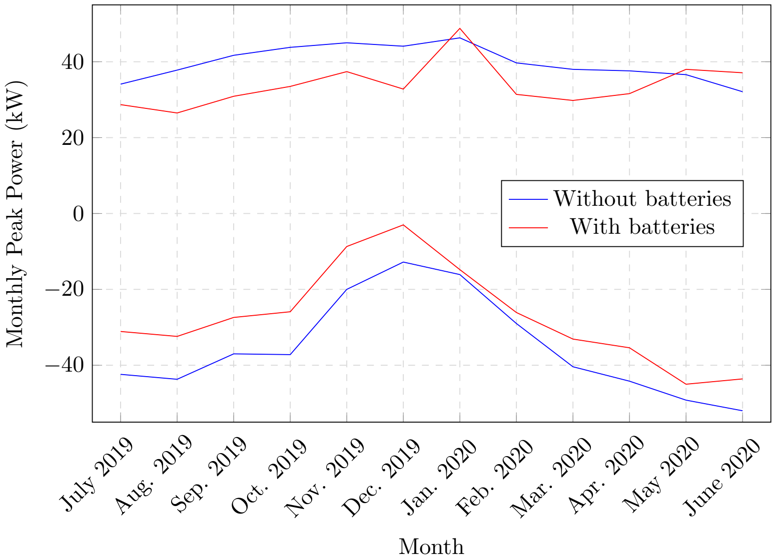


Figure 6.2: Highest and lowest monthly peak with and without the batteries.

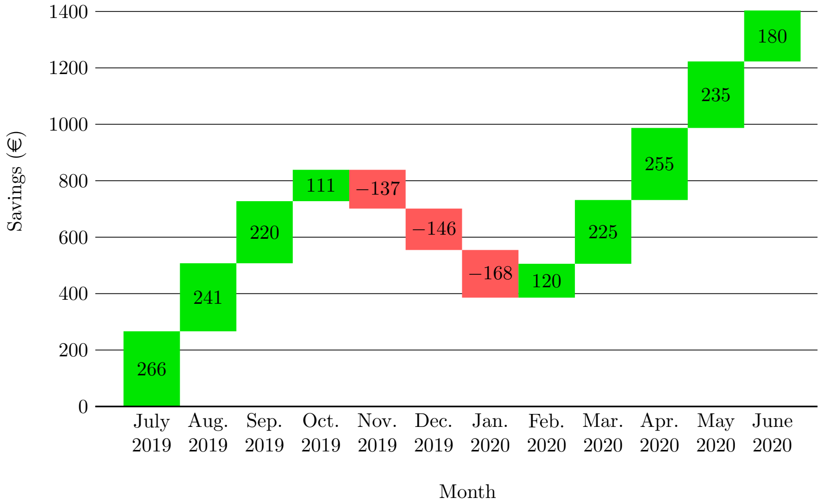


Figure 6.3: Cumulative savings obtained by the hybrid pricing mechanism.

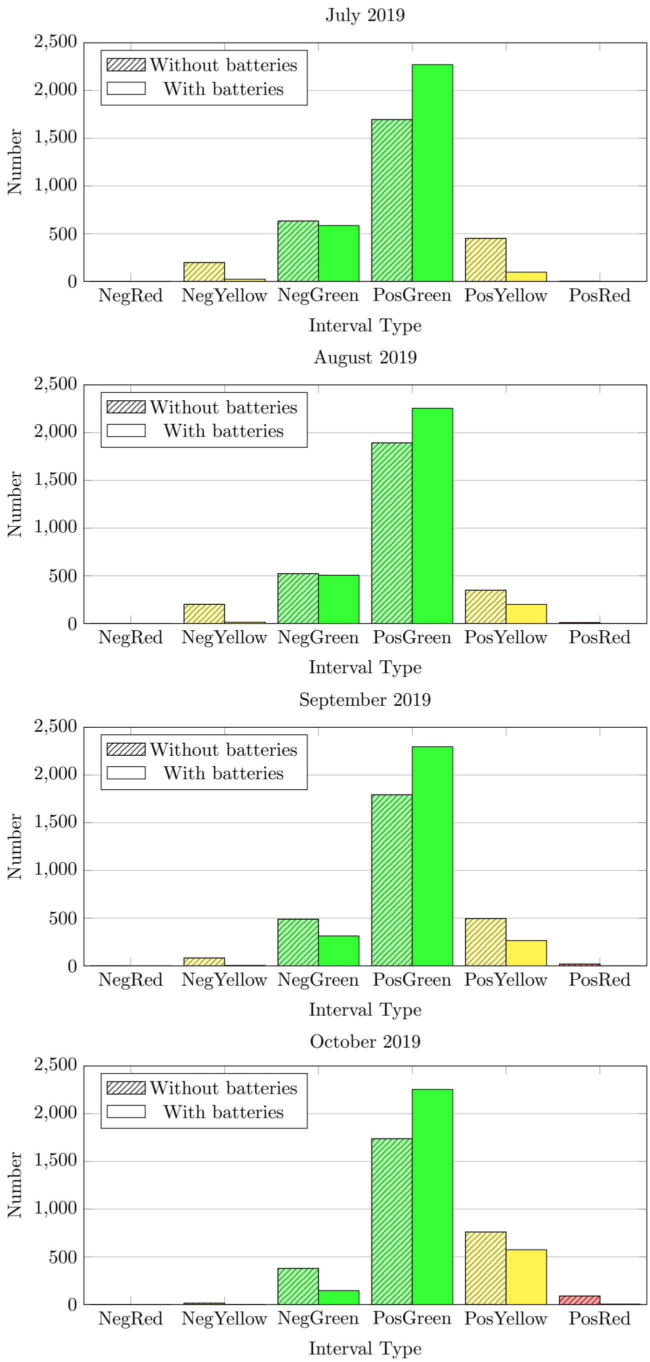


Figure 6.4: Number of 15-minute intervals per price region for July 2019 to June 2020 with and without the effects of the batteries.

