THESIS

UNIVERSITY OF TWENTE - ISTANBUL TECHNICAL UNIVERSITY

A Novel Demand Response Program

USING THE FLEXIBILITY OF RESIDENTIAL PROSUMERS FOR STABILITY ON BOTH NATIONAL AND LOCAL LEVEL

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Abstract

Using the flexibility of domestic electricity appliances, batteries and electric vehicles to help reducing the upcoming increasing gap between the demand and supply of energy is an emerging field of study. On a national level, demand response programs are already offered to residential energy users in order to reduce cost and the need of fossil fuel plants. More recently also on a local level such programs are set up in order to help the distribution system operator keep the distribution network stable. This research proposes a novel demand response program for residential energy users in the low voltage distribution network that gives them the opportunity to both react on fluctuations on the national electricity market and help resolving local grid-related issues in the distribution network. A comprehensible pricing scheme is created that, based on the concept of a traffic light, offers different prices to the prosumers, reflecting the stability of the low voltage network. To test this program, heuristics are designed for the flexible devices in a household in order to react on the varying prices. An IEEE European LV Test Feeder network with 21 households having own generation, smart appliances, batteries and electric vehicles is then simulated minutely for a complete day. In a computer study using the simulation's environment the steering approach is compared with a situation without management, thereby analyzing different penetrations of own generation, batteries, electric vehicles and air conditioners.

Preface

This thesis is the result of my graduation project at the Electrical Engineering department of the Istanbul Technical University that I did from February until July 2017. After having done my internship there and having become used to the people and the city, I decided that I wanted to prolong my research in Istanbul. With the knowledge gained about demand response and power system during my internship and the excellent supervision I had both in Istanbul and Twente, I decided that it should be possible to come up with an own research proposal for my final project. After six months of hard work and again great guidance, this proposal is now materialized into this thesis.

I would like to thank in the first place Alparslan Zehir for spending so much time with me both in the laboratory and in the yemekhane, I feel this project would not be half as good without him. Furthermore I am very grateful to Professor Aydoğan Özdemir for giving me the opportunity to do this project in Istanbul and for the attention he gave to our ideas. I am very much obliged to Professor Johann Hurink for always making time for me, giving me feedback on ideas and numerous versions of this thesis, and on giving me the opportunity to present my previous research in Manchester at the IEEE Power Tech Conference. Furthermore I am thankful to Doctor Judith Timmer for being part of my assessment committee and lastly I would like to thank Professor Mustafa Bağrıyanık, Dr. Alp Batman and Ünal Küçük for their hospitality at both ITU and Makel.

Contents

1 Introduction

1.1 Problem description

Pushed by public opinion and climate agreements like the one resulting from the Paris climate conference in 2015, a big energy transition is taking place at this moment. Reducing the use of fossil fuels is essential for battling climate change and the introduction of a higher amount of renewable energy sources in the energy mix seems to be a good solution. Both on a local and on a national scale, the amount of energy generated by two of the most important renewable sources, wind and solar PV, has increased rapidly. Furthermore, the electrification of transportation and heating is on the rise, giving further potential for a decrease in the need of fossil fuels.

This energy transition however, comes with its own problems. Three of the most important challenges that are relevant for this research are:

- The traditional electricity grid structure, from generation to transmission to distribution, is now complemented with generation at the distribution level. This is because residential energy consumers at the distribution level are now also producing their own energy, and can inject their generated energy into the grid if their supply is higher than their demand (they become prosumers, a combination of producer and consumer). This has a big impact on the distribution grid, as this grid was only designed to supply a relatively steady amount of energy to the residential electricity users connected to it. The cables in the distribution grid therefore traditionally did not require a very low resistance, which can now turn out to be rather problematic if many prosumers are injecting a high amount of energy into the grid, for example at a sunny and windy day. Two of the most important problems that can occur in the distribution grid are overloading, which might happen if too much power is sent over a line, and over- and under-voltage, caused by too much electricity injection or demand. These problems may occur in the traditional situation as well and it is the task of the distribution system operator (DSO) to solve these problems. The risk of any of them occurring however is increased in the new situation and the DSO will need serious measures to secure a stable distribution grid. These overloading and over- and under-voltage issues are discussed and analyzed in detail in Section 2.3.
- Solar and wind are variable non-dispatchable energy sources, which means that they do not have a constant output of power and the amount of energy they supply cannot be increased or decreased like fossil fuel or hydro plants can. With the increase of solar and wind power on both local and national level, an increasing amount of generated energy is now 'uncontrollable'. This means that it is more difficult to match the supply to the demand, as all demanded energy has to be supplied at the exact moment the demand occurs. The problem is clearly visible in the duck curve, shown in Figure 1 [1]. In this figure, the net load represents the difference between the energy demand and the renewable energy production by solar energy. This is exactly the amount of energy that has to be generated with sources other than solar power. Therefore, the amount of fossil fuels needed may be reduced during the middle of the day (between noon and 4 p.m.), but the peak demand at around 8 p.m. does not decrease. As the power generation of big conventional power plants is not very flexible, for example because of long start up times, it may not be possible for them to increase their production as fast as the ramp indicated in the figure. This means that even during the middle of the day the conventional power plants are running at almost full capacity to meet the peak demand in the evening. Therefore, the need for fossil fuel plants stays, which may be a problem economically as now the introduction of renewables do not reduce the cost of energy from conventional power plants. Furthermore, during the middle of the day there is even a chance of overproduction of energy. As can be seen in the figure, this problem is expected to only increase in the future.
- Not only the supply of energy, but also the demand for energy is changing. With the

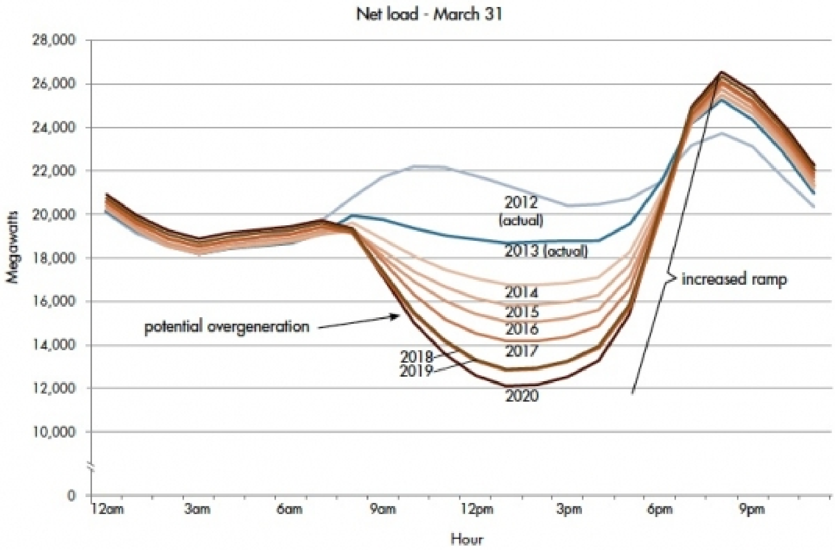


Figure 1: 'Duck curve', showing the actual and future daily fluctuations of power that has to be generated with conventional power plants.

introduction of electric vehicles and electric heating, an increasing amount of electricity is needed to fulfill the demand that was previously met by petrol and natural gas. A higher demand of energy results in higher stress for the grid, which again is especially problematic for the distribution grid. A too high demand can lead to the same problems as the ones described in the first bullet, overloading and over- and under-voltage.

Basically, the above three problems all come down to an increasing mismatch between demand and supply of energy. This mismatch is faced on a national level, but equally (and maybe even more) important, on the distribution grid level. On both levels it leads to undesirable environmental results, as renewable energy might be discarded in times of overproduction. This is mainly the responsibility of policy makers. However, on the distribution grid level, it can also lead to grid malfunctioning, of which the DSO is responsible.

1.2 Solutions from literature

Much research is done to suggest solutions for the problems mentioned in the previous section, see e.g. [2] for an excellent review article about optimal operation and [3] for a review article about active management. The mentioned solutions can be divided into two categories:

1. Solutions that reduce the stress on the distribution grid,
2. Solutions that reduce the gap between demand and supply.

An overview of suggested solutions is given below, followed by a (1) and/or (2) to indicate the category of the solution. Note that reducing the gap between demand and supply at the distribution level automatically results in reducing the stress on the distribution grid.

- Literally enforcing the grid by replacing old cables with thicker new ones. This way, more power can flow without violating the capacity constraints and also voltage fluctuations will be lower because of lower line resistance. Depending on the location and the type of cable needed, the costs for this option can be very high. (1) Research usually focuses on finding alternatives for this option, which are listed in the following.

- Network configuration changes. By changing switches and therefore the grid topology, the power can be send via different routes to resolve stress on certain parts of the grid. For (nearly) critical situations in the distribution grid, the local grid can also be switched to islanded mode, meaning that it is disconnected from other parts of the grid as to not influence the rest of the network. Changing the network configuration might also be used for phase balancing for multi-phase networks. The deployability of this method however depends on the grid topology, as there should be space to install switches and extra connecting lines. (1)
- Coordinated voltage control. The voltage profile within the distribution grid can be regulated by using controllable devices like on-load tap changers, decreasing the chance of facing over- or under-voltage. (1)
- Reactive power compensation and adaptive power factor control. Reactive power should be balanced as well as active power, and this can be done both by taking or injecting reactive power into the grid and by using the reactive power from distributed generation. It has to be noted that as in the distribution network the R/X ratios are generally quite high (i.e. the resistance is a lot higher than the reactance), using the reactive power generally has a low impact. (1)
- Curtailing renewable energy sources. This means that part of the electricity generated by wind and solar is not allowed to be injected in the grid, implying that it is wasted, in order to lower supply. This can be done either for state or corporate owned solar or wind farms (1) and for domestic generation. (1) & (2) However, as mentioned before, this option reduces the amount of electricity generated from renewable energy sources, while it was the initial goal to increase their share. Therefore, curtailing renewable energy sources is undesirable and the use of it should be minimized. To enforce this, some governments already have set a maximum for the amount of domestic generation that can be curtailed, also in order not to discourage civilians to install distributed generation. A DSO should have good agreements with its customers about when curtailment is allowed, and using it in order to resolve stress in the local network should be done in a fair way, such that all households are treated equally. This is discussed in more detail in Section 2.4.
- Curtailment of demand. This means that part of the energy demanded by the customers is denied by the DSO, in order to lower the demand. This option is undesirable and the use of it should be minimized because it can effect customer comfort quiet severely. Therefore good arrangements should be made with the customers about how often it is allowed and what form of compensation is possible. (1) & (2)
- Flexible appliances. Instead of changing the supply of energy or forcing a change in demand, demand can be altered voluntarily as well. This is also known as demand side management, or more specifically demand response, and implies that electricity consumption is shifted by making changes in the usage of appliances. This can be done for industrial (2), commercial (1, if connected to distribution grid) & (2) and residential (1) & (2) energy usage. Residential energy is consumed by home appliances. These appliances have either no or different levels of flexibility. For example, some appliances such as a television, are considered to be non-flexible, as the consumer wants to use them at a certain moment and changing this behavior results in undesired comfort loss. Other devices, like dish washers or clothes dryers, may be postponed or started earlier without (substantially) affecting customer comfort, and they are known as shiftable appliances. Thermal appliances, such as deep freezers or air conditioners, are devices that control the temperature in a certain space. As the temperature may have a small range (known as the deadband) to vary around a given set temperature, thermal appliances have some flexibility in when they consume energy. Flexible appliances may help reducing the gap between supply and demand by increasing the demand in times of high supply and lowering demand in times of low supply. On a local scale, they can increase the consumption of self-generated electricity, which also reduces the stress in the distribution

network. The flexibility of these appliances is however limited, and it is expected that they are only partially able to solve the problems. Furthermore, changing the behavior of appliances can lead to a decrease in comfort, depending on the customer, the appliance and the situation. Therefore, customers willing to shift their flexible appliances should be compensated by giving them monetary or social incentives. See [4], [5] and [6] for detailed descriptions of how flexible devices can be used for both grid stability and reducing peaks.

- Batteries. A battery stores energy to use it at a later moment, meaning that it shifts energy over time. It can be used to reduce the gap between supply and demand, as it can be charged at times of high supply and discharged in times of low supply. Ideally, this could totally match supply and demand and therefore solve all the aforementioned problems. However, a very large amount of batteries would be needed for this, and at quite a high price. Furthermore, batteries do not have an efficiency of a hundred percent, which means that energy is lost while shifted over time. Next to this, a battery has a finite life time, as it loses capacity with each charge/discharge cycle. Batteries can both be used to (partially) mitigate the variability of big wind or solar farms (1) and on a domestic scale to aid smart management of a household (1) & (2). The reader is referred to [6], [7] and [8] for ideas for optimal charging/discharging strategies.
- Electric vehicles. An electric vehicle can be seen as part of the problem, as it increases the total demand of energy. However, it can also be seen as part of the solution, as an electric vehicle is a very flexible appliance. If the charging time of an electric car is smaller than the time it is connected to the grid until it is needed again, the vehicle can be charged in times of highest supply. An electric vehicle can even be seen as a supplementary battery, as energy stored in the vehicle can be used to fulfill demand of a household or even be injected into the grid in times of low supply. This principle is known as vehicle to grid (V2G) and is an upcoming strategy to maintain grid balance, see [9] for a good example of how this flexibility can be used. (1) & (2)

1.3 Research question and organization of the thesis

It is probable that all solutions listed in the previous section are of importance and should be combined to face the problems caused by the energy transition, as they all have their strengths and weaknesses. This research however focuses only on the solutions that both reduce the stress on the distribution grid and reduce the gap between supply and demand, i.e. the solutions characterized by (1) & (2). These are: curtailing renewable energy sources, curtailment of demand, flexible appliances, batteries and electric vehicles. To the best knowledge of the author, no research has yet been done that uses this combination of solutions for trying to reduce the gap between demand and supply on both the national and the local level.

Note that all the mentioned solutions are taking place within the residential distribution network. The two stakeholders involved in these solutions are:

- The DSO: The distribution system operator has the power to forcefully lower demand or supply, as he can curtail the residents both if they are demanding too much energy from the grid or if they are injecting too much energy into the grid.
- The residentials: The residentials can use the flexibility of their flexible appliances, batteries and electrical vehicles, to either increase or decrease their net power (which is defined as their supply subtracted from their demand).

As it is the DSO's responsibility to prevent undesired issues in the distribution grid, it is natural that he is a key player in solving grid related problems. On the other hand however, it is not the responsibility of residentials to maintain grid stability and neither is it (directly) their responsibility to balance supply and demand. Therefore, residentials should be motivated, either intrinsically or extrinsically, to actually make use of their flexibility. Note that for this, extensive communication and management systems are needed to use the flexibility of the residentials in the right way. This is the core of this research, leading to the following main research question:

How can residential energy prosumers be motivated to use their flexibility to reduce the gap between supply and demand, while at the same time increasing distribution grid stability?

To be able to answer this question, this thesis is divided into sections that give answer to subquestions. As one of the goals of this thesis is to investigate methods to increase grid stability with the help of residential energy prosumer flexibility, knowledge about the topology of the distribution grid, the kind of issues that can arise in this grid, and how they can be solved, is needed. This issue is discussed in Section 2. In Section 3, possible incentive structures are discussed that can be used to motivate prosumers to use their flexibility. Furthermore, a novel energy pricing scheme is proposed that might be the solution for the main research question. To find out whether this pricing scheme actually meets the goal of the main research question, it has to be investigated how the prosumers react to this scheme. To do this, first an optimization is proposed, but due to time constraints, heuristics are designed to influence the behavior of the prosumers. This is all described in Section 4. To evaluate the proposed method, a simulation is set up, for which the input is given in Section 5. In Section 6, the results of the simulations based on the proposed pricing scheme and the designed heuristics are presented. This thesis is concluded in Section 7, in which the results are concluded and discussed, followed by some recommendations.

2 Distribution grid topology

In this section the distribution grid topology is discussed. With the knowledge of this grid structure, the problems that can occur in the LV-grid are addressed and it is examined how residential energy users can help solving these problems. Furthermore, it is discussed how a distribution system operator (DSO) can ensure grid stability by forcefully changing the demand or supply of the prosumers, and how this can be done in a fair way.

2.1 Formal definition of the grid topology

For this research, a single-phase low voltage distribution grid with multiple households is considered that is connected to the medium voltage grid with a transformer. The voltage level at the transformer can vary slightly due to fluctuations in the medium voltage grid, but it is assumed that this level is not affected by changes in the distribution grid. The transformer is supplying the households with energy and is also able to transport injected energy by the households to the medium voltage grid and it is assumed that the transformer is not limited in its capacity, meaning that it can handle infinite supply and demand. However, at the household level we take into account restrictions on the supply and demand because of limited grid capacity. The topology of the grid analyzed in this research can be characterized as radial in contrast to a mashed structure, i.e. the households are connected with lines in a branch-like structure, so there are no cycles in the network. Bidirectional power flow is possible and the lines can have different specifications for type and thickness, resulting in varying line resistance and maximum power flow. All households produce a time-dependent net power curve over the day, which represents their energy demand minus their supply at a certain time. As prosumers are assumed to be able to both supply to and demand from the grid, the net power can be either positive in times of higher demand, negative in times of higher supply or zero in times of equal demand and supply. The voltage level at each household is varying, dependent on the power flows and the properties of the cables.

More formally, the distribution grid is defined as a directed rooted tree $RT = (V, E)$, where all edges are pointed away from the root, known as an out-tree. Here, $V = \{v_{TR}\} \cup V_H \cup V_C$ is the set of vertices, where v_{TR} is the transformer and the root of the tree, V_H is the set of households and V_C the set of connection points where multiple lines come together. As we are interested in the evolving of the grid over time, we also have to model the time. We do this by discretizing the given time horizon in a set T of time steps. To specify the net power injected or withdrawn from the grid at a node $v \in V$ at time $t \in T$, a variable $NP_v(t)$ is attached to vertex v. As connection points $v \in V_C$ do not supply or demand energy, we have $NP_v(t) = 0$ for these vertices. For all households $v \in V_H$, a total power injection at time t is represented with $NP_v(t) < 0$ and a power demand is denoted with $NP_v(t) > 0$. As the transformer is the root of the tree and should consume or supply the energy of all other nodes, it follows that $\sum_{v \in V_H} NP_v(t) = -NP_{v_T}(t)$. Furthermore, to each vertex $v \in V$, a time-dependent variable $VL_v(t)$, representing the voltage level, is attached. This value depends on the overall values $NP_{v'}(t)$ for all $v' \in V_H$ and this relation is explained in more detail in Section 2.2. The set E is defined as the set of edges, which are all the different lines in the network. Each edge e connects two different vertices $v^{in}(e)$ and $v^{out}(e)$ with each other and is assumed to be directed away from the root, which is from v^{out} to v^{in}. All the edges have associated parameters R_e and CCC_e representing respectively the resistance and the current carrying capacity of the line e. Furthermore, variables $PF_e(t)$ and $C_e(t)$ represent respectively the power flow and the current over line e. A power flow or current in the direction of the edge results in a positive value for $PF_e(t)$ or $C_e(t)$, whereas a power flow in the opposite direction is depicted with a negative value.

2.2 Load flow analysis

Now that we have a formal definition of the grid topology, we can make a load flow analysis. With this analysis, we can find the power flow $PF_e(t)$ and current $C_e(t)$ over the edges and the voltage level $VL_v(t)$ of the vertices, given the topology of the grid, the resistance R_e of the lines and the net power $NP_v(t)$ of the households. The load flow analysis for meshed networks or 3-phase distribution grid is quite complicated, and special power system simulation software can be used for this analysis. However, for a single-phase radial network as considered in this research, the load flow analysis is rather simple. It is known as a forward/backward sweep algorithm [10], and is shown in the following subsections. First, the power flow is analyzed, which is needed to find the voltage level at each household. With the knowledge of the voltage, the current over all lines can be calculated. It is important to know both the currents of all lines and the voltage level at each household, as the grid-related issues discussed in this research (overloading and over- or under-voltage) are direct consequences of these values.

2.2.1 Power flow

If power losses due to line resistance are neglected, the power flow $PF_e(t)$ over an edge can be found by summing over the net power $NP_v(t)$ of all households that are descendants from this line (all the vertices further away from the root). If $V_{D_{v^{in}(e)}}$ is defined as the set of all vertices in the subtree with $v^{in}(e)$ as root including vertex $v^{in}(e)$ itself, it follows that $PF_e(t) = \sum_{v \in V_{D_{v^{in}(e)}}} NP_v(t)$ is the flow in edge $e = (v^{out}(e), v^{in}(e))$. A negative power flow is a flow in the direction towards the root and a positive power flow is a flow away from the root. See Figure 2 for a graphical representation of a LV distribution network and the set $V_{D_{v^{in}(e)}}$.

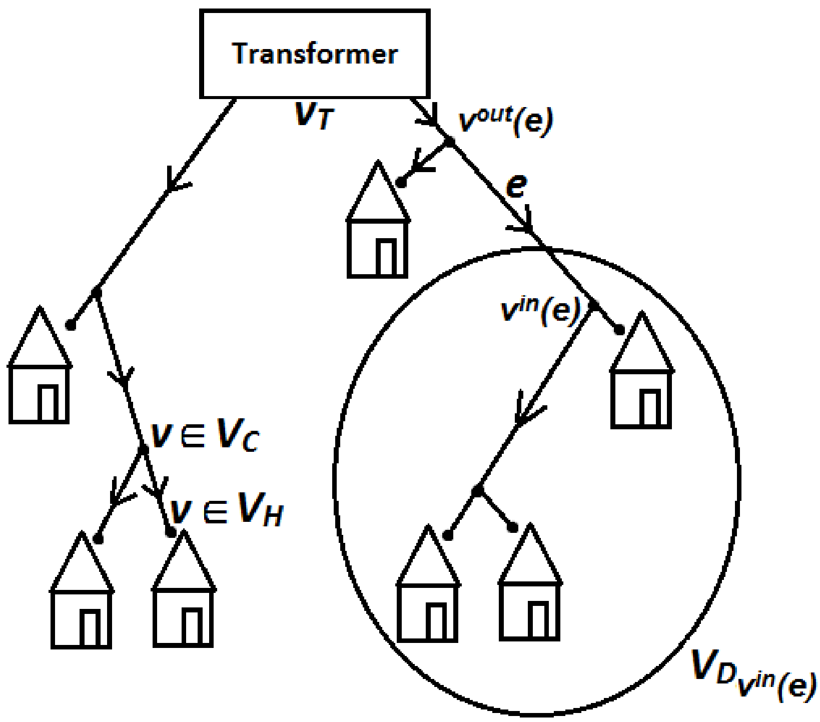


Figure 2: Graphical representation of a LV distribution network.

2.2.2 Voltage level

The voltage level $VL_v(t)$ is varying across the grid, because sending power over an edge $e = (v^{out}(e), v^{in}(e))$ requires a difference in voltage between the two vertices. The exact amount of voltage difference is dependent on the resistance and the reactance of the lines, as well as both the active and reactive power flow. However, as for low voltage networks the reactance of lines is relatively small compared to their resistance, the reactive power is often neglected and therefore the following simplification for the voltage difference is made:

$$VL_{v^{out}(e)}(t) - VL_{v^{in}(e)}(t) = \frac{R_e \cdot PF_e(t)}{VL_{v^{in}(e)}(t)}. \tag{1}$$

As we assume that the voltage of the transformer VL_{v_TR} is known, the voltage levels of the other vertices can be found iteratively, starting from the transformer down the entire tree. Rearranging (1) results in

$$(VL_{v^{in}(e)}(t))^2 - VL_{v^{in}(e)}(t) \cdot VL_{v^{out}(e)}(t) + R_e \cdot PF_e(t) = 0. \tag{2}$$

The value for $VL_{v^{in}(e)}(t)$ can be found by solving the quadratic equation (2). This results in two values, where the smallest solution represents the voltage drop, and the largest solution is the desired voltage level at the incoming vertex.

2.2.3 Current

The current $C_e(t)$ can then easily be found by using Ohm's law, which states that

$$C_e(t) = \frac{VL_{v^{out}}(t) - VL_{v^{in}}(t)}{R_e(t)}. \tag{3}$$

2.3 Potential grid problems

In this section two potential grid problems are described. As this research focuses on mitigating these problems by using the flexibility of consumers, it is also discussed which households have influence on these problems. Then, possible solutions to the problems are proposed.

2.3.1 Overloading

A problem occurs when too much current is send over a line, resulting in too much heat generation within some components of the electricity circuit. Every type of line has a specific value for the maximum amount of current that is allowed to flow through it. This means that for every edge $e = (v^{out}(e), v^{in}(e))$ and all times $t \in T$, we should have $|C_e(t)| \leq CCC_e$, where CCC_e represents the current carrying capacity for edge e. We speak of overloading if the current becomes higher than the current carrying capacity.

Overloading occurs when households are either demanding or injecting too much power from the grid. However, not all households are necessarily responsible for an overloading case on a particular line. Looking back at section 2.2.1, a too high current on an edge $e = (v^{out}(e), v^{in}(e))$ is caused by a too high absolute net power of the households $v \in V_{D_{v^{in}(e)}}$, as the current is proportional to the power flow. Therefore, the only households that are able to mitigate this problem, are those households $v \in V_{D_{v^{in}(e)}}$, see Figure 2.

