Title: Operation of flexible demand in an integrated energy system. Quantification of the load profile evolution driven by the demand shifting operation of the technologies linking the power sector to other sectors within the energy system of the Netherlands.

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1 Introduction

It is well known that anthropogenic emissions are a key driver behind the evidenced climate changes that planet earth is ongoing. Therefore, as a response to the threat of such change and to limit the potential negative impact that it could have on humanity, the Paris Agreement was adopted in 2015 by most countries of the world. This resulted in a global convention to deeply transform the technological framework that sustains human economic activities and to deliver adequate financial flows to promote it. The EU, as a frontrunner in the green revolution has already spent a significant amount of money and effort on the adoption of policy frameworks to activate the transition, being the *Climate strategies and targets*[1] package the guide rule for the policy alignment. Hence, a steep increase in the adoption of renewable energies can be appreciated in Europe’s last decade trend.

However, the vast majority of newly adopted renewable technologies is arriving in the form of renewable electricity (namely wind and solar generation), which results in two main issues. First, the intermittency of wind and solar electricity supply represent a complex dispatch problem that requires a new operative scheme to avoid excessive investments. Second, electricity represents less than 20% of the energy consumption mix in Europe, and not even in the most electrified scenarios is this share expected to exceed 50% of the mix by 2050, which means that a massive share of the energy system is still required to decarbonize if targets are going to be met. Those issues have made of integrated energy system analyses a topic which has attracted attention from diverse flanks in recent years. And, within this field, it has become of particular importance to understand the patterns of electricity demand from different sectors of the energy system due to the potential flexible response of emerging technologies.

Within the academic sphere research has been conducted to quantify the costs of the energy transition and the potential of responsive demand to alleviate them. The link between demand response and power system modelling (PSM) has been presented by Göranson et al. [1], where the possibility to reduce load congestion in Europe and the related costs via the means of demand response (DR) has been evaluated. Later, Zerrahn and Schill [2], proposed a conceptual upgrade to the previous

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[1] The European Commission has established an emission reduction target of 40% by 2030 as compared with 1990 GHG emission levels. Also by 2030 the cumulative efforts of member states should reach to a share of 32% of renewable energies in the European mix, and at least 32.5% of energy efficiency improvements. For 2050 the targets are less clear-cut. First, the emission target was defined to reach at least 80% reductions. However, as it is not considered sufficient to avoid the 1.5° in temperature increase which Paris agreement calls for, it was therefore framed as a minimum of 80 to 95% emission reductions by 2050.

methodology to resolve the problem of undue DR recovery in a formulation that can be adapted in linear PSM. Gils [3] described a similar formulation which considers time shifting constraints in a case study performed for the German power system, concluding that DR has a strong potential to reduce capacity requirements. A condensed approach gathering all previous concepts is provided by Morales et al. [NR] where a, very practical, generic conceptual formulation for PSM models is provided. Another interesting perspective was provided by Brouwer et al. [4], where DR impact in PSM was evaluated in a case study by simultaneously applying DR with other flexibility alternatives as flexible generation, electricity storage, cross-border electricity trading, and curtailment.

Outside the PSM studies, DR has also been explored to understand the impacts of their flexible nature within integrated energy systems modelling (IESM). Kwon and Østergaard [5] assesed, using the Energy Plan model, the value of simultaneous flexible demand in the residential, services, and industrial sectors, using the gradients in the residual load profiles as a simplification to trigger demand response. Using JRC-EU-TIMES, Herib et al. [6],[7], explored cost optimal configurations and operation of the European energy sector while considering DR together with a wide variety of flexibility options such as storage, hydrogen, power-to-methane, power-to-liquids, and power-to-heat. Furthermore, Brown et al. [8] applied a state-of-the-art approach for sector coupling via the means of the PyPSA model. With it, they provided a European wide representation of the impact that flexibility from power-to-gas, vehicles to grid, and long-term energy storage have on the grid reinforcement requirements under a highly decarbonized energy system with a large deployment of intermittent renewable energy sources. Similarly, DR was explored, together with flexible generation; cross-border interconnection; power-to-X (methane, ammonia and heat); and flexible EV charging, in a report consisting of three detailed phases by Sijm et al. [9]. The later was achieved via the soft-linking of COMPETES (a European PSM) and OPERA (a Netherlands' IESM), focusing on the highlight of potential paths towards a cost-efficient integration of renewables in the Netherlands via the means of flexibility.

However, within such a set of integrative studies there are still some crucial gaps to be filled in order to provide a wider analysis on demand side flexibility capabilities. For this study, two crucial ones are highlighted. First, none of the studies provided an extensive repertoire of technological assets with flexible demand. Commonly, integrated energy system models consider the most crucial forms of flexibility in a grouped way (e.g. residential demand response, smart charging, responsive built environment, power-to-X), failing to provide a complete multi-sectoral approach to the topic. Secondly, highly detailed operational constraints are usually found in papers focusing on the implementation of specific technologies, but are often ignored in integrated energy system models, which results in overestimations of their real potential. Furthermore, it is crucial to adequately fill these gaps by accounting for the feedbacks within a highly integrated energy system environment that describe the electricity market with an adequate temporal resolution and while accounting for the paramount impact of cross-border electricity trading.

Thus, the aim of this study is to quantify the potential of flexible electricity demanding technologies to respond to an intermittent energy system; helping to abate the expected cost increase of the Netherlands' energy transition. The latter via the means of an optimization model which considers a highly integrated energy system with a deep penetration of renewable energies, and by focusing in providing it with an extensive range of technological options and their specific operational constraints.

2 Overview of energy system flexibility options from the demand side

Energy system flexibility requires (1) understanding the different forms of flexibility, (2) the technologies able to provide it, and (3) the drivers behind flexible operation. This section describes the way in which the three previous concepts are included in this project, and shares some examples of diverse perspectives to analyze demand side flexibility in literature and how this paper complements them.

2.1 Flexibility characterization of demand side alternatives

The not-so-new challenge of adapting to the intermittency of renewable energy sources has resulted in a wide variety of solutions able to provide such flexibility [10]. Solutions raised in many different technological forms and shapes, from the straightforward ones like flexible clean generation [11]; strengthening the local, regional, and cross-border transmission lines [8], [12]; or energy storage in all sort of "batteries" types [13], [14], to more elaborated solutions as integration of different sectors [8], [15]; coordinated decentralized demand side management [16], [17]; the use of the electric vehicles batteries and their charging infrastructure [18], [19]; and several others [20].

The focus of this study[2] restricts to all the inland technologies that can be included in diverse demand side management programs (DSM), that are able to temporarily deviate from their baseline energy consumption in response to an economic or reliability trigger, commonly known as Demand Response (DR) [21]. This means that this study focuses in the short time operation of such flexible assets, and does not includes DSM that rely mostly in long term effects such as energy efficiency measures. However, the scope of this study falls in a wider category of DR as it also considers technologies that may have not a predefined energy consumption program. The considered group include the following flexible assets: (1) different forms of demand response technologies within the residential, services, and industrial sectors; (2) energy conversion technologies in different sectors (such as power to heat, hydrogen, ammonia, or others) and their respective storage buffers; (3) batteries and electricity storage options; and (4) electric vehicles, both via smart charging and vehicle-to-grid mechanisms. Here we will address to such group as Assets with Flexible Demand (AFD).

In this regard, the technologies that fit within the AFD scope can operate their flexibility capabilities in a way that impact the demand profile in the short term in three different manners. As illustrated in figure 1, when they increase their demand they are valley filling technologies. When they decrease their demand they behave as peak shaving (or load shedding) technologies. And when they are able to operate in both directions, they behave as load shifters [20], [22].

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[2] Other flexibility options such as flexible generation, trade and curtailment are also present in the integrated energy system descriptions of the models used in this study as they can influence the potential contributions of DSM.

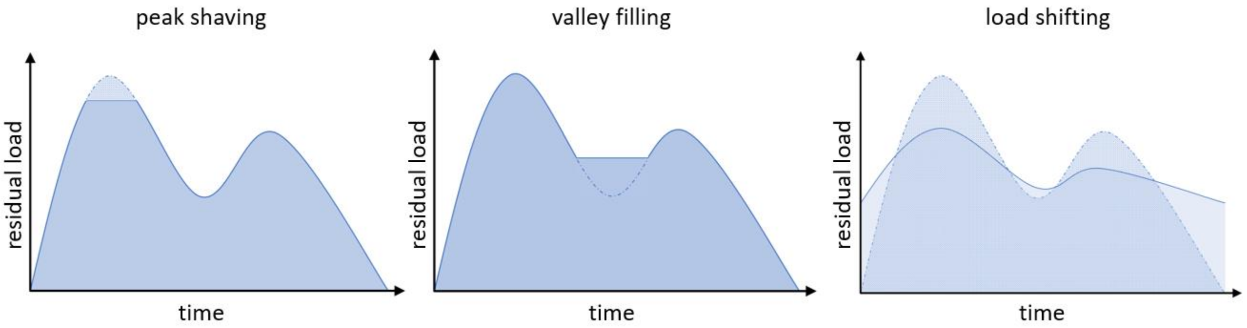

Figure 1. Visual representation of the three different impacts on the profile of flexible demand assets.

Next to the direction of the load changes within the demand profile of AFD technologies, it is important to categorize the drivers of such changes. In this regard, AFD operation can be either driven by system operators' incentives (or penalties), or/and by price variations [23]–[26]. The DSM driven by incentives often correspond to dispatchable demand that can easily contribute to alleviate system disruptions within the options of ancillary services, and therefore usually respond to intra-hourly dynamics of the local grids or the balancing markets. On the other hand, AFD driven by price variations strongly rely on the level of exposure to such variations. Therefore, as the most uttered variations occur in the wholesale market[3], whether the technologies take part in the retail or wholesale electricity markets ends up being crucial for their impact and application.

It is because of the latter differentiation that in this paper two categories of AFD are distinguished. We will call independent market participants, IMPs, to the technologies with large amounts of energy consumption (or with a large share of consumption behind a physical connection to the grid) which directly take part in the wholesale market. And we will call aggregated market participants, AMPs, to those technologies with small loads which do not hold direct participation in the wholesale market and whose energy requirements are facilitated by an aggregated representative (either via retailers or aggregators) in the market.