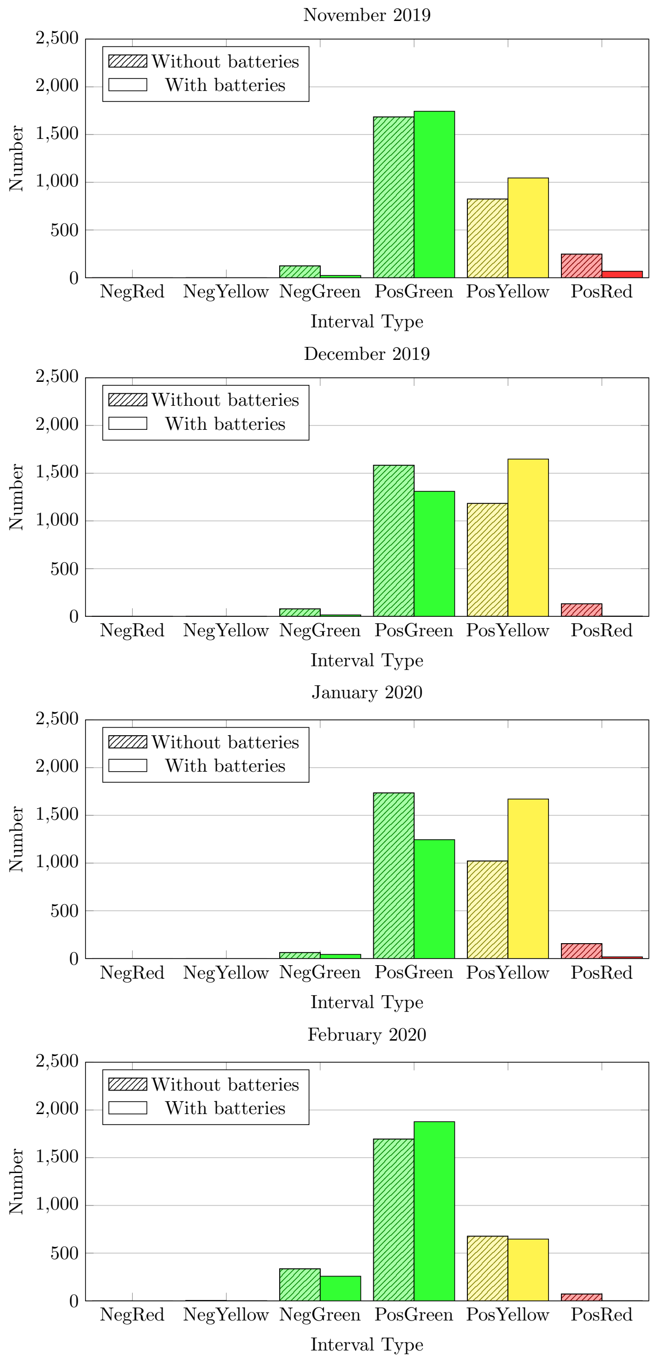


Figure 6.4: Number of 15-minute intervals per price region for July 2019 to June 2020 with and without the effects of the batteries (cont.).

