D4.2 – Sectoral flexibility options in electricity market simulation models

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Authors information (alphabetical)		
Name	**Organisation**	**Email**
Christoph Schimeczek	DLR	Christoph.schimeczek@dlr.de
Evelyn Sperber	DLR	Evelyn.Sperber@dlr.de
Johannes Kochems	DLR	Johannes.kochems@dlr.de
Niina Helistö	VTT	niina.helisto@vtt.fi
Tiago Pinto	ISEP	tcp@isep.ipp.pt

Acknowledgements/Contributions		
Name	**Organisation**	**Email**
Juha Kiviluoma	VTT	juha.kiviluoma@vtt.fi

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Review and approval		
Prepared by	**Reviewed by**	**Approved by**
Christoph Schimeczek, Evelyn Sperber, Johannes Kochems, Niina Helistö, Tiago Pinto	Milos Cvetkovic	Ana Estanqueiro

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Executive Summary

Sector coupling refers to energy system integration through linking the various energy carriers with each other and with the end-use sectors. Sector coupling can contribute to decarbonisation of the energy system by allowing fossil fuel dependent sectors to switch to electricity, produced with renewable energy sources. However, larger amounts of variable renewable electricity generation will increase the flexibility needs of energy systems. While poorly designed sectoral links can even exacerbate the flexibility needs, many of the sector coupling technologies can also serve as an effective source of flexibility. This will require fair policies and market designs. This deliverable goes through the existing capabilities to model sector coupling aspects in the agent-based models and the ways to enhance those models for some capabilities. The focus is on two models: AMIRIS and MASCEM.

In order to give an overview of sectoral flexibility options, an overview of energy conversion alternatives and flexibility constraints is first presented. The energy conversion alternatives identified in TradeRES are: A1) electricity is the only possible source of energy to fulfil a local demand, such as building heat demand or electric vehicle energy demand; A2) alternative sources of energy besides electricity exist to fulfil a local demand (hybrid systems); A3) electricity is converted and delivered to networks and/or markets of other energy vectors (subcategories for local and pan-European type of markets); A4) other energy vectors are converted to electricity (subcategories for electricity-only generation, electricity produced together with another vector, and electricity coming from other networks); and A5) a round-trip of electricity through another energy vector or sector. The flexibility constraints identified are: B1) time-shifting and other temporally restricted flexibility, such as something that can be provided only for limited duration (subcategories for short-term flexibility for ancillary service markets and flexibility for balancing time scales from storage); and B2) fully controllable demand (subcategories for flexibility that is temporally unrestricted but quantity-wise limited and flexibility that is temporally unrestricted and fully controllable from offline state to nominal power). By combining the representations of these energy conversion and flexibility alternatives, it is possible to model various types of flexible sector-coupling technologies.

Before the start of TradeRES, AMIRIS already incorporated sectoral flexibility in the form of residential heat pumps, which are used to cover the heat demand of buildings. All heat pumps are coordinated by heat pump trading agents, which calculate the electricity demand of heat pumps and bid accordingly on the electricity exchange. Wholesale electricity prices are considered in order to shift the operation of heat pumps away from price peaks to phases of low electricity prices. Two different forms of thermal storage are implemented which ensure that thermal comfort in the buildings is not compromised: passive storage, where the structural thermal mass of buildings is used as storage, and active storage, where a thermal storage tank disconnects power consumption and heat demand.

MASCEM's existing sectoral flexibility representations comprise the modelling of Electric Vehicles (EV). Two methods exist for studying their participation in electricity markets: 1) the representation of EVs as general MASCEM Buyer Agents, which are allowed to participate in local electricity markets, due to individual EVs trading volume, and 2) the representation of a set of EVs as an Aggregator Agent that buys (or sells if considering Vehicle-to-Grid, V2G) the entire energy demand (or supply) of all aggregated EVs. In second method,

EVs are able to participate in multiple market opportunities at different scales, e.g. local, regional, continental.