The main reason for the segregation in these two groups is to highlight the essence of the economic drivers behind the flexible operation of the technologies. In the first group, the IMPs, the operators of the technologies have control of their positions in the electricity market, and their bids are placed to maximize their economic benefits [27], analogically as how the generators place their offers (but subject to the operational constraints due to the production or logistic specifics of the particular industry [28], [29]). Therefore, the economic driver for these technologies is the gradient between the market price and the maximum bidding price that they are willing to pay for electricity in a given time, so their operation is determined within the market accordingly with the setting of the supply and demand curves[4].

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[3] The retailers often include some schemes such as time of usage, critical-peak pricing, or real time pricing to increase the exposure of the end users to the price variations[25].

[4] The demand curve consists of the meritoriously aligned bids of the participants buying electricity. In order to maximize social welfare, the market is settled at the intersection between the supply curve (merit order) and demand curve [172]–[174].

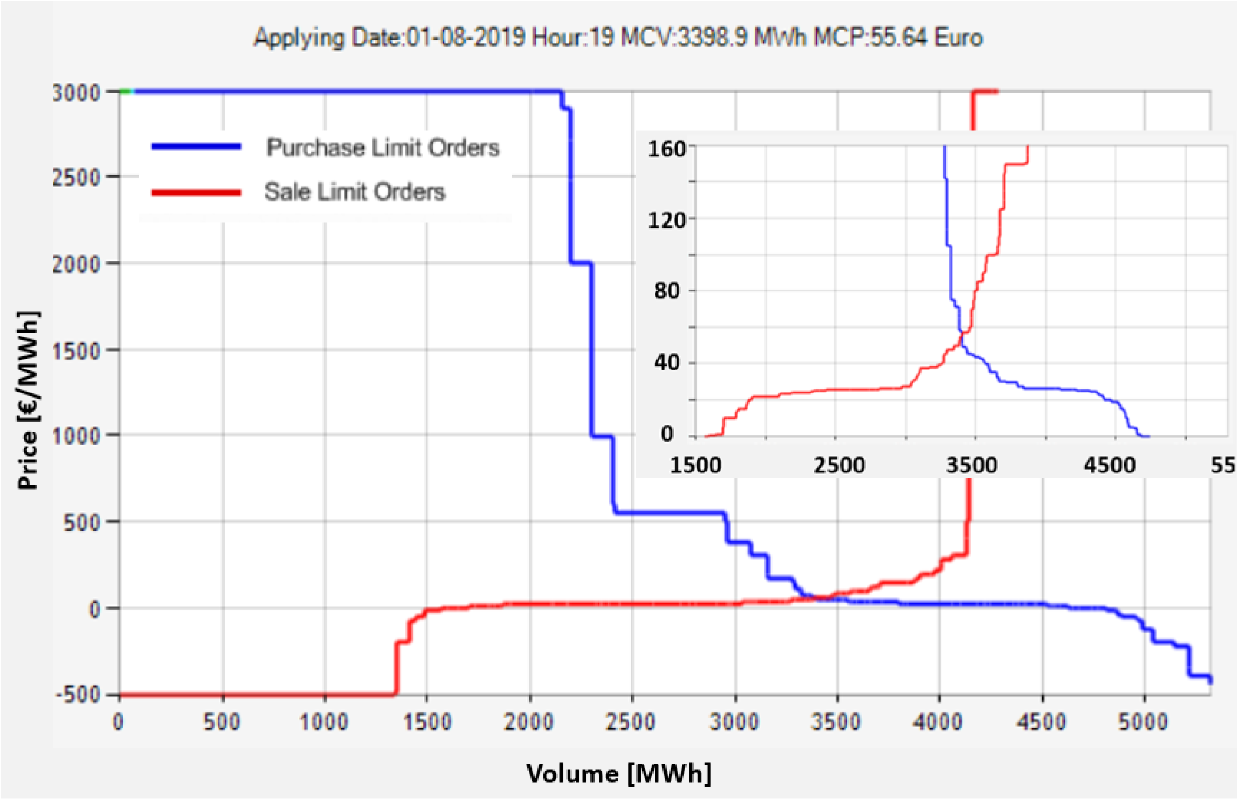

Figure 2. Aggregated curves of the APX spot Day-Ahead market in the Netherlands for the timeslot of August 1st, 2019 at 19:00 hrs. [30].

On the other hand, the AMPs economics are, in principle, also triggered by market price variations. However, these variations reach very diluted to the end user given their retail contract structure and their tiny share of consumption behind the physical connection nodes with market representation[5]. This result in a lack of motives to adopt and apply distributed DR in an effective way [31], [32]. In Europe this topic has received some attention in recent years, and several proposals have emerged to decrease regulatory, financial, and technical barriers for the adoption of aggregated management clusters of decentralized flexibility resources that would expose end users to a more perceptible feedback with the real time price signals coming from the market [33]–[39].

Another difference with IMPs is that AMPs positions allocate flexible demand in the day-ahead market (DAM) and intra-day market (IDM) accordingly with predicted price variations in order to obtain a maximum benefit from such flexibility in a certain time frame. Resulting in a market bidding that cannot take the risk of not meeting the agreed requirements stipulated in the contracts with aggregated end-users. This risk constraint will make those biddings to fall within the "baseload" region of the demand curve in the electricity market. Being this the main difference between how independent market participants and aggregated market participants provide flexibility to the system. IMPs take advantage

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[5] The connection node between the distribution and transmission networks works as a bottleneck for everything that happens beyond the transformer. Therefore, the impact of distributed flexibility resources inherently depends on the other participants of the grid, resulting in an incomplete feedback between a desired action and the reward.

of the “large” and “centralized” flexible loads to increase the elasticity of the demand curve. While AMPs coordinate smaller flexible resources to bring them together to the market at convenient times to take advantage of common planning, but without increasing so drastically the elasticity of the DAM and IDM demand curves.

Next to the above explained economic drivers, both IMPs and AMPs can engage in bilateral contracts with system operators to receive incentives (or incur penalties) to provide ancillary services [40]. Ancillary services can be provided in many directions such as voltage control, restarting the system, frequency control or stability control [41]. However, in most of the cases the sourcing of these services via bilateral contracts highly rely on location and application specifics and are subject to the particularities of each grid at very short time levels. Therefore, from the elevated energy system perspective it makes more sense to focus on the potential of the market price variations to drive the operation of DR, both centralized and distributed. However, when analysis is provided from such perspective it is important to bear in mind that the extra monetary incentives from providing ancillary services can further contribute to the adoption and implementation of such technologies.

More papers about DSM, Aggregators, and relevant regulations: [42]–[51]

2.2 Flexibility applications within the electricity demanding sectors

The following collection of publications was raised from literature to identify possible flexibility solutions from the electricity demanding sectors. And, according to the previous concepts of impact in the load profile of AFD and level of aggregation for market participation, they were tagged as (1) shifters, shaver, or fillers; and (2) as suitable for aggregated or independent market participation (or both). The criteria for the latter categorization is based on the potential of a specific application to share a large share of the consumption behind a physical connection to the grid that can be represented in the market. This mapping of DSM technologies and applications as well as the sectors in which they can be applied, and some publications in which they can be found is presented in the below table.

Table 1 – DSM solutions in different sectors.

Technology or application	*Sector*	*Impact*	*Market*	*Publications*
Washing machines, dryers and dishwashers	Residential	Shifter	AMP	[20], [52]–[55]
Built environment and hot water	Residential, services	Shifter, shaver	AMP	[20], [56]–[61]
Refrigerators/Freezers	Residential, services	Shifter	AMP	[20], [62], [63]
Air conditioning	Residential, services	Shifter, shaver	AMP	[20], [62], [64], [65]
Ventilation systems	Residential, services, industry	Shifter, shaver	AMP	[20], [64]
Distribution level batteries/storage	Residential, services, industry	Shaver, filler	AMP	[20], [59], [66]–[68]
Municipal water services	Services	Shifter	AMP, IMP	[20], [69]–[71]
Utility plant at micro-grid level	Services, industry	Shifter, shaver	AMP	[72]

Technology or application	Sector	Impact	Market	Publications
Power sourced heat for processes	Industry	Shaver	IMP, AMP	[20], [73]–[78]
Chlor-alkali electrolysis	Industry	Shaver	IMP	[20], [79]–[82]
Air liquefaction/compression	Industry	Shaver	IMP, AMP	[20], [80], [83]–[85]
Wood/paper pulp refining	Industry	Shaver	IMP, AMP	[20], [40], [79], [86]–[88]
Aluminum electrolysis/smelters	Industry	Shaver	IMP	[20], [40], [72], [79], [89]–[91]
Cement milling	Industry	Shaver	IMP	[20], [40], [72], [79], [90], [92]
Steel melting/casting in electric arc furnaces	Industry	Shaver	IMP	[20], [40], [79], [84], [93]–[96]
Cooling and freezing in food and other processes	Industry	Shaver, shifter	IMP, AMP	[20], [40], [62], [72], [97]
Flexibility in textile processes	Industry	Shifter	IMP, AMP	[40]
Other processes	Industry	Shaver, shifter	IMP, AMP	[40], [97]
Flexible processing in refineries	Energy	Shifting	IMP	[40], [98]
Transmission level batteries/storage	Energy	Shaver, filler	IMP	[20], [99]–[104]
Power sourced hydrogen	Energy	Filler	IMP	[20], [105], [106], [115]–[119], [107]–[114]
Power sourced ammonia/fertilizers	Energy	Filler	IMP	[20], [120]–[128]
Power sourced methane	Energy	Filler	IMP	[20], [6], [111], [136]–[145], [117], [146]–[149], [129]–[135][20]
Power sourced fuels	Energy	Filler	IMP	[20], [7], [150]–[153]
Smart charging	Transport	Shifter	AMP	[18], [20], [162], [154]–[161]
Vehicle-to-grid	Transport	Shaver, filler	AMP	[19], [20], [156], [158], [163], [164]
EV charging clusters	Transport	Shifter	IMP, AMP	[20], [165]–[169]

Comment to supervisors: Next to, the impact on the load profiles and the level of aggregation in the market participation, the previous section highlighted the difference between incentivized and price driven DSM. This differentiation was not included in the above table as in principle all the DSM can be financially driven by a mixture of both schemes.