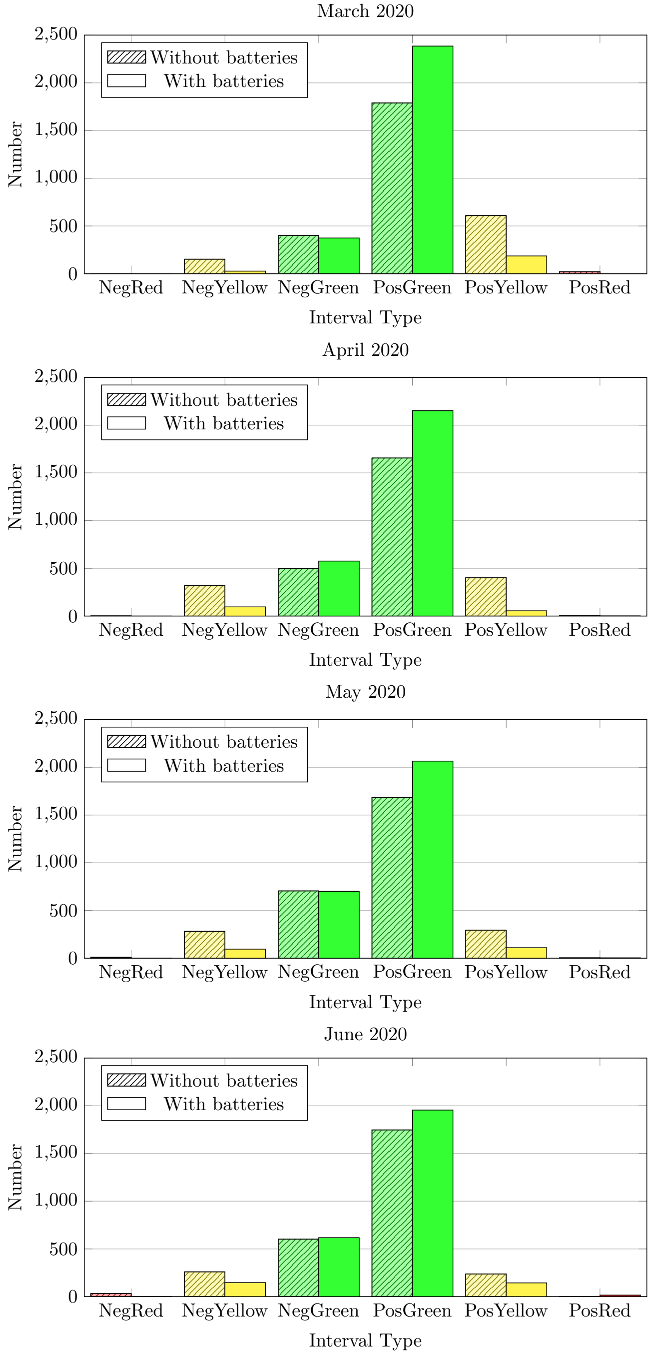


Figure 6.4: Number of 15-minute intervals per price region for July 2019 to June 2020 with and without the effects of the batteries (cont.).

In June 2020, we do see an increase in the red consumption intervals when using the batteries. A more detailed analysis shows that this is due to some prediction errors, which had as consequence that the batteries were charging when this was not necessary. However, we do see that the energy is transferred from red to yellow intervals, and from yellow to green intervals. Furthermore, the savings are still quite substantial in this month.

The overall savings are not substantial, as €1 403.38 in total corresponds to about €30 per household per year. In this context it needs to be noted that losses in the batteries had to be compensated for, which were quite high (see Section 6.6). Also, the amount of change possible in the electricity prices is small due to high taxes, as mentioned in Chapter 3, so the total amount of savings also cannot be that much. Still, the total achieved amount allows the neighbourhood to focus on some communal goals.

The implementation of this pricing mechanism led to some lessons learned. Firstly, the household consumption fluctuates heavily during the year, with high PV production peaks in spring and summer and high consumption peaks in winter. These fluctuations make it hard to determine breakpoints for the pricing mechanism. Either the breakpoints do not provide enough incentive during summer to decrease consumption peaks, or, in winter, the breakpoints are too close to 0 kW and shifting to a lower bandwidth is almost impossible. This goes hand in hand with the observation that determining where the breakpoints should be can be difficult, as a small change in the breakpoint might cause a huge cost difference. Moreover, when devices with a large effect on the electricity consumption profile are added to households, e.g., an EV or heat pump, the costs for the households may also change drastically.

There are some options for dealing with the mentioned difficulties. One of the options is to have different breakpoints or prices per month. This way, the fluctuation during the year can be captured, and adjustments can be made to account for large changes in the consumption profiles of households. However, this also increases the uncertainty for the consumers, making it less socially acceptable (see Chapter 5). Another option is to set the breakpoints and prices for a year, but make sure the fluctuation over the year balances out (like we did in GridFlex Heeten). This needs some additional insight in the energy consumption of the neighbourhood beforehand, but it does give more certainty for the consumers. One thing to note here, is that consumers should not be allowed to terminate their contract halfway through. Otherwise, this could lead to cherry-picking, as the summer months lead to more savings, but the winter months lead to losses (see Figure 6.4). As a final option, the exact breakpoints could be set dynamically during the day, or even in hindsight (simply stimulating consumers to flatten their profile as much as possible), to make sure the incentives are enough to stimulate changes in behaviour and the costs are reasonable. However, this option is currently the least socially acceptable, as it gives no certainty at all to the consumers.

The steering of smart devices based on pricing mechanism can be automated, independently of whether or not consumers are stimulated enough to change their energy consumption behaviour manually. However, also in such a case the pricing mechanism first needs to be accepted by the inhabitants, as we also mentioned in Chapter 5. Fortunately, with these type of pricing mechanisms, the information and prices can be shared easily with the consumers, e.g., with the colours, to provide insight. This can increase the acceptance of the pricing mechanism [154]. It is worthwhile to mention that batteries, in combination with this pricing mechanism and a steering algorithm, can already have a huge effect on the electricity consumption of the neighbourhood, once the pricing mechanism is accepted and the flexibility is enabled by the consumers. This also shows that the pricing mechanism should work in tandem with some automatic steering to achieve savings instead of relying only on manual changes in consumption, as the effects of this are negligible (see Section 6.4.3).

6.4.2 Neighbourhood net metering

The second pricing mechanism evaluated in the GridFlex Heeten project is based on the concept of neighbourhood net metering mechanism. Currently, in the Netherlands, for a household the annual production of energy is subtracted from the annual consumption of energy, and the household only pays for the resulting net-energy left over. This principle is called net metering. This also implies that all consumption up to the level of the production surplus is not taxed. If the annual production exceeds the consumption, the household receives a compensation for the excess energy, albeit at a lower price than paid for consumption. This principle was introduced in 2004 to encourage consumers to purchase PV installations and to stimulate the local energy production, as with this measure the payback period of PV installations was drastically lowered [19, 97].