In TradeRES, AMIRIS will be improved regarding the representation of heat pumps and EVs. In order to reinforce the price signal for heat pump operators, time-variable electricity price components will be introduced. It is envisaged to link heat pump traders to retailer agents which offer different (dynamic) end user tariffs. Thus, tariffs can be assessed that are best suited to align heat pump operation to the electricity markets. In addition, the representation of flexible EV charging will be added to AMIRIS. For this, an existing load shifting optimisation algorithm will be applied to data that represents the base load for charging a fleet of EVs and the flexibility of deviations from that base load. It is expected that this approach will not be fully suitable to model, e.g., V2G transactions. Therefore, the employed load-shifting algorithm might be modified to better reflect flexibilities related to energy demand of and energy storage within EVs.

MASCEM's capabilities to model the flexibility of EVs under distinct market settings are being enhanced. Potential business models in the context of distribution networks with high penetration of EVs are being refined and adapted to enable the integration in MASCEM during TradeRES. The business models focus on the interactions between the distribution system operator (DSO) and EVs' aggregators, the DSO and independent EVs users, and EVs' aggregators and EVs. Demand Response (DR) models shaped for EVs in an electricity market context are addressed, and the enhancement of the local market models to accommodate EVs transactions within MASCEM is being accomplished. Furthermore, a new model is being developed and integrated in MASCEM to enable the optimal coordinated bidding of multiple self-interested EV aggregators in wholesale electricity markets.

Some of the implementations may be further tuned according to the modelling needs identified in TradeRES Work Packages 3 and 5. Furthermore, in order to get a fuller picture of sector coupling and to provide background data for the agent-based models, TradeRES project will also utilize optimization models.

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1. Introduction

1.1 Goals of Task 4.1, Subtask 4.1.2, and Deliverable 4.2

Task 4.1: Representation of flexibility options in electricity market simulation models

This task combines three subtasks targeted at enhancing involved electricity market models to incorporate the requirements identified in WP3 with respect to temporal, sectoral and spatial flexibilities. The subtasks will develop corresponding modelling concepts and deal with their implementation. The enhanced models will then be able to assess impacts of these flexibilities on the electricity markets in WP5.

Subtask 4.1.2: Representation of sectoral flexibility

The aim of this subtask is to enhance and improve market models to represent interactions of the electricity sector with heat, hydrogen and transport sectors reflecting requirements from Task 3.5. To keep model complexity at bay the involved models stay limited to the electricity sector, but interactions with the other sectors are considered, according to their relevance in the reference optimal energy mixes found in WP2.

Deliverable 4.2: Sectoral flexibility options in electricity market simulation models

This report explains implementations of subtask 4.1.2., namely the integration of sectoral flexibilities in market simulation models. Delivery month: M21

1.2 Background

Sector coupling represents energy system integration through linking the various energy carriers—electricity, heat, cold, gas, solid and liquid fuels—with each other and with the end-use sectors, such as buildings, transport, or industry. Sector coupling can contribute to decarbonisation of the energy system by exploiting more renewable electricity generation and decreasing reliance on fossil fuels. Thus, sector coupling in practice leads to stronger electrification of the energy system, either directly—for example, through electric vehicles (EVs) and heat pumps—or indirectly—for example, using hydrogen.

However, larger amounts of variable renewable electricity generation will increase the flexibility needs of energy systems. With careful planning and fair policies and market designs, sector coupling technologies can serve as an effective source of flexibility. TradeRES project will improve the representation of sectoral flexibility options in system optimization models and agent-based models so that the models can be used to assess the impacts of these flexibilities on electricity markets in different market designs.

1.3 Scope

This deliverable goes through the existing capabilities to model sector coupling aspects in the agent-based models and the ways we plan to enhance those models for some capabilities. As agent-based models require the representation of decision-making logic for different actors, it is a very demanding and difficult task to include agents that consider also other energy sectors in their decision making. This limits the possibilities what can be modelled to specific examples instead of including every kind of sector coupling possible. That can be better achieved with optimization models, and therefore, TradeRES project will use those to get a fuller picture and to provide sector coupling containing background data for the agent-based models.

This deliverable is accompanied by a series of other deliverables from TradeRES Work Package 4 “Development of Open-access Market Simulation Models and Tools”. All of these deliverables are to be published within a timeframe of a few months. Please refer to these deliverables to gain deeper insights on their specific topics:

- Deliverable 4.1 [1] covers model enhancements with respect to temporal flexibility.
- Deliverable 4.3 [2] describes spatial flexibility options and their implementation in TradeRES models.
- Deliverable 4.4 [3] looks at new actor types in electricity market simulation models, starting with the given agent configurations of the ABMs.
- Deliverable 4.5 [4] covers modelling requirements for new market designs and policy options that shall be studied within TradeRES.