The problem of an overloading of the edge $e = (v^{out}(e), v^{in}(e))$ can be solved by adjusting (either voluntarily or forced) the total net power $NP_v(t)$ of the households $v \in V_{D_{v^{in}(e)}}$. Because the net power is proportional to the current, the total net power should be reduced with the same factor as the current is outside its flow limit. If $\alpha = |C_e(t)| / CCC_e$ represents the factor of how much the current carrying capacity is exceeded, then the needed total net power $NTNP_{V_{D_{v^{in}(e)}}}(t)$ is calculated as

$$NTNP_{V_{D_{v^{in}(e)}}}(t) = \frac{\sum_{v \in V_{D_{v^{in}(e)}}} NP_v(t)}{\alpha}. \tag{4}$$

The households $v \in V_{D_{v^{in}(e)}}$ should therefore change their net power to values $NP_v^{new}(t)$, such that

$$\sum_{v \in V_{D_{v^{in}(e)}}} NP_v^{new}(t) = NTNP_{V_{D_{v^{in}(e)}}}(t). \tag{5}$$

2.3.2 Under- and over-voltage

The voltage level $VL_v(t)$ at each household $v \in V_H$ and time $t \in T$ should stay in between a minimum and maximum voltage level VL^- and VL^+, because too high or too low voltage is harmful for electrical components. Voltage regulation is therefore very important and can be done in multiple ways, as discussed in Section 1.2. In this report however, the focus is on keeping the voltage level within bounds by using the flexibility of customers. This can be achieved because, looking back at Section 2.2.2, the voltage drop between two households depends on the amount of power that is sent over the line between them. Basically, a higher net power (by increasing demand or reducing injection) decreases the voltage and a lower net power (by decreasing demand or increasing injection) results in a voltage increase.

If a household changes its net power, a different amount of power is send over all the lines leading from the transformer to that household. Because the voltage drop depends on the power send over a line, the voltage level changes at all households on that path. Furthermore, all descendants (i.e. vertices further away from the root) of those households also get a different voltage level, because the voltage level at a vertex depends on its ancestor vertices. Therefore, in case of an under- or over-voltage at a certain household, all household that are descendants from the edge from the transformer to the highest ancestor of the household with a problem $e = (v_{TR}, v^{in}(e))$ are responsible for and able to help solving the under- or over-voltage problem. In Figure 3 this situation is sketched, where $V_{D_{V^{in}(e)}}$ is the associated set of households. Note, that if only one branch is going out from the transformer, all households in the grid are responsible for and able to help solving an under- or over-voltage problem.

The exact influence that a household's net power change has on another household's voltage can be calculated by going through the load flow analysis described in Section 2.2. However, a simplification can be made by setting up a sensitivity matrix SM_{ij} that states how much the voltage of household i is changing as a result of a net power change of 1 at household j:

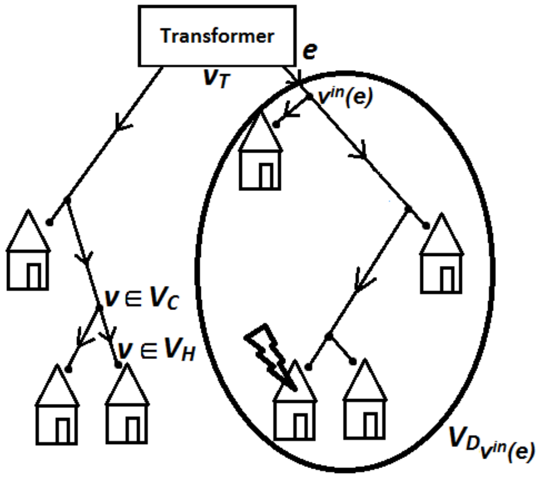


Figure 3: Graphical representation of a LV distribution network with an under- or over-voltage problem at the bolt icon.

$$SM_{ij} = \begin{bmatrix} \frac{\partial VL_1(t)}{\partial NP_1(t)} & \frac{\partial VL_1(t)}{\partial NP_2(t)} & \cdots \\ \frac{\partial VL_2(t)}{\partial NP_1(t)} & \frac{\partial VL_2(t)}{\partial NP_2(t)} & \cdots \\ \vdots & \vdots & \ddots \\ \end{bmatrix} \tag{6}$$

Note that if there is only 1 outgoing edge from the transformer, all entries of the sensitivity matrix are strictly bigger than zero, whereas in the case of multiple outgoing edges from the transformer, households in different branches (with the transformer as root) will have a sensitivity of zero. Using this sensitivity matrix, we assume that the change of net power in household i is proportional to the change in the voltage level for household j for all i and j. To check whether this assumption is reasonable, first we look at Ohm's law. According to this, the change in voltage of a household is proportional to the change in net power for the same household. To see why the voltage level in one household is also (approximately) proportional to the voltage level in other households, one has to look back at (2) in Section 2.2.2. Solving this equation leads to

$$VL_{v^{in}(e)}(t) = \frac{VL_{v^{out}(e)}(t) + \sqrt{(-VL_{v^{out}(e)}(t))^2 - 4 \cdot (R_e \cdot PF_e(t))}}{2}. \tag{7}$$

Above equation gives the direct relation between the voltage levels of two neighboring households. To see why these voltage levels are approximately proportional, we look at the derivative $\frac{\partial VL_{v^{in}(e)}(t)}{\partial VL_{v^{out}(e)}(t)}$, which represents the change in the voltage level of the incoming vertex due to a change in voltage level in the outgoing vertex. For typical LV-grid values $R_e = 0.0738$, $PF_e(t) = 3000$ and $VL_{v^{out}(e)}(t) = 230$, the derivative of (7) to $VL_{v^{out}(e)}(t)$ is 1.00424. A value of 1 would mean a perfect proportional relation, so we see that using the sensitivity matrix gives us a rather good approximation for the change in voltage levels.

This sensitivity matrix can be found by changing the net power of one household, and calculate the voltage change in all other households with the load flow analysis. This has to be done once for all households, and after that no load flow analysis is needed anymore to calculate the voltage change. With the sensitivity matrix, it is now rather simple to calculate the amount of net power that the households should shift if an under- or over-voltage problem occurs. Let $VV_v(t)$ represent the voltage violation at household v and time t. It can be defined as

$$VV_v(t) = \begin{cases} VL_v(t) - VL^+ & \text{if } VL_v(t) > VL^+ \\ 0 & \text{if } VL^- \leq VL_v(t) \leq VL^+ \\ VL_v(t) - VL^- & \text{if } VL_v(t) < VL^-. \end{cases} \tag{8}$$

Now the goal is to solve the voltage violations by changing the net powers $NP_v(t)$ for households v at time t. As can be seen from (8), the voltage violation $VV_v(t)$ at household v at time t is zero when the voltage level $VL_v(t)$ is within bounds. Therefore, a corrective action from the households is needed such that the voltage level increases (for under-voltage) or decreases (for over-voltage) at least with $VV_v(t)$. The size of the corrective action for an under- or over-voltage problem at household i, that we define as $NP_v^{change}(t)$, can easily be calculated with the sensitivity matrix defined in (6):

$$\sum_{v \in V_H} NP_v^{change}(t) \cdot SM_{i,*}^T = VV_i(t), \tag{9}$$

where $SM_{i,*}$ represents the i^{th} row of the sensitivity matrix. Similar to the overloading scenario described in Section 2.3.1, the households should therefore change their net power to desired values NP_v^{new}, where these new net powers are defined as

$$NP_v^{new}(t) = NP_v(t) + NP_v^{change}(t). \tag{10}$$

2.3.3 Phase imbalance

In this research a single-phase network is analyzed for reasons of simplicity. However, using the flexibility of energy prosumers is expected to be able to mitigate another potential problem that occurs in a 3-phase network as well. In a 3-phase network it is important that the total loads on the three different phases have similar values. Therefore, it should hold that $\sum_v NP1_v(t) \approx \sum_v NP2_v(t) \approx \sum_v NP3_v(t)$, where $NPj_v(t)$ represents the net power on the j^{th} phase. Using the flexibility of the households, the load on the three phases can be changed towards for example the average of them. This idea is out of the scope of this report, but can be used for future research.

2.4 Incentives, curtailment and fairness

In the previous sections it was seen that local grid problems can be (partially) solved by the flexibility of the energy prosumers in that network. However, it is the responsibility of the distribution system operator (DSO) to maintain grid stability, and not that of the households. Therefore, the energy prosumers should be motivated by the DSO to actually use their flexibility and adjust their net power in the direction needed by the DSO. In Section 3, possible incentive structures offered by the DSO are discussed in more detail.

Incentives can be a good way to persuade prosumers to change their behavior, however not in all cases they are enough to change their energy usage sufficiently to completely solve the given grid problem. Therefore, despite these incentives, the local grid problems described in previous sections can still occur and more drastic measures are needed. DSO's have various possibilities to solve these issues without the flexibility of prosumers, like spinning reserve in case of too much demand or batteries in case of too much injection. In this research however, it is assumed that the DSO does not have access to these options and should solve the problem with the flexibility of the prosumers only. This means that in extreme cases the DSO can force households to increase or decrease their net power, by not allowing respectively part of their injection into the grid or part of their demand from the grid. In this report, they are named respectively injection curtailment and demand curtailment (note that demand curtailment is not a common term, but is used here because of the similarity with injection curtailment). In reality, it depends on regulations and agreements between the DSO and the prosumers whether injection and/or demand curtailment are allowed [11] [12].

Assuming that DSO's can forcefully change the net power of the households in the grid, a grid-related issue can be completely solved by curtailing (some of) the prosumers. However, it is not clear from previous sections which of them should be curtailed. The solutions proposed in (5) and (9) to solve the grid-related issues state a vector of new desired net power $NP_v^{new}(t)$, which is a joint solution of all households that have influence on the grid related issues, i.e. $v \in V_{D_{vin(e)}}$. This vector of new desired net powers is however not unique, as different combinations of curtailed households can solve the grid-related issue.

The problem is therefore that there are many possible actions that reach our goal of solving grid related issues, but it is not clear which one to choose. For example, assume that an over-voltage problem occurs at household i and both households i and j are able to solve it. Should household i solve it, because the issue is located at his household? Or should the household with the lowest net power (the biggest contributor to the over-voltage problem) solve it, or should they solve it together in a certain ratio? There is no best solution for this problem, but there are some ideas in literature about how to divide curtailments in a 'fair' way. Fairness is a very subjective term, but it basically comes down to treating all households (as much as possible) in the same way, and not curtailing one household more because of e.g. its physical location in the grid. Some options include [13]:

- All households that have influence on the problem should change their net power with the same amount. In this option everybody is curtailed equally.
- All households that have influence on the problem should change their net power with the same percentage. In this option prosumers that have a higher absolute net power are curtailed more than prosumers with a lower absolute net power, which means that bigger contributors to the problem should also help more.
- Households with a greater influence, i.e. higher value in the sensitivity matrix for under- or over-voltage, should change their net power more than households with a lower influence. This option is less fair, as now the physical location in the distribution grid is taken into account for the amount a household is curtailed. However, with this option a lower total amount of curtailment is often needed, as higher values in the sensitivity matrix result in a bigger voltage change per net power change for under- and over-voltage problems.
- A maximum (for demand curtailing) or minimum level (for injection curtailing) for the net power is set for all households that have influence and values below or above these bounds are curtailed up to this bound. In this option only the highest contributors of the problem are curtailed.

In this research the last option is chosen. This is because intuitively this option stimulates the households the most to lower their absolute net power by smart management of their devices, because only the highest contributors of the problem are curtailed. It is unfair in the way that a six-person family generally consumes more energy than a 1 person household and is therefore curtailed more often. This can be adjusted for example by setting a maximum demand level dependent on family size. However, this is out of the scope of this research, and a completely fair curtailment rule is not possible anyway.

The main idea of this research is to first motivate the prosumers to voluntarily change their net power in case of an upcoming problem, by giving them proper incentives. If this turns out not to be enough, the DSO can curtail the households with the above discussed fairness rule to make sure the problem is solved. At the same time, the prosumers should be able to react on the fluctuation of the energy price at the markets so they can also help reduce the gap between supply and demand at the national level. This incentive structure is presented in more detail in the next section.

3 Incentive structure for residential energy users

In this section it is discussed by which means residential energy users can be motivated to use their flexibility. First it is discussed which types of incentives are available, then it is analyzed what the requirements are for an incentive structure that is suitable for the problem formulated in this research and lastly a novel price/incentive structure is proposed.

3.1 Possible incentives

To motivate consumers to offer their flexibility to the grid, they should be offered some form of reward. A consumer might have made an investment by buying a battery, or his comfort may decrease because of a change in the operation of his appliances. To compensate him/her for this, an incentive is needed that results in the desired behavior of consumers. Incentive structures that are offered in the field can be divided into three categories [14]:

- Social incentives. Ideas are emerging to gamify demand response, which means that elements from game playing are applied to intrinsically motivate people. For example, households can all be connected to a sort of scoring board, to rate them based on their sustainable performance. It is expected that in many cases intrinsic motivation is not enough to persuade people, especially when a monetary investment has to be earned back, but it can be combined with monetary incentives for extra motivation.
- Price based incentives. By offering different energy prices during different times of the day, people are motivated to shift their energy consumption to cheaper time periods and their injection to more expensive periods. This can range from a Time of Use (ToU) program, in which generally two or three pre-set price levels are offered, to a Real Time Pricing (RTP) program, in which the price can fluctuate real-time over the whole time period, following in general the market price of electricity.
- Event based incentives. In this option an event that lasts for a certain time is announced to which people can react. This can be a monetary reward for increasing or decreasing normal energy consumption within the event, a bonus for self-consumption within the event, a penalty for injection within the event, a periodic reward for offering a certain amount of flexibility, etc.

3.2 Requirements for an incentive structure

Using the possible incentives described in the previous section, a price/incentive system can be designed that is suitable for the problem formulated in this research. This means that the incentive structure should enable prosumers to benefit from price fluctuations at the utility level, because of a gap in supply and demand or instabilities in the national grid, while at the same time enable them to help solving local grid issues. So first of all, residential energy consumers should have the possibility to respond on Demand Response (DR)-signals given by the utility or an aggregator. These signals can either be in the form of price based programs or incentive based programs, and usually they reflect the energy market prices in a certain way. This market price is mainly dependent on the balance between the demand and supply of energy and on potential problems in the national grid. Therefore, residential users can help reducing the gap between supply and demand at the national level and help solving the problems in the main grid when they respond to these DR-signals, resulting in some benefits for them in the form of a lower electricity bill. Furthermore, the incentive structure should also be able to motivate customers to help reducing the stress in the case of a (risk of a) problem in the local distribution grid. As the residential energy users have the biggest influence on their local distribution network, solving these local issues has the highest priority. Therefore, the DR-signals based on the national situation offered by the utility or an aggregator should be able to be changed or overruled in case of a local distribution grid problem, so that customers are motivated to help mitigating these local issues first.

3.3 Multi-level real time pricing with traffic light

The basic idea for a novel price/incentive structure for residential energy users that fulfills the requirements of the previous section is a price based DR-program that is dependent on both the national situation and on the situation in the local distribution network. A multi-level real time pricing (RTP) is proposed, in which the energy price can change minutely, quarterly or hourly, but can only switch between a fixed amount of price levels. For example, a 5-level RTP would look as follows:

- ++ lowest price (per kWh), extreme amount of generation, possible injection curtailment.
- + low price (per kWh), larger need for demand than for supply.
- 0 average price (per kWh), normal situation.
- − high price (per kWh), larger need for supply than for demand.
- −− highest price (per kWh), extreme amount of demand, possible demand curtailment.

For every time frame the utility offers one of these prices to its customers, based on e.g. the prices at the national energy markets. However, this price can be adjusted or overruled if an issue arises within the local grid, because local issues should be solved first. This is done by assigning a traffic light to each household that can change with time, reflecting the local grid situation at that particular household at that time. The three colors of the traffic light imply the following:

- Green: No problems in the grid (that the household can help solving); apply the price offered by the utility.
- Orange: Risk of problems (that the household can help solving); dependent on the type of problem, the price level offered by the utility is adjusted one level up (in case of desired lower net power) or down (in case of desired higher net power).
- Red: Extreme problem (that the household can help solving); dependent on the type of problem, move to level −− or ++, curtailment necessary.

A red light is given in situations where the limits for the voltage level VL^- and VL^+ or the current carrying capacity CCC_e are really exceeded, so that curtailment is necessary. The orange traffic light is a warning signal and can be set at for example 80% of the limits to encourage households to change their loads before they have the risk to be curtailed.

To clarify the traffic light mechanism, an example is given here. If there is a risk of under-voltage in one of the households, all households that have influence on its voltage level will get an orange light. If the utility is offering price level +, these houses are now offered level 0, so that with this higher price they are stimulated to demand less or supply more, increasing thereby the voltage level. If this is not enough and the voltage level decreases to a problematic value, these houses will get a red light and are offered −−, to stimulate them with even higher prices to further increase the voltage. If offering high prices does not suffice in decreasing demand or increasing supply, the DSO will curtail the prosumers with the highest demand.

The advantage of such a pricing scheme is that it is easy for the prosumers in the sense that they are dealing with only one comprehensible pricing system. It does not matter to them whether the price they are offered is reflecting the energy market price or that it is based on local grid problems. Therefore, it is easy for them to respond to these prices in the proper way and by trying to minimize their electricity bill, they reduce the gap between demand and supply on both the national and local level.

Another advantage is that the orange traffic light is sort of an in-between state that hopefully results in a smaller amount of curtailment, because local grid problems are (partially) solved by using the prosumers' flexibility instead of using curtailment. Furthermore, more extreme prices due to a red traffic light possibly lead to even a higher amount of flexibility, further reducing the need of curtailment. A lower amount of demand curtailment will in general not lower the prosumers' energy bill, assuming that curtailed demand will be shifted to a later time. However, it is extremely beneficial for the comfort of the users and therefore their satisfaction about their DSO. Reducing the amount of curtailed supply is beneficial for the energy bill of the consumer as more energy can be sold, but also for the environment and for policymakers, as it increases the share of renewable energy in the (national) energy mix.

4 Household optimization

In this section, first the situation for the households is sketched, followed by an optimization program that is derived for the flexible devices. As it might be too time-consuming to solve this optimization, heuristics are designed that find sub-optimal management decisions for the flexible devices.

4.1 Situation

In the previous section a new pricing scheme was suggested in which the price of energy that prosumers pay for demand and receive for injection could change every time step, e.g. minutely. In this scheme, the prosumers are motivated by these different prices to lower their demand or increase their injection (e.g. by discharging their battery) in times of high prices, and increase their demand or decrease their injection in times of low prices. However, it is not clear how exactly they should use the flexibility of their devices to respond to these changing prices in an optimal way. An optimal strategy is difficult to find, as the decisions depend on for example the current and future energy prices, the current and future generation, the situation in the local grid and therefore the chance of curtailment, the state and parameters of all flexible devices, the demand of the non-flexible devices, their comfort preferences, etc.

As the price might change minutely in this pricing scheme, it is assumed that all decisions are made automatically, as it is extremely impractical for humans to change the behavior of their appliances constantly. Therefore, it is assumed that within a household a very advanced communication system exist that connects all devices with an automatic managing entity, and that this entity can control all these devices. Furthermore, it is assumed that it is possible for DSO's to curtail an exact amount of both demand and injection. Next to this, the assumption is made that a good prediction of both the energy prices and the generation is available for the managing entity. The decisions that the management entity makes for the flexible devices is discussed in the following subsections.

4.2 Optimization for the flexible devices

The flexible devices are divided into four different groups [15]: shiftable appliances, thermal appliances, batteries and electric vehicles. They are all managed so that the energy costs are minimized, based on the current and predicted energy prices, using discretized time steps. In the following four subsections, the optimization is derived for the four groups of flexible devices individually, followed by a combined optimization program.

4.2.1 Shiftable loads

Shiftable loads are loads that can be shifted in time (i.e. they can be run later or earlier), like dish washers or clothes dryers. Let A be the set of all shiftable loads. The flexibility of such a load $a \in A$ is its starting time ST_a. A consumer can restrict times for the use of the appliance to limit his comfort reduction, by defining an earliest starting time EST_a and a latest finishing time LFT_a. If the running time of an appliance $a \in A$ is denoted by RT_a, the set of (discrete) possible starting times PST_a can be described as:

$$PST_a = \{EST_a, EST_a + 1, ..., LFT_a - RT_a\}. \tag{11}$$

Let the energy profile of a shiftable appliance $a \in A$ be denoted by $(SAP_{a,1}, ..., SAP_{a,RT_a})$. As mentioned before, it is assumed that the energy price EP_t is known or a prediction can be made for all future times $t \in T$. To minimize the energy cost, a start time ST_a should be found so that the appliance runs in the cheapest times. Mathematically, this means that we minimize

$$\min_{ST_a \in PST_a} \sum_{t=ST_a}^{ST_a+RT_a} EP_t \cdot SAP_{a,t-ST_a+1}. \tag{12}$$

4.2.2 Thermal loads

Thermal loads are loads that control the temperature in a certain space, like an air conditioner or a deep freezer. Let B be the set of all thermal loads. Usually, a thermal load $b \in B$ is used to keep the temperature $TEMP_{b,t}$ in a space at time $t \in T$ close to a set point temperature SPT_b. It is assumed that the temperature always has to be within a deadband temperature DBT_b and this constraint is mathematically defines as

$$SPT_b - \frac{1}{2}DBT_b \leq TEMP_{b,t} \leq SPT_b + \frac{1}{2}DBT_b \quad \forall b \in B, \forall t \in T. \tag{13}$$

Thermal appliances can be either on or off. This is represented by a binary variable $TAS_{b,t}$ which expresses the thermal appliance state of appliance b at time $t \in T$ (1 for on, 0 for off). It is assumed that the change in temperature is independent of the outside temperature, and that the thermal appliance is used to cool a space (the optimization is similar for a heating device). This implies that there is a cooling parameter CP_b that depicts the amount of temperature change in one time step when the appliance is on, and a heating parameter HP_b for the temperature change in one time step if the appliances is off. If $TEMP_0$ represents the temperature at the start of the time horizon, the course of the temperature is then described by

$$TEMP_{b,t+1} = TEMP_{b,t} + TASb, t \cdot CP_b + (1 - TAS_{b,t}) \cdot HP_b \quad \forall b \in B, \forall t \in T. \tag{14}$$

Let the electricity consumption of thermal load $b \in B$ be denoted by TAC_b. This implies that the electricity demand $TAD_{b,t}$ at time t of the thermal appliance is given by

$$TAD_{b,t} = TAC_b \cdot TAS_{b,t} \quad \forall b \in B, \forall t \in T. \tag{15}$$

To minimize the energy cost, the thermal appliance should be scheduled such that it produces demand in the cheapest time steps. This results in the following optimization problem

$$\min \sum_t EP_t \cdot TAD_{b,t} \quad \forall b \in B, \tag{16}$$

under the constraints of (13), (14) and (15). It should be noted that this optimization will always result in the highest temperature $SPT_b + \frac{1}{2}DBT_b$ at the last time frame $t = |T|$. To prevent this, the objective function can be adjusted so that a lower temperature at the last time frame is rewarded accordingly, this leads to the following objective;

$$\min \sum_t EP_t \cdot TAD_{b,t} + \frac{TEMP_{b,|T|} - (SPT_b - \frac{1}{2}DBT_b)}{CP_b} \cdot EP_{|T|} \quad \forall b \in B. \tag{17}$$

4.2.3 Battery

A battery is a device that can store energy by charging it at one time and discharging it at another time. The battery's state of charge BSC_t at time $t \in T$ is chosen as a variable between 0 and 1 that reflects the relative state of charge, i.e. it is found by dividing the battery's current stored energy BSE_t by the maximum possible amount of stored energy BSE^+. A customer can set a minimum and maximum state of charge BSC^- and BSC^+ other than 0 and 1 according to his preferences, implying the constraints

$$BSC^- \leq BSC_t \leq BSC^+ \quad \forall t \in T. \tag{18}$$

The amount of energy that a battery charges or discharges in time step t is denoted by a variable BCD_t, which is positive for charging and negative for discharging. It is assumed that a battery can charge and discharge at all levels between the maximum charge and discharge speeds MBC and MBD, i.e. we have

$$MBD \leq BCD_t \leq MBC \quad \forall t \in T. \tag{19}$$

Let the state of charge of the battery at the beginning of the planning horizon be denoted by BSC_0. Then the course of the battery's state of charge is described by

$$BSC_{t+1} = BSC_t + \frac{BCD_t}{BSE^+} \quad \forall t \in T. \tag{20}$$

Unfortunately, due to technical constraints, some of the energy is lost when it is first charged and later discharged, meaning that the efficiency BE of a battery is not 100%. To model this, a variable α_t is introduced that is defined as

$$\alpha_t = \begin{cases} 1 & \text{if } BCD_t \leq 0 \\ BE & \text{if } BCD_t > 0. \end{cases} \tag{21}$$

This implies that we consider the inefficiency of the battery only when charging. The optimal charging and discharging of the battery looking at future prices can now be solved by finding

$$\max \sum_t EP_t \cdot \alpha_t \cdot BCD_t, \tag{22}$$

under the constraints (18), (19), (20) and (21). As with the thermal loads, the above optimization always results in an empty battery at the end of the time period, and therefore the following adjustment can be made to reward a higher state of charge at the end of the time period accordingly:

$$\max_{BCD_t} \sum_t EP_t \cdot \alpha_t \cdot BCD_t + BSE_{|T|} \cdot EP_{|T|}. \tag{23}$$

4.2.4 Electric vehicle

An electric vehicle can be seen as a flexible demand, as the energy it requires for driving can be supplied at variable times, as long as it is charged in time. On the other hand, when the vehicle is idle and connected to the LV distribution grid, it can be seen as a battery as well. This means that not only energy may be taken from the grid for storage, but also energy stored in the electric vehicle may be injected back into the grid. This concept is known as 'vehicle to grid' (V2G). Based on the above, the electric vehicle is modeled like the battery, only with some extra constraints. Instead of a constant minimum state of charge for the battery, the consumer can set a variable minimum state of charge for the electric vehicle VSC_t^-, so he/she can ensure for example that his/her car is fully charged in the morning, or that he always has a certain amount of energy in case of an emergency. This is modeled as

$$VSC_t^- \leq VSC_t \leq VSC^+ \quad \forall t \in T, \tag{24}$$

where VSC_t denotes the state of charge of the electric vehicle at time $t \in T$. The amount a vehicle can charge and discharge VCD_t is, similar to the battery, limited by MVC and MVD;

$$MVD \leq VCD_t \leq MVC \quad \forall t \in T. \tag{25}$$

For an electric vehicle, it should furthermore be known in which time steps it is connected to the grid. When it is not connected, the vehicle cannot be used as a flexible device and it is consuming energy for transportation. Whether or not the vehicle is connected to the grid is depicted with a binary parameter VG_t.