This support scheme has resulted in a higher stress on the grid, as having a net zero consumption often comes with huge peaks in consumption at certain times and also with high production peaks at other times. This regulation of the tax refund scheme is currently still in place, but will most likely be phased out in the coming years [15]. This probably will imply that the production surplus may have to be sold for low prices and will therefore not yield as much cost reduction as before. As such, this stimulates the market for batteries, and stimulates the households to consume energy when it is produced. Instead of stimulating annual self-consumption, this stimulates instantaneous self-consumption, and by that, should lower the peaks in the grid.

However, as indicated when introducing the first pricing mechanism, individual households do not have enough flexibility to completely balance their energy profile. Following what we did for the first pricing mechanism, we solve this by acting at a local energy community, or a neighbourhood level. To accomplish this, we use a different (lower) price for selling the energy outside the neighbourhood, than for selling it within the neighbourhood. Similar for buying, internal prices were lower than buying energy from outside the neighbourhood. This way, self-consumption is still promoted, but with the added benefit of being able to use the flexibility of the whole neighbourhood.

This neighbourhood net metering mechanism was evaluated in the GridFlex Heeten project and ran from March 2020 to June 2020. Note again, that this period coincided with the COVID-19 pandemic and the resulting lockdown, so the results might be less representative because of that. The prices used were 23 euro cent per kWh for buying the energy from outside the neighbourhood, 18 euro cent per kWh for selling to outside, and 20.5 euro cent per kWh for buying and selling energy internally. The savings for the neighbourhood were calculated as the difference between internal net metering and the regular prices of 22 euro cent for buying or selling energy. This was done in addition to the savings from the first pricing mechanism. These total savings were used for a purpose chosen by the participants of the neighbourhood.

The inhabitants still received information via the app using the colours, similar to the first pricing mechanism. For this second mechanism most of the steering signals aligned with those of the first pricing mechanism. Only for the green colour, as mentioned in the previous section, the meaning was altered to indicate that there was a surplus of energy in the neighbourhood and that this would be a good moment to consume more electricity. Note that the batteries were automatically steered to account for both pricing mechanisms simultaneously.

It is not easy to assess what the added benefit of this second pricing mechanism was, as it ran alongside the hybrid pricing mechanism. In the months from March 2020 to June 2020, we do not observe an additional reduction in peaks or red intervals (see Figure 6.2 and Figure 6.4). However, using the neighbourhood net metering mechanism, additional savings of €753.47 for the neighbourhood have been obtained. Next to these savings, the inhabitants also indicated that this pricing mechanism was easy to understand, and that this scenario made sense to them.

Note, that the neighbourhood net metering mechanism on its own is not a pricing mechanism that would be ideal for the future grid. This can be seen from the fact that for batteries it is optimal to simply charge when there is an energy surplus in the neighbourhood and to discharge when there is a shortage (a greedy approach). Especially with a limited battery capacity and a smaller PV production, the resulting energy profile of the neighbourhood might still have huge consumption peaks. To compensate for this, the project focussed on the combination of the two described pricing mechanisms, as they complement each other. The neighbourhood net metering mechanism focusses more on increasing self-consumption, while the hybrid pricing mechanism focusses on lowering the peaks.

6.4.3 Consumer behaviour

Next to the effects of the batteries, also the response of the participants to the signals from the app was studied, since one of the project research goals was to investigate what the effects of the pricing mechanisms are on the behaviour of the participants. To study the effects of this behaviour, we take a look at the consumption data.

To analyse this consumption data, we categorize the data based on certain features and created average daily energy consumption profiles from these categorization sets, both normalized and unprocessed. The used features were:

- *Day type*: specific day of the week, weekend/holidays, weekdays, all days
- *Participants*: individual households, all consumers from De Veldegge, all consumers from the reference group, all households
- *Signals*: Green, yellow, red, all (including no signals)
- *Time period*: periods as indicated in Figure 6.1, each month separately.

For the average daily energy consumption profiles resulting from these categorizations, we used several methods to analyse if changes in behaviour could be detected:

- k-Nearest Neighbour Dynamic Time Warping (kNN DTW) [83] indicates similarity between different consumption profiles.
- For some cases, also a visual inspection was done to investigate similarities.
- The Wilcoxon signed-rank test [180] and the Mann-Whitney U test [103] analyse if profiles come from the same distribution, or if they have statistically significant differences.

For all the executed analyses, none of these methods indicated a change in behaviour.

To further investigate this, we compared the energy consumption just before and after predicted red intervals with the energy consumption during these red intervals. Any change here would indicate that the participants specifically lowered their consumption during red intervals. However, also in this case, there was no indication of a statistically significant difference. This, of course, does not exclude any incidental actions of inhabitants using their flexibility, but it shows that no structured actions can be observed using those methods.

These results are not surprising. Firstly, from the co-creation sessions, most of the inhabitants indicated they checked the app once in a while, but not frequently, and that they did not change their electricity consumption. Secondly, in [31], it was already shown that burdening the participants with extra control action is not a very promising approach. Instead, they concluded automated choices should be implemented. This should be done while taking the social acceptance of the intended control into account.

6.5 Consumer participation

A further theme of research questions within the project concerned the consumer participation. The questions from this theme are:

- How can we keep a clear line of communication to the participants?
- How can we support the participants to achieve the project goals and the intended effects on the KPIs?
- How can we involve the participants in the project and maximize consumer inclusion?