1.4 Structure

The rest of this report is organized as follows. Chapter 2 presents an overview of sectoral flexibility options, including energy conversion and flexibility alternatives. Then, Chapter 3 describes existing implementations of sectoral flexibility options in electricity market simulation models as well as model enhancements made in TradeRES. Finally, Chapter 4 concludes.

2. Overview of sectoral flexibility options

In the following, we first define the term of sectoral flexibility in the context of this report (Section 2.1). Then, we present energy conversion alternatives identified in TradeRES and describe how they couple different sectors, grids, or energy carriers (Section 2.2). Finally, we describe constraints related to flexibility (Section 2.3), and suggest to combine the representations of conversion alternatives and flexibility constraints when modelling sectoral flexibility options (Section 2.4).

2.1 Definitions

This report is part of the TradeRES Work Package 4 report series. We define terms relating to flexibility options as specified in Table 1.

Table 1: Terminology within TradeRES

Term	Explanation
Flexibility option	Asset or measure supporting the power system to balance electric demand and supply and compensate for their stochastic fluctuations stemming from, e.g., weather or consumer behaviour…
Temporal flexibility option	… by adjusting demand and/or supply over time or by reducing their forecast uncertainty;
Sectoral flexibility option	… by coupling the power sector to other sectors, the power grid to other grids, or electricity to other energy carriers;
Spatial flexibility option	… by connecting electricity surplus areas to electricity deficit areas;

This report focuses on sectoral flexibility options, while temporal and spatial flexibility options are described in TradeRES Deliverables 4.1 [1] and 4.3 [2], respectively. The implementation of sectoral flexibility options in the models is done in parallel with the implementation of temporal and spatial flexibility options in order to exploit the synergies.

2.2 Energy conversion and its alternatives

Table 2 compiles the energy conversion alternatives identified in TradeRES. The alternatives have been previously identified and reported in TradeRES Deliverable 3.4 [5]. The categorization stems from actual cases of sector coupling, while reflecting modelling relevant distinctions. Alternatives A1–A3 represent electricity consumption, alternative A4 represents electricity generation, and alternative A5 represents storage.

Table 2: Energy conversion categories relevant for power and energy system modelling

Cate-gory	Subcat-egory	Energy source	Energy sink	Examples
A1		Electricity as the only possible source	Local demand	EV; case dependent: local space heating, H_2 from electrolysis
A2		Electricity and alternative energy sources, providing a full or a partial supplement in a hybrid system	Local demand	PHEV, gas heated house with heat pump, hybrid gas and electricity hot water boiler, heat from a heat pump or from a district heating network
A3		Electricity	Networks of other energy vectors or, for example, fuel markets	H_2 network, district heating network, gas network, fuel markets
	A3.1		Local markets with a local market price (significant import/export costs)	electrolyzers in a local H_2 network, heat pumps in a district heating network
	A3.2		Pan-European type of markets	power-to-gas in a gas network, power-to-liquids in fuel delivery
A4		Other energy vectors than electricity	Electricity network and market	
	A4.1	Energy source exogenous to the model (price for fuels, availability/energy flow time series for non-fuels)	Electricity-only generation	CCGT
	A4.2		Electricity is produced together with another vector	DH CHP plant, micro-CHP plant
	A4.3	Electricity coming from other networks		CCGT connected to gas network
A5		Electricity network and market	Electricity network and market	EV V2G; combination of electrolyzer, fuel cell system and H_2 storage

Energy conversion alternative A1 represents an option where electricity is the only possible source of energy to fulfil a local demand, such as heat demand of a building or EV energy demand. The option is illustrated in Figure 1. The local demand can be exogenous or endogenous, but it cannot be served by other means than electricity and it is indeed local, i.e., energy is not fed or sold to another network or market.

Figure 1: Energy conversion alternative A1

Energy conversion alternative A2 represents an option where there are one or more alternative sources of energy besides electricity to fulfil a local demand (Figure 2). This type of alternative is also called a hybrid solution. A plug-in hybrid electric vehicle (PHEV) is an example of this category. The capacities of the alternative sources may be designed so that

- each of them can fulfil the demand independently;
- only some of them can fulfil the demand independently; or
- two or more sources must be utilized concurrently to cover the demand, at least during peak demand situations.