3 Methods

To understand the effects that flexible demand-loads of the different sectors can inflict to the stability of the system, we require an integrated energy system model with an adequate level of temporal resolution. For this purpose, IESA-Opt will be used to identify the optimal presence and operation of technologies within an available portfolio of AFD in the Netherlands towards the transition for the target year 2050. This model determines the cost-optimal energy system configuration of energy consuming and supplying technologies within the integrated industrial, services, residential and transport sectors of the Netherlands.

Simultaneously, it is desirable to understand how feasible it is to reach such operation by incorporating the difference between AMPs and IMPs. For this purpose, a simulation model of the integrated energy system of the Netherlands, IESA-Sim, will be used to explore this issue. This will be done by feeding into IESA-SIM the system configuration of the different sectors resulting from IESA-Opt, and operating such system considering that AMPs use predictive price signals to define their positions in the market, while IMPs participate directly in the market using their operational marginal costs as the maximum bidding prices.

For this effect, we provide in the first section of this chapter a general description of the formulation consisting of the economical drivers and technical constraints for the implementation of the flexible technologies. The second section of the chapter specify how to implement such formulations in IESA-Opt, the cost optimizing model of the integrated energy system of the Netherlands. And the last section of the chapter will describe how to include such formulation while considering the distinction between IMPs and AMPs in IESA-SIM.

3.1 Formulation to represent AFD in integrated energy system models

The main criteria for flexibility to occur in the system is the economic viability of the shifting. Being the latter denoted by a positive economic outcome resulting from the rescheduling of the operation of an existing flexible asset from one hour to another. For this to occur, the fuel price at the original hour, P_j, has to be higher than the fuel price of the operation at the target hour, P_i. How much higher does this price to be is defined, as shown by equation 1, by the net efficiency of the rescheduling, η, and the variable costs of shifting the operation[6], v, which results in the net fuel price after conversion, P'_i.

$$1) \qquad \frac{P_i}{\eta} + \nu = P'_i \leq P_j$$

This economic viability will produce a shift in the load, ΔQ_i, the size of such shift will depend whether an optimization or a simulation approach is adopted, and it will be detailed ahead. However, it is also

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[6] This variable cost can be positive as well as negative (e.g. the incentives collected by providing ancillary services in the balancing market could be included within this parameter).

crucial to consider the process technicalities to determine the final form of the reallocation. As mentioned before, the technical description of the shifting process is the one determining the final form of the reallocation. This description is mainly provided by three elements: (1) the energy balance, (2) the speed at which the reallocation can occur, and (3) the capacity that can be shifted in a certain period of time.

1) The energy balance states that the energy demand should remain constant within the reallocation process, implying that the total net shifted load should add to zero for the considered period. This means that the total gross shifted load plus the total losses should add to zero as described in equation 2. This is important as for some technologies energy losses occur within the rescheduling process (e.g. heat pumps and batteries).

$$2) \qquad \sum_i \Delta Q_i + \sum_i L_i = 0$$

2) The load shifts, ΔQ_i, are subject to the physical installed capacities of the equipment's to determine how abrupt can the redistribution of the loads be. It is important to note that these limits can be asymmetrical to each other and not necessarily constant.

$$3) \qquad \Delta QLim_i{}^{min} \leq \Delta Q_i \leq \Delta QLim_i{}^{max}$$

3) Similarly, the cumulative volume of the shifted load can be constrained in a certain period of time, either because storage constraints or because the limited energy consumption associated to the technology. These constrains follow the typical form described by:

$$4) \qquad SLim_i^{min} \leq \sum_{i=i-n}^{i+m} \Delta Q_i \leq SLim_i^{max}$$

The final shape of the implementation used for each technology is based on the previous set of equations, but its interpretation differs accordingly to the technical characteristics of each technology. Below is presented the interpretation of these equations according to represent the following technologies: (i) Load shifting appliances, (ii) decentralized built environment appliances, (iii) smart charging of electric vehicles, (iv) batteries and electricity storage appliances, (v) vehicle-to-grid installations, (vi) industrial peak shavers, (vii) energy conversion technologies

(i) Load shifting appliances

This set of technologies applies demand response constrained mainly for their installed capacities, and are considered to be able to swift their energy consumption to another hour within a certain timeframe. For them it is also considered that the shifting process is fully efficient and does not involve energy losses. Some examples of these technologies are: smart fridges, smart freezers, smart washing machines, municipal water treatment plants, some sorts of aggregated industrial demand, among other similar technologies.

The previous formulation is applied by modifying (in)equation 3 by defining the shifting boundaries as follows. The maximum boundary corresponds to the total available operational capacities of the appliances defined as the difference between their installed capacities, IC_{LS}, and the reference load of these technologies, R_{LS}. And a minimum load shifting boundary corresponding to stop using the appliance, which is represented by the load of the reference profile, $-R_{LS}$.

$$5) \qquad -{R_{LS}}_i \leq \Delta Q_i \leq IC_{LS} - {R_{LS}}_i$$

However, the total volume of load that can be shifted in the time interval *i ϵ [1 T_f]*, where T_f represent the possible shifting timespan, cannot exceed the total cumulative consumption in that timespan. Therefore, the following constraint derived from equation 4 applies.

$$6) \qquad \sum_{i=1}^{T_f} \Delta Q_i \leq \sum_{i=1}^{T_f} {R_{LS}}_i \qquad \forall\, i \mid \Delta Q_i > 0$$

As well as the mirror constraint for downwards shifting:

$$6) \qquad \sum_{i=1}^{T_f} \Delta Q_i \leq \sum_{i=1}^{T_f} -{R_{LS}}_i \qquad \forall\, i \mid \Delta Q_i < 0$$

(ii) Decentralized built environment appliances

Built environment per se is not an energy transformation, as it represents the required setting to provide a comfortable environment for humans to unwind within residential or service indoor spaces. This service is provided by means of ventilation, humidifiers, cooling, and heat (the predominant share in Northern Europe). Therefore, the energy consumption profile for the built environment depends mainly on the following three elements: 1) The temperature profile in the surroundings; 2) The thermal insulation of the space; and 3) The appliance used to provide the heating requirements (where the actual energy transformation takes place).

This means that the implementation of the formulation for the built environment technologies is constrained in a similar fashion as for the load shifting appliances, as the load shifting faces the same upper and lower boundaries descriptions provided by (in)equations 5 and 6. However, these appliances cannot shift the demand without suffering efficiency losses. Therefore, the losses of the energy balance on the equation 2 are not zero and correspond to the efficiency losses considered within the economic viability of the shifting of these technologies accordingly with the following equation.

$$7) \qquad L_i = (1 - \eta)\Delta Q_i$$

This approach has the downside that the losses are not directly determined by the cumulative amount of load that is redistributed through time. Which has to be considered when assigning a value to the parameter, η, so the true losses are represented for both the economic viability and the energy balance.

(iii) Smart charging of Electric Vehicles

Again, the shifting within the charging profile of electric vehicles follows the similar application of constraints than for the load shifting appliances described by (in)equations 5 and 6. However, there is a key difference, the band width of the capacity able to provide flexibility is not constant, as the number of electric vehicles connected to the grid differs within each hour. Therefore, the shifting boundaries changes in time accordingly to the reference profile and to the available capacity, AC_{EVi}. This result in the following approach, which is very similar to the constraint used for the load shifting appliances and built environment.

$$8) \qquad -R_{EV\,i} \leq \Delta Q_i \leq AC_{EV\,i} - R_{EV\,i}$$

(iv) Batteries and electricity storage appliances

The batteries have a very different implementation of the 3rd and 4th elements of the formulation. This is because they are technologies that have a maximum storage capacity, S^{max}, rather than an associated demand profile. So as long as it is economically viable, they can provide energy (if they have enough stored) at most at their discharge rate constraint, D_r. And they can purchase energy (if they have available space) at most at their charging rate constraint, C_r. This result in the demand reallocation constraint:

$$9) \qquad -D_r \leq \Delta Q_i \leq C_r$$

Also we should modify the reallocated capacity (or storage capacity) constraint:

$$10) \qquad 0 \leq \sum_{i=1}^{i} \Delta Q_i + S_0 \leq S^{max}$$

And the energy balance for the batteries:

$$11) \qquad \sum_{i=1}^{n} \Delta Q_i + \sum_{i=1}^{n} L_i = S_n - S_0$$

Batteries cannot provide the reallocation service in a fully efficient way, so the net cycle efficiency is considered in the economic viability as described in equation 1, and in the total losses associated to the process as described by equation 7.

(v) *Vehicles-to-grid installations*

This form of providing flexibility to the grid is different to the smart charging of electric vehicles, as they have different participation[7], and different operative restrictions. The operative restrictions are driven by the number of vehicles able to provide a v-to-g service connected to the grid at a certain moment, and by the amount of energy stored in their batteries. Also, these appliances are not only batteries, so they need to ensure that their activity requirements can be satisfied. For this reason, they first need to ensure their charging requirements and then they provide flexibility to the grid based on their remaining available resources. It is based on the use of these latter remaining resources that the losses of using a car as a battery are quantified.

The ensuring of their activity requirements results in the following variations of the batteries constraints illustrated in the formulations 9 and 10.