The GridFlex Heeten project was mainly successful due to the cooperation and participation of the inhabitants of Heeten, and in particular the neighbourhood De Veldegge. In this section, we describe the way these participants were involved in the project and what helped or hindered their participation. By this, we aim to answer the mentioned research questions.

For a smooth cooperation with the inhabitants of the energy community in De Veldegge, a group of representatives from this neighbourhood was established. This group was called the neighbourhood team ('buurtteam' in Dutch). The project partners had regular sessions with the neighbourhood team to present status updates, and ask them for input on project decisions. During these sessions, the team was also asked what would be the best methods to communicate to the neighbourhood, both for project events and for pricing signals. This team also used input from the whole neighbourhood to decide on a concrete neighbourhood goal for which the savings achieved by this projects should be used: an automated external defibrillator (AED) and trainings on how to use this AED.

Using this bottom-up approach to involve the neighbourhood in the project showed to be very successful. The local project partners, together with the neighbourhood team, achieved that all households in the neighbourhood participated in the project.

One of the important discussion topics during the sessions with the neighbourhood team were the pricing mechanisms. They were asked if the pricing mechanisms as proposed made sense to them, were considered to be fair, and were understandable. Furthermore, the team was asked for their requirements for an app to support them in their decision making. Several of the design choices within the project were based on this input of the neighbourhood team. Examples of this are:

- The number of colours used for the signals.
- The signals in the app giving a prediction of the next 24 hours with the prediction being updated every five minutes.
- The decision to no longer update colours and corresponding prices for the upcoming three hours to ensure the participants could plan ahead.

At the end of the project, the neighbourhood team indicated that they checked the app once in a while, but not often, as is in line with the results presented in the previous section. An overview of the app is shown in Figure 3.6.

Besides communicating with the neighbourhood team, also several ways of communicating with all participants of the project were established. Posters and flyers were used to promote the information sessions, during which the project partners presented the plans of the project and the results up to that point. Also, 'neighbourhood evenings' were organised where the inhabitants of De Veldegge could easily ask some questions to the neighbourhood team about the project. Furthermore, after the first batteries were installed in the neighbourhood, a 'walk in' was organised to share the first experiences of the installation and the use of the device.

During the project, technical issues arose regarding the production, control and installation of the batteries. In this time period, the project partners worked on resolving these issues. As there was not a lot of progress during some periods, the communication towards the participants in these periods stopped. This resulted in a loss of the connection with the neighbourhood and by that less participation. An important lesson learned from this period is that it is essential to keep communicating regularly, even if there is no or only minimal progress to report.

At the end of the project, the project partners organized a webinar to present the results and the lessons learned [33]. After the webinar, a well visited closing event for the neighbourhood was held to official mark the end of the project, and to reveal the neighbourhood reward: the AED. This reward was well-received by the participants and, together with the event, helped to partly rebuild the connection to the participants.

6.6 Batteries

The final theme of research questions in the GridFlex Heeten project concerned the battery sizing and type. In the project, the only steerable devices were batteries and therefore, the project relied heavily on their flexibility. The questions related to this topic include:

» What specifications of the batteries are ideal for making as little use of the grid as possible?

» What battery specifications are suitable for the project?

In this section, a reflection on aspects around the batteries used in the project is given, next to treating the mentioned project research questions simultaneously.

The initial project plan was to distribute 24 sea salt batteries [64], with a total capacity of 120 kWh, over the neighbourhood. However, the development of the sea salt batteries and their integration with a battery management system (BMS) proved to be challenging and by that, a research project on its own. A main reason for this was the unique behaviour of sea salt batteries that is not directly compatible with the existing BMSs designed for traditional battery technologies (see Section 5.6.4 of [64]). The additional effort and time required for solving these issues made it hard to combine the development of the battery with the given goals of the GridFlex Heeten project.

To still achieve some of the project goals, it was decided to also use lithium iron phosphate batteries and a semi-traction lead-acid battery within the project. As shown in the timeline (Section 6.2), these batteries were installed between June 28, 2018 and the April 22, 2020. At the end of the installation period, there were three sea salt batteries in the neighbourhood in total, each with an approximate capacity of 2 kWh and a peak power of around 300 W. Next to those, there were also five lithium iron phosphate batteries and one semi-traction lead-acid battery, with capacities of 3.5 and 5 kWh, respectively, and a peak power of around 500 W.

Due to the incompatibilities with the BMS, the sea salt batteries achieved only an effective capacity of 2 kWh (compared to the planned capacity of 5 kWh) and a maximum power of 300 W. These incompatibilities limited the energy efficiency of these batteries to around 18%. However, as the sea salt batteries have already shown an energy efficiency of 65.5% in other tests [64], we conclude that it is important to integrate and tailor all aspects in the technology chain properly to each other.

To compensate for the difference between the planned and realized total battery capacity available in the neighbourhood, simulated batteries were used for answering some of the research questions within the project. Along with the real batteries that received steering signals (see Chapter 5 for more information on this), also these virtual batteries were used in the simulation tool DEMKit, leading to a total of 24 batteries in the test scenarios (as was the original project plan). The virtual batteries had a capacity of 3 kWh each, and a peak power of 500 W, and the same losses as were measured for the sea salt batteries were applied to the virtual batteries. This way, the initial idea of the project still could be carried out.

The results of this study are presented in Chapter 3, Chapter 4, and Chapter 5 for the simulated batteries, and in Chapter 3 and Section 6.4 for the real batteries. Originally, the project plan also included research as to where the batteries should be placed within the neighbourhood. However, due to limitations on the placement of the batteries in a house, this part of the research could no longer be carried out.