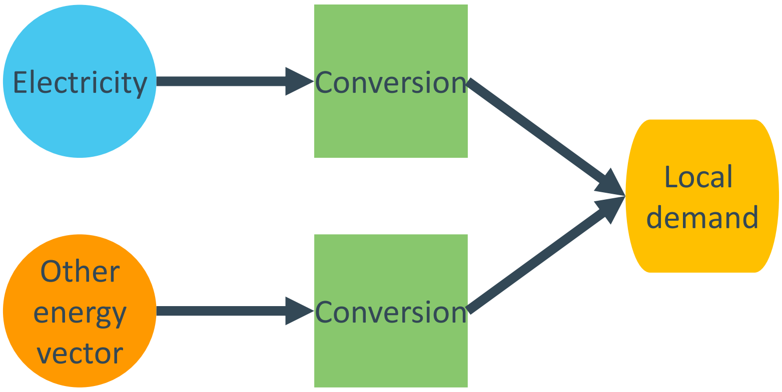

Figure 2: Energy conversion alternative A2

Energy conversion alternative A3 represents a situation where electricity is converted to another energy vector and delivered to other energy networks and/or markets (Figure 3). The target market may be a local market with a local market price, or it can be a wider, e.g. pan-European or global, market.

Figure 3: Energy conversion alternative A3

Energy conversion alternative A4 represents electricity generation with three sub-alternatives: A4.1, A4.2, and A4.3. Alternative A4.1 is electricity-only generation (Figure 4). Here, energy source is exogenous to the model. For example, a combined cycle gas turbine

(CCGT) power plant is modelled so that the price of its fuel has a predefined value, or a hydro power plant is modelled so that a predefined inflow runs into the power plant. However, this is not interesting from the sector coupling point of view and is not in the focus of this report. Alternative A4.2 is a case where electricity is produced together with another energy vector or other energy vectors, e.g. in a combined heat and power (CHP) plant (Figure 5). The outputs may be produced with a fixed, constrained, or free ratio. In alternative A4.3, electricity is generated by converting energy from another energy network (Figure 6). For example, the CCGT example from case A4.1 could also be modelled so that the power plant is connected to both the electricity network and gas network, and the price of electricity and gas are determined by the model based on supply and demand in the respective markets. Naturally, a gas-fired CHP plant could also be connected to the gas network, district heating network, and electricity network according to the principles of alternative A4.3.

Figure 4: Energy conversion alternative A4.1

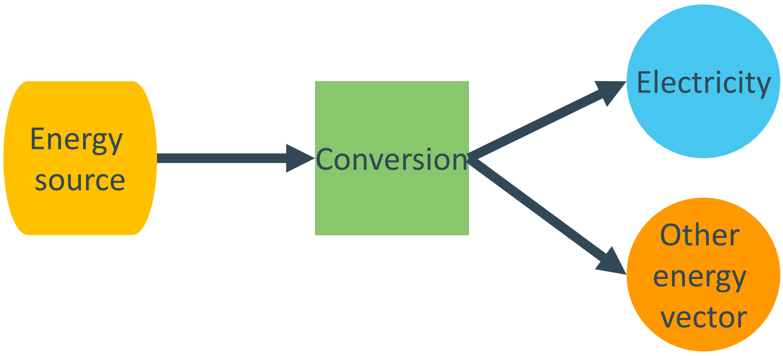

Figure 5: Energy conversion alternative A4.2

Figure 6: Energy conversion alternative A4.3

Energy conversion alternative A5 represents storage that takes place in another energy sector or vector than electricity (Figure 7). For example, it can be Vehicle-to-Grid (V2G) charging of EVs, thus creating a link to the transport sector, or it can be a combination of an electrolyzer, a fuel cell system, and hydrogen (H_2) storage connected to a H_2 network or local demand. However, technologies such as batteries and pumped-storage hydropower, which do not create a link to another sector or network, are excluded from this storage category.