The amount of energy that an electric vehicle consumes for transport is very dependent on the user of the vehicle, e.g. how far his/her work is and whether a charger is available there. Research can be done to analyze the driving behavior of owners of electric vehicles and even machine learning strategies can be used to make more precise predictions. However, this is not part of this research and therefore a simplification is made. It is assumed that the energy consumed is proportional to the time that the car is not connected. This implies that for every time step t that the vehicle is not connected to the grid, it consumes a constant amount of energy VEC. A variable VCD_t^* is introduced to model this, and is defined as

$$VCD_t^* = \begin{cases} VCD_t & \text{if } VG_t = 1 \\ VEC & \text{if } VG_t = 0. \end{cases} \tag{26}$$

Let the state of charge of the vehicle at the beginning of the planning horizon be denoted with VSC_0. The course of the vehicle's state of charge is then described by

$$VSC_{t+1} = VSC_t + \frac{VCD_t^*}{VSE^+} \quad \forall t \in T. \tag{27}$$

Like a normal battery, the battery of the electric vehicle also does not have an efficiency VE of 100%, therefore a variable β_t is introduced that is defined as

$$\beta_t = \begin{cases} 1 & \text{if } VCD_t^* \leq 0 \\ VE & \text{if } VCD_t^* > 0. \end{cases} \tag{28}$$

Similar to the normal battery, this implies that we consider the inefficiency only while charging. Now, the optimal strategy for the electric vehicle can be found by solving

$$\max_{VCD_t^*} \sum_t EP_t \cdot \beta_t \cdot VG_t \cdot VCD_t^* + VSE_{|T|} \cdot EP_{|T|}, \tag{29}$$

under the constraints of (24) - (28). The term $VSE_{|T|} \cdot EP_{|T|}$ was added in (29) to reward a higher state of charge of the vehicle at the end of the planning period accordingly. Furthermore, note that the term VG_t is added so that energy is only paid for in times the vehicle is connected.

4.3 Joint optimization

The four optimization problems described in the previous subsections can now be combined. To this combined model we add the own generation of a household. For this, let G_t represent the current or predicted own generation at time step t. Furthermore, for a shiftable device $a \in A$, let $SAI_{a,t}$ be an integer variable that only takes value 1 if $t \in PST_a$, i.e. if the time step is a possible starting time for device a. If we now define the net power NP_t of a household as the amount the household is demanding ($NP_t > 0$) or injecting ($NP < 0$) at time t, we get

$$NP_t = \sum_{a \in A} SAI_{a,t} \cdot SAP_{a,t-ST_a+1} + \sum_{b \in B} TAD_{b,t} - \alpha_t \cdot BCD_t - \beta_t \cdot VCD_t^* - G_t \quad \forall t \in T. \tag{30}$$

Then the function that should be minimized is given by

$$\sum_{t \in T} EP_t \cdot NP_t, \tag{31}$$

which has decision variables $ST_a, TAS_{b,t}, BCD_t$ and VCD_t^*. This objection function is just the combination of the objective function of the four different kind of flexible units described in (12), (17), (23) and (29), however without the extra objective for preventing minimal energy storage at the last time step. This objective function should be minimized under the constraints for the four types of flexible units described in the previous subsections.

Within the pricing scheme with traffic light described in Section 3.3, the energy price EP_t is dependent on the net powers of all households at time t, because for high values of NP_t the traffic light can result in different prices and curtailment. Note, that curtailment can also be seen as a change in energy price, where injection curtailment corresponds with a price of $EP_t = 0$ and demand curtailment with an extremely high price. Therefore, the objective function (31) is not a linear function. Only if we assume that a prediction of the prices (including curtailment) can be made, the objective function is almost linear. Almost, as looking at the first part of (30) we see that the objective function for the shiftable devices is not linear, as the decision variable ST_a is used within the index of the variable $SAP_{a,t}$. However, there are standard techniques available to also change this part into a linear program, by making the start time a time-dependent vector and setting $\sum_t ST_a(t) = 1 \ \forall a \in A$. (This is not further worked out here, and the reader is referred to [16] for more details.) As the objective function can be made linear, all constraints are linear and some variables and artificial variables needed for the constraints are integers, the described optimization problem can be identified as a mixed integer linear program (MILP).

In general, an MILP is an NP-hard-problem, and even though various methods and software exist to efficiently solve reasonable sized instances, it is rather time consuming, especially with a high amount of variables. If time steps are chosen as minutes and an optimization is to be made for a whole day, we need to model 1440 time steps, resulting in a very large amount of variables. Furthermore, as the prediction for the energy price and own generation and consumption can change quite often, it probably will not suffice to make one schedule for the whole horizon, so the optimization preferably runs every time new data is available. Lastly, the assumption that the energy price EP_t (including changes due to the traffic light) can be predicted is a little unreasonable, as the traffic light depends on the behavior of all other prosumers in the grid and is therefore very difficult to predict. Dropping this assumption would only further complicate the optimizations.

Because of the above stated reasons, it is chosen not to try to optimize the behavior of the flexible devices, but to develop heuristics that are not so time consuming. These heuristics decide on the behavior of the devices at every time step, and should have a sufficiently good performance. The developed heuristics are discussed in the next subsection.

4.4 Heuristics for the flexible units

Because of the high calculation time needed to optimize the problem for a large amount of time steps and the assumption made about the predictability of future energy prices, it seems to be more suitable to find a heuristic that is executed every time step to determine the actions that should be taken for the current moment, and leads to a sufficiently good solution. This heuristic does not have to make a whole schedule for the flexible units like the optimization tried to do, but it only has to make a decision for the present time step, based on predicted prices, generation and consumption. The goal of the heuristics is to choose the decision variables for the present time for the four types of flexible devices as good as possible, i.e. the total energy bill should be as low as possible. The heuristics make decisions like in a rolling horizon method, where the decision for the current time CT is based on the planning horizon $CT, CT+1, ...CT+T$, where T is now the size of the planning horizon. In the following we describe such a heuristic approach, whereby we give for each of the four types of flexible devices a separate heuristic. Before giving these heuristics, we give in Subsection 4.4.1 some background on the role of self-consumption in these approaches.

4.4.1 Self-consumption

To prevent curtailment and changes of the prices as the result of traffic lights, it is beneficial for the prosumers to have a high self-consumption. This means that the energy they produce by for example solar panels, should be as much as possible consumed by themselves. A higher self-consumption reduces the stress on the local network, as it reduces both the total demand and total supply of a household. Therefore, the heuristic should take into account that it is better to consume energy in times of high own generation.

Within the 5-level pricing system, however, self-consumption is not always desired. For example, if the energy is expensive but is expected to become cheaper in the near future, a consumer that is generating energy at this moment can better sell his energy to the grid now, and consume energy at a later time when the energy is cheaper. This is both better for his energy bill and for the grid, as a high price indicates that more injection is needed and low prices indicate that more consumption is desired.

Because of the reasons stated above, only in the case that the price is expected to be constant for a longer time, the own generation should be taken into account. This is in order to match the own generation (as much as possible) with the energy demand, so that the risk of curtailment will decrease. Especially in price levels $--$ and $++$, when risk of curtailment is highest, it is important that the heuristic takes self-consumption into account.

4.4.2 Shiftable appliances

Shiftable devices are assigned a set of possible starting times PST_a, defined as the time steps from the earliest starting time EST_a till the latest starting time LST_a. If the current time is within the set of possible starting times, i.e. if $CT \in PST_a$, and the device has not started yet, the only decision to be made is whether the device should be started now (i.e. in the time frame CT), or later (i.e. in one of the time frames $CT+1, CT+2, ..., LST_a$). Based on the current and future electricity prices $EP_{CT}, EP_{CT+1}, ...$ and the shiftable appliance profile $SAP_{a,t}$ it can be calculated how much it would cost to start now. Then, we iteratively compare the cost of starting now with the cost of starting in the next time steps $CT+1, CT+2, ...,$ up to the last possible starting time LST_a. The comparison is stopped when a cheaper future start time is found, or when the costs are the same, but a higher own generation follows for the future time step (i.e. larger amount of self-consumption). In this case, the shiftable appliance will not start at the current time CT. If the iterative comparison does not find a better starting time than CT, the current time is the best option and it is decided to switch on the shiftable appliance.

4.4.3 Thermal appliances

Thermal devices only have two possible states, they can be either on or off. Therefore, the only decision that has to be made is which of the two states should be chosen at the current time. The only constraint for thermal appliances is that it should keep the temperature within a certain deadband around the set point temperature. Based on the current temperature and the current and future energy price (and later also on the own generation), a heuristic is designed that tries to minimize costs within the temperature constraint. The heuristic is based on six principles:

- The thermal appliance should keep the temperature within bounds.
- The thermal appliance should be on in times of injection curtailment and off in times of demand curtailment.
- The thermal appliance should be on in cheap time steps and off in expensive time steps.
- The thermal appliance should not be on if an even cheaper time step is coming, and not be off if an even more expensive time step is coming.
- The thermal appliance should make sure that the room is cooled down to the minimum allowed temperature just before a more expensive time step is coming, and make sure that the room is heated up to the maximum allowed temperature just before a cheaper time step is coming.
- The thermal appliance should keep the room at the minimum allowed temperature in times of high prices (when there is a risk of demand curtailment) and at the maximum allowed temperature in times of low prices (when there is a risk of injection curtailment). This is done in order to have more response when demand or injection is curtailed. Note, that this seems to be in contradiction with the fifth principle. They can be combined, however, by keeping the temperature high in times of low prices, and only cool down just before the price is expected to increase, and vice versa.

Taking these principles into account, the heuristic basically consist of three steps: First, it is checked whether the temperature is out of its bounds. If this is the case, we switch the thermal appliance on or off so that the temperature changes towards the bound. If the temperature is within the bounds, we check if curtailment is applied. If this is the case and injection is curtailed, the thermal appliance chooses to switch on and cool down. If demand is curtailed, it chooses to switch off. Thus, in both cases the absolute net power is reduced. If the temperature is not out of bounds and there is no curtailment, the heuristic makes a decision on the state of the thermal appliance based on the current and future energy prices and the current temperature. The goal of the heuristic is to minimize the cost of the thermal appliance, and it basically does this by lowering the temperature to the minimum allowed temperature just before a more expensive energy price is coming, and increasing the temperature to the maximum allowed temperature just before a cheaper future energy price is coming up. More precisely, in the three cheapest price levels ++,+ and 0, the heuristic checks for how many time steps the price will not be higher than the current price. If there are enough of these time steps to bring the temperature from the current temperature to the minimum temperature, the heuristics decides not to cool down yet. Only if there are not enough of these time steps, the device will cool down so that just before the price increases, the temperature is at the minimum level. Similarly, in the two expensive price levels $--$ and $-$, the heuristic checks for how many time steps the price will not be lower than the current price. If there are enough of these time steps to bring the temperature from the current temperature to the maximum temperature, the heuristics decides not to heat up yet. Only if there are not enough of these time steps, the device will heat up so that just before the price decreases, the temperature is at the maximum level.

More formally, if the current temperature $TEMP_{CT}$ is too high, i.e. $TEMP_{CT} > SPT_b + \frac{1}{2}DBT_b$, where SPT_b and DBT_b represent respectively the set point temperature and the deadband temperature, the appliance has to cool down (i.e. be on). If the temperature is too low, i.e. $TEMP_{CT} < SPT_b - \frac{1}{2}DBT_b$, the appliance should be off, resulting in a warmer temperature. If the temperature is within bounds, it is checked whether curtailment is applied. Two binary variables ICB and DCB representing respectively the injection curtailment and demand curtailment are introduced, which take on value 1 if curtailment is applied, and value 0 if no curtailment is applied. If $ICB = 1$, the appliance switches on, if $DCB = 1$, the appliance switches off, and if $ICB = DCB = 0$, the heuristic makes a decision based on the current temperature $TEMP_{CT}$ and the current and future energy prices $EP_{CT}, EP_{CT+1}, ...EP_{CT+T}$. For this decision, some new variables are introduced. Let TTC_b be the number of time steps it takes to get from the current temperature $TEMP_{CT}$ to the coldest allowed temperature $SPT_b - \frac{1}{2}DBT_b$ while cooling. Furthermore, let TTH_b represent the amount of time steps it takes to get from the current temperature to the hottest allowed temperature $SPT_b + \frac{1}{2}DBT_b$ while heating. Furthermore, let $NCT(EP_{CT})$ be the number of future time steps within the planning horizon $CT+1, CT+2, ..., CT+T$ that are consecutively cheaper or equal to the present electricity price EP_{CT} and let $NET(EP_{CT})$ be the number of future time steps within the planning horizon that are consecutively more expensive or equal to the present electricity price. Then the heuristic makes the following decision:

- if $EP_{CT} \in \{++, +, 0\}$:

$$\text{state} = \begin{cases} \text{on} & \text{if } TTC_b \geq NCT(EP_{CT}) \\ \text{off} & \text{if } TTC_b < NCT(EP_{CT}) \end{cases} \tag{32}$$

- if $EP_{CT} \in \{--, -\}$:

$$\text{state} = \begin{cases} \text{on} & \text{if } TTH_b < NET(EP_{CT}) \\ \text{off} & \text{if } TTH_b \geq NET(EP_{CT}) \end{cases} \tag{33}$$

As an example, Table 1 shows the temperature progression of the heuristic for an artificial cooling appliance that should keep the temperature between 18 and 22 degrees. In this example it is assumed that there is no curtailment. The temperature in the room is assumed to be decreasing with half a degree per time step when the device is switched on and assumed to be increasing with half a degree per time step when the device is switched off. In the first time step, the energy price is at level + and the temperature is 19 degrees. The temperature is not at the boundary, and we assumed that no curtailment was applied. Then, because the price is at level +, the number of time steps to cool down (TTC_b) and the number of cheaper time steps ($NCT(+)$) have to be found and should be compared. As in every time step the temperature will decrease with half a degree, it takes 2 time steps to get from 19 to 18 degrees. $NCT(+)$ is 7, as after 7 time steps the price will increase. As $TTC_b < NCT(+)$ the appliance switches on, and therefore in the next time step the temperature will be increased with half a degree. So even though the price is at a cheap level, the appliance does not switch on, because there are enough future time steps that are cheap (or even cheaper). In the second time step, exactly the same decisions is made. As only in time step 3 and 4 the price is at the cheapest level (++), in these time steps the appliance is on. At time step 6, the heuristic decides to cool down, as a more expensive period is coming up in time step 9, so it makes sure that at this time the temperature is at the lowest level, at 18 degrees. In time steps 11-14 the heuristic makes sure that the temperature is kept at the lowest level, as a period with the highest prices is coming from time step 15 onwards. Note, that for this example the heuristic is executed for time 1-15, where the prices of time 16-22 are needed for finding $NET(EP_{12})$ and $NET(EP_{14})$.

Table 1: Progression of the heuristic for artificial cooling appliance.

Time	EP_{Time}	**Temp**	**Bound**	TTC_b	TTH_b	$NCT(EP_{Time})$	$NET(EP_{Time})$	**state**
1	$+$	19	no	2		7		off
2	$+$	19.5	no	3		6		off
3	$++$	20	no	4		1		on
4	$++$	19.5	no	3		0		on
5	$+$	19	no	2		3		off
6	$+$	19.5	no	3		2		on
7	$+$	19	no	2		1		on
8	$+$	18.5	no	1		0		on
9	0	18	yes					off
10	0	18.5	no	1		1		on
11	0	18	yes					off
12	$-$	18.5	no		7		> 9	on
13	$-$	18	yes					off
14	$-$	18.5	no		7		> 7	on
15	$--$	18	yes					off
16-22	$--$	-	-	-	-	-	-	-

In this particular example, the heuristic found the optimal solution. However, in general this is not always the case, especially if prices are fluctuating fast. For small time steps (e.g. minutes) the energy price is not expected to fluctuate too much, so the heuristic is probably has a performance close to the optimal solution. Note, that in order to keep the temperature at the highest or lowest level (like in time steps 9-15), the appliance will switch between off and on very often. If this is inconvenient or harmful for the appliance, an extra rule can be added that makes the appliance run with longer heating and cooling cycles when the energy price is constant. For example, in time step 13 the temperature could have been 19 degrees by switching the on and off state from time steps 13 and 14. This would not change the cost and the temperature (after time step 13), but results in a longer cooling/heating cycle.

Self-consumption

The heuristic described above does not take the own generation into account, so self-consumption is not considered. However, from the discussion in Subsection 4.4.1 it follows that self-consumption is important for prosumers that have a risk of being curtailed, and that self-consumption should only influence their decisions in times of constant electricity prices. Therefore, a few additions can be made to the heuristic to increase self-consumption for times when the price is constant for a long time.

The idea is that within a large set of consecutive time steps with the same price, the appliance is going through some on/off-state cycles. However, from the perspective of prices, a time step with on-state can be interchanged with another time step with off-state, as long as the temperature deadband is not violated. For example, looking at the same cooling device as used in Table 1, the off-state at time 13 could be switched with the on-state at time 12 without any change in temperature (after time step 13) or price. If the own generation at time 13 is higher than the own generation at time 12, this switch would result in a higher self-consumption.

The addition to the heuristic therefore follows the following principle: First, we determine the amount of consecutive time steps with the same price. For these time steps, we calculate how many time steps should have on-state and off-state. Furthermore, we sort these time steps, based on the amount of own generation. We split the time steps in two sets, one with the highest generations that has the size of the number of on-states, and one with the lowest generations that has the size of the number of off-states. Preferably, the thermal appliance is on in the time steps with the highest amount of own generation and off in the time steps with the lowest own generation. This however might violate the temperature constraints. Therefore if the temperature deadband allows it, we switch from off-state to on-state if the own generation at the current time is within the set of the highest own generations. Similarly, we switch from on-state to off-state if the own generation at the current time is within the set of the lowest own generations.

Formally, let NST be the number of consecutive future time steps within the planning horizon $CT, CT+1, ..., CT+T$ where the price is equal to the price now. We check for the NST following time steps how many times the device is planned to be 'on' and how many times to be 'off', and call them TS_{On} and TS_{Off}. Then, we sort the NST time steps, based on the amount of own generation G_t. We split the time steps in a set with the highest TS_{On} own generations and a set with the TS_{Off} lowest generations. Basically, the state should be on in the TS_{On} time steps with highest generation and off in the TS_{Off} time steps with lowest generation. Therefore, if the price is in one of the three cheapest levels $++$, $+$ or 0 and the heuristic gives off-state, we check whether the current own generation is within the set of the highest TS_{On} generations. If this is the case, we switch to on-state, as the generation at this moment is higher than at least one other time step in which the state would be on. Similarly, if the price is in one of the two most expensive levels $--$ or $-$ and the heuristic gives on-state, we check whether the current own generation is within the set of the lowest TS_{Off} generations. If this is the case, we switch to off-state, as the generation at this moment is lower than at least one other time step in which the state would be off. The flowchart for the extended heuristic is shown in Figure 4.

Note that although this extended heuristic tries to decrease the chance of being curtailed by increasing self-consumption and therefore lowering the stress on the local grid, it also risks having a smaller buffer in the case of a curtailment. This can be seen for the example given in Figure 5. It is assumed that a cooling device should keep the temperature between 18 and 22 degrees, and that each time step in which the device is on, the temperature reduces with half a degree, and if it is off, the temperature increases with half a degree. Nine time steps are considered, in which it is assumed that the price is constant and low, and that the price will increase at time step 10. This means that the goal is to be completely cooled down to 18 degrees at time step 9, starting from 20 degrees. Two scenarios are shown in the figure. On the left a scenario is given that takes self-consumption into account, and on the right a scenario is given that does not take self-consumption into account. While in the self-consumption based scenario (left) the risk of injection curtailment is lower, as the consumption is higher in times of high generation, the flexibility based scenario (right) keeps the room warmer (between time step 2 and 7), which means that in case of injection curtailment between those times, the prosumer has more possibility to consume energy and therefore the prosumer might be curtailed less. This is something the consumer has to take into consideration and it is probably very case-dependent whether or not the heuristic that keeps self-consumption in mind gives a lower energy cost than the heuristic that does not take this into account. As the self-consumption based heuristic results in more social desired behavior, the DSO may consider giving a self-consumption bonus. The difference between these two strategies is analyzed in Subsection 6.2.5.

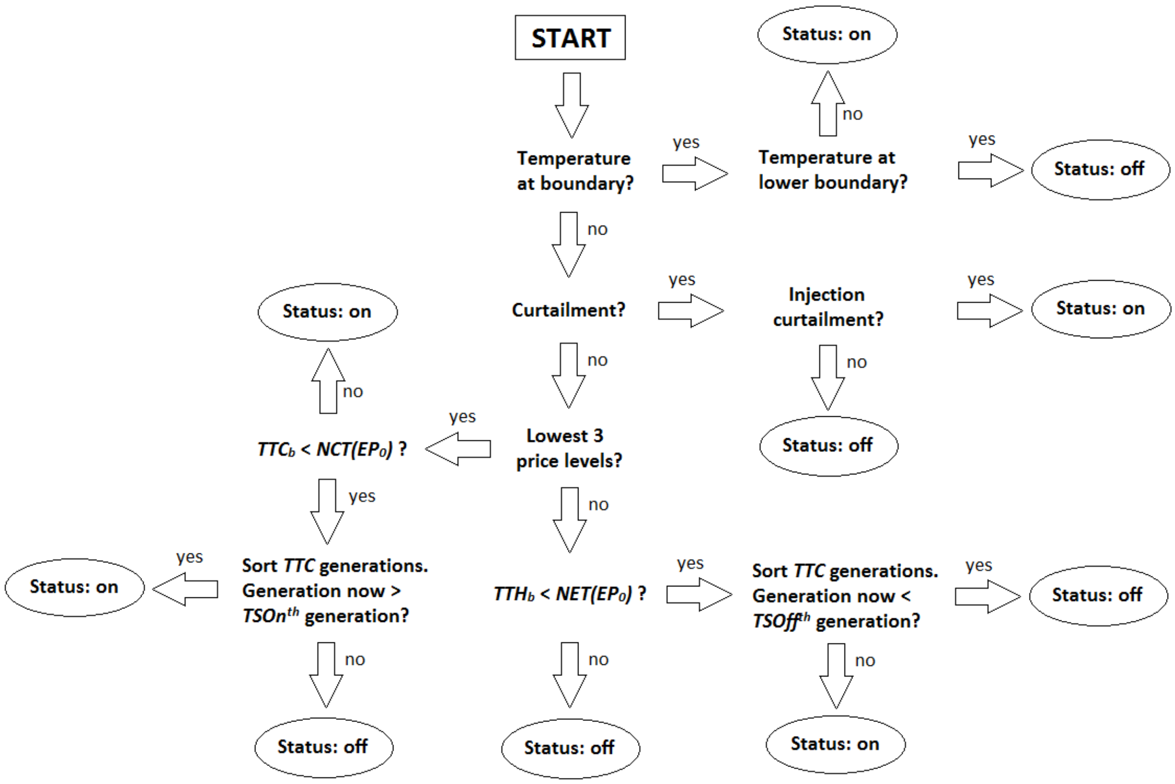


Figure 4: Flowchart for the extended thermal device heuristic.