Finally, as one of the project goals was to investigate methods for becoming (mostly) self-sufficient, the size of batteries needed to achieve this self-sufficiency were determined in simulation. The results of these simulations are presented in the next section. Becoming fully self-sufficient showed to be very difficult, as fully balancing all peaks increases the investment costs tremendously [65]. Thus, the focus of the research has mainly been on lowering the peaks. Summarizing, even with the difficulties and limitations regarding the batteries in this project, still the potential of this technology can be clearly seen.

6.6.1 Battery sizing

For projects in practice, occasionally estimates on the size and power of batteries may be needed without having exact details of the considered neighbourhood or energy community. When the first data within such projects gets available, it is important to evaluate how reasonable the initial estimates were, and to use a tool to determine which capacity and power of batteries are sufficient in the considered neighbourhood to reach the intended goals.

In the GridFlex Heeten project, this issue arose as well. Since the focus of the project was on reducing the stress on the network, measures for reducing peaks in the energy profile were crucial to decide if the specific batteries were sufficient for this goal. To quantify this, we chose four key performance indicators (KPIs) reflecting the peaks and spread in the energy profile: the Gini coefficient, the median absolute deviation (MAD), the peak-to-average ratio (PAR), and the standard deviation (SD).

The Gini coefficient is used in economics as a measure of statistical dispersion of a countries wealth [50, 144]. However, as it essentially measures inequality, it can also be used to indicate the 'unevenness' in an energy profile. The Gini coefficient can be formulated as

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|x_i - x_j\right|}{2n^2\bar{x}}, \tag{6.1}$$

where n is the number of considered time intervals, x_i is the energy consumption in time interval i, and $\bar{x}$ is the average energy consumption over the considered time intervals.

Secondly, the MAD (or median absolute deviation) is a robust statistic that gives the median deviation of values in a set to the median of that set, where the median is the value that separates the lower half from the upper half of a set [44]. More formally,

$$MAD = \text{median}_{i \in N}\left\{|x_i - \tilde{x}|\right\}, \tag{6.2}$$

where $\tilde{x}$ is the median energy consumption of all considered time intervals, and $N = \{1, \ldots, n\}$, the set of considered time intervals.

The PAR (peak-to-average ratio) takes the maximum total electricity consumption of a neighbourhood and divides it by the average electricity consumption of this neighbourhood. This gives a measure of how unbalanced the grid is used. This measure can be expressed as

$$PAR = \frac{\max_{i \in N} \{|x_i|\}}{\bar{x}}. \tag{6.3}$$

Lastly, the SD is simply the standard deviation of the dataset, calculated as

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}. \tag{6.4}$$

Some assumptions were made to evaluate these indicators. Firstly, the battery was assumed to be ideal, with only a constant loss over time. Secondly, we assumed that we have perfect predictions on the energy consumption of the neighbourhood. We do this to eliminate the effect of inaccurate predictions and only focus on the effect of the battery.

To simulate the effect of the different battery setups on the indicators, we used DEMKit (Decentralized Energy Management toolKit [66], see Section 5.6.1 for more information on DEMKit) in combination with the profile steering algorithm [47]. The used data was from the GridFlex Heeten project collected during the spring and summer of 2019 ([VR:4], more information can be found in Section 2.7.1). Batteries with total capacity between 60 and 240 kWh and total peak power between 6 to 60 kW were simulated.

The default goal of profile steering is to steer the electricity profile of a group of households to using no electricity, and penalizing any peaks. As such, the resulting profile should be as flat as possible, within the battery capabilities. Therefore, it may be expected that by using profile steering to control the battery, the peaks and deviations of the profile decrease, thereby decreasing our KPIs.

In general, we observed that increasing the battery capacity or peak power both significantly decreases the indicator values. Especially when going from 20 kW to 30 kW power, the PAR value decreased by up to 35%. This is mainly due to the production peaks that otherwise cannot be substantially captured by the battery. This observation led us to conclude that fo the neighbourhood in Heeten a minimum power of 30 kW is necessary to flatten the neighbourhood profile.

When increasing the battery capacity, all indicators decrease, as expected. However, the decrease becomes asymptotically smaller. Therefore, selecting a final capacity solely based on the indicators proves to be difficult. Above a capacity of 120 kWh, there is no further significant decrease in the PAR, although the SD still decreases substantially. Therefore, this capacity may be taken as an estimate for the ideal capacity of the neighbourhood battery.

Future research on these indicators may result in a decision scheme for determining the capacity and power needed in a neighbourhood, which would be a helpful tool for smart grid planners.

6.7 Conclusions

This chapter summarised the project results of GridFlex Heeten that are relevant to this thesis. Additional project results can be found in [55]. The research questions set up during the project gave a more clear direction to the project, even though this was done relatively late in the project. These research questions were grouped in three themes: pricing mechanisms and their effect on certain KPIs, consumer participation, and battery sizing and type.