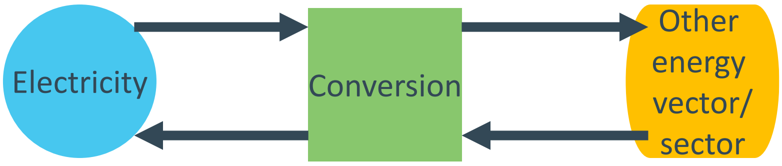

Figure 7: Energy conversion alternative A5

2.3 Constraints on flexibility

Table 3 compiles the flexibility provision alternatives identified in TradeRES. The alternatives have been previously identified and reported in TradeRES Deliverable 3.4 [5]. Similar to the energy conversion alternatives in Section 2.2, the categorization stems from actual cases, while reflecting modelling relevant distinctions. There are two main categories of alternatives: B1 for time-shifting and other temporally restricted flexibility, such as something that can be provided only for limited duration, and B2 for fully controllable demand. B1 is further divided into short-term flexibility for ancillary service markets (B1.1) and flexibility for balancing time scales from storage (B1.2). B2 is further divided into flexibility that is temporally unrestricted but quantity-wise limited, such as operation either at nominal power or switching to offline mode (B2.1), and flexibility that is temporally unrestricted and fully controllable between offline state and nominal power (B2.2). Price signals for flexibility provision should take into account the possible degradation of components due to switching and regulating the assets.

These flexibility provision alternatives are also linked to the temporal flexibility options described in TradeRES Deliverable 4.1 [1]: load shedding, electricity storage, rolling market clearing, trade shorter time units, real-time pricing, load shifting, and variable market closure lead times. However, the categorization in Table 3 takes a more abstract point of view and puts more emphasis on technical capabilities and less on market rules.

Table 3: Flexibility alternatives

Category	Subcategory	Description	Examples
B1		Time-shifting and other temporally restricted flexibility	
	B1.1	Short-term flexibility for ancillary service markets	e.g., air-to-air heat pump
	B1.2	Flexibility for balancing time scales from storage	e.g., building heat storage
B2		Fully controllable demand/supply: Energy conversion can be arbitrarily curtailed or switched off if the price is right	
	B2.1	Temporally unrestricted but quantity-wise limited flexibility	e.g., process that can be shut down
	B2.2	Temporally unrestricted and fully controllable flexibility	e.g., alternative conversion is available, also very long-term energy storage appears as fully controllable from the electricity market perspective

2.4 Combining energy conversion and flexibility alternatives

When modelling a sector-coupling technology with flexibility provision capabilities, the right energy conversion alternative should first be chosen from Table 2, and then, the right flexibility alternative should be chosen from Table 3. By combining these energy conversion and flexibility alternatives, and their representations, it is possible to model various types of flexible sector-coupling technologies. For example, heat pumps, electric boilers, and radiators can be modelled as type A1 or A2 energy conversion alternatives with flexibility constraints according to B1 or B2. Likewise, EVs with vehicle-to-grid charging can be modelled as type A5 energy conversion alternative with B1 flexibility constraints (see also Deliverable 3.4 [5]).

3. Modelling capabilities and enhancements

This chapter goes through the existing capabilities to model sector coupling aspects in the agent-based models and the ways we plan to enhance those models for some capabilities.

3.1 Existing implementations of sectoral flexibility options

This section covers the existing implementations of sectoral flexibility options in AMIRIS and MASCEM.

3.1.1. AMIRIS

Before the start of TradeRES, AMIRIS already incorporated sectoral flexibility in the form of residential heat pumps. The current status of implementation is described below; model enhancements concerning sectoral flexibility with heat pumps within TradeRES are explained in Section 3.2.1.

The application of heat pumps in AMIRIS is to cover the heat demand of buildings. They are operated monovalently and are thus a representative of energy conversion alternative A1. Different types of heat pumps are generically parameterized by their power and coefficient of performance,. All heat pumps are coordinated by heat pump trading agents, which calculate the electricity demand of heat pumps and bid accordingly on the electricity exchange.

Heat pumps in AMIRIS can provide flexibility from category B1.2. Thus, (forecasted) wholesale electricity prices are considered in order to shift the operation of heat pumps away from price peaks to phases of low electricity prices. Two different forms of thermal storage are implemented which ensure that thermal comfort in the buildings is not compromised:

- *Passive storage*: The structural thermal mass of buildings is used as storage. Thus, the internal temperature is varied within certain comfort limits in order to store or withdraw energy.
- *Active storage:* A thermal storage tank disconnects power consumption and heat demand.