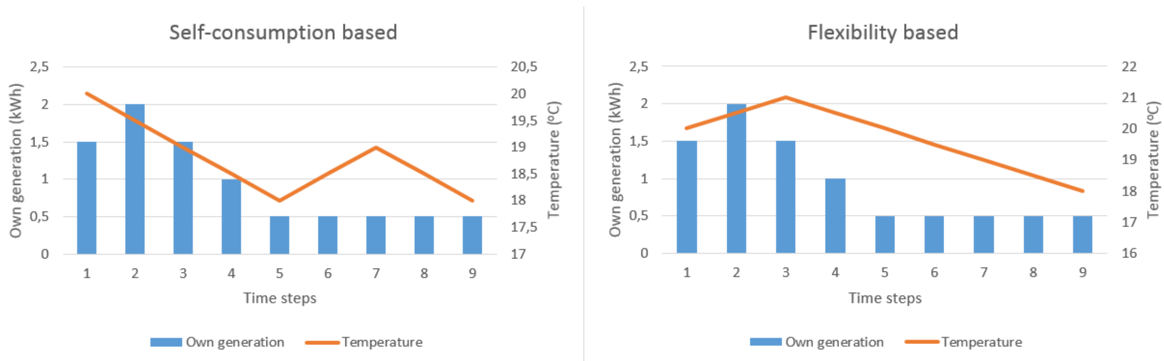


Figure 5: Self-consumption strategy (left) versus Flexibility strategy (right) in case of low constant price level.

4.4.4 Battery

Batteries have similar modeling characteristics as thermal devices, as for example the temperature in a room can be compared to the state of charge of a battery, i.e. a thermal device can be seen as a device storing thermal energy. Therefore a heuristic can be designed for the battery that is similar to that for thermal devices. However, there are some different characteristics, as thermal devices are consuming energy and batteries (in essence) do not. Furthermore, the temperature in a space is changing both in on-state and in off-state (assuming that the outside and inside temperature are different), whereas a battery's state of charge can also be constant when it is not charging or discharging, which we call being idle. Finally, a battery does not have an efficiency of 100% and therefore charging and discharging an equal amount in equal price levels is not cost neutral, but leads to a loss of money. Because of these differences, the developed heuristic has some differences compared to the heuristic of the thermal devices, even though the basic principles are the same.

The heuristic for the battery is trying to make a cost optimization and has to decide for the current time which of the three possible actions for the battery to choose; charge, discharge or idle. It should make this decision based on the current state of charge and the current and future energy price (and later also based on the own generation). The first step for the heuristic is to check whether the household is curtailed or not. If demand is curtailed, it chooses to discharge (only if enough energy is available in the battery, if not, it stays idle). If injection is curtailed, it chooses to charge (only if the battery is not full, if it is, it stays idle). If no curtailment is applied, the heuristic decides whether it is of advantage to charge. This is considered to be the case if we are in the two cheapest price levels (+ and ++), unless there are enough future time periods that are cheaper or have equal price to charge the battery fully, in which case the battery stays idle. For the two expensive price levels (− and −−), the battery will discharge, unless there are enough future time periods that are more expensive or have equal price to discharge the battery fully, in which case the battery stays idle. For the middle price level (0), the strategy of the lowest two levels (+ and ++) is chosen if the next future price different than 0 will be higher, and the strategy of the highest two levels (− and −−) is chosen if the next future price different than 0 will be lower.

More formally, let the two binary variables ICB and DCB again represent respectively the injection curtailment and demand curtailment, which take on value 1 if curtailment is applied, and value 0 if no curtailment is applied. If $ICB = 1$, the battery will charge, but only if the battery is not full, i.e. $BSOC_{CT} < BSOC^{+}$. If it is full, the battery will be idle. Similarly, if $DCB = 1$, the battery will discharge, but only if the battery is not empty, i.e. $BSOC_{CT} > BSOC^{-}$, if it is empty, the battery will be idle. If no curtailment is applied, i.e. $ICB = DCB = 0$, the heuristic makes a decision based on the current state of charge of the battery $BSOC_{CT}$ and the current and future energy prices $EP_{CT}, EP_{CT+1}, \ldots$. For this, some new variables are introduced. Let BCT be the number of time steps it takes to get from the current state of charge $BSOC_{CT}$ to the maximum state of charge $BSOC^{+}$ while charging. Furthermore, let BDT represent the amount of time steps it takes to get from the current state of charge $BSOC_{CT}$ to the minimum state of charge $BSOC^{-}$ while discharging. Again, let $NCT(EP_{CT})$ be the number of future time steps within the planning horizon $CT, CT+1, ..., CT+T$ that are consecutively cheaper or equal to the present electricity price EP_{CT} and $NET(EP_{CT})$ the number of future time steps within the planning horizon that are consecutively more expensive or equal to the present electricity price. Then the heuristic makes the following decision:

- if $EP_{CT} \in \{++, +\}$ or $EP_{CT} = 0$ and price will increase:

$$\text{state} = \begin{cases} \text{charge} & \text{if } BCT \geq NCT(EP_{CT}) \\ \text{idle} & \text{if } BCT < NCT(EP_{CT}) \end{cases} \tag{34}$$

- if $EP_{CT} \in \{--, -\}$ or $EP_{CT} = 0$ and price will decrease :

$$\text{state} = \begin{cases} \text{discharge} & \text{if } BDT \geq NET(EP_{CT}) \\ \text{idle} & \text{if } BDT < NET(EP_{CT}) \end{cases} \tag{35}$$

Self-consumption

As for the thermal devices, an adjustment to this heuristic for charging/discharging the battery can be made to improve self-consumption. When there is enough time to charge (or discharge), and therefore the battery is idle, it might be better to charge when generation is high and be idle when generation is lower (or discharge when generation is low and be idle when generation is higher). The addition to the heuristic is therefore very similar to that of the thermal devices: First, we determine the amount of consecutive time steps with the same price. For these time steps, we calculate how many time steps should have charge-state (or discharge-state) and how many should have idle-state. Furthermore, for these time steps we sort the amount of own generation. We split the time steps in two sets, one with the highest own generations and the size of the number of time steps with charge-state, and one with the lowest own generations and the size of the number of idle-state (vice versa for discharging). If the battery is not yet full (or empty), we switch from idle-state to charge-state (or discharge-state) if the own generation at the current time is within the set of the time steps with the highest (or lowest) own generations.

Formally, let NST again be the number of consecutive future time steps where the price is equal to the price now. Check for the NST following time steps how many steps it would be charging (or discharging), and call it TSC (or TSD). For these time steps, sort the amount of generation G_t. Basically, the state should be charge (or discharge) in the TSC (or TSD) time steps with highest generation and idle in the other time steps. Therefore, if the heuristic gives idle-state, we check whether the current own generation is within the highest TSC (or lowest TSD) generations. If this is the case, we switch to charge-state (or discharge-state), as the generation at this moment is higher (or lower) than at least one other time step in which the state would be charge (or discharge). Like with the thermal devices, the self-consumption extension in the heuristic might lead to lower flexibility, see Figure 5. The flowchart for the extended heuristic for batteries is shown in Figure 6.

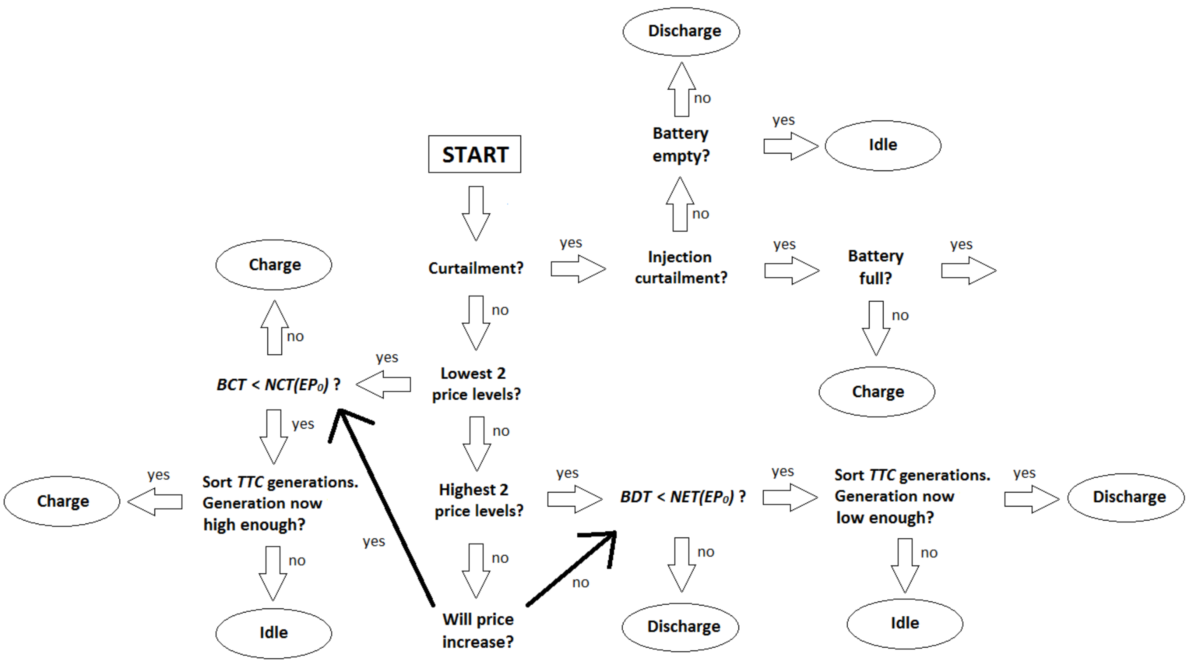


Figure 6: Flowchart for the extended battery heuristic.

Remark on battery use

In the optimization for the use of the battery, the battery life time is not taken into account. Unfortunately, the lifetime of a battery is limited, and it is generally expressed in the number of complete charge/discharge cycles a battery can go through before it loses a certain amount of capacity. Little is known about the exact reduction of a battery's life time when it is used with non-complete charge/discharge cycles, but it is assumed that it is worse than completing full charge/discharge cycles. Therefore, it might not be profitable to charge and discharge a battery within only one price level difference (e.g. 0 and +). A prosumer can choose for example to always be idle at price level 0, only charge and discharge at levels ++ and −−, or only use it in times of curtailment or to improve self-consumption. The customer will lose flexibility this way and therefore possible (direct) income, so a balance between battery life time and direct profit should be made.

4.4.5 Electric vehicle

As electric vehicles are powered with batteries and these batteries are assumed to be able to provide extra flexibility (i.e. V2G is possible), the heuristic for the electric vehicle is very similar to that of the battery. The difference with a battery however is that a battery's main goal is to provide flexibility, whereas the main goal of the electric vehicle is to drive. Therefore, the flexibility of the battery of the electric vehicle can only be used when the vehicle is connected to the household and when the state of charge of the battery is high enough to allow the owner to make his/her trips. It depends on the owner's preferences what this minimum state of charge is, and it is assumed that for all time steps a minimum state of charge level is given by the owner. For example, an owner can set his/her daily minimum at 30% e.g. for the case of emergency usage, and his minimum at 80% at 8 a.m. when he/she has to leave for work. Note that this would result e.g. in a minimum of 70% at 7 a.m. if the battery can be charged at 10% per hour, etc. The difference between a regular and an electric vehicle battery also results in the fact that electric vehicles should be charged more than that they can be discharged, whereas for batteries these amounts are the same.

The first step for the heuristic is therefore to check whether the electric vehicle is connected to the house. If it is not, nothing has to be done, and if it is, the heuristic proceeds. The second step is to check whether the current state of charge is higher than the minimum state of charge at this time. If it is not, the electric vehicle is not able to provide flexibility so it will always charge, if it is, the heuristic will make almost exactly the same decisions as it did for the battery, with only two differences:

- For the battery the variable BDT was used to represent the time it takes to discharge, whereas the electric vehicle should not discharge fully. For the electric vehicle it should be found how much time it takes to reach the minimum time-dependent state of charge level, denoted by VDT.
- As an electric vehicle is netto consuming energy, it has to charge more than it can discharge. Because of the previous bullet point, the electric vehicle loses its flexibility whenever its state of charge is too low, as it can only charge at these times. To keep its flexibility as long as possible, the heuristic should decide to charge more often than it decides to discharge. This can be done by choosing to only discharge in the most expensive price level (−−).

Self-consumption

The same comments about improvement of self-consumption for the battery can be made for electric vehicles. As an electric vehicle is netto consuming energy, self-consumption for electric vehicles might even be more important than it is for batteries. Self-consumption can however reduce the flexibility of a prosumer (see again Figure 5), and again it is up to the owner which strategy to choose. In the case that a prosumer has both an electric vehicle and a battery, it can even be specified to choose the self-consumption strategy for the EV, while choosing a flexibility strategy for the battery. The extension for the heuristic is exactly the same as for the case of the battery, and the flowchart for the extended heuristic for the electric vehicle is shown in Figure 7.

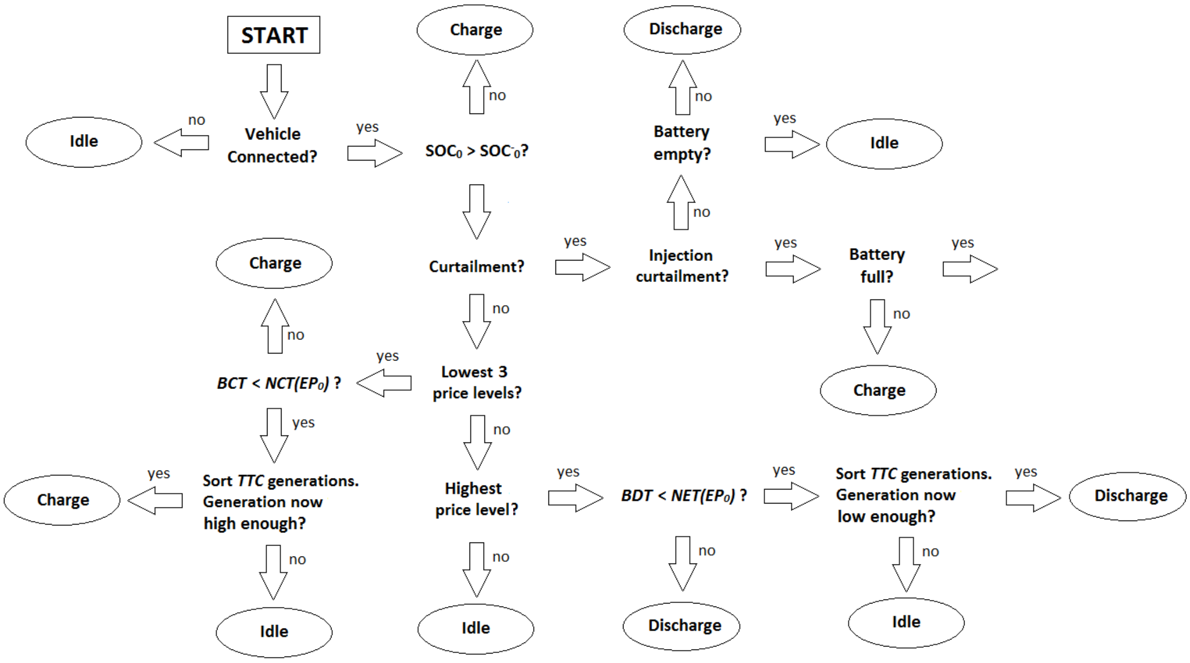


Figure 7: Flowchart for the extended battery heuristic.

Remark on electric vehicle use

The same remarks about battery life for batteries can be made for electric vehicles. Different owners can have different strategies as in at which pricing levels to charge/discharge or be idle to balance between flexibility and battery life. An owner of both an electric vehicle and a battery can even choose different strategies for the two flexible devices. For example, if he/she wants to preserve the quality of the electric vehicle's battery but does not care too much about the life of the normal battery (this can be a depreciated old EV-battery), it can be chosen to only use the vehicle's flexibility to inject in times of demand curtailment, while the normal battery is using its full capacity of being flexible.

5 Simulation

Now that we have defined a novel pricing mechanism and designed heuristics for the flexible devices to see how prosumers can respond on these prices, we can test how they perform in a simulation environment. In this section such a simulation, which for this research is done in Matlab, is described. First, the simulated distribution network is presented, then the input for the devices, appliances and own generation of the households are given, followed by the details of the traffic light mechanism. The simulation is done for a 24-hour period with time steps of 1 minute, resulting in 1440 simulated minutes.

5.1 Distribution network

For this simulation an IEEE European LV Test Feeder distribution network [17] is used. This is a 3-phase network with 906 buses, 55 connected households and a nominal voltage at the substation of 240.17 V. Because for this research only 1 phase is modeled, only the 21 households that are connected to phase A are taken into account, see Figure 8 for a schematic overview of the topology of this network. Note that a single line in the figure can consist of different lines. The 905 connecting lines can be of ten different types, having varying resistances and current carrying capacities.

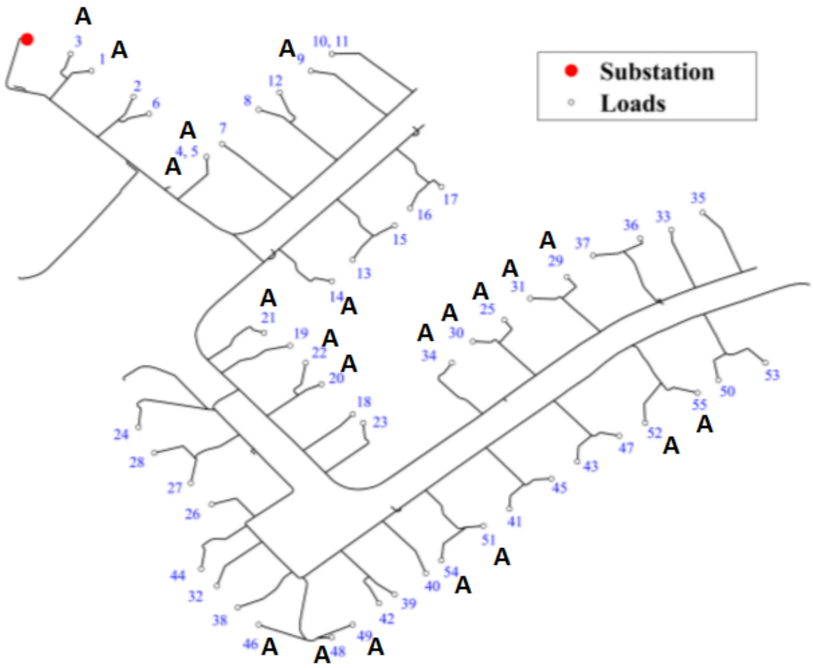


Figure 8: Topology for IEEE European LV Test Feeder with houses connected to phase A marked.

5.2 Household

The 21 households that are connected to phase A are all modeled using the heuristics introduced in Subsection 4.4. They only differ in the parameters they use for the flexible devices. These parameters are given in the next subsections, together with the input for non-flexible devices and the own generation.

5.2.1 Non-flexible devices

Data for non-flexible devices is taken from a load simulator in Microsoft Excel called 'Integrated Domestic Electricity Demand and PV Micro-generation Model - Single Dwelling Simulation Example for 24 Hours', designed by researchers from Loughborough University [18]. In this simulator, first an occupancy simulation is run. For our case, we have chosen to have 2 times a single-person household, 5 times a two-person household, 5 times a three-person household, 5 times a four-person household and 4 times a five-person household. Then at random appliances out of 34 possible appliances are allocated to each household (not including the flexible devices). Using these devices, the electricity demand simulation is run to determine the base load of the households.

The resulting electricity demand of the non-flexible devices for one of the households is shown in Figure 9. This is representing a four-person household where most electricity is used in the morning (between 07:30 - 10:00 a.m.) and in the evening (between 05:30 - 07:00 p.m.). Furthermore, smaller consumption is seen during the middle of the day and later in the evening for usage of e.g. a vacuum cleaner, a computer or TV. Also, the electricity consumption of devices in stand by-mode is taken into account, resulting in a minimum consumption of 54 W during night time

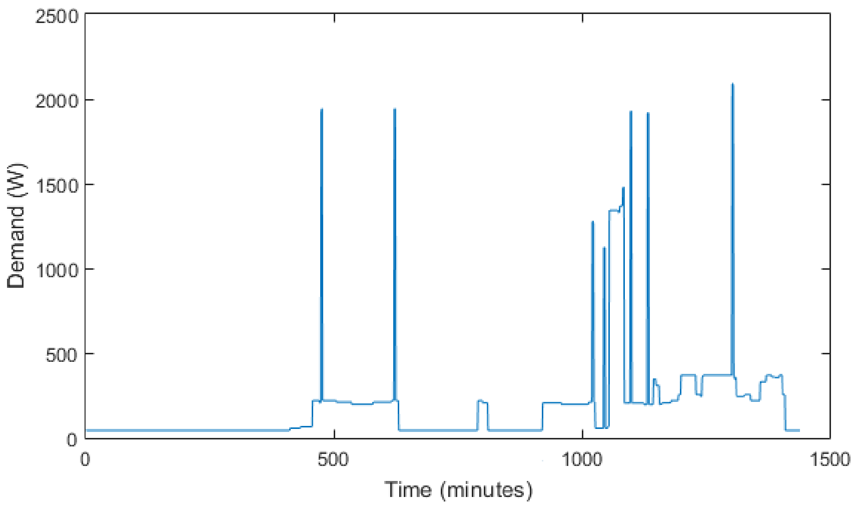


Figure 9: Electricity demand of non-flexible devices for household 21 for one day of 1440 minutes.

5.2.2 Shiftable devices

For this simulation, 3 shiftable devices are considered; washing machines (2 different types), dish washers (2 different types) and clothes dryers (1 type). For these devices, only one program is considered, of which the minutely electricity consumptions is shown in the Appendix. The probability of existing in a household P_{ex}, the probability of running the device at a certain day P_{run}, the earliest start time EST and latest start time LST are summarized in Table 2. Note that 'rand(a,b)' depicts an integer chosen uniform randomly from the interval [a,b]. Furthermore, note that the simulation is only done for 1440 minutes, therefore the latest starting time cannot be after $1440 - RT$, where RT is the run time of a device and is maximum for Dish Washer 1 with $RT = 135$. It is assumed that a household has exactly one washing machine and one dish washer, with the probability of half for being type 1, and half for being of type 2.

Table 2: Input for the 5 different shiftable devices.

Appliance	P_{ex}	P_{run}	EST	LST
Washing Machine 1	0.5	0.14	rand(1,1000)	EST+rand(1,300)
Washing Machine 2	0.5	0.14	rand(1,1000)	EST+rand(1,300)
Dish Washer 1	0.5	0.2	rand(1,1000)	EST+rand(1,300)
Dish Washer 2	0.5	0.2	rand(1,1000)	EST+rand(1,300)
Clothes dryer	0.5	0.1	rand(1,1000)	EST+rand(1,300)

5.2.3 Thermal devices

For this simulation, 2 thermal devices are modeled; refrigerators (2 different types) and air conditioners (1 type). For thermal devices, the probability of being present in a household P_{ex}, the set point temperature SPT, the dead band temperature DBT, the start and end time ST and ET, the initial temperature $TEMP_0$, the cooling and heating parameters CP and HP and the energy consumption TAC are summarized in Table 3. It is assumed that a household has exactly one refrigerator, with the probability of half for being type 1, and half for being of type 2.

Table 3: Input for the 3 different thermal devices.

App	P_{ex}	SPT	DBT	ST	ET	$TEMP_0$	CP	HP	TAC
Ref 1	0.5	4	2	1	1440	rand(3,5)	1/39	1/47	200
Ref 2	0.5	4	2	1	1440	rand(3,5)	1/7	1/26	64
AC	0.4	20	rand(2,4)	rand(600,720)	rand(1020,1140)	rand(19,21)	1/22	1/15	2000

5.2.4 Battery

Every household is modeled to have at most one battery. The probability of being present in a household P_{ex}, the initial, minimum and maximum state of charge BSC_0, BSC^- and BSC^+, maximum charge and discharges speed MBC and MBD, the maximum amount of stored energy BSE and the inefficiency of the battery α are summarized in Table 4. Note that BSE is expressed in kWh and MBC and MBD in kW.

Table 4: Input for the battery.

P_{ex}	BSC_0	BSC^-	BSC^+	MBC	MBD	BSE	α
0.5	rand(0.3,0.7)	0.2	0.9	rand(1,2)	$= MBC$	rand(8,12)	0.9

5.2.5 Electric vehicle

Every household is modeled to have at most one electric vehicle. The probability of being present in a household P_{ex}, the initial, minimum and maximum state of charge VSC_0, VSC^- and VSC^+, maximum charge and discharges speed MVC and MVD, the maximum amount of stored energy VSE, the vehicle energy consumption VEC and the inefficiency of the battery β are summarized in Table 5. Note that VSE is expressed in kWh and MVC, MVD and VEC in kW.

Table 5: Input for the electric vehicle.

P_{ex}	VSC_0	VSC^-	VSC^+	MVC	MVD	VSE	VEC	β
0.5	rand(0.3,0.7)	rand(0.2,0.5)	0.9	3.7	$= MVC$	rand(24,54)	rand(1,2)	0.9

For this simulation it is assumed that the owner of an electric vehicle has one continuous time period in which the car is being used. This is modeled with a parameter for his leaving time LT and returning time RT. Using these parameters, the binary variable VG_t, depicting whether the vehicle is connected to the grid or not, is defined as

$$VG_t = \begin{cases} 1 & \text{if } t < LT \;\&\; t > RT, \\ 0 & \text{if } LT \leq t \leq RT. \end{cases} \tag{36}$$

It is furthermore assumed that the time-dependent minimum state of charge VSC_t^- is always set at the value defined in Table 5, and that this value only differs at the time that the car is leaving, i.e. at $t = LT$. The used values for the simulation are summarized in Table 6.

Table 6: Input for the connectedness and minimum charge of the electric vehicle.