In the project, two pricing mechanisms were implemented, whereby the participants received information on the mechanisms via an app and batteries were steered automatically. The pricing mechanism presented in Chapter 5 focussed on reducing the peaks, while the neighbourhood net metering mechanism focussed on maximizing self-consumption of the neighbourhood. During the test phase, the peaks in electricity consumption and production were decreased by around 25%, resulting in a much flatter neighbourhood profile, and the self-consumption increased by a factor of 16.2. Using the pricing mechanisms allowed the participants to obtain annual savings of €1 403.38 and €753.47 for the two pricing mechanisms, respectively. The response of the participants to the signals from the app showed no statistically significant structural changes in the behaviour. However, via a neighbourhood team whose input was used throughout the project the participants still were involved in the project. This helped to build up the project from the bottom up. However, a lesson learned was that the communication to the participants is an important feature to keep them involved in the project. Lastly, it is concluded that control algorithms, together with the batteries, can play an important role in adjusting the electricity consumption profile based on the pricing mechanisms. However, the battery technology and the BMS still need some further development to be better integrated in energy communities. Additionally KPIs have been proposed to more easily determine which capacity and power of batteries are sufficient in a neighbourhood for flattening their energy profile.

7 Conclusions

As the goal of this thesis is to study how pricing mechanisms and energy communities can aid the energy transition, with a focus on the energy community GridFlex Heeten, this chapter reflects on the research questions from this thesis. Section 7.1 presents some final conclusions based on the research questions from Section 1.2 and in Section 7.2, recommendations for future research are given.

7.1 Research questions

In Section 1.2, the core research questions of this thesis were stated as follows:

» How can we fairly attribute the grid costs to the members of an energy community?

» How can monetary incentives be used to stimulate an energy community to achieve their grid goals?

The suggested solutions were validated in the field test GridFlex Heeten, as introduced in Chapter 2. Furthermore, in Chapter 3 additional background information for answering the questions was presented. The concrete answers to the two research questions were then given in the subsequent chapters. In the following, we summarize these answers.

7.1.1 How can we fairly attribute the grid costs to the members of an energy community?

First, in Chapter 3, an overview of different existing pricing mechanisms was presented as a starting point to attribute grid costs fairly. Then, in Chapter 4, we proposed a pricing mechanism for this. There, the grid costs were allocated to members of an energy community based on the losses they caused in the grid. However, this led to a locational bias in costs, which is considered unfair by the consumers.

To address this, we adapted the pricing mechanism to use an average location in the grid for each household, removing (some of) this locational bias. The two presented options both ensured that the polluters would pay more. However, this also led to a more complex pricing mechanism, making it difficult to convince people to use it.

This touches upon another fairness criterion for attributing costs: complexity. This aspect was explicitly taken into account in Chapter 5, where we presented a framework for pricing mechanisms that are socially acceptable. For this we used a piecewise linear cost function that approximates a quadratic function. By this, it lets the larger consuming or producing users pay more, but only when this is causing issues on the network. A pricing mechanism based on this framework was implemented in a field test and it is considered as socially accepted, both according to users and to criteria from literature.

For the considered field test GridFlex Heeten, introduced in Chapter 2, two pricing mechanisms were implemented, namely the hybrid pricing mechanism from Chapter 5 and a neighbourhood net metering mechanism, which is described in Chapter 6. The participants of the field test had to decide how to attribute the savings obtained by using these different pricing mechanisms in combination with the flexibility of the batteries and inhabitants. They agreed to use it for a communal goal: an AED and training for how to use it.

Therefore, for this energy community, we can state using a socially accepted pricing mechanism to achieve a communal goal is the way to fairly attribute the grid costs. In general, for each different energy community, the members should have a say in how they want the costs or savings to be distributed, as we have seen in Chapter 5. For this, using the pricing mechanism from Chapter 5 provides a way to calculate and incentivize those savings (see also the next research question).

7.1.2 How can monetary incentives be used to stimulate an energy community to achieve their grid goals?

In Chapter 3, the effects of pricing mechanisms on the electricity usage were discussed as a background for potential pricing mechanism. Furthermore, energy communities and their benefits were investigated alongside the current barriers. Together these were used as input for discussing which monetary incentives can be used to stimulate an energy community to achieve their grid goals.

As a possible incentive, a pricing mechanism was proposed in Chapter 4, with the goal of having the polluter in the community pay more, based on the losses they cause. This pricing mechanism stimulates the community to better achieve grid goals relating to, e.g., asset degradation, preventing losses, and reducing peaks. However, as already mentioned, this mechanism is too complex for the members of the energy community to use it in practice.

Therefore, to better stimulate an energy community, in Chapter 5 a framework for pricing mechanisms was proposed that takes the social acceptance into account. These pricing mechanisms provide incentives to an energy community to flatten their energy profiles. Flatter profiles are also more predictable profiles, which could result in a monetary benefit from an aggregator connected to the community. Moreover, flatter profiles also lead to fewer losses, less degradation of assets and less CO_2 emissions (as was mentioned in Chapter 2). When the grid goals of the energy community align with the aforementioned goals, the hybrid pricing mechanisms as proposed in Chapter 5 would be beneficial for stimulating the energy community, especially as the pricing mechanism is considered to be socially accepted.

To get insight in this monetary incentive, we validated it in the GridFlex Heeten field test. The real-time information on the pricing mechanism was shared with the energy community members through an app, and the batteries in the neighbourhood automatically responded to the pricing. As mentioned in Chapter 6, also a neighbourhood net metering mechanism was implemented in GridFlex Heeten. These two pricing mechanisms, together with the batteries, resulted in peak reduction of approximately 25%. Furthermore, the electricity profiles were much flatter and the community obtained annual savings of €1 403.38 and €753.47 for the hybrid pricing mechanism and the neighbourhood net metering mechanism, respectively.