Flexibility provision with *passive storage* is simulated by means of a thermal response model within AMIRIS. This internal model features a simplified physical description of building archetypes. Thereby, assumptions about building thermodynamics are transformed into a network of lumped thermal resistances and capacitances. For each building type, the model calculates the indoor temperature depending on the heat pump power as well as weather data. Models are available for twelve representative German building types in three insulation states. The development and validation of the thermal response models is described in detail in [6].

As a simple demonstration of the model capability, Figure 8 illustrates the operation of flexible heat pumps using *passive storage*. As can be seen from the upper part of the figure, heat pumps are increasingly operated when electricity prices are low[1]. Thereby, the structural thermal mass of buildings is "charged" by raising the indoor temperature (lower part of the figure). It can thus be “discharged” during periods with high electricity prices. The figure also shows the feedback effect of the use of decentralized heat pumps with a high market penetration on electricity market prices.

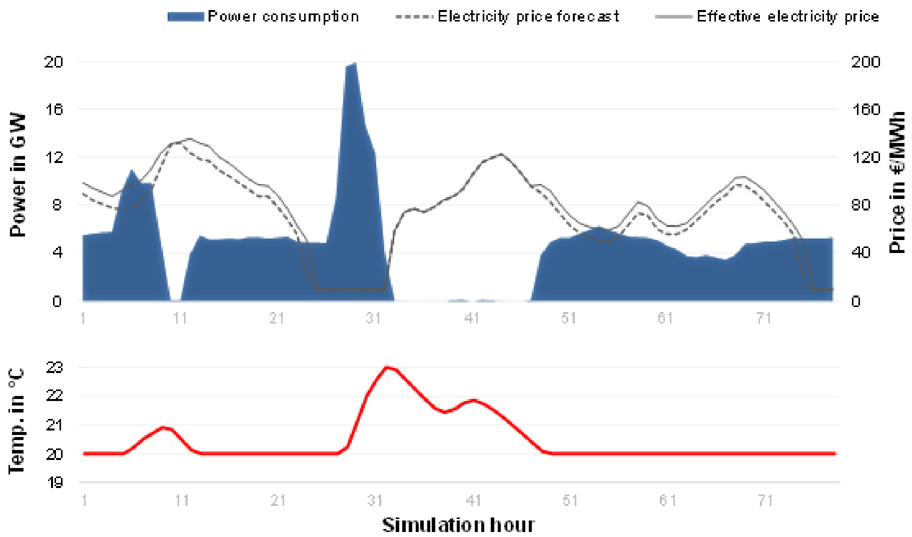

Figure 8: Flexible heat pump operation with *passive storage*

In contrast, an exogenously specified heat demand profile is used when *active storage* is applied. In favour of computing time, only one generic, aggregated storage tank is modelled. It is characterised by a thermal capacity, an energy-to-power ratio, standby losses as well as charge and discharge efficiency. Figure 9 shows an example of the operation of flexible heat pumps using *active storage*. It can be seen that heat generation is partly disconnected from heat demand by charging or discharging the aggregate thermal storage.

[1] No taxes and levies for electricity are considered in this example.