The ramping capacity of the electric vehicles working as storage options is bounded on one side by the total available unused ramping up capacity of the connected vehicles, and on the other side by the net

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[7] Not all smart charging vehicles provide vehicle to grid response.

available discharging capacity plus the potential load reductions of the interconnected vehicles enhanced with vehicle to grid capabilities. This results in the following capacity constraint:

$$12) \qquad -DC_{EV_i} - R'_{EV_i} \leq \Delta Q_i \leq AC_{EV_i} - R'_{EV_i}$$

The storage capacity constraint ensures that the service that electric vehicles provide to the grid does not exceed the storage capacity provided by the amount of cars connected at a certain moment, and that the amount of energy stored in the vehicles is never lower than the required to satisfy their activities (considering the stock of electric vehicles that are also applying smart charging).

$$13) \qquad S^{min}{}_i \leq \sum_{i=1}^{i} \Delta Q_i + S_0 \leq S^{max}{}_i$$

(vi) Industrial peak shavers (and hybrid electric heat)

Industrial peak shaving is perhaps the most difficult form of demand flexibility to predict within an energy system modeling approach. This as both the economic drivers and the shedding tolerance, are directly linked to the activity that each industry satisfies, and therefore the fuel price sensitivity is highly dependent on the share of their energy costs in the process. However, some industrial peak shaving, as electric hybrid heat appliances, are fully located within the energy system scope, and can work as a perfect specimen to illustrate the formulation considered for peak shaving in this study. Below the formulation of the technical description of a hybrid heat pump operation is provided.

When an electric hybrid heat pump is installed in an industrial facility, it means that heat can be produced via two paths. Where the electricity path is used as a baseline, and the boiler path is used at certain crucial hours of expensive electricity. For those hours, the change in the load for the heat pump is constrained by:

$$14) \qquad -IC_F{}^{DW} \leq \Delta Q_i \leq IC_F{}^{UP}$$

Where $IC_F{}^{DW}$ refers to the installed capacity of the appliance that provides flexibility downwards, in this case the boiler. $IC_F{}^{UP}$, similarly, stands for the installed capacity of the appliance able to provide flexibility upwards, which in the case of the hybrid electric heat pump is zero. For this specific case of peak shaving the boiler can operate for as long as required, which means that no cumulative capacity constraint is restringing the fuel substitution.

However, when describing peak shaving from technologies linked to elements outside of the energy system boundaries there will be a cumulative constraint, *ST*, defining the shedding tolerance that the process allows for as described by the (in)equation 15. In this case $IC_F{}^{DW}$ stands for the capacity of the process to lower its electricity demand in a specific hour. When the latter technologies are described, both the installed capacity that can provide flexibility and the shedding tolerance will be exogenously provided to the model. Thus, a sensitivity analysis is performed to explore the impact of such parameters[8].

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[8] When producing the reports do not forget to modify this section of the paper with the results from the sensitivity analysis.

$$15) \qquad -ST \leq \sum_{i=1}^{T_f} \Delta Q_i \leq 0$$

Some processes allow for process curtailment, but some other must satisfy production requirements. For this reason, in order to compensate for the lost load from shedding in the following hours, when the electricity price lowers again the process will increase its demand accordingly with IC_F^{UP} as shown in (in)equations 14. As it can be inferred, processes with attached storage utilities (e.g. heaters with ground water or geothermal storage, or a flexible inventory of steel or aluminum production) can be represented as well with this formulation, where the shedding tolerance will be then described by the available storage. It is important for this technologies to consider the efficiency of the storing process accordingly with the energy balance of equation 7.

(vii) Energy conversion technologies

Energy conversion technologies, such as power-to-hydrogen, power-to-methane, power-to-fuels, power-to-ammonia, among others, behave as valley fillers[9]. This means that these group of technologies will exploit relatively cheap hours of electricity to convert it into other energy carriers with more stable price dynamics. Therefore, when electricity prices break the economic viability threshold, these technologies will start to operate accordingly with their operational capabilities. These capabilities, as the generic formulation describes, also consider an operational capacity constraint and a volume constraint within a time frame. For these technologies, the change in the reference load profile, which is constant at zero, is constrained by:

$$16) \qquad 0 \leq \Delta Q_i \leq {IC_F}^{UP}$$

However, these technologies cannot process an unlimited amount of product. For example, a power-based ammonia plant would provide flexible demand via the means of an electrolyzer, but it would still have to process the converted hydrogen into Ammonia. This either by a high temperature and pressure Haber process, a catalytic synthesis, or another similar path. And the rate at which this process can be performed, together with the storing capacities will inflict a production constraint over the electrolyzer operation. This cumulative capacity constraint, *CC,* can be analogically extended to the production process of other power conversion options, and it is described accordingly with formulation 4 as follows:

$$17) \qquad 0 \leq \sum_{i=1}^{T_f} \Delta Q_i \leq CC$$

3.2 Implementation on the optimization model IESA-Opt

Mention that the economic drivers within the optimization approach is to provide a feasible solution set within the available decision variables to provide the simultaneous investment and operational cost-

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[9] Mature technologies together with low fuel prices could turn them into baseload technologies. However, the principle is the same. In other words, the valley filler formulation can be used to describe peak shaver technologies from another point of view.

efficient solution. Show IESA-Opt's objective function formulation. Mention that this formulation is used to determine all the decision variables in the system, not only the ones related to flexible operation.

Describe/ mention the specific details of the implementation of the formulation provided in section 3.1 for certain flexibility for the previously mentioned archetypes.

3.3 Implementation on the simulation model IESA-SIM

Include economic dynamics for the following technologies:

AMP: Firm price signals (shifters) and relative price signals (batteries, vehicle-to-grid)

IMP: Firm bids (peak shavers, energy conversion) and relative bids (batteries).

Mention that the flexible operation is determined by the economic dynamics as described in the next section, and is set to meet the operational constraints described in section 3.1.

3.3.1 Price signals for aggregated market participants (AMP)

The main characteristic of the technologies included under this category is that they are driven by price signals, but they do not settle inside the electricity market. This means that they respond to a reference signal emitted previous to the market settling, and their positions are covered by the aggregators as "non-negotiable" baseload demand in the market. Therefore, these reference signals require price predictions which will possibly differ from the resulting market prices. Therefore, the final form of this decentralized demand side response depends on two aspects: the predictive price signals and the criteria to which the response to these signals will occur. The predictive price signal rationality approach is described below.

This economic viability will produce a shift in the load, ΔQ_i, proportional to the gap between the left and the right side of the inequation 1, and will be constrained by the technicalities of the appliances involved. The proportionality of the jump is described accordingly with the traditional definition of elasticity [170], as shown in the following formulation.

$$n) \qquad \Delta Q_i \propto \frac{P_j - P'_i}{P'_i} Q_i$$

The constant of proportionality in the previous formulation is the elasticity, which for the rescheduling process has an implicit value. This means that the value of this elasticity should be assigned in order to ensure that the technical constraints are the ones binding the redistribution of the loads. For this purpose, this elasticity only needs to be high enough to reach to an asymptotic behavior in the quantity of the shifted loads[10]. This formulation satisfies two paramount requirements of the approach. First, it considers the relative differences in the motivations to switch to different operational times within the group of competing hours. And secondly, it ensures that the technical description of the operation is the one driving the redistribution process.

Impact on electricity prices, feedback rationality, and number of iterations

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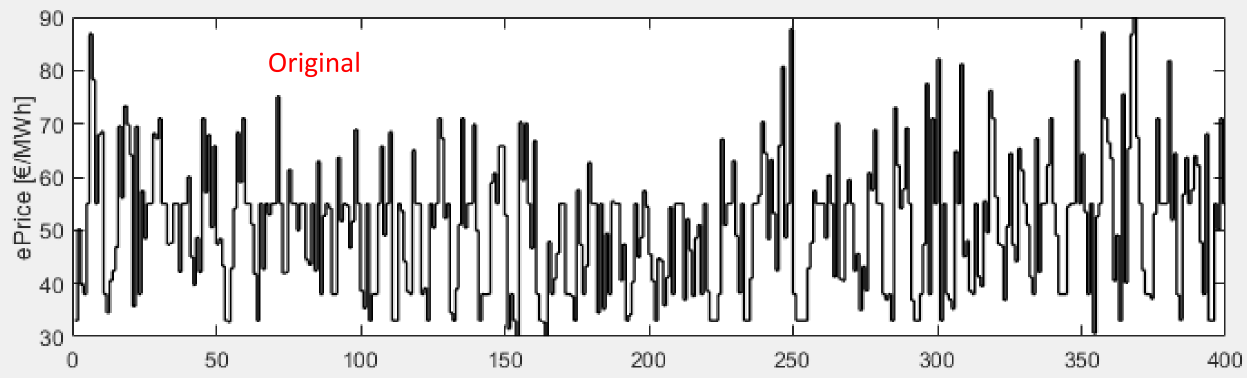
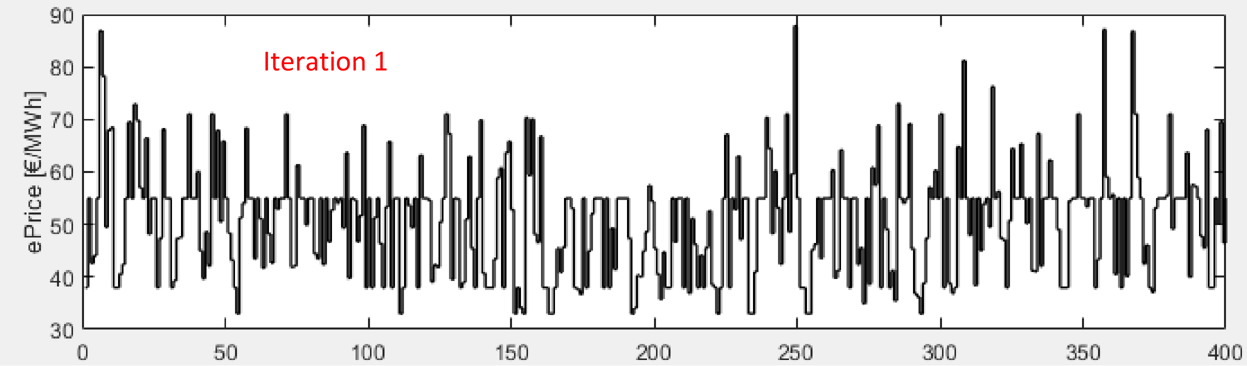
[10] For more information, consult Appendix X.

Hairder 2016: "… most DR schemes suffer from an externality problem that involves the effect of high-level customer consumption on the price rates of other customers, especially during peak period."