7.2 Recommendations for future work

As demonstrated throughout this thesis, there are still many challenging and important problems to be solved in the electricity grid. Pricing mechanisms could be a direction to help here, but the difficulties lies in finding the proper mechanism for a given problem, which also will be used and accepted in practice. For this, at least focussing on pricing mechanisms targeting energy communities is a first step.

For these communities, many challenges remain, especially legal barriers and missing, or only marginal, options for savings. However, energy communities may have a severe impact on the energy transition in the coming years. So it is interesting to see how these frameworks (both for legislation and for their structure) develop over the years to further support the energy transition.

The pricing mechanism presented in Chapter 4 works well for distributing the grid costs based on the losses incurred in a community. However, next to some technical recommendations mentioned in that chapter, a crucial step is to find ways to overcome the barriers for implementing these more complex mechanisms in real communities. An alternative for these type of pricing mechanisms may be to only implement them in systems without human interference (automated systems for example). For these cases, more research needs to be performed to fully understand the behaviour and interaction of devices based on this pricing mechanism.

Similarly, the framework for pricing mechanisms proposed in Chapter 5 does overcome the social barriers, but, still, needs more testing with larger user groups and a more extensive surveying. This pricing mechanism was tested in GridFlex Heeten, together with the neighbourhood net metering mechanism, but also for the latter pricing mechanism, more tests are needed.

Furthermore, the method to determine the capacity and power needed to flatten a neighbourhood electricity profile could be extended. As the project installed and used several types of batteries with different characteristics, the results of the battery behaviour could help in creating a method for choosing the ideal battery type and characteristics for a neighbourhood based on their goals.

All in all, enabling energy communities, but also setting them up in the first place, is crucial for the ongoing energy transition. Therefore, it is important to identify business cases/enablers for this, and also accompanying legislation. Pricing mechanisms have the potential to help energy communities by giving them incentives to achieve their specified goals, but legal frameworks needs to be developed, and social acceptances needs to be considered. Keeping explanations simple to get communities members to understand the problem at hand, and by that, helping them to realize why certain actions or adaptations are necessary, is of the utmost importance. A technical solution for the energy transition is wonderful, but without the people using it, it is hardly worth anything.

Acronyms

A	ADMM	Alternating Direction Method of Multipliers
	AED	Automated External Defibrillator
B	BMS	Battery Management System
C	CPP	Critical Peak Pricing
D	DEMKit	Decentralized Energy Management toolKit
	DER	Distributed Energy Resource
	DiBu	Diffusion Buffer
	DR	Demand Response
	DSM	Demand-Side Management
	DSO	Distribution System Operator
E	ESD	Energy Storage Devices
	EV	Electric Vehicle
H	HEMS	Home Energy Management System
	HPM	Minimization of the hybrid pricing mechanism
	HV	High Voltage
K	kNN DTW	k-Nearest Neighbour Dynamic Time Warping
	KPI	Key Performance Indicator
L	LEC	Local Energy Community
	LV	Low Voltage
M	MAD	Median Absolute Deviation
	MV	Medium Voltage
N	NO	Using no steering
P	PAR	Peak-to-Average Ratio
	PPA	Power Purchase Agreement
	PS	Using profile steering
	PV	Photovoltaic
Q	QC	Minimization of a quadratic cost function
R	RES	Renewable Energy Sources
	RTP	Real-Time Pricing
S	SD	Standard Deviation

T	ToU	Time of Use
	TSO	Transmission System Operator
U	USEF	Universal Smart Energy Framework
V	V2G	Vehicle-to-Grid
	VPP	Virtual Power Plant

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List of Publications

[VR:1] V. M. J. J. Reijnders, M. E. T. Gerards, and J. L. Hurink. A hybrid electricity pricing mechanism for joint system optimization and social acceptance within energy communities. *Energy Reports*, 8:13281–13292, 2022. doi: 10.1016/j.egyr.2022.10.021.

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[VR:3] V. M. J. J. Reijnders, M. D. van der Laan, and R. Dijkstra. Energy communities: a Dutch case study. In *Behind and Beyond the Meter*, pages 137–155. Elsevier, 2020. doi: 10.1016/b978-0-12-819951-0.00006-2.

[VR:4] V. M. J. J. Reijnders, M. E. T. Gerards, and J. L. Hurink. Energy consumption data of the GridFlex Heeten project, Apr 2021. URL `https://doi.org/10.4121/14447257.v1`. Dataset.

[VR:5] B. Homan, V. M. J. J. Reijnders, G. Hoogsteen, J. L. Hurink, and G. J. M. Smit. Implementation and verification of a realistic battery model in the DEMKit simulation software. In *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. IEEE, 2018. doi: 10.1109/isgteurope.2018.8571691.

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[VR:11] J. L. Hurink, S. Klootwijk, B. Manthey, V. M. J. J. Reijnders, and M. H. H. Schoot Uiterkamp (Eds.). Proceedings of the 17th Cologne-Twente Workshop on Graphs and Combinatorial Optimization. In *DSI Workshop Proceedings Series*, number WP 19-01. University of Twente, 2019.

Victor M. J. J. Reijnders is the main author for all the listed publications, except for [VR:5], [VR:8] and [VR:9] where he is second author, [VR:10] where the main authorship is shared between all authors, and [VR:11] where all listed names are editors.

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