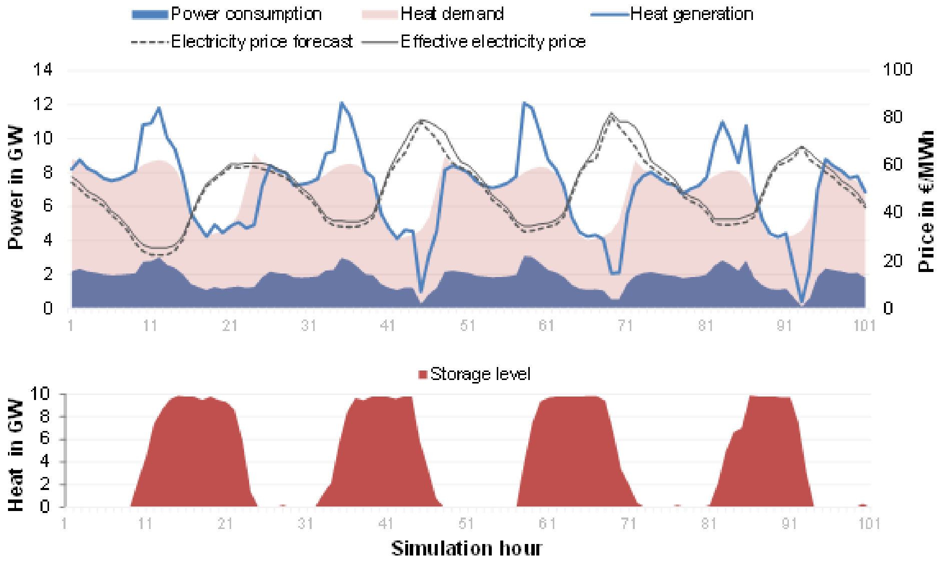

Figure 9: Flexible heat pump operation with *active storage*

3.1.2. MASCEM

MASCEM's representation of sectoral flexibility is limited and comprising solely the modelling of EVs, and their integration in electricity markets. The current version of MASCEM enables the study of EVs participation in electricity markets in two ways. The first regards the representation of EVs as general MASCEM Buyer Agents (buying the necessary volume throughout the time), which are allowed to participate in local electricity markets, due to individual EVs trading volume. In this case, the EV model can be categorized by the energy conversion alternative A1 – Electricity as the only possible source, as defined in Table 2 and by flexibility model B1.2 – Flexibility for balancing time scales from storage, as defined by Table 3. The second way is by using an Aggregator Agent to represent a set of EVs and buying (or selling if considering V2G – in this case considering energy conversion alternative A5 – Electricity network and market as well as flexibility model B1.2) the aggregated amount of all aggregated EVs. In this way, EVs are able to participate, although indirectly, through an aggregator, in multiple market opportunities at different scales, e.g. local, regional, continental.

Despite MASCEM's limited EVs modelling capabilities, several studies have already been made and initial models have been developed regarding business models for flexibility of EVs [7], integration of EVs in local energy markets [8] and novel specific market models for EV participation [9]. These models are, however, not yet integrated in MASCEM, and are being further refined and adapted to enable the integration in MASCEM during TradeRES.

3.2 Model enhancements within TradeRES

This section describes the enhancements that will be made to AMIRIS and MASCEM to improve the representation of sectoral flexibility options.

3.2.1. AMIRIS

Within the next months, AMIRIS will be improved regarding the representation of heat pumps and EVs. Therefore, the modelling of price-oriented heat pump operation will be enhanced. In the current implementation, heat pumps only consider dynamic wholesale prices plus additional static price components such as charges and levies. These static components distort the price signal at the end customer level. Thus, they can reduce the benefits of price-based sectoral flexibility for end users and for balancing supply and demand. In order to reinforce the price signal for heat pump operators, time-variable electricity price components will be introduced based on given implementations and then further improved (compare Deliverable 4.1 Section 3.2.1.5 [1]). Therefore, it is envisaged to link heat pump traders to retailer agents which offer different (dynamic) end user tariffs. Thus, tariffs can be assessed that are best suited to align heat pump operation to the electricity markets.

In addition, the representation of flexible EV charging will be added to AMIRIS. For this, the load shifting optimisation algorithm presented in Deliverable 4.1 [1] will be applied to data that represents a base load for charging a fleet of EVs and the flexibility of deviations from that base load. The corresponding data can be obtained from vehicle fleet models like, e.g., VencoPy [10]–[12]. Such models consider the driving patterns, grid connection times, charging preferences, vehicle energy consumptions and other relevant factors to model the energy demand of a vehicle fleet and associated charging flexibilities. The existing approach based on a general load shifting strategy is likely to not be able to reflect all possible flexibilities associated with EV charging. We especially expect that this approach will not be fully suitable to model, e.g., Vehicle-to-Grid transactions since this would require a detailed tracking of battery state of charges introducing new degrees of freedom on the one hand and major complexity addition on the other. Therefore, the employed load shifting algorithm might be modified to better reflect flexibilities related to energy demand of and energy storage within EVs. Such changes will be done in concert with data available from Work Package 2 and according to the modelling needs defined by Work Packages 3 and 5.