An important feature of the aggregated market participants is the fact that they respond to price predictions and therefore their operation does not depend on the real-time market setting. This missing feedback is important to keep in mind, as their actions do not only have the potential to decrease demand (and therefore electricity prices) in peak hours, but also to increase demand and electricity prices in the hours where demand is redistributed.

This means that the reference price prediction that will be used as the price signal triggering the shifting is not a straightforward choice, as there are many options available for the aggregators to choose. For instance, this reference price could be directly selected as the one where no decentralized flexibility occurs. If every aggregator makes the same choice, then the resulting price at the shifted hours will increase. However, aggregators are aware of that, so if they use the resulting prices as the price signals, they can avoid this price increase. This prediction dynamic, as illustrated in figure 2, could go on and on falling on a k-step thinking problem[171], whose outcome would depend on the rationality criteria of the aggregators.





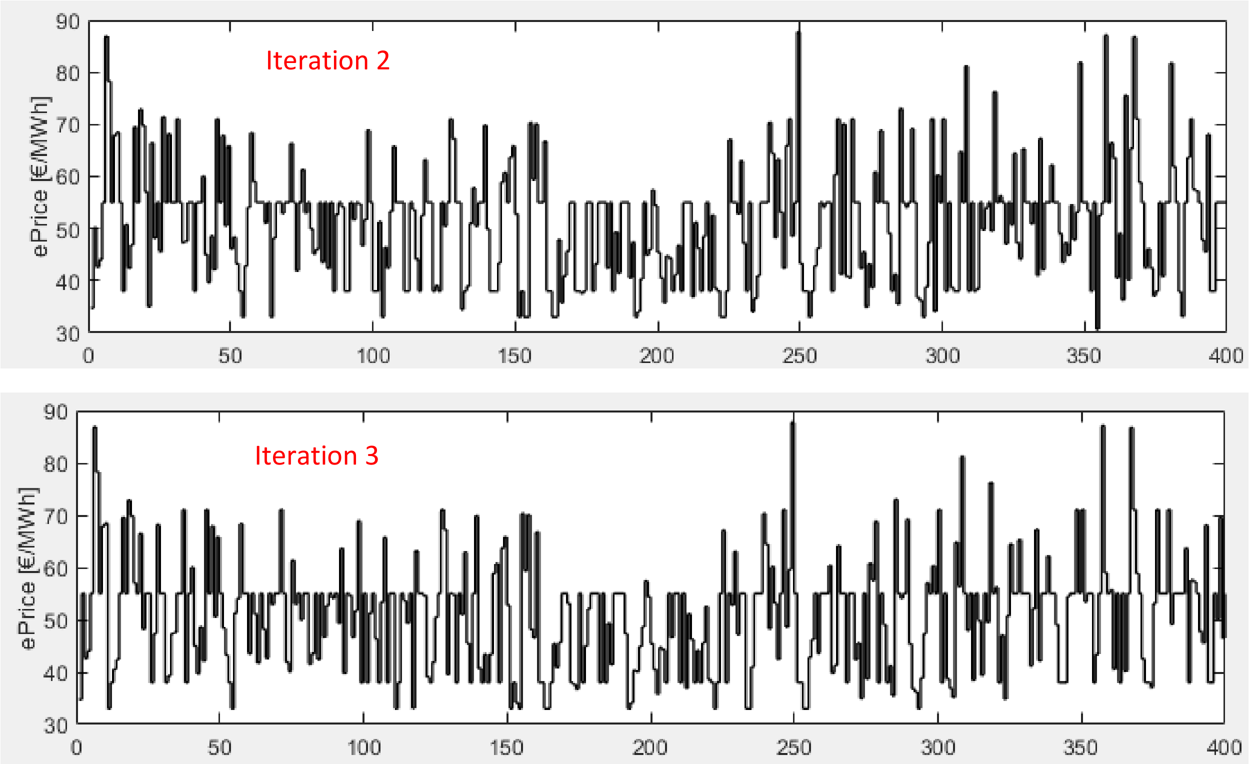


Figure 2 – Electricity price profiles after iterations. Extracted from the same example as the appendix. The progression of the resulting electricity price profiles after the load shifts from AMPs technologies is shown from the top figure to the bottom figure.

Trying to predict the psychology behind these decisions addressing the rationality behind the load shifting would be a research topic itself that would require a very complex sectoral dependent analysis, non-feasible from the integrated energy system analysis perspective. This is why to address this issue in IESA-SIM, the results will be provided from three perspectives: (1) the first shifting iteration, (2) the iteration with lower electricity costs within n iterations, and (3) the iteration with higher electricity costs within n iterations.

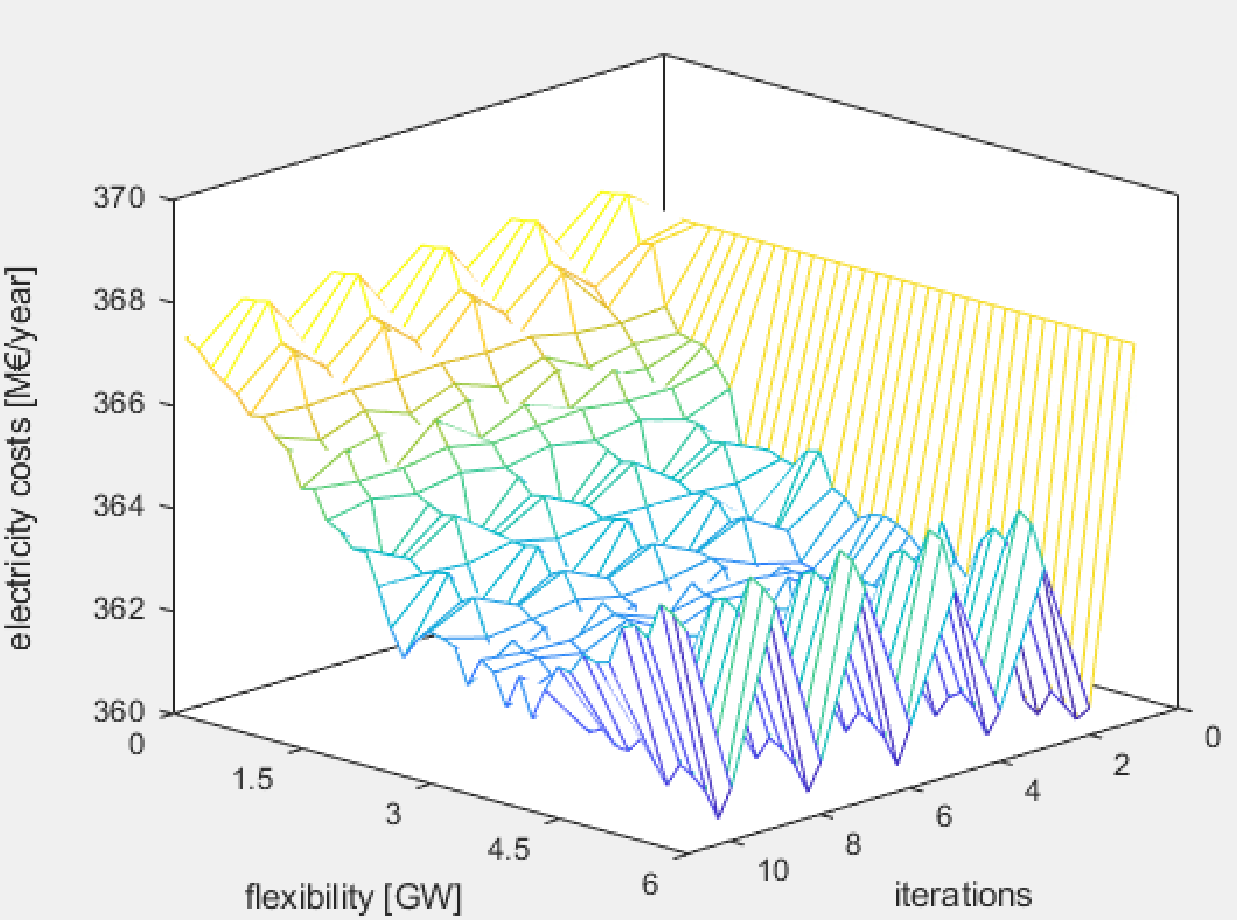


Figure 3 – Electricity costs in the analyzed year under different flexibility scenarios after 10 iterations. Extracted from the same example as the appendix. The flexibility is being progressively and proportionally increased in all the different forms on the different scenarios.

3.3.2 Participation in the market of independent market participants (IMP)

The IMP technologies directly take part of the market settling by defining their willing price to pay for electricity, which will result in their position in the demand curve. This "negotiable" demand may or may not enter into the dispatch, so their hourly operation is defined by the settling of the market, together with the price to be paid for the purchased electricity as illustrated by figure 4. In this section we describe the methodologies that are used for peak shavers, valley fillers, and battery alike technologies to define their positions (volumes and prices) in the demand and supply curves within the IESA-SIM's electricity hourly dispatch module, as well as their impact on the market setting and their relationship with AMPs technologies rationality.