LT	RT	VSC_{LT}^-
rand(6,9) · 60	rand(15,19) · 60	rand(0.7,0.9)

5.2.6 Own generation

For this simulation only solar PV is considered as a source of own generation for the prosumers. To simulate a daily profile of generation from solar energy, again a model from Loughborough University [18] is used. A summer day with a small amount of clouds is simulated and the corresponding PV-generation is shown in Figure 10.

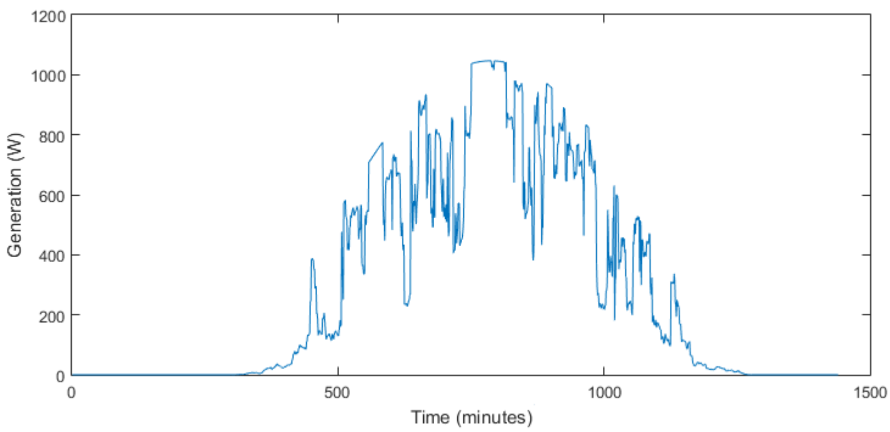


Figure 10: PV generation for one day by the Loughborough University model.

As in a distribution network the households are quite close to each other, it is assumed that all households with solar PV have the same generation curve. The only difference is that they can have a different amount of panels. This is modeled by multiplying the generation curve with a random number between 1 and 5, resulting in a maximum possible generation of around 5kW. Furthermore, it is assumed that 80% of the households have installed solar PV.

5.3 Pricing and traffic light mechanism

For the five-level RTP the levels are set at €50/MWh (++), €100/MWh (+), €150/MWh (0), €200/MWh (−) and €250/MWh (−−). Based on the market clearing price of the Turkish day ahead market [19], the used energy prices over time are shown in Figure 11.

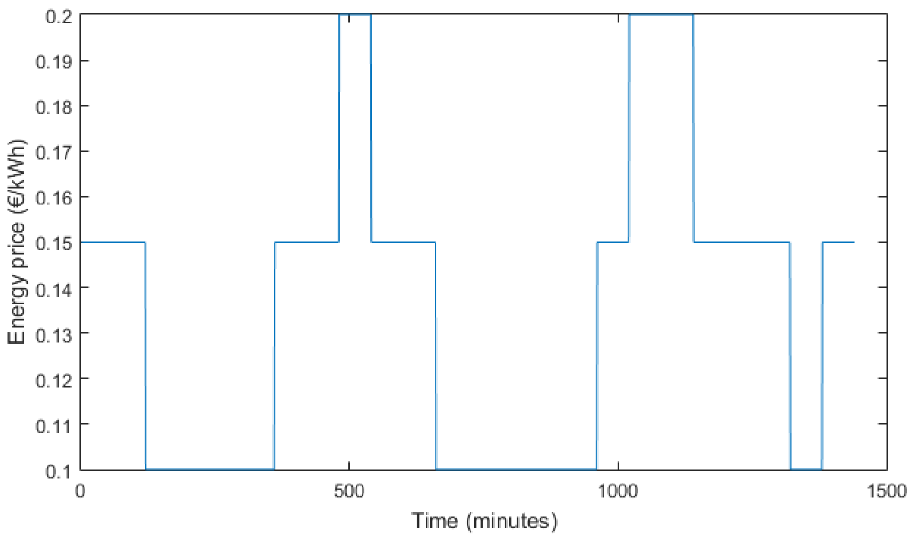


Figure 11: Predicted energy price for the simulated day based on market clearing price of Turkish day ahead market (01-07-2017).

The used traffic light mechanism is depicted in Figure 12. Every minute the following steps are performed in the simulation: First, all households calculate their net power NP based on the decisions of the heuristic, where the current electricity price that is given to them is based on the 'normal' price in Figure 11 possibly adjusted by the current traffic light that is assigned to that household. Using these net powers, a load flow analysis is done to calculate both the current and voltage at all lines and buses, so that (potential) problems can be identified. Based on these (potential) problems, each household is assigned a traffic light for the next time step, as described in Section 3.3. In order not to harm prosumers that only have a low net power too much, a red traffic light is only given if for this household we have $|NP| > 1500W$. A red traffic light means that the problem has to be solved with curtailment. Following the discussion about fairness in Subsection 2.4, this is done by setting a maximum level for the absolute net power $|NP|$ such that the problem is exactly on the border between an orange and a red light, i.e. the voltage level is brought back to the limits VL^- or VL^+ or the current brought back to the current carrying capacity CCC. All demand and injection that is higher than this level is curtailed. If demand is curtailed, a household always chooses to first curtail the demand of the battery, then the demand of the electric vehicle, and then of the shiftable, non-shiftable and thermal appliances. If injection is curtailed, a household always chooses to first curtail injection of the battery, then injection of the electric vehicle, and then injection of the solar PV generation.

To determine this maximum level for the net power, first the households are ordered from the household with the highest absolute net power to the household with the lowest absolute net power. Then an iterative process starts that checks whether the problem is resolved if the household with the highest absolute net power reduces its net power till the net power of the household with the second highest net power. This is done following (5) in Subsection 2.3.1 for overloading cases and following (9) and (10) in Subsection 2.3.2 for under- and over-voltage cases. If it is enough, only the first household has to be curtailed, and the exact amount can be determined with the aforementioned formulas. If the reduction of net power is not enough, it is checked whether it is enough for the two households with highest absolute net power to reduce their net power till the net power of the household with the third highest net power, etc. In the worst case all households are curtailed and a maximum level for the absolute net power is found that is even lower than the household with the lowest absolute net power.

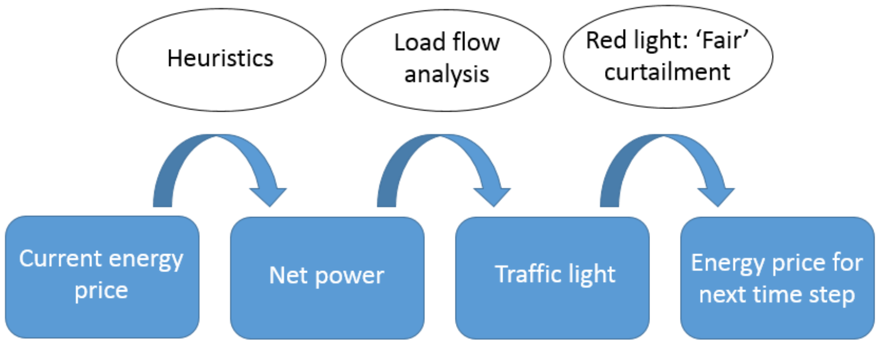


Figure 12: Schematic overview of the traffic light mechanism.

5.4 Remark on the simulated network, loads and generation

The combination of the network and the amount of loads and own generation that are proposed in this section are expected to give some issues. The IEEE European LV Test Feeder distribution network is a typical network that is currently being used in rural European areas. These networks are generally not suitable for high penetrations of own generation and loads (especially electric vehicles). See for example [20] for a stress-test representing the possible amount of loads for a year 2025 scenario in the Dutch village of Lochem. In this test, the distribution network for around 90 households already faced serious under-voltage and phase imbalance problems because of three electric vehicle chargers and a couple of pizza ovens. With a 50% penetration of electric vehicles proposed in this section, major grid issues are almost inevitable for the simulation.

6 Results

In this section first some results of the simulation based on the parameters given in Section 5 are given. These results however show some unwanted behavior in the sense that our traffic light mechanism does not handle the grid-related issues in the proper way. This seems to be a result of the high penetration of loads and generation. Therefore we execute a second set of simulations with a lower amount of loads and generation than proposed in the previous section. The setting and results of these simulations are presented in Subsection 6.2. This is followed by the results of a third set of simulations in Subsection 6.3, in which larger amounts of loads and generation is tested on a stronger grid. This grid is similar to the one used in Section 5, but has a lower resistance and higher current carrying capacities, resulting in the ability to host more loads and generation.

6.1 Results of first simulation

In this subsection, the results of the simulation done with the setting given in Section 5 are given.

Firstly, the general situation in the grid over the whole day is considered for a specific household. We will observe household 12, as this is a household with own generation, a battery, an electric vehicle and an air conditioner. Figure 13 shows the traffic light (left) and the resulting electricity price (right) over the day given to household 12. The values 1 till 5 in the left part of Figure 13 representing the traffic light mechanism have the following meaning:

1. Green traffic light,
2. Orange traffic light, too much injection (either from overloading or over-voltage)
3. Red traffic light, too much injection (either from overloading or over-voltage)
4. Orange traffic light, too much demand (either from overloading or under-voltage)
5. Red traffic light, too much demand (either from overloading or under-voltage)

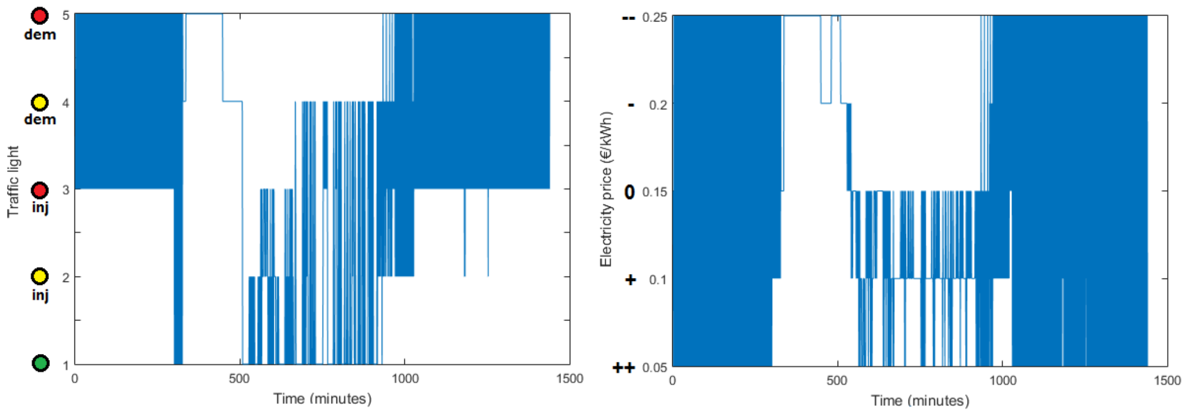


Figure 13: Traffic light (left) and energy price (right) during one day for household 12.

The blue 'blocks' in Figure 13 are a result of a very fast (minutely) fluctuation of traffic lights and energy price between two levels. From the figure it is therefore clear that in this simulation the traffic light mechanism gives a very undesirable result. The price fluctuates minutely between the lowest and highest level, which is clearly not a useful outcome. The traffic light is not really reflecting the situation of the local grid, as now for example in times of high demand the traffic light is red half of the time for too much supply. It seems that the traffic light mechanism is only increasing the grid instability, and that mainly the electric vehicles are responsible for this. This is because the fluctuation is worst from time 0 to 350 and 1000 to 1440, which are exactly the times that they are connected to the grid.

As expected, the cause of this fluctuating behavior is a combination of too many loads and generation for this particular distribution network, and the heuristics for the flexible devices. The IEEE European LV Test Feeder distribution network used for this simulation is a typical European rural network that is not designed to host 10 electric vehicles and high amounts of solar generation, which is used for this simulation. After some tests with this network, we found that an under-voltage already occurred if all households were demanding around 2.2 kW. As an electric vehicle demands 4.7 kW while charging (and supplies the same while discharging), it is not a surprise that this network cannot handle the amount of loads and generation proposed in the previous section. The designed heuristic of for example the electric vehicle is not able to deal properly with this large amount of loads and generation. Within our pricing mechanism, if too many cars are being charged (e.g. because of a cheap price), an under-voltage issue arises, so the traffic light becomes red, resulting the price to rise to the highest level. With this price, all cars decide to discharge, and an over-voltage problem occurs, resulting in a cheap price, due to another red traffic light. This process will repeat itself, resulting in the observed price fluctuations.

After this simulation, it becomes clear that the amount of loads and generation really is too high for the proposed network to handle. Our management strategy, in which most households are offered the same incentives at the same time, turned out not to be very successful in handling this, and probably even makes it worse. For these situations, the heuristic might be improved by adding a mechanism that for example sets a maximum for the amount of cars that can be charged/discharged at the same time. However, it is very difficult to keep such a system fair. Especially when there is such a high amount of cars, it might even be that some will not even have the chance to charge at all. This idea is out of the scope of this research, but is worth investigating in the future.

It is questionable whether any management system can deal with such a mismatch between the loads and the network and whether such a mismatch would ever occur in real life, as it is the DSO's responsibility to keep the grid strong enough to deal with high amounts of loads and generation. Therefore, it is more interesting to test our traffic light system for more realistic situations in which the network is more suitable for the amount of loads and generation. In such a scenario, the grid would only have a small amount of issues without steering, and our management system hopefully is able to prevent them. There are two options that are investigated in this research to have a better balance between the grid and the loads and generation:

- Reducing the amount of loads and generation: As this network is just not able to handle the amount of loads and generation that we would like to have modeled, we can adapt the scenario by lowering the amount of loads and generation. This option is further elaborated in Subsection 6.2.
- Enforcing the grid: The amount of generation and loads suggested in Section 5 (for example, 50% electric vehicles and 80% solar energy) is not a very unlikely scenario for the future. Therefore it would be interesting to see whether this management system is able to handle this situation properly, given that the grid is strong enough. This can be done by taking the IEEE European LV Test Feeder distribution network and artificially enforcing the grid, by for example doubling the current carrying capacities and halving the resistance of the cables. This option is further elaborated in Subsection 6.3.

The two aforementioned options hopefully reduce the extreme price fluctuations that we observed in the first simulation. Another trick to limit these fluctuations is to use prolonged traffic lights. This means that once a red traffic light is given to a household, the traffic light will stay red for longer than only one time step (i.e. one minute), and then first turn orange for a while before it jumps back to green, as the problem might not be over immediately. To create variety between the different households, the amount of time the light stays red is a random number between 10 and 20 minutes, and after that it stays orange for another randomly chosen time between 10 to

20 minutes. This way, the households will not all make the same decisions at the same time, so hopefully this helps reducing the amount of fluctuations in price. For the following results, we use this prolonged traffic light trick, and we test it in Subsection 6.2.6.

6.2 Simulation with lower loads and generation

In this subsection, again the IEEE European LV Test Feeder distribution network is simulated, but with a lower amount of loads and generation than before. For this simulation, all parameters stay the same as described in Section 5, with the exception of the probability that the loads and generation is present at a household. The new values are summarized in Table 7.

Table 7: Old and new probabilities of being present in a household.

	Generation	EV	Battery	AC
P_{ex} (old)	0.8	0.5	0.5	0.4
P_{ex} (new)	9/21	2/21	4/21	4/21

These devices are divided over the households as follows:

- Own generation: Households 3, 6, 7, 10, 12, 13, 15, 18 and 20.
- Electric vehicle: Households 5 and 12.
- Battery: Households 8, 12, 13 and 17.
- Air conditioner: 3, 9, 12 and 20.

In the rest of this subsection, first the results of the traffic light mechanism and curtailment are shown. Then some results are given that give insight in the working of the different heuristics, followed by an analysis of the traffic light and the heuristics combined. After that, it is investigated in more detail whether the traffic light mechanism has a positive influence on the results. Lastly, some results are presented comparing the self-consumption and the flexibility approach, and checking the influence of the prolonged traffic light proposed in the previous subsection.

6.2.1 Traffic light mechanism and curtailment

For this new simulation, again the traffic light and the electricity price over the day are given in Figure 14 for household 12, a household having all flexible devices. For the scenario with a smaller amount of loads and generation, the traffic light mechanism seems to work more decently. A big price fluctuation only occurs once at around 1150 minutes, but this is resolved automatically after eight minutes. Note, that this simulation still depicts a rather extreme day with a high amount of generation and loads, as in only around 15% of the day a green traffic light (nr.1) is given to household 12, and there is three times a red traffic light for too much demand (nr.5) and three times a red traffic light for too much injection (nr.3).

The exact amount of demand curtailment for this simulation is shown in Figure 15, where on the left the demand curtailment of all households over time is shown, and on the right the demand curtailment per household. In this figure, only the demand curtailment of the shiftable, non-shiftable and thermal appliances is shown, and not the demand curtailment of the batteries and electric vehicles. This is because it is not very harmful for batteries and electric vehicles to be curtailed in demand, as they can easily charge at a later time. From the figure it can be seen that only household 4 and 5 are curtailed, and only at one time, just near 1000 minutes (around 5 p.m.). The curtailment happened because at that time many households use electricity for cooking, and the two mentioned households were both using over 4100W.

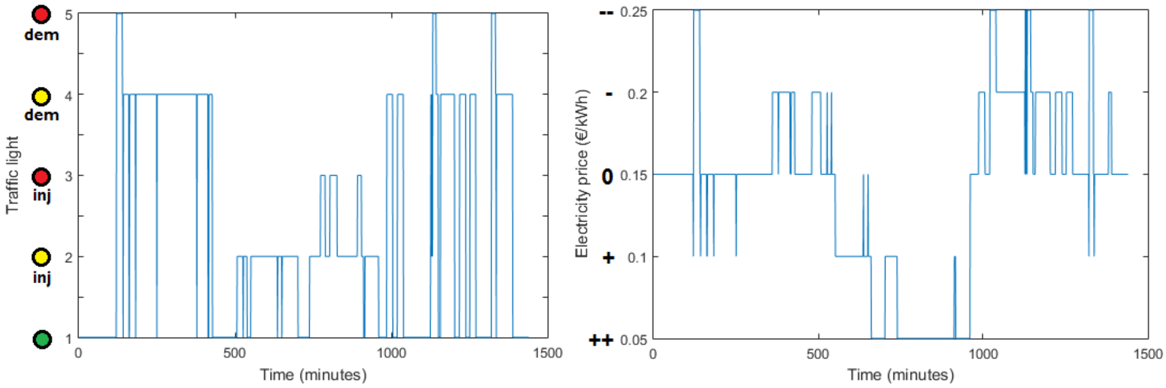


Figure 14: Traffic light (left) and energy price (right) during one day for household 12.

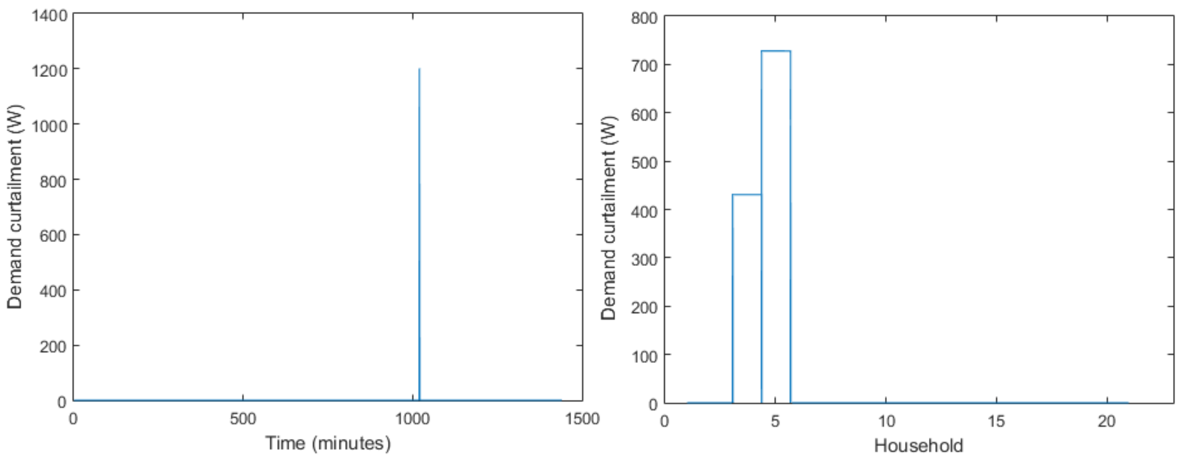


Figure 15: Demand curtailment for all households over time (left) and per household (right).

Note, that it seems that Figure 14 and 15 do not match, i.e. the three red traffic lights for household 12 are not at the same time as the curtailed demand of households 4 and 5 and it seems that household 12 is not curtailed after all. This has the following two reasons:

- Figure 15 only depicts the curtailed demand of the shiftable, non-shiftable and thermal appliances, the curtailed demand of batteries and electric vehicles is not shown. This is because a curtailment of demand for batteries and electric vehicles is not very harmful, they can easily be charged at a later time. This means that at the three red traffic lights of household 12 only the demand of batteries and electric vehicles is curtailed.
- Household 12 does not have a red traffic light at the time around 1000 minutes, where demand of the other two households is curtailed, because it has a net power of lower than 1500W at this time. However, households 4 and 5 do have a red traffic light at this time.

The amount of injection curtailment for this simulation is shown in Figure 16, where again on the left the curtailment over time is shown, and on the right the curtailment per household. For the injection curtailment, only the curtailment of injection from the own generation is shown. Injection curtailment from batteries and electric vehicles is not taken into account, as it is not harmful if they are not allowed to inject energy. It is interesting to see that all households with own generation are curtailed, except for the two households that have a battery (12 and 13), and one household that has an air conditioner (3).

Note, that Figure 14 and 16 do match. The times in which household 12 receives a red traffic

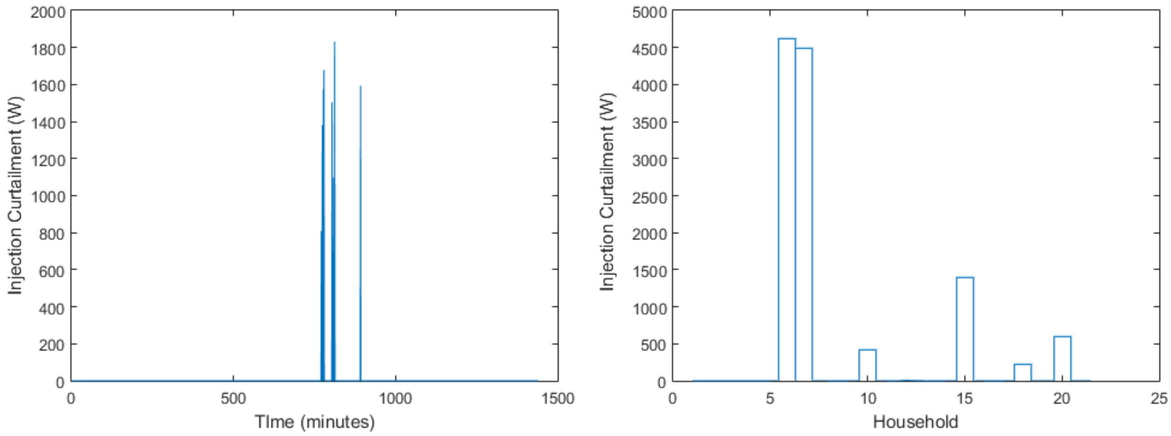


Figure 16: Injection curtailment for all households over time (left) and per household (right).

light are also the times that injection is curtailed. Household 12 is however not curtailed, as its absolute net power is not higher than the maximum limit (because it has a battery and an air conditioner, giving him enough flexibility).

The amount of money that all households have to pay for their electricity bill for this 24 hours is shown in Figure 17. Household 5 has by far the highest bill, as this household has to charge the electric vehicle and does not have a battery or own generation. Furthermore, almost all households with own generation have a negative amount on their bill, which means that they made money this day with selling their own generation. From the households with own generation, only household 3 has to pay, which is due to the use of the air-conditioner and a high amount of non-shiftable loads. For the calculation of the electricity bill, the difference between the state of charge at the beginning and end of the day for the batteries and the electric vehicles is taken into account with the average price of €0.15/kWh.

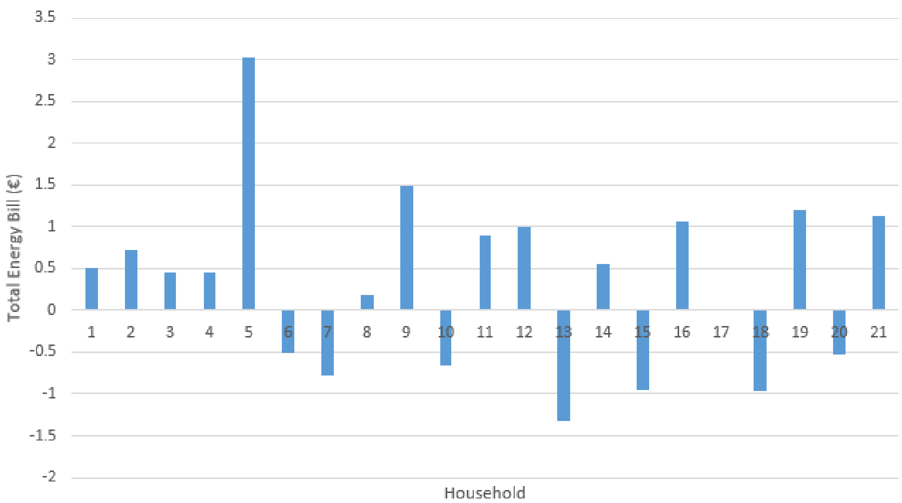


Figure 17: Electricity bill per household for the simulated 24 hours.