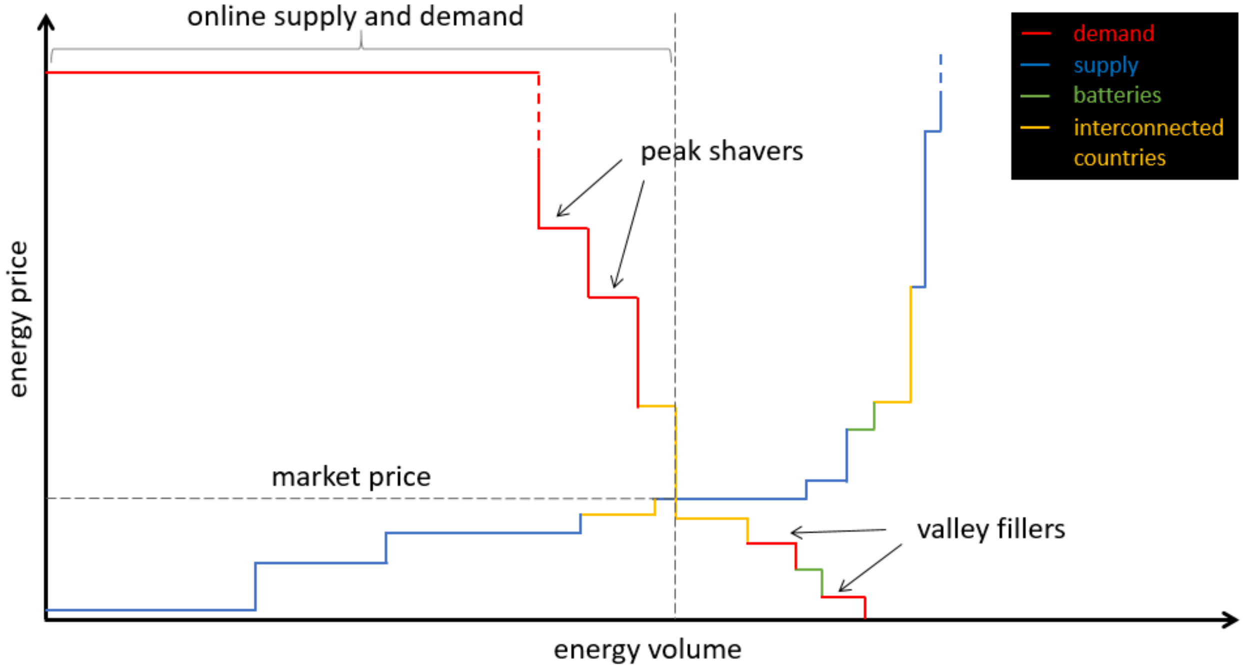


Figure 4 – Supply and demand curves in IESA-SIM's electricity dispatch. In each modelling hour IESA-SIM defines the market participants and electricity prices by finding the intersection of the supply and demand curves. The supply curves are constructed accordingly with the traditional merit order curve approach by including interconnected countries based on stochastic processing of data coming from power system models. The demand curve is built in a similar fashion where the flexible demand is added to the 'non-negotiable' baseload demand in a decreasing asking order.

3.2.2.1 Load shifting criteria for the different variants of IMP technologies

Independent market participants shift their demand under the same two underlying concepts that were previously exposed for the aggregated market participants: the operation has to be economically viable, and it is subject to a set of technical limitations. The first concept is still described by the formulation exposed in (in)equation 1, where the set of technical limitation has to be described for each particular technological case. Below we provide the methodological approach considered for: electrified industry and peak shaving technologies, conversion technologies and valley filling technologies, TSO-level storage batteries, and macro EV charging clusters.

Outline of the missing sections in the draft

4 Results (2500 words)

The results of the two experiments (RQ3 and RQ4 of the research proposal) will be reported and commented here.

4.1 Cost-optimal operation of flexible technologies in 2050 (**RQ3** of the Module 1 in the research proposal)

4.2 Simulated operation of cost-optimal configuration of flexible technologies in 2050 (**RQ4** of the Module 1 in the research proposal)

4.3 Gaps between the potential optimal performance and the simulated performance of flexible operation (**RQ5** of the Module 1 in the research proposal)

5 Discussion and conclusions (1000 words)

The discussion will be focused around the analysis of the results that lead to answering the main research question of *“What is the potential impact of demand side flexible technologies in a variable energy system driven by the presence of intermittent renewable electricity generation technologies in 2050?”*. Special analytical attention will be paid to the issue of the concepts (like the number of potential aggregators and the k-level of thinking concept) that create a divergence between simulated flexible operation from the optimal performance, and we will simultaneously comment on the modelling assumptions and missing conceptual elements that can influence the results. Based on this discussion the logical conclusions will be extracted.

Check the numbers and referencing of equations and figures.

Appendix X

I need to rephrase everything here as I made enormous changes today to the text. A useful approach focusing in response to price signals has been provided two decades ago to coarsely describe the load rescheduling mechanism in Kirschen et al. 2000 [170]. In this report, the authors propose a method in which each hour (or a timeslot in general, they use 30 min) will compete with each other hour contained within a specific timeframe based on price to capture some demand after the system perturbation. They propose an iterative loop that redistribute the demand accordingly to the typical form of elastic response described by:

$$\varepsilon_{i,j} = \frac{\Delta Q_i / Q'}{\Delta P_j / P'} \qquad eq. 1$$

Being, ε the elasticity of demand in hour i to differences in price with hour j, ΔQ the demand variations of each hour, ΔP the price difference between hours I, and j. And Q’ and P’ a reference point on the original demand curve.

However, next to the fact that it is designed to deal with perturbations after an initial dispatch, this approach was adapted for this study to further represent the technicalities rather than the macro-economics of the market. The resulting approach uses a dummy elasticity parameter to represent the relative motivation to switch to another hour given the differences in prices using a load shifting appliance. It must be noticed that the value of this elasticity does not influences the output of the approach as long as it is “sufficiently high” to trigger the response of the technologies. This is shown in figure X1. To obtain this figure a sensitivity analysis was conducted varying this elasticity within a dispatch experiment. In the graph can be perceived the asymptotical increase on the shifting volume as the elasticity becomes higher until reaching to the maximum value possible determined by the technical constraints.

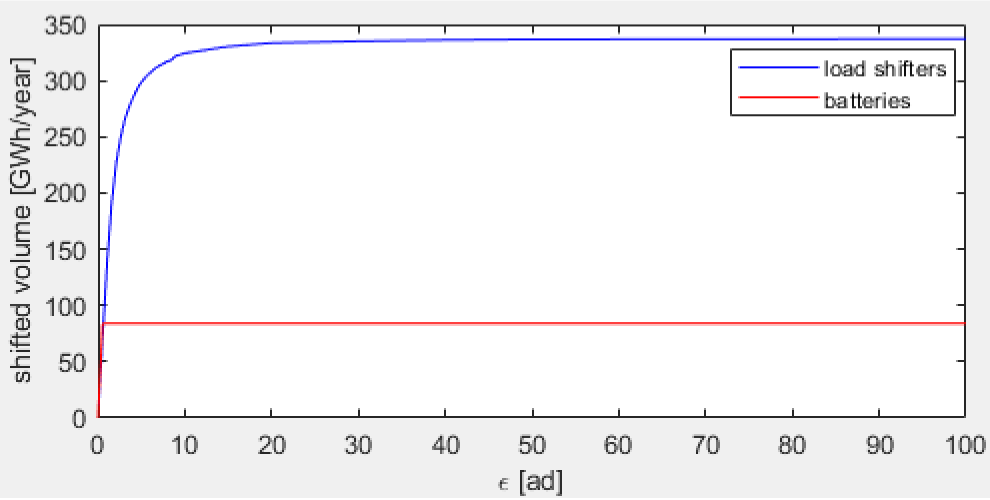


Figure X1 – Impact of the elasticity in the volume shifted within the demand profile for AMPs technologies. In blue: technologies working as load shifters. In red: technologies working as batteries.

In Figure X1 is possible to appreciate that the asymptotic behavior of load shifting technologies and batteries differ. The reason for this is that load shifting technologies response is driven not only by price variations, but also by their load profiles. Batteries on the other hand does not have a demand to reallocate, and operate driven only by the economic viability of their shifts. Therefore, batteries only require an elasticity higher than zero to operate, and the result of the operation does not depend on this value. While for load shifting technologies, the value of this dummy elasticity is important to ensure that the maximum rescheduling is triggered, and that the technical restrictions are the ones limiting the shifting volumes.

Appendix Y

A small illustrative experiment was performed to visualize the impact of the proposed approach by applying it to a testing energy system which dispatches electricity by matching supply and demand curves at each hour[11]. The experiment is placed in a year with four seasons of 10 days each, and 10 hours within each day (so kind of like a planet which rotates like Jupiter located a bit outside from Venus' orbit). The predicted electricity price profile is shown in figure Y1[12]. The original and new demand profiles are shown for each AMP technology as well as the shifted load and the effects of the technical constraints.

Electricity price profile

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[11] Should I further describe this little experiment? Should I use this experiment to illustrate this? Should I use IESA-SIM to illustrate it? Should I illustrate it?

[12] Obtained by running the experiment without any source of flexibility.

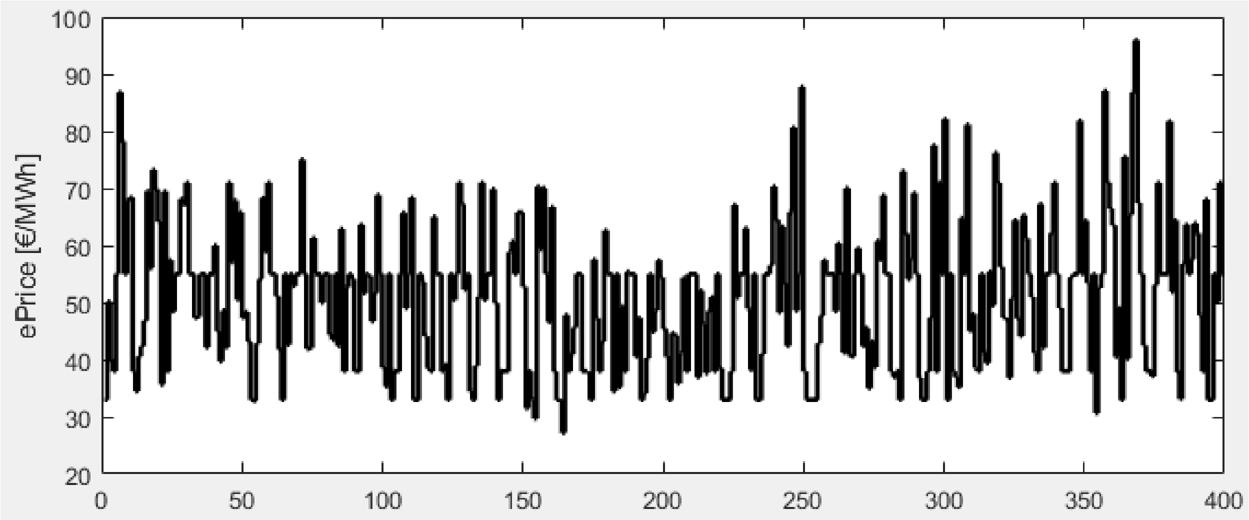


Figure Y1 – Electricity price profile working as price signals to stimulate the response from AMPs technologies.

Load shifting appliances

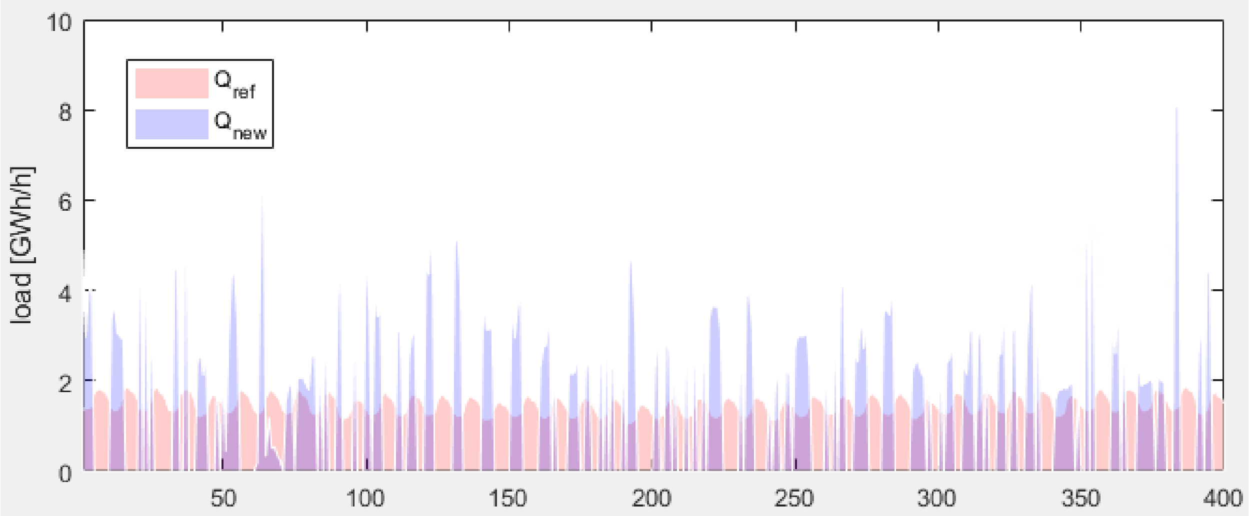


Figure Y2 – Demand profile before and after shifting.

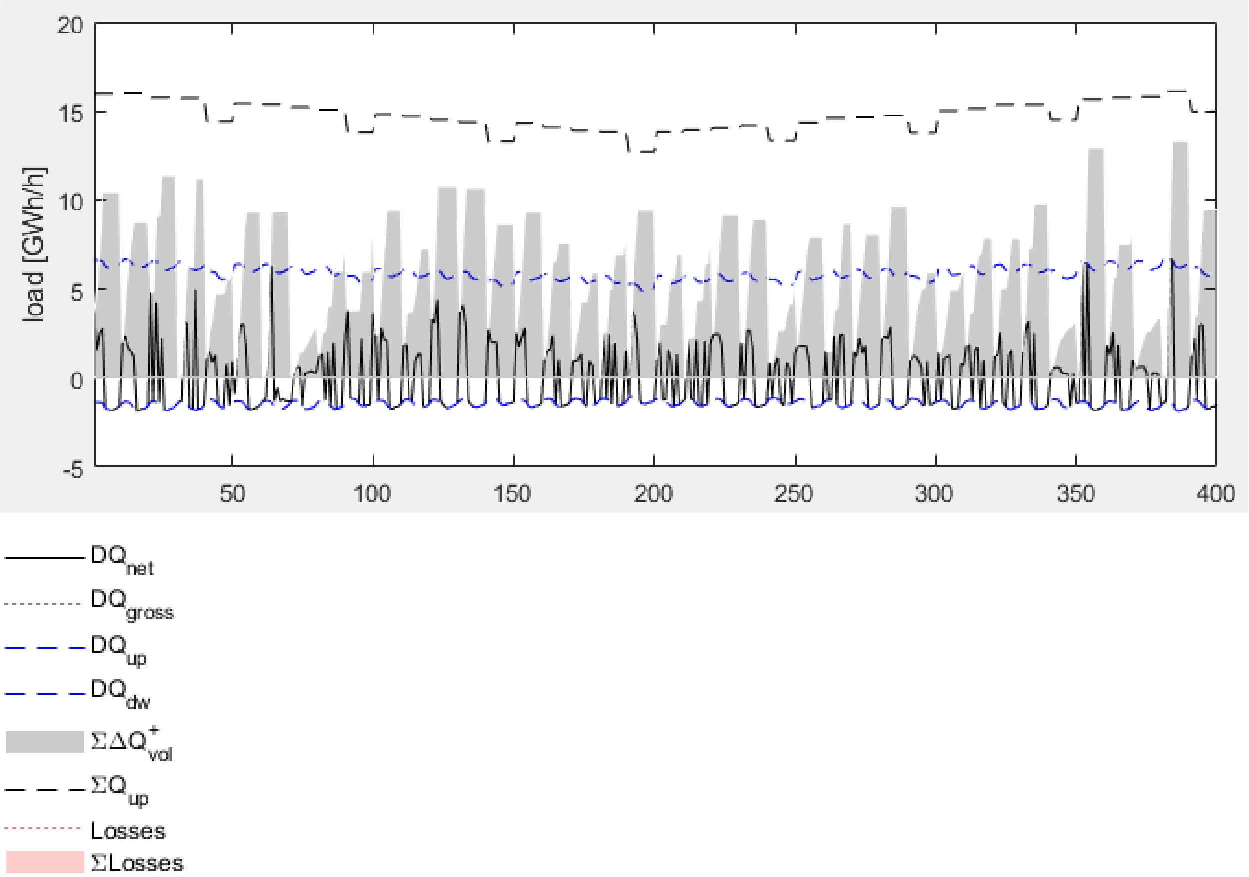


Figure Y3 – Load shifts and the interaction with the speed of demand reallocation constraint and the cumulative reallocated capacity constraint.

Decentralized built environment appliances

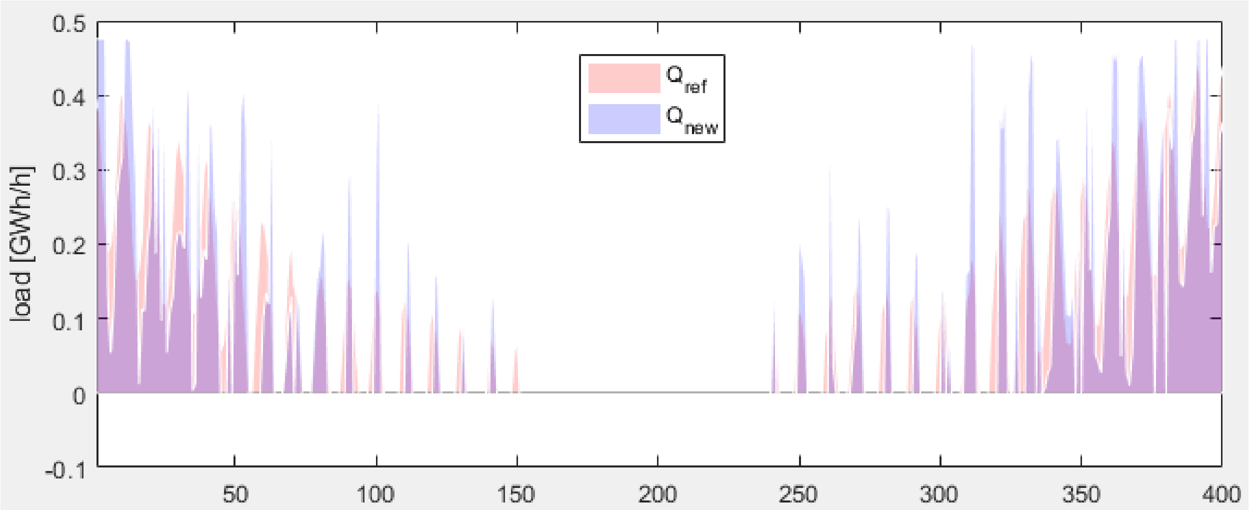


Figure Y4 – Demand profile before and after shifting.