In Figure 18 the average price (€/kWh) over the whole day for buying (i.e. demanding) and selling (i.e. injecting) is presented for all households. For these values, the price for buying is taken over all time steps (minutes) for which the net power is larger than zero, and the price for selling over all time steps with a negative net power. Note, that some households do not have an average selling price as they neither have own generation, a battery nor an electric vehicle, so their net load is always positive. The households with the highest average selling price are households 5, 8 and 17, which are the households that do have flexibility in the form of a battery or an electric vehicle, but do not have own generation. This is expected, as they only sell in times of a high price. The households that have both own generation and a battery or an electric vehicle (households 12 and 13) have a little lower average selling price, as their average is reduced by the low prices that they receive for selling their generated energy during the day time. The households with only own generation therefore also have the lowest average selling price.

The households with the highest average buying price are households 3, 6, 10 and 18. These all do not have a battery or an electric vehicle, but do have own generation. Their average buying price is high because they do not have the flexibility to buy at cheap times. Because they have own generation, they are not buying any energy at day time, just when the energy is at the cheapest level. The households with the lowest average buying price are households 8, 9, 14 and 17. Households 8 and 17 both do have a battery, but not own generation, so they can charge their battery in times of low prices and their average buying price is not reduced because of generation during day time. Household 9 has an air conditioner but no own generation, so it uses a lot of energy in the day time, when the energy is cheap. Household 14 only has a shiftable load, which is a washing machine running in day time, also resulting in the low average price. Households 5 and 12 both have an electric vehicle, and their average buying price is pretty high. Even though they can charge their vehicle in a flexible way, it is not connected to the grid at day time, when energy is cheapest. Furthermore, if both vehicles are being charged at the same time, the traffic light jumps to orange in many cases, resulting in high prices as well.

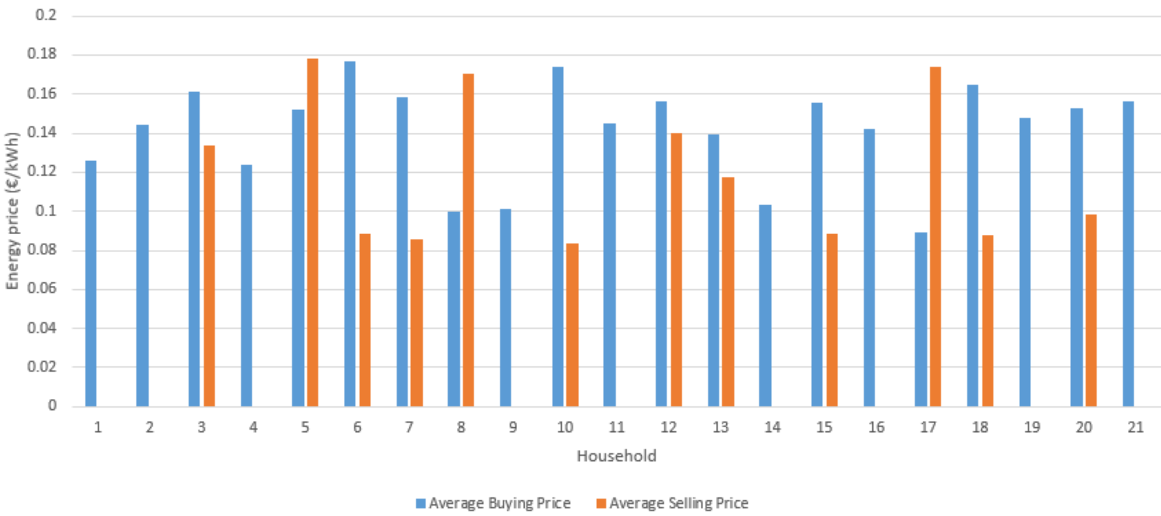


Figure 18: Average buying price and average selling price for the 21 households.

6.2.2 Heuristics for flexible devices

As in the current simulation the traffic light mechanism seems to work properly, we have a more detailed look at how the heuristics for the flexible devices designed in Subsection 4.4 make decisions, and compare that with a situation without control. For shiftable appliances it is not very interesting to graphically represent this, as only their start time might be delayed. However, for the refrigerator, the air conditioner, the battery and the electric vehicle we show the progression of temperature and state of charge over the whole day to analyze how they are controlled by the heuristic.

Refrigerator

The temperature of the refrigerator of household 12 is shown in Figure 19. This temperature progression is a result of the heuristic, which bases its decision on the current energy price, also shown in the figure, and the future energy prices, as shown in Figure 11.

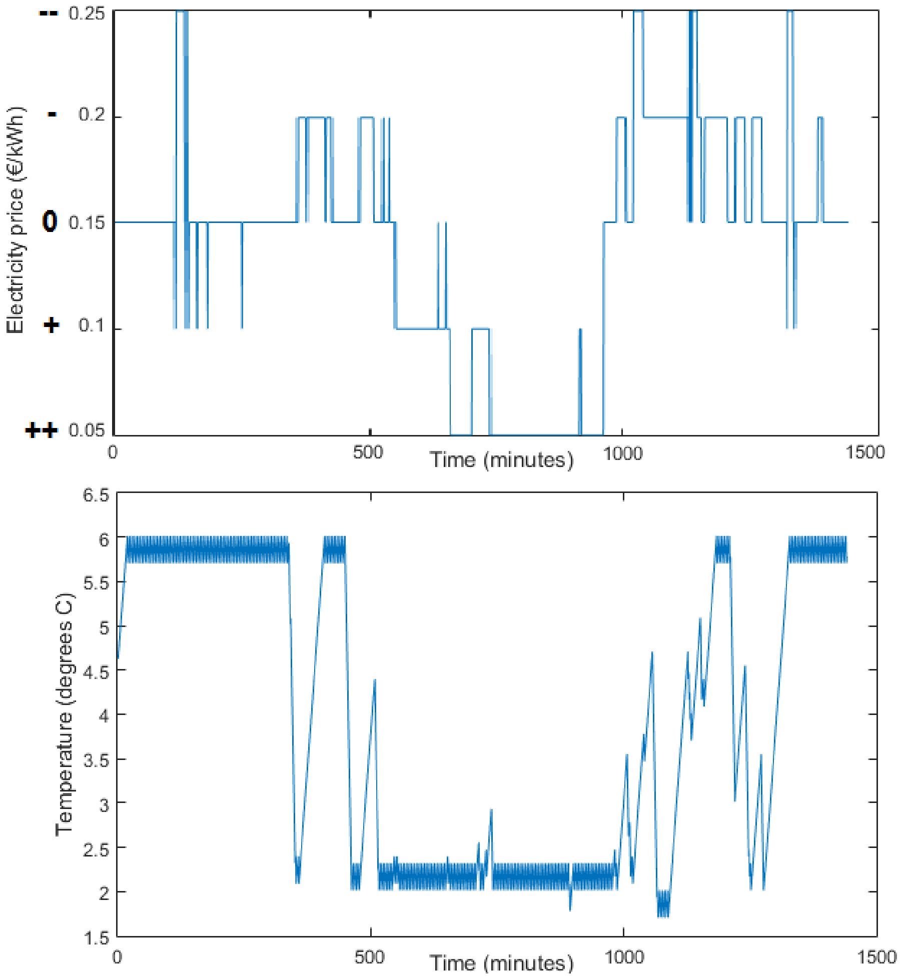


Figure 19: Refrigerator temperature of household 12 over time (down) and energy price of household 12 (up).

In the first hours, the temperature in the refrigerator is kept high, as there are enough future periods where the price is lower or equal. As the predicted energy price is expected to increase from level − to level 0, the refrigerator cools down just before that. A similar thing then happens when the price is going up from level 0 to level + just before 500 minutes. Then during the day time, the heuristic would normally keep the temperature high, because the energy is cheap at this time. However, due to the almost constant orange traffic light during the day time, the price becomes even cheaper, so the heuristic is mainly trying to cool down. Only at around 730 minutes there is no orange traffic light, and at this time the temperature is going up a little. Then the heuristic makes sure that at around 950 minutes the temperature is minimum, because a more expensive time period is coming. In the evening, the price fluctuates a lot because of orange and red traffic lights. The heuristic has a good response on this, as it tries to cool down as long as there are enough minutes left to completely heat up at the end of the expensive period (−) at around 1150 minutes. This leaves space to switch the refrigerator off in times of curtailment. At the end of the day the temperature stays high as first the energy price is going down and then stays constant.

We compare the consumption of the refrigerator controlled by the heuristic with a refrigerator that has normal cooling/heating cycles, shown in Figure 20. As it is assumed that the temperature in the refrigerator changes independent of the outside temperature, the total consumption should be equal. However, because the energy is consumed at other moments, we found that the price for running the refrigerator controlled by the heuristic was 4.0 eurocents per day, and without heuristic 4.3 eurocents. For this comparison, in both cases the same price curve, shown in Figure 14 is considered, meaning that we make the assumption here that a different consumption pattern of the refrigerator would not have changed the electricity price.

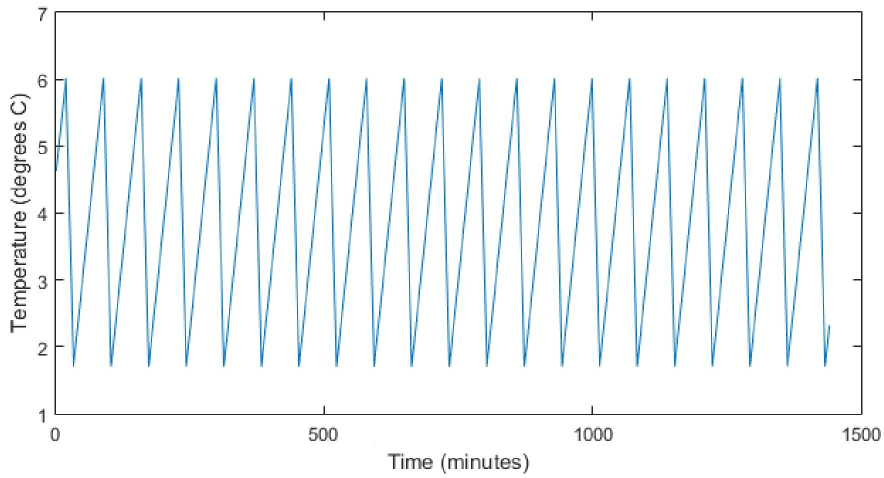


Figure 20: Refrigerator temperature of household 12 over time.

Air conditioner
The room temperature resulting from the control of the air conditioner of household 12 is shown in Figure 21. Note that the air conditioner is only functioning between around 10:30 a.m. and 7 p.m. The air conditioner has a very similar pattern with the refrigerator, which makes sense as they are steered with the same heuristic. At around 730 minutes the orange traffic light becomes green for a little while so the temperature rises here a bit. The only difference is at the end at around 1050 minutes, where the refrigerator was trying to cool down, but the air conditioner stays warm to save energy, as it is close to the end time of the control for the air conditioner.

The consumption of the air conditioner controlled by the heuristic can be compared with an air conditioner that has normal cooling/heating cycles, similar to that of the refrigerator in Figure 20. As it is assumed that the room temperature controlled by the air conditioner changes independent of the outside temperature, the total consumption should be equal. However, because the energy is consumed at other moments, we found that the price for running the air conditioner controlled by the heuristic was 78.2 eurocents per day, and without heuristic 97.9 eurocents. For this comparison, the exact same price curve (including changes due to traffic light) is considered, so we again make the assumption here that a different consumption pattern of the refrigerator would not change the electricity price.

Battery

The state of charge of the battery of household 12 is shown in Figure 22. In the first two hours, the battery is discharging as a cheaper period is coming up. After these two hours the predicted price

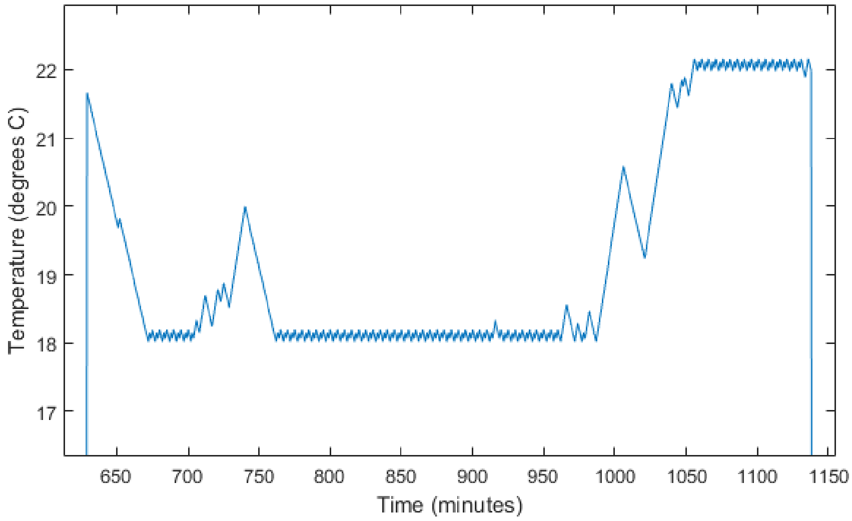


Figure 21: Air conditioner temperature of household 12 over time.

decreases, so the battery would charge if there would have been a green light. However, because the traffic light is almost constantly orange or red during these times, the battery continues to discharge due to high prices. During this time, only at the short times that the traffic light is green, the battery is charging. At around 450 minutes, the battery is charging because a more expensive period is coming, followed by a small period of discharging up to 500 minutes due to an expensive price (−) at this time. From 500 minutes onwards the traffic light becomes orange because of too much injection, so the battery starts to charge then because of lower prices. When the price increases again just before the 1000 minutes, the battery starts to discharge again, with some small interruptions because of price fluctuations or curtailments.

The consumption of the battery cannot be compared with the consumption of a battery without a heuristic, as there is no 'normal' charging/discharging pattern for a battery. However, we can easily calculate how much money the battery has made during the simulated day, which is 68.8 eurocents for a 9kWh storage capacity battery, assuming 100% efficiency. For a 90% efficient battery, this reduces to 56.3 eurocents, and for 80% efficiency, it is 43.7 eurocents. Hereby we assume a price of 0.15 €/kWh for the difference between the state of charge at the beginning and the end of the day. Note that again we assume here that if no battery would have been available, the price would have been the same.

Electric vehicle

The state of charge of the electric vehicle of household 12 is shown in Figure 23. At the beginning of the day, the electric vehicle is idle as a more cheaper period is coming up and the current electricity price is at level 0. Only at the red traffic light at around 120 minutes the electric vehicle is discharging. After being idle again for a while, the vehicle is being charged to meet the minimum state of charge at the time that the vehicle is leaving at around 450 minutes. The vehicle returns at around 1100 minutes and used around 28% of its battery. Then in the evening time, the prices are high because the traffic light is almost constantly orange. Therefore, the vehicle is almost constantly discharging. This is only interrupted by some small periods that are idle. These idle periods are either a result of the traffic light jumping from orange to green, reducing the price with one level and therefore stopping to discharge, or because of injection curtailment. In the last hours, the electric vehicle is at a minimum state of charge, with only two small tries to charge at times where the price was at level −.

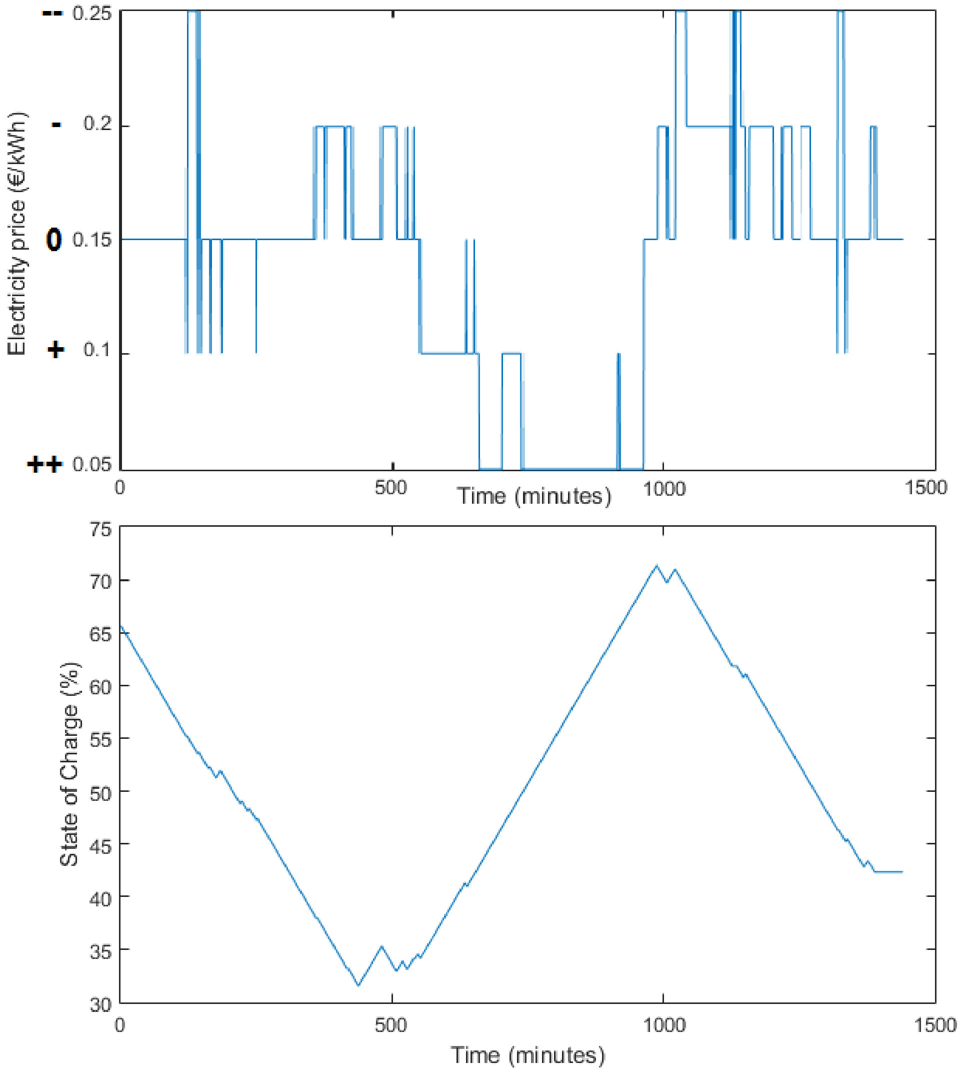


Figure 22: Battery state of charge of household 12 over time (down) and energy price for household 12 (up).

The consumption of the electric vehicle controlled by the heuristic can be compared with an electric vehicle that has normal charging behavior, shown in Figure 24. The two scenarios are difficult to compare, as the heuristic leaves the battery of the electric vehicle at 30% at the end of the day, while without heuristic the battery is full at the end of the day. Again, we assume that this difference is paid for with the average price of 0.15 €/kWh. With the heuristic, the cost for the electric vehicle for the whole day is 78.0 cents assuming 100% efficiency (91.8 cents with 90% efficiency and €1.05 with 80% efficiency), and the cost for the electric vehicle without heuristic is €3.59. The difference of 60% state of charge is worth €2.48 with aforementioned price, resulting in a net price of €1.11. Again, we make the assumption here that the price would not have been changed for the charging scheme without heuristic.

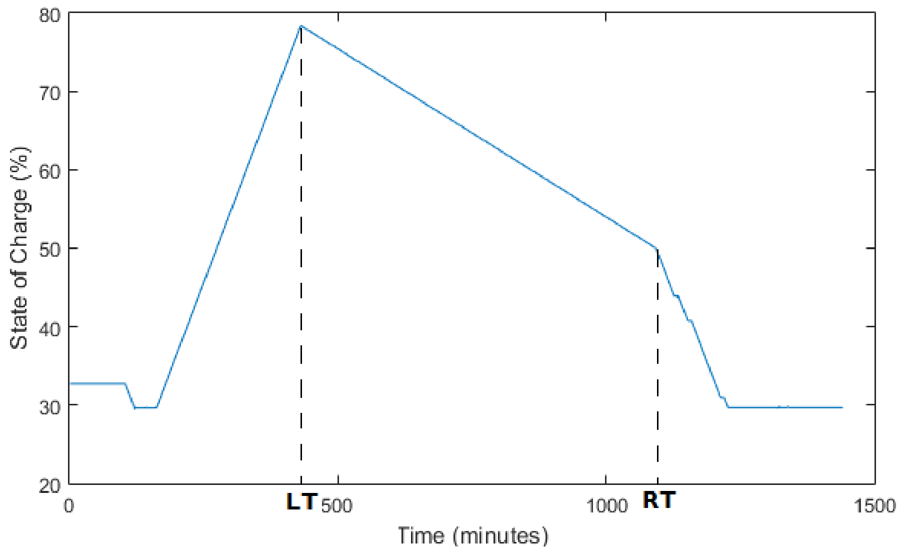


Figure 23: Electric vehicle state of charge of household 12 over time with leaving time LT and return time RT.

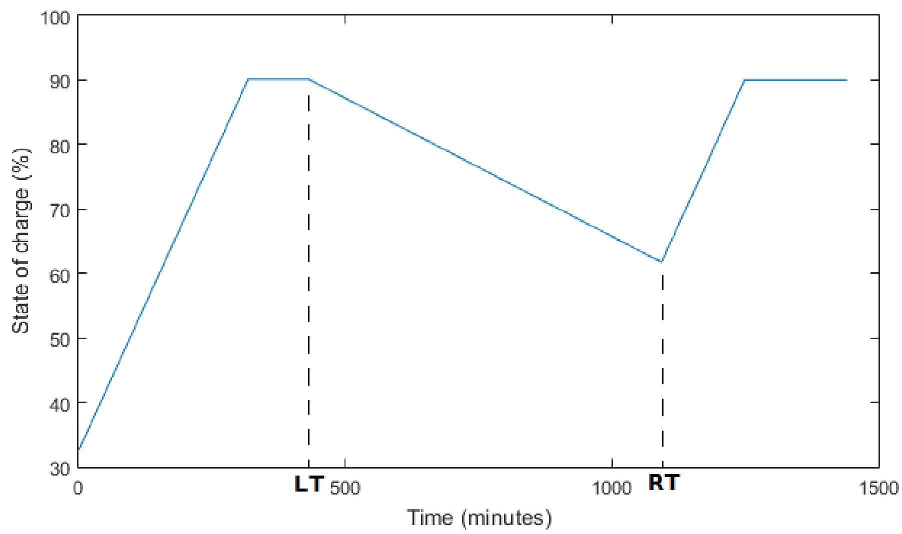


Figure 24: Electric vehicle state of charge of household 12 over time, without heuristic.

Direct and indirect cost savings

In the previous paragraphs, we saw that using the heuristics can result in some direct cost savings for the prosumers. They are summarized in Table 8. Next to the already mentioned savings, also the cost for running the dish washer of household 12 with and without heuristic is added. For shiftable devices like dish washers, it is assumed that if no heuristics are used, the appliance starts running at the earliest possible starting time.

In this comparison, we assume that the price of electricity would be the same for running the simulation with and without the heuristic. However, the heuristic is designed in such a way that it is supposed to relieve the stress in the distribution network, so probably the price could have been different. Moreover, the heuristic (hopefully) makes sure that less demand and injection are

Table 8: Direct cost savings for different flexible devices.

Appliance	Cost in €(no heuristic)	Cost in €(heuristic)	Savings
Dish Washer	0.082	0.078	5%
Refrigerator	0.043	0.040	7%
Air conditioner	0.979	0.782	20%
Battery	-	-0.563	-
Electric Vehicle	1.11	0.918	17%

curtailed, and therefore result in indirect cost savings as well. Unfortunately, it is very difficult to check per individual flexible device what the contribution is to these indirect cost savings, as a potential reduction in curtailment is a result of the combination of all flexible devices of all households. In the next subsections we investigate what the effect of the heuristics combined with the traffic light mechanism is on the curtailments.

6.2.3 Traffic light mechanism and heuristics

In this subsection, we look at four different scenarios to check how the traffic light mechanism and the heuristics are functioning. The scenarios differ in whether the traffic light mechanism is used or not, and whether the heuristics are used or not. If the traffic light mechanism is switched off, the energy prices exactly follow Figure 11, without being affected by traffic lights. If the heuristics are switched off, the devices follow the strategy described in the previous subsection and in Figure 20 and 24. As there is no 'no heuristic' option for the battery, in all four scenarios no batteries are simulated. For the rest, the penetrations of Table 7 are used. We are interested in the daily energy bill EB in euro's, the amount of injection curtailment ICA in Watt minutes (1 kWh = 60,000 Wm) and the amount of demand curtailment DCA in Watt minutes. For each of these values we want to know the value for the household with the minimum amount (EB^-, ICA^- and DCA^-), the value for the household with the maximum amount (EB^+, ICA^+ and DCA^+), and the total amount over all households (EB_{tot}, ICA_{tot} and DCA_{tot}). The results are shown in Table 9.

Table 9: Results of 4 scenarios, with and without traffic light, and with and without heuristics.

Heur.	TL	EB^-	EB^+	EB_{tot}	ICA^-	ICA^+	ICA_{tot}	DCA^-	DCA^+	DCA_{tot}
Yes	Yes	-0.92	2.96	9.36	0	29,000	78,000	0	1,850	2,900
Yes	No	-1.60	2.29	2.36	0	12,500	33,500	0	7,000	17,700
No	Yes	-0.95	6.18	17.44	0	36,500	85,500	0	7,900	18,700
No	No	-1.58	4.79	8.95	0	36,500	85,500	0	7,900	18,700

Looking at the daily energy bill EB, we see again that using the heuristics has a positive effect on the energy bill, especially for the households with an already high energy bill. This is probably because of the electric vehicles, as they mainly result in a high energy bill, and a lot of money can be saved by charging them in a smart way. Furthermore we see that not using the traffic light mechanism has a positive effect on the energy bill as well. This is expected as the traffic light generally increases the price in times of high demand and decreases the price in times of high supply. Especially because there are no batteries in this simulation, the advantage of the higher price fluctuations due to the traffic light cannot be used too much. If this pricing scheme is offered by a third party, this party will receive the difference between the pricing with and without the traffic light mechanism. If he is not out to make profit by this, he can use this money for example for gamification methods to stimulate self-consumption, so that this money is brought back to the prosumer. For this simulation, the amount of money that the third party receives is €6.33 for the case that the heuristics are used. This results in a net daily energy bill of €9.36 − €6.33 = €3.03. This is still a little higher than the total energy bill for the case that no traffic light is used.

The results for the amount of curtailed injection are rather surprising, as the scenario with both heuristics and traffic light results in a way higher amount of injection curtailment than in the case without traffic light, even though one of the main reasons to design them was to reduce the injection curtailment. The reason for this might be that injection curtailment is at the middle of the day, and at this time there is only a small amount of flexibility. This is because at this moment no electric vehicles are available, and in this simulation there are no batteries either. Therefore, the difference between both scenarios is due to the heuristics of the shiftable and thermal devices. Because of all the orange traffic lights at day-time reducing the energy price, the air conditioner is trying to cool down constantly (see Figure 21). This keeps the temperature at the minimum level, so there is no space left to further cool down and thereby consuming energy in times of injection curtailment. In the case that no traffic light is used, and when the energy price is at level + (during the day time), the air conditioner is keeping the temperature as high as possible, leaving more flexibility in case of curtailment. So basically, because of too much traffic lights, the thermal devices already use up their flexibility for periods that are not curtailed. For the case that no heuristics are used (see the last two rows), the amount of curtailment is the highest and is exactly the same for with and without traffic light, as in both cases exactly the same decisions are made.

The results for the amount of curtailed demand look more promising, as in the case of both heuristics and traffic light this has the lowest value. This might be because the electric vehicle is only discharging at price level $--$ when demand is curtailed, and as without traffic light this price level is never reached, the electric vehicles are helping to release grid stress in the evening time. In case no heuristics are used, the amount of curtailment is just a little higher than the case with heuristics and without traffic light, and is exactly the same for with and without traffic light, as again in both cases exactly the same decisions are made.

In general, it can be concluded that the addition of heuristics are beneficial for the results. The addition of the traffic light mechanism to the heuristics, however, does not always have a positive impact. This is probably because the heuristics are not really designed to respond on a situation with too many traffic lights and therefore the flexibility is used too soon. In the next subsection, we look in more detail at the difference between the presence and absence of traffic lights next to the heuristics.

It should be noted here that the scenario with heuristics and without traffic light might have especially good results in this simulation regarding injection curtailment, because the prices offered shown in Figure 11 are very similar to the situation in the grid, i.e. the price is high when there is a risk of too much demand and the price is low when there is a risk of too much supply in the distribution grid. In general it is a reasonable assumption that the situation at the national and the local level are similar, but of course it can also happen differently. In that case, the traffic light mechanism might perform better on all fronts, as it makes sure that the prices depict the situation in the local grid as well. This is also investigated in the next subsection.

6.2.4 Traffic light mechanism vs. no traffic light mechanism

In this subsection, more detailed results are presented for the difference between using the traffic light mechanism and not using the traffic light mechanism, both while the flexible devices make decisions based on the heuristics. For different penetrations of own generation, batteries, electric vehicles and air conditioners, the energy bill EB, the amount of curtailed injection ICA and the amount of curtailed demand DCA are compared. For these simulations, the values in the last row of Table 7 are used as the base case, while changing the penetration of one of the flexible devices. Lastly, the two cases (with and without traffic light) are compared for a scenario in which the situation on the national level is different from the local grid situation, i.e. the local grid needs more supply, whereas the national grid is in need of more demand, or vice versa.

Different penetration of own generation
In this paragraph, the results of five different penetrations of own generation are shown. The simulation is run for 3, 6, 9, 12 and 15 households with solar PV with a maximum generation between 1 and 5 kW. In Figure 25, 26 and 27 the total energy bill EB_{tot}, the total amount of injection curtailment ICA_{tot} and the total amount of demand curtailment DCA_{tot} are shown for the different penetrations of own generation, with and without traffic light.

The difference in the total energy bill is very small for both scenario's, so money-wise they perform equally well for different amounts of own generation.

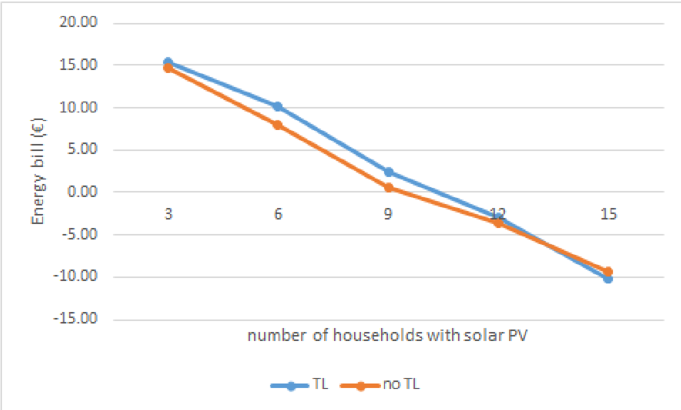


Figure 25: Total energy bill for different penetrations of own generation, with and without traffic light.

Looking at the amount of curtailed injection, the results are similar to that of the previous subsection. The amount of curtailed injection is higher for the scenario with traffic light, especially with a high penetration of own generation. Only in the case of 9 households with solar PV the traffic light strategy has a slightly lower injection curtailment. Note that in the simulation of the previous subsection also 9 households with own generation were modeled, but in that simulation the injection curtailment was higher for the traffic light strategy. The difference is that in the previous subsection 0 households had a battery, whereas in this simulation 4 households have a battery. Therefore, it looks like the traffic light system might have a lower amount of lower curtailed injection, as long as there are enough batteries to handle the amount of own generation. This will be further discussed later.

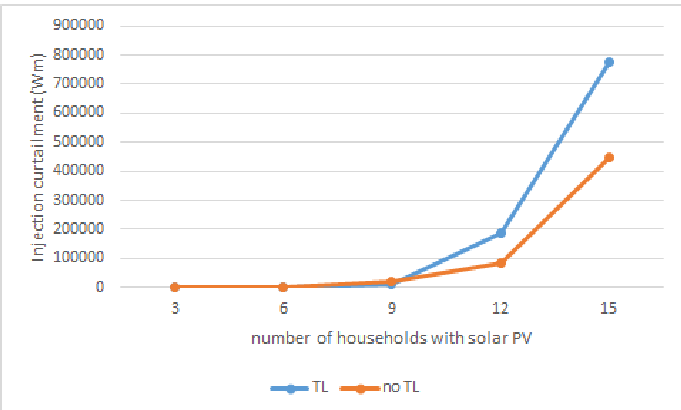


Figure 26: Total amount of injection curtailment for different penetrations of own generation, with and without traffic light.

The amount of curtailed demand is again a lot smaller for the traffic light strategy, independent of the penetration of own generation. The amount of curtailed demand is decreasing for a larger amount of own generation, as probably the batteries are charged more when there is a higher amount of own generation.

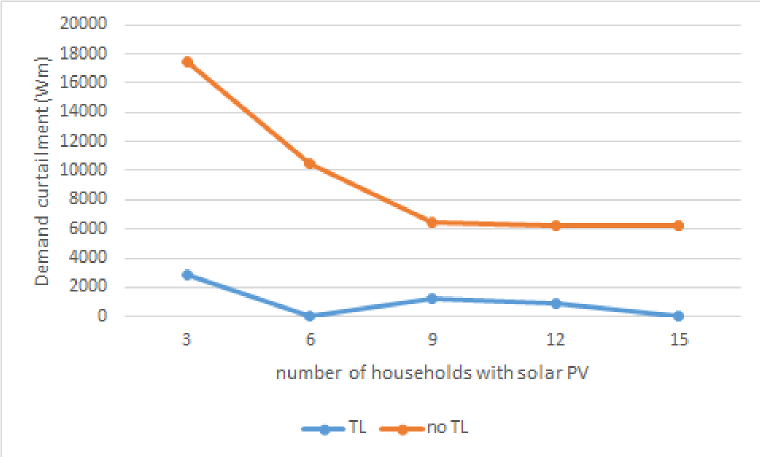


Figure 27: Total amount of demand curtailment for different penetrations of own generation, with and without traffic light.

Different penetration of batteries

In this paragraph, the results of seven different penetrations of batteries are shown. The simulation is run for 0, 2, 4, 6, 8, 10 and 12 households with a battery. In Figure 28, 29 and 30 the total energy bill EB_{tot}, the total amount of injection curtailment ICA_{tot} and the total amount of demand curtailment DCA_{tot} are shown for different total amounts of battery, with and without traffic light.

The total energy bill is lower for the scenario without traffic light, and the difference seems to increase with an increase in the number of batteries. This means that the heuristic for batteries makes better money-wise decisions in the scenario without traffic light.

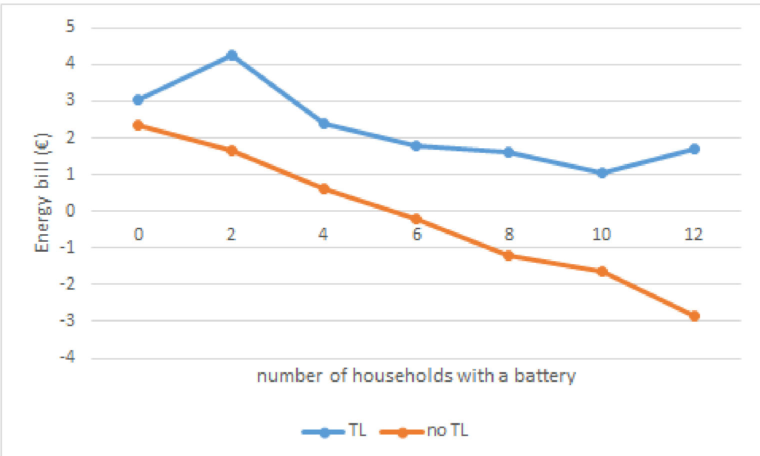


Figure 28: Total energy bill for different total amounts of batteries, with and without traffic light.

Looking at the amount of curtailed injection, it seems that the conclusion drawn in the previous paragraph about penetration of own generation is right. The injection curtailment is lower for the scenario without traffic light for a small amount of batteries, but as more batteries are available, the traffic light scenario starts to perform a lot better than the scenario without traffic light. In the scenario without traffic light, a bigger amount of batteries does somehow not really result in a lower amount of curtailed injection.

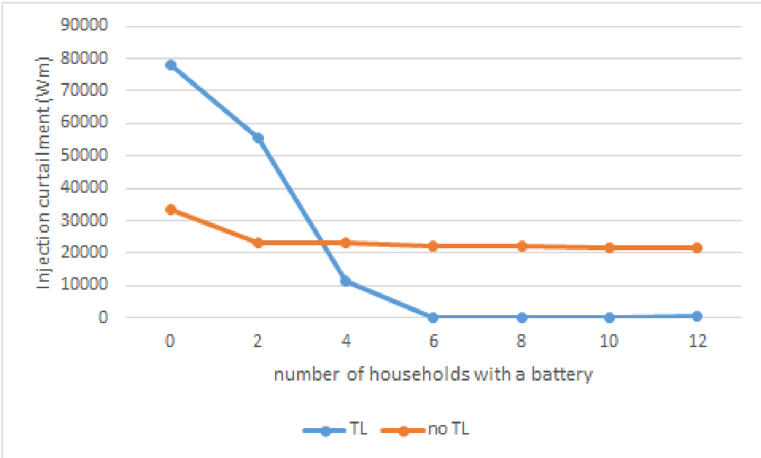


Figure 29: Total amount of injection curtailment for different total amounts of batteries, with and without traffic light.

For the amount of curtailed demand it almost looks like there is an optimal amount of batteries, both in the scenario with and without traffic light. This is a little curious, as you would expect that a higher amount of batteries always results in a lower amount of demand curtailment. Because we see this in both the scenario with and without traffic light, this is probably not because of the traffic light mechanism, but more likely because of the heuristic for the battery. As the batteries are all steered by the same heuristic and the price signals are almost the same, the decisions of the different batteries are very similar. Therefore, an increased amount of batteries may increase the stress in the network if all batteries are charging or discharging at the same moment. For the scenario with traffic light, the optimal amount of batteries is 2, which is very low, as 4 different batteries charging or discharging at the same time is not expected to create a grid-related problem immediately. For the scenario without traffic light the optimal amount of batteries is 6, which is also a lower amount than expected. Most probably, a household without a battery is curtailed in demand, and with the extra batteries that are charging (because the future price might rise), the amount of total demand is increasing and therefore more demand should be curtailed, resulting in a higher curtailment for the household without a battery. The total amount of demand curtailment is almost for all amounts of batteries a lot lower in the scenario with traffic light than without.

Different penetration of electric vehicles

In this paragraph, the results of four different penetrations of electric vehicles are shown. The simulation is run for 0, 2, 4 and 6 households with an electric vehicle. In Figure 31, 32 and 33 the total energy bill EB_{tot}, the total amount of injection curtailment ICA_{tot} and the total amount of demand curtailment DCA_{tot} are shown for different total amounts of electric vehicles, with and without traffic light.

The total energy bill is again lower for the scenario without traffic light, which means that again the heuristic for batteries makes better money-wise decisions in the scenario without traffic light. It is very curious that the energy bill for the scenario with traffic light is decreasing from 4 to

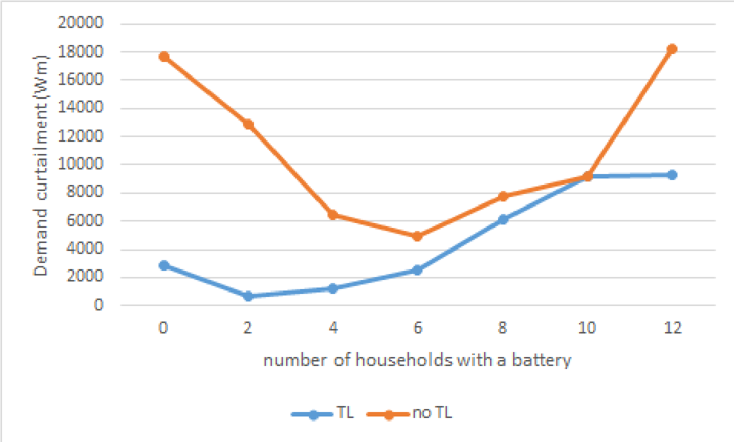


Figure 30: Total amount of demand curtailment for different total amounts of batteries, with and without traffic light.

6 vehicles, as charging 2 extra vehicles would normally require more money. This is a result of extreme price fluctuations, as explained in Subsection 6.1, because 6 electric vehicles is way too much for this network, and the traffic light mechanism sort of explodes. Therefore, the results of 6 vehicles in the traffic light mechanism scenario are not very useful.

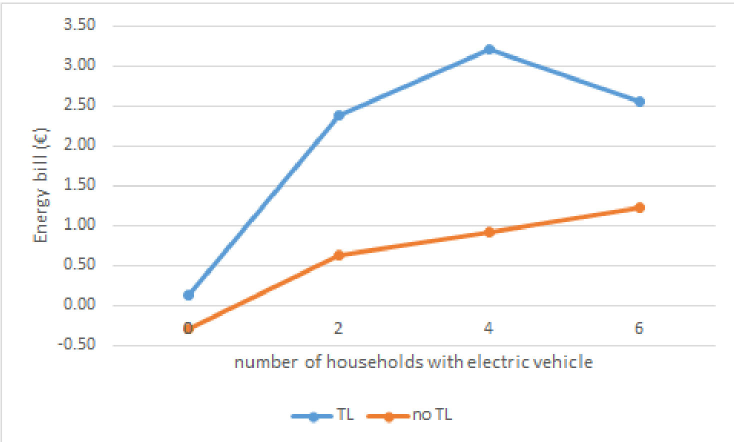


Figure 31: Total energy bill for different total amounts of electric vehicles, with and without traffic light.

Looking at the amount of curtailed injection, it seems that a bigger amount of electric vehicles has a positive effect for the scenario with traffic lights. This is a bit strange, as electric vehicles are not connected to the household in times of own generation. However, it might be that the charging of electric vehicles in the night time results in a discharging of batteries, which gives the batteries extra flexibility to charge in times of injection curtailment. For 2 or more electric vehicles, the results are very similar, with a little better performance of the traffic light scenario.

The amount of curtailed demand is very similar in both cases, however in the scenario with traffic light and 6 electric vehicles, the demand curtailment is very high. This is again because of the extreme price fluctuations as described in Subsection 6.1, as the network cannot handle 6 electric vehicles.

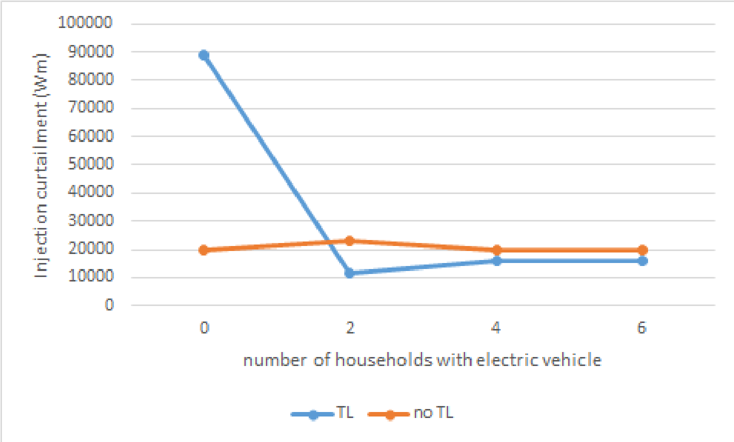


Figure 32: Total amount of injection curtailment for different total amounts of electric vehicles, with and without traffic light.

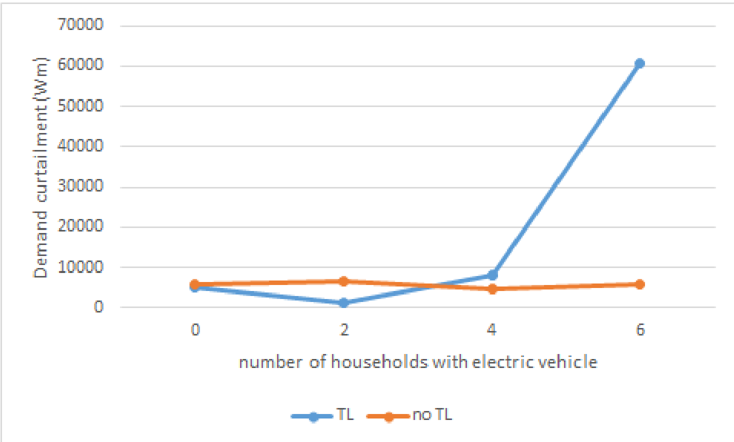


Figure 33: Total amount of demand curtailment for different total amounts of electric vehicles, with and without traffic light.

Different penetration of air conditioners

In this paragraph, the results of five different penetrations of air conditioners are shown. The simulation is run for 0, 2, 4, 6 and 8 households with an air conditioner. In Figure 34, 35 and 36 the total energy bill EB_{tot}, the total amount of injection curtailment ICA_{tot} and the total amount of demand curtailment DCA_{tot} are shown for different total amounts of air conditioners, with and without traffic light.

The results of the total energy bill are very similar to that of the electric vehicle. In general, the energy bill is higher for the scenario with traffic lights, and the energy bill is increasing for a higher amount of air conditioners. The energy bill only decreases from 6 to 8 air conditioners in the scenario with traffic light, again because of high price fluctuations. An amount of 8 air conditioners is too high for this network to handle, as they demand a large amount of power.

Looking at the amount of curtailed injection, we see clearly that a high amount of air conditioners has a positive effect on the injection curtailment. This makes sense, as air conditioners demand energy at the same time as the own generation faces risk to be curtailed. For a low amount of air

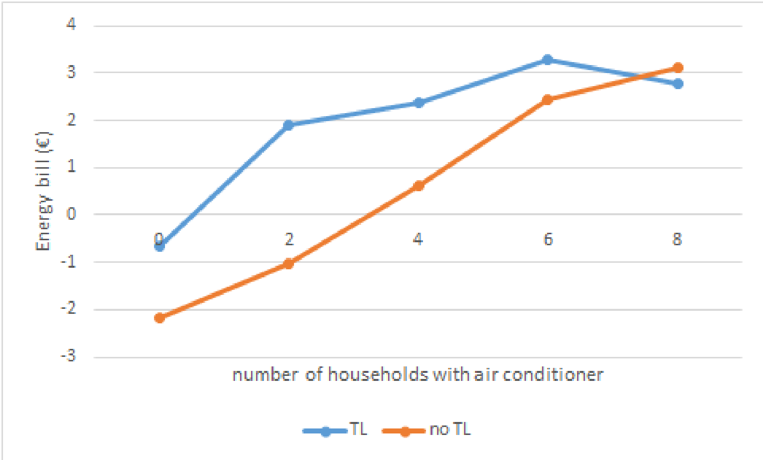


Figure 34: Total energy bill for different total amounts of air conditioners, with and without traffic light.

conditioners, the scenario without traffic light performs better, while for more air conditioners the scenario with traffic light performs a bit better. This confirms our former belief that the traffic light mechanism only has a better performance (injection curtailment-wise) if there are not too many traffic lights.

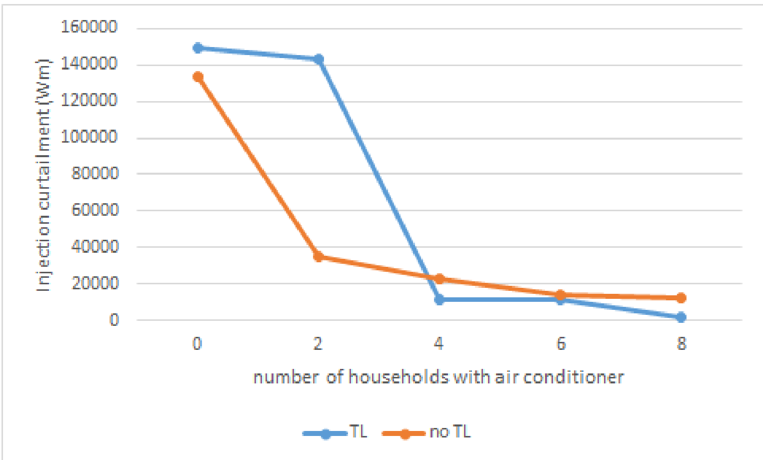


Figure 35: Total amount of injection curtailment for different total amounts of air conditioners, with and without traffic light.

Again, the amount of curtailed demand is a lot lower for the scenario with traffic light than in the scenario without traffic light. For the scenario without traffic light, the more air conditioners, the more demand is curtailed. This is logical, as there is more demand if there are more air conditioners. For the scenario with traffic light, the results are a bit different, but this is probably again because of the extreme price fluctuations in the case of 8 electric vehicles.

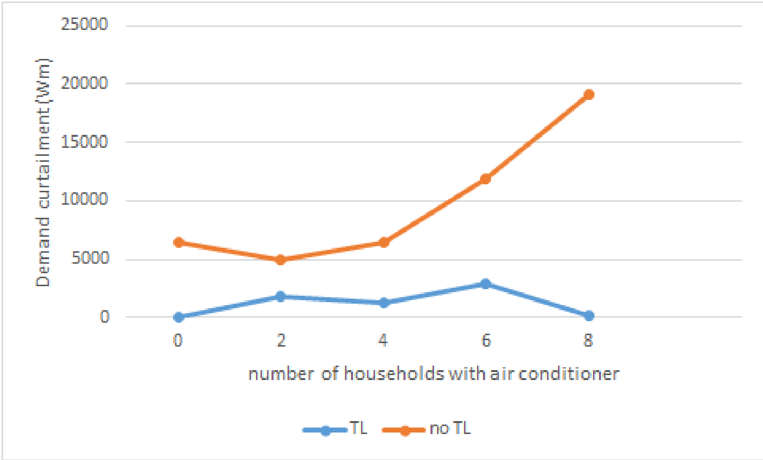


Figure 36: Total amount of demand curtailment for different total amounts of air conditioners, with and without traffic light.