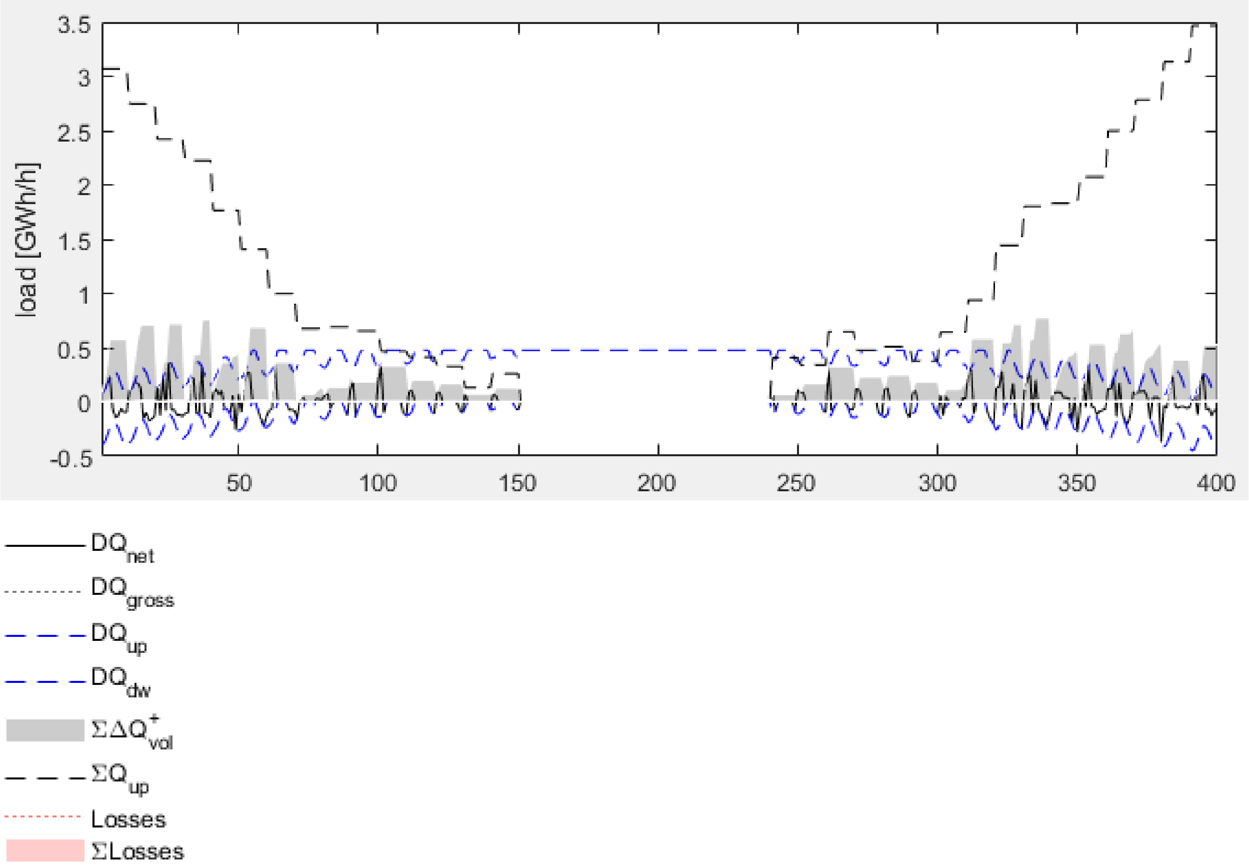


Figure Y5 – Load shifts and the interaction with the speed of demand reallocation constraint and the cumulative reallocated capacity constraint.

Smart charging of Electric Vehicles

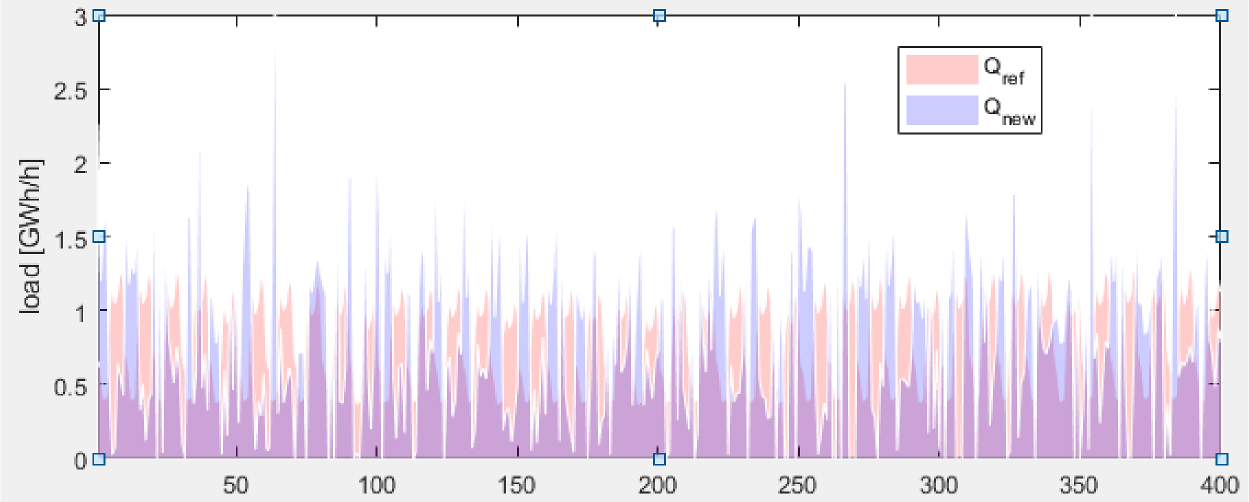


Figure Y6 – Demand profile before and after shifting.

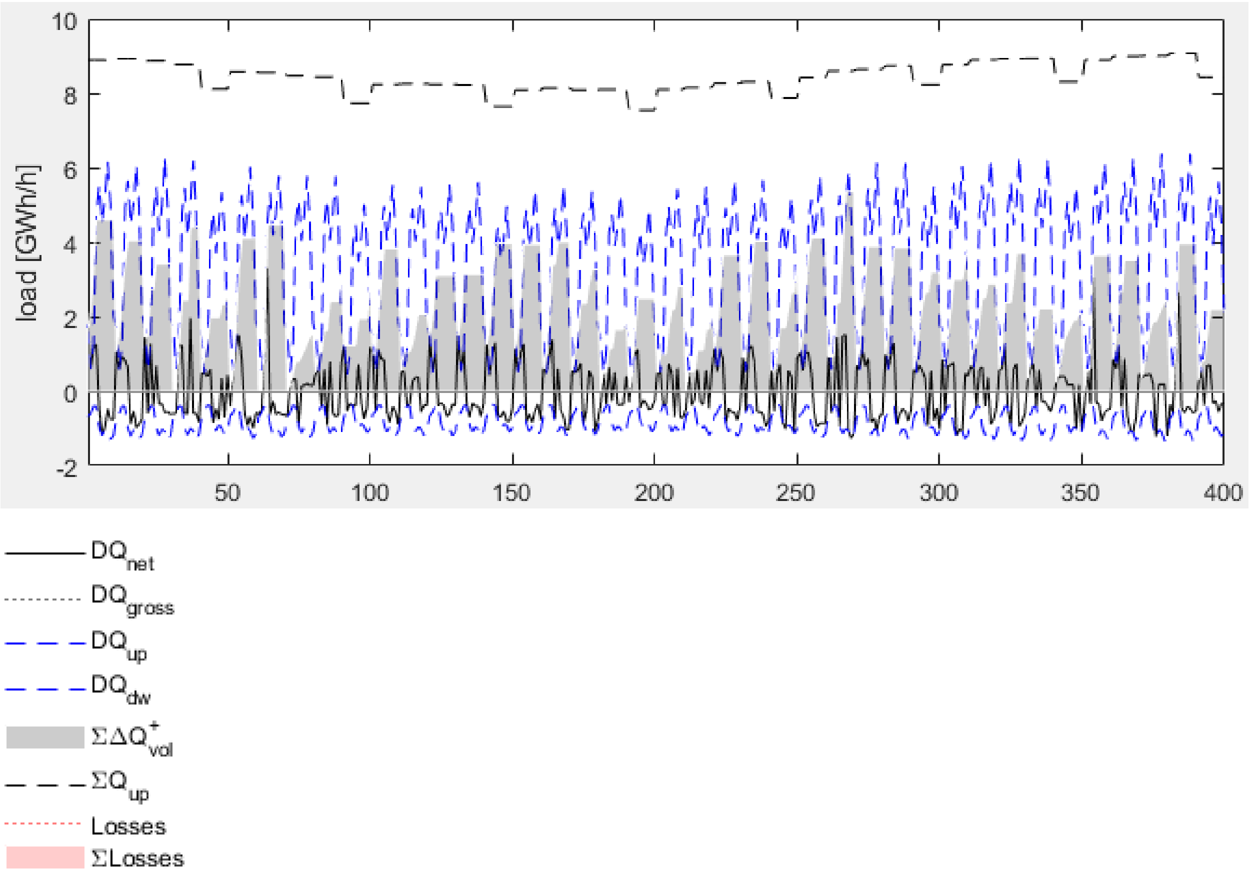
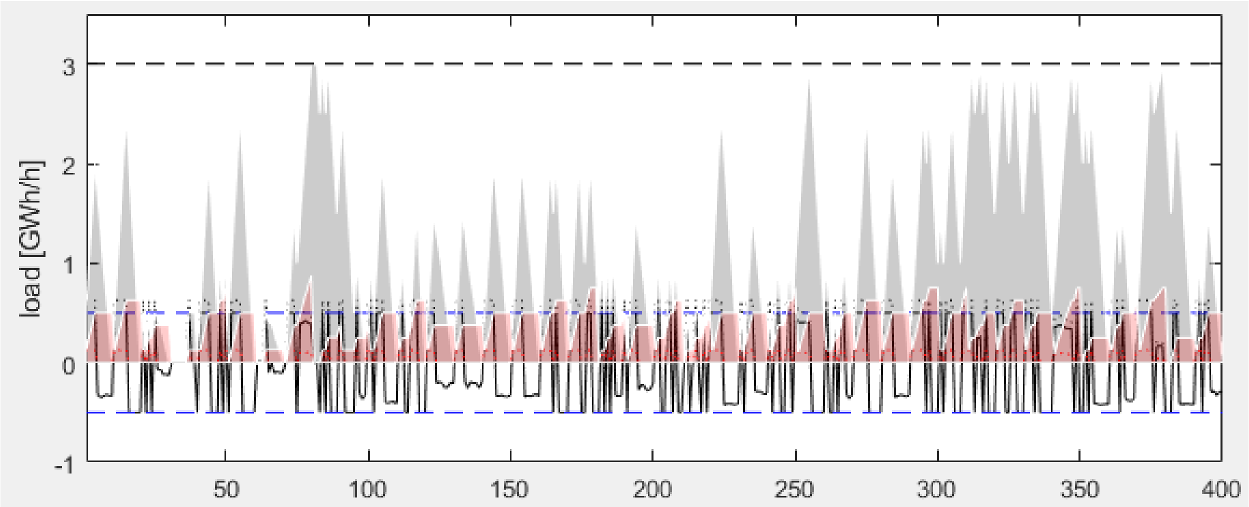


Figure Y7 – Load shifts and the interaction with the speed of demand reallocation constraint and the cumulative reallocated capacity constraint.

Decentralized batteries



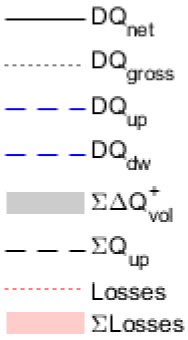


Figure Y8 – Load shifts and the interaction with the speed of demand reallocation constraint and the cumulative reallocated capacity constraint.

Vehicles to grid installations

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