Not matching national and local grid situation

From Subsection 6.2.3 and previous paragraphs, we have seen that in some cases the heuristics for the flexible devices have a lower amount of injection curtailment without the traffic light mechanism than with it. As mentioned before, the heuristics without traffic light may have such a good performance because the situation in the local grid is similar to the situation in the national grid, i.e. the prices that are given to the prosumers shown in Figure 11 are high when there is a risk of too much demand in the local grid, and the prices are low when there is a risk of too much supply. In this paragraph, we check whether the no traffic light scenario performs equally well in a case where the national and local situation are different.

To check this, different prices than the ones in Figure 11 are offered throughout the day. The new prices are now high during the middle of the day and low in the beginning of the evening, and they are shown in Figure 37.

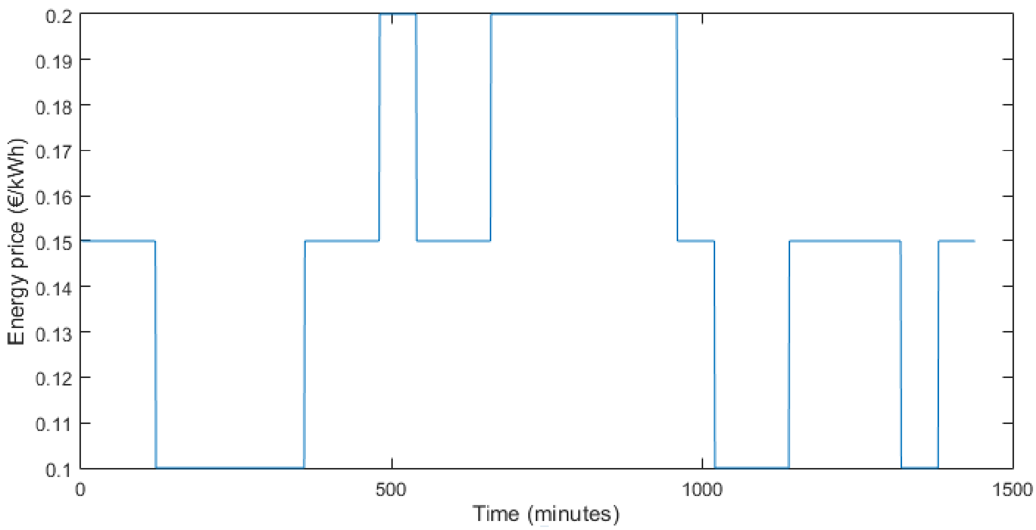


Figure 37: Adjusted price offered during the day.

The results of this comparison are summarized in Table 10. The energy bill EB of the scenario without traffic light is way lower than that of the scenario with traffic light. As mentioned in Subsection 6.2.3, in the traffic light scenario the prosumers pay a different price due to the traffic lights. Therefore, the party that offers them this pricing scheme usually receives some extra income. In this case, the prosumers pay in total €5.83 too much. This means that the net total energy bill is €5.28 − €5.83 = −€0.55, which is still a lot higher than without traffic light. This is because without traffic lights, the batteries decide to discharge in day time because of a high price and charge in the evening because of a low price, resulting in profits. The traffic light however pushes the price down in day time and up in the evening time, so that the battery decides not to discharge in day time and charge in evening time.

Looking at the amount of both injection and demand curtailment, we see that the heuristics perform way better with the traffic light mechanism than without. This is expected, as in the scenario without traffic light, the local grid situation is not taken into account at all. For example, if the prices are high at the national level, the prosumers will choose to discharge their battery, even though they are already injecting energy from their own generation. Similarly, they will charge their batteries in the evening time, even though they already have a lot of other demand at those times. The traffic light mechanism however creates a lot more flexibility in a scenario where the situation at local level is different from the situation at the national level, as it forces the prices to resemble the situation in the local grid first.

Table 10: Traffic light vs. no traffic light for different prices.

Strategy	EB^-	EB^+	EB_{tot}	ICA^-	ICA^+	ICA_{tot}	DCA^-	DCA^+	DCA_{tot}
TL	-1.63	3.07	5.28	0	12,500	31,500	0	2,000	6,500
no TL	-2.52	2.37	-4.41	0	51,300	159,000	0	14,900	19,200

6.2.5 Self-consumption vs. Flexibility based approach

In Figure 5 in Section 4.4 the difference between a self-consumption and a flexibility based approach for the heuristic was depicted. Basically, in the self-consumption based approach the heuristic tries to maximize its self-consumption in order to minimize the risk of curtailment, whereas in the flexibility based approach the heuristic tries to maximize the response on a possible curtailment. These two approaches are compared in Table 11.

Table 11: Self-consumption vs. Flexibility based approach results.

Strategy	EB^-	EB^+	EB_{tot}	ICA^-	ICA^+	ICA_{tot}	DCA^-	DCA^+	DCA_{tot}
Self-cons.	-1.30	2.91	6.48	0	4,500	11,500	0	750	1,200
Flexible	-1.28	2.94	6.30	0	5,800	14,800	0	650	1,050

The difference in energy bill EB is negligible, so money-wise there is not really a difference. The amount of injection curtailment ICA however is lower for the self-consumption strategy. This is a good result, as the addition of the self-consumption rule in the heuristic was designed to lower the injection curtailment. On the other hand, the self-consumption strategy results in a little bit larger amount of demand curtailment DCA.

6.2.6 Prolonged traffic lights

In Section 6.1, we faced extreme price fluctuations in the case of too many loads and generation. A trick proposed to reduce this fluctuating behavior, was to leave a traffic light red for a random amount of time between 10 and 20 minutes, and then first switch to an orange light for 10 to 20 minutes (randomly). In this subsection, it is investigated what the influence of this adjustment is. The results are presented in Table 12.

Table 12: Longer traffic lights vs. normal operation.

Strategy	EB^-	EB^+	EB_{tot}	ICA^-	ICA^+	ICA_{tot}	DCA^-	DCA^+	DCA_{tot}
Longer TL	-1.30	2.91	6.48	0	4,500	11,500	0	750	1,200
Normal	-1.56	2.49	3.67	0	6,500	16,700	0	1,400	6,550

The energy bill EB for the strategy with longer traffic light is higher than that of the normal operation. This makes sense, as there are more traffic lights that increase the price in times of high demand and decrease the price in time of high supply. The amount of money that the prosumers pay too much (due to the traffic lights) to the party offering this pricing mechanism is €4.11 for the longer traffic light strategy and €1.28 for the normal operation. This means that the net energy bills are €2.37 for the longer traffic light strategy and €2.39 for the normal operation, which is almost identical. Both the amount of injection curtailment and demand curtailment are lower for the traffic light strategy, which is a positive result and justifies our use of it.

6.3 Simulation with enforced grid

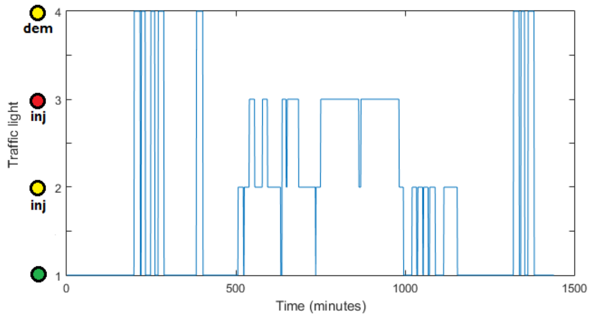
As discussed in Subsection 6.1, the IEEE European LV Test Feeder distribution network is not able to decently handle the amount of loads and generation that was proposed in Section 5. One of the proposed solutions was to use a stronger network by artificially enforcing this distribution network so that it is capable of managing a higher amount of loads and generation, by lowering the resistance and increasing the current carrying capacity of the cables. In this subsection, the results are shown for two simulations with higher amounts of loads and generation.

The input for these two simulations is shown in Table 13. Basically, in the simulations the loads and generation is doubled and quadrupled (compared to the values in the previous subsection, see the last row of Table 7), and the grid is enforced by a factor of 2 and 4 by decreasing the resistance R and increasing the current carrying capacity CCC. Basically, by decreasing resistance with a certain factor, the voltage change decreases with the same factor, reducing the chance on over- and under-voltage. Furthermore, by increasing the current carrying capacity with a certain factor, the chance of overloading is reduced with the same factor. Note that for the case of quadrupled generations, there are 18 households with generation, but their installed capacity is doubled compared to the normal case.

Table 13: Amount of loads and generation for the old and two new scenarios.

R	CCC	Generation	EV	Battery	AC
$\div 1$	$\times 1$	9/21	2/21	4/21	4/21
$\div 2$	$\times 2$	18/21	4/21	8/21	8/21
$\div 4$	$\times 4$	18/21 (double)	8/21	16/21	16/21

The traffic lights over time given to household 12 is shown in Figure 38, where on the left side the scenario with double loads and generation is shown, and on the right side the scenario with quadrupled loads and generation. In both cases the traffic light mechanism performs reasonably well, as there are no extreme price fluctuations. It is interesting to see that in both cases, there is no red traffic light for too much demand (nr.5), so no demand is curtailed. However, the amount of red traffic lights for too much injection (nr.3) is higher than in the normal situation, see the left part of Figure 14 for comparison.



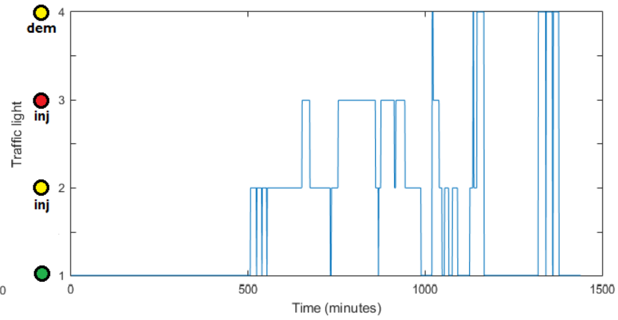


Figure 38: Traffic lights over time for household 12 for double (left) and quadruple (right) loads and generation.

In Table 14 more details of the simulations are shown. Again, the minimum, the maximum and the total of the energy bill EB of the customers, the amount of curtailed injection ICA and the amount of curtailed demand DCA is shown. The values of the normal non-enforced grid are shown as well for comparison.

Table 14: Results for normal, double and quadruple enforced grid and amount of loads and generation.

Enforced	EB^-	EB^+	EB_{tot}	ICA^-	ICA^+	ICA_{tot}	DCA^-	DCA^+	DCA_{tot}
Normal	-1.30	2.91	6.48	0	4,500	11,500	0	750	1,200
Double	-1.78	0.15	-13.78	0	13,000	34,800	0	0	0
Quadruple	-2.87	-0.31	-36.27	0	16,900	44,200	0	0	0

Looking at the energy bill, we clearly see that higher loads and generation leads to a lower energy bill. This makes sense as both batteries and generation reduce the energy bill significantly. For the quadrupled case, even the minimum energy bill is negative, as in this scenario there are no households without both generation and batteries. The amount of injection curtailment is almost three times as high for the double enforced grid and four times as high for the quadruple enforced grid. This is not very unexpected, as there is no variation in the generation (all households have the same generation curve, only multiplied with a different factor). Therefore, as the generation and loads increase with a certain factor, the amount of injection curtailment is likely to increase with the same factor. For the amount of curtailed demand this is different, as a bigger amount of loads also results in a bigger amount of variability. Therefore, the peak demands are not increased with the same factor as the increase in total loads, resulting in zero curtailed demand.

7 Conclusion, discussion and recommendations

In this research we proposed a novel pricing mechanism that aims to allow prosumers to react on price fluctuations based on the situation in both the national and local electricity network. Furthermore we designed heuristics for the flexible devices to be able to test our proposed traffic light mechanism. In this section, we first draw conclusions about them, based on the results found in Section 6. After that, a discussion about the results and the conclusions drawn is given, and based on them, finally some recommendations for improvement and ideas for further research are stated.

7.1 Conclusion

First of all, the heuristics designed for the flexible devices seem to have a reasonably good performance. In all simulated cases, using the heuristics for all flexible devices instead of a 'normal' no-management approach, resulted in a lower energy bill and in lower curtailments. Each appliance individually also had a better money-wise result if steered by the heuristic than without steering. It is very difficult, however, to differentiate for the individual heuristics which of them resulted in which amount of reduction of curtailment, as they all indirectly influence each other. It is also difficult to benchmark the heuristics individually, as the optimal steering for a flexible appliance can only be found if the future prices are predictable, which they are not within the traffic light mechanism. For the heuristics of the flexible devices combined, this is even more difficult, as we have found that optimizing all flexible devices and own generation simultaneously within the traffic light mechanism requires very large amount of time, due to the high amount of variables within the MILP and the unpredictability of the future prices. There are cases in which the heuristics do not make optimal decisions, but after looking at many different instances, it seems that they make reasonable choices, especially when the price is not fluctuating too much. As the heuristics make a new decision every minute, they are also quite well suited to take into account updated information and by that they are able to deal with wrong price predictions.

The most important conclusion of this research is that the proposed traffic light mechanism is not very robust and rather sensitive to the amount of loads and generation that are available in the local grid. With a too high amount of loads and generation, extreme price fluctuations are observed, which do not lead to the desired behavior. It is of course difficult in general to design a proper management system that is able to handle a situation with way too much demand and supply, but a more centralized system would probably do a lot better in this case. In such a system, (some) electric vehicles can for example be forbidden to demand or inject energy for a while. However, it is difficult to do such a management in a fair way, but it would be interesting to see if a centralized part can be added to the traffic light mechanism for cases of extreme price fluctuations.

The question is whether a situation ever occurs where so many loads and generation are available on such a fragile network. Normally, a DSO would enforce the grid before it would allow very high amounts of generation and loads. However, even in a scenario where these amounts are more suitable for the grid, the traffic light mechanism (in combination with the heuristics for the flexible devices) does not always result in a better performance than if the heuristics are used without traffic lights.

One first aspect resulting from the simulations that tested the traffic light mechanism, is that the energy bill normally is higher in cases where the traffic light mechanism is used. This is because within the traffic light mechanism, the prices are going up in times of high demand and down in times of high supply. If we assume that this extra money is payed to a third party organizing this pricing scheme and that it is given back to the prosumers, still the energy bill is higher when the traffic light is used. This is mainly because without traffic light mechanism, the prosumers focus only on the national price level, while within the traffic light mechanism they also respond on the local situation.

Whether the amount of curtailed injection is lower for the scenario with traffic light mechanism, is very dependent on the amount of generation and flexible devices available in the local grid. When there is enough flexibility in the form of thermal appliances and batteries available in the local network, the traffic light mechanism improves the use of this flexibility as the amount of injection curtailment is lower. However, for a low amount of flexibility and a high amount of generation, the traffic light mechanism uses this flexibility already in times of risk of curtailment, so that no flexibility is left over for when injection is really curtailed.

The traffic light mechanism is reducing the amount of curtailed demand in almost every tested scenario. This might be because most curtailed demand is curtailed in the evening time, when the electric vehicle is connected to the grid. In most simulations two electric vehicles were available, which provide a lot of flexibility. As discussed before, the traffic light mechanism seems to have a better performance when there is enough flexibility available.

If the network gets stronger, the traffic light mechanism can more easily handle a big amount of loads and generation, and it seems that if the network is enforced with a certain factor, it can handle an increase in loads and generation of the same factor. Compared to a non-enforced network, an enforced network with higher loads and generation has a higher amount of curtailed injection, due to no variability in the generation, but a lower amount of curtailed demand, due to a high variability of loads.

A major advantage of using the traffic light mechanism, is that it stimulates behavior that is both beneficial for the national situation and on the local grid level. Most of the time those situations are pretty similar, however when for example the national grid prefers extra demand (with low prices) but on the local level it is better to inject more or lower demand (with high prices), the traffic light mechanism performs significantly better in terms of reducing both demand and injection curtailment.

Lastly, it turned out that the self-consumption approach that tries to prevent curtailment has a better performance than the flexibility approach that tries to maximize the flexibility in case of curtailment. Furthermore, the prolonged traffic light that was introduced to reduce the amount of extreme price fluctuations is beneficial to the performance of the traffic light mechanism as well.

7.2 Discussion

In this subsection, we describe the made assumptions and simplifications, and discuss the results and conclusions of the heuristics and the traffic light mechanism.

The proposed traffic light mechanism and designed heuristic are obviously not designed for a normal local distribution network today. In order for it to work, we need that good and very frequent measurements can be made over the grid. Furthermore, a communication network should exist that makes sure that all management actions are carried out immediately. Also, the flexible appliances should be smart appliances that can measure temperature or state of charge, and they should be able to be remotely controlled. Next to that, it is assumed that the distribution system operator is allowed and able to curtail a given amount of demand or supply of the prosumers.

In order to ease computation, many simplifications are made for both the flexible devices and the grid calculations. For thermal appliances, it is assumed that heating and cooling is a linear process, independent of the outside temperature. For batteries and electric vehicles, it is also assumed that charging and discharging is a linear process, and that their efficiency is always 90%. Furthermore, it is assumed that in the case of curtailment, batteries and electric vehicles can charge or discharge at a fraction of their maximum charge/discharge level. Also, the amount of energy used by the electric cars is assumed to be linear with the amount of time they left the household. For shiftable appliances, the possible start times are just made up and not based on any research. For the load flow analysis, it is assumed that the transformer is independent of the medium voltage grid, so that its incoming voltage is constant. Furthermore, line losses and reactive power are not taken into account in the calculations.

For the thermal devices, the heuristics sometimes decide that the temperature should stay at the highest or the lowest level. In order to do this, the thermal appliance has to be switched on and off alternately. It is doubtful whether this behavior is good for these appliances and desirable for their owners. Especially for a refrigerator, for which the heuristic saves 0.3 eurocents per day, it is questionable whether it is worth to risk damaging the appliance. For the batteries and electric vehicles, similar remarks can be made. In cases of big price fluctuations, they can both start to charge and discharge alternately. For batteries, it is unknown what the exact influence is of not making proper charge/discharge cycles, but it surely does not have a positive effect on the battery life time.

Within the traffic light mechanism, the price increases in time of high demand and decreases in time of high supply. Without a battery or an electric vehicle, this usually results in a higher energy bill. On the other hand, prosumers with a battery or vehicle can make extra profit due to these higher price fluctuations. Furthermore, as only prosumers with the highest amount of absolute net power are curtailed, prosumers with a higher amount of flexibility are having even more benefit. The question is whether this is a fair system, as residential energy users that cannot afford purchasing extra flexibility are now disadvantaged. To be able to answer this, we should know how to define the price of flexibility. For example, we found that within the traffic light mechanism, a battery with 9kWh of storage could make around 56 eurocents per day. With a price of $100/kWh (a very optimistic guess for electric vehicles hinted by Elon Musk to be possible by 2020), a battery can be earned back in under 4 years, assuming that it keeps its capacity. However, if batteries are also able to decrease the amount of curtailment for the whole neighborhood, and thereby help reducing the amount of grid enforcements or emergency generation/storage by the distribution system operator, the battery's return of investment can even be lower, if rewarded accordingly. The question of how to value flexibility is an extremely important and difficult one, and the reader is referred to [21] and [22] for excellent reads and suggestions to answer this question.

7.3 Recommendations

Based on the conclusions and the discussion in the previous subsections, in this subsection we give some recommendations for possible extensions and improvements of the heuristics and the traffic light mechanism and ideas for future research are proposed.

For this research, a radial 1-phase distribution network was modeled. This is done as the load flow analysis is then very easy and programmable in Matlab. If proper software is used to make these calculations, and the heuristics and traffic light mechanism can be implemented in that software, the traffic light mechanism can be tested also for meshed networks. Furthermore, an attempt can be made to solve phase imbalances with the traffic light mechanism as well.

Using the above mentioned kind of software also reduces the amount of simplifications made about the grid. Other simplifications can also be discarded if more realistic models are used for shiftable appliances regarding usage time, for thermal appliances regarding temperature change, for batteries regarding charging/discharging and for electric vehicles regarding their usage.

Regarding the results, more simulations can be done to have even better insight in how the heuristics and the traffic light mechanism perform, based on different scenarios. For example, for this research only one instance of generation is modeled, which is a rather sunny summer day. Furthermore, the self-consumption approach is tested against the flexibility approach for only one instance, but more varying approaches can be designed and tested using a larger number of instances.

We have found that the traffic light mechanism in combination with the heuristics is quite sensitive to the amount of flexible devices and own generation. First of all, a centralized management system can be designed and added to the traffic light mechanism in order to prevent extreme price fluctuations in case of too much generation and flexible devices. Furthermore, we saw that the traffic light mechanism did not always result in a lower amount of injection curtailment, because the flexible devices used up their flexibility too soon. The heuristics can be slightly adjusted so that if the total amount of flexibility is low, they only use their flexibility in case of (a serious risk of) curtailment. Furthermore, better predictions for the energy price can be made, especially since in the current heuristics the future price is not yet based on potential traffic lights.

Lastly, a cost-benefit analysis can be made that quantifies both the worth of flexibility and the damage to flexible devices. This way, it can really be analyzed whether the traffic light mechanism in combination with the heuristics is a feasible solution for both the prosumers and the distribution system operator.

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Appendix

Load profiles

In this part of the appendix the load profiles of the five shiftable appliances are shown, taken from [23].

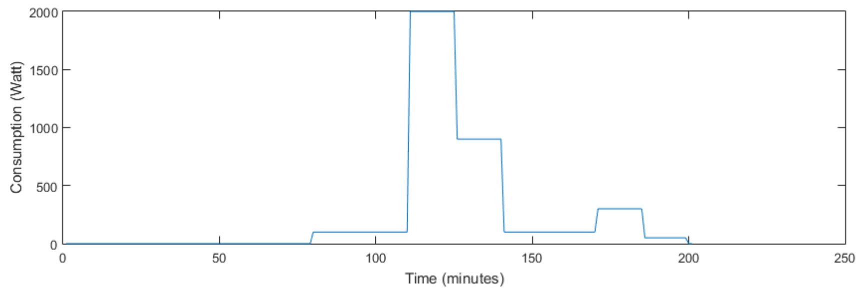

Figure 39: Load profile for washing machine 1.

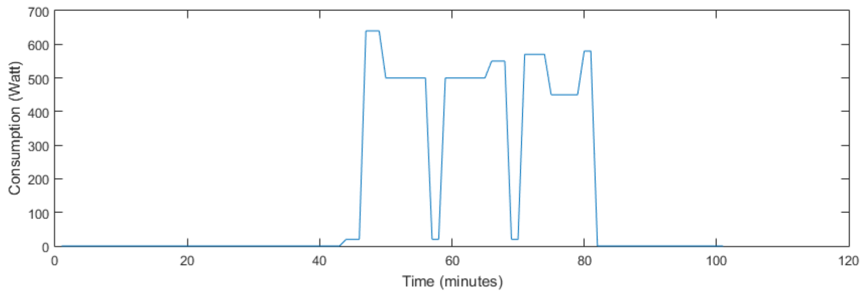

Figure 40: Load profile for washing machine 2.

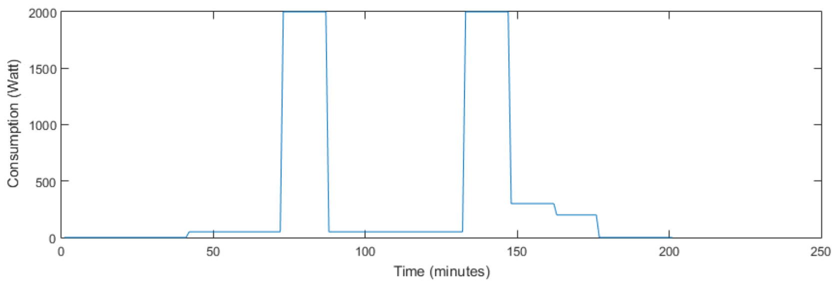

Figure 41: Load profile for dish washer 1.

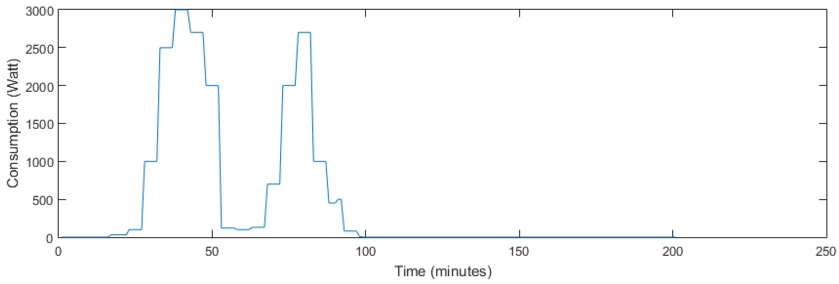

Figure 42: Load profile for dish washer 2.

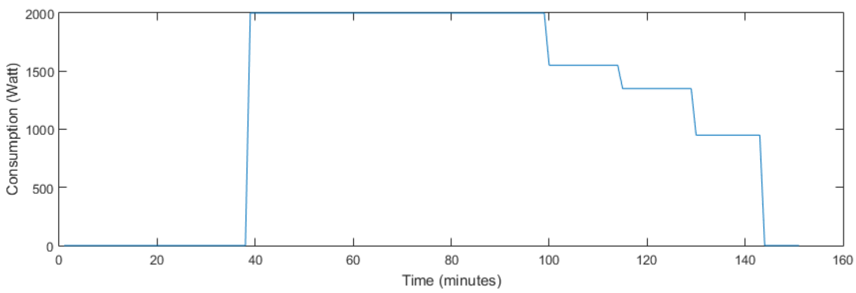

Figure 43: Load profile for the clothes dryer.