3.2.2. MASCEM

Significant work is being developed towards the enhancement of MASCEM's capabilities to model the flexibility of EVs under distinct market settings. In [7], we have explored and proposed potential business models (BMs) in the context of distribution networks with high penetration of EVs, which are being further refined and adapted to enable the integration in MASCEM during TradeRES. In the different BM the product to be traded is flexibility, while the agents and interactions among them give way to the differences in the definition. In this way, BM1 is focused on the interactions between the distribution system operator (DSO) and EVs' aggregators. Therefore, in BM1 the DSO can request flexibility to the aggregators to alleviate management issues in the distribution network. The aggregators should receive monetary compensation for the service provided. Similarly, BM2 is focused on the interactions between the DSO and independent EVs users through a marketplace. As the flexibility provided by a single EV is lower than the flexibility provided by an EVs' aggregator, efficient communication/interaction processes, needed to obtain large amounts of the product, may increase the complexity of the transactions. Finally, BM3 defines the interactions between EVs' aggregators and EVs. Due to the complex mechanisms needed to fulfil the interactions between agents in such a scenario, computational intelligence (CI) techniques are envisaged as a viable option to provide efficient solutions to the optimization problems that might arise by the adoption of the different BMs.

These BMs provide the means for EVs integration in the market. In [8], we have presented some developments already conducted in taking advantage of the EVs' battery flexibility in a local electricity market environment. Demand Response (DR) models shaped for EVs in a local market context are addressed, comprising opportunities related to V2G, Time of Use (ToU), Real Time Pricing (RTP) and Smart Charging (SC). These opportunities are analysed as means to provide alternatives to current retail market mechanisms. These initial studies are being used as basis for the development of the mature models to be integrated in MASCEM during the project.

The enhancement of the local market models to accommodate EVs transactions within MASCEM is being accomplished through the evolution of the model initially proposed in [9]. This model represents a market between prosumers and EVs. Energy communities with different types of prosumers is considered (e.g. household, commercial and industrial), and each of them may be equipped with photovoltaic panels and battery systems. This prosumer-to-vehicle (P2V) market is a local market model because it takes place within a distribution grid and a local energy community, where prosumers can sell their excess electricity to the EVs. The P2V market enables sellers profiting from selling at higher prices (compared to selling to the network) and the consumers profiting from buying at lower prices (compared to retailers' prices).

Besides EVs participation in local electricity markets, MASCEM is also working towards their integration in wholesale markets. Such integration is envisaged by means of intermediary players, namely EV aggregators. This entity is able to control the charging and discharging of its fleet, hence enhancing the potential for informed collective decisions. In contrast with individual EV operation, the much higher degree of coordination possible when an aggregator centrally manages a fleet offers excellent benefits, such as the spreading of electricity consumption for charging over time and avoiding expensive and polluting demand peaks. However, despite the ability of the aggregator in controlling its EV fleet, it cannot control the actions of other competing aggregators. Each aggregator can optimize its operation and market bids, but lack of coordination can cause global inefficiencies, such as increased prices and congestion issues, especially during high demand periods. Therefore, a new model is being developed and integrated in MASCEM to enable the optimal coordinated bidding of multiple self-interested EV aggregators in wholesale electricity markets. The proposed model finds the optimal coordination of the bidding process of a group of EV aggregators in the day-ahead electricity market through a decentralized optimization algorithm based on the alternating direction method of multipliers (ADMM). The impact of the proposed bidding coordination scheme is assessed using a power flow validation in the distribution network (already described in TradeRES D4.5 [4]), which identifies voltage and line congestion problems.

The problem can be formalized as follows: consider a group of *N* EV aggregators who participate in the market to purchase the electricity needed to charge their clients' batteries. Mathematically, each aggregator *i* will purchase an hourly energy schedule given by $E^i = \left(E_0^i, E_1^i, E_2^i, \dots , E_{23}^i \right)$ with the objective of minimizing its energy costs. Each aggregator *i* encodes its forecasted energy requirements using the vector $\hat{R}^{min,i} = \{\hat{R}_0^{min,i}, \hat{R}_1^{min,i}, \hat{R}_2^{min,i}, \dots, \hat{R}_{23}^{min,i}\}$ and $\hat{R}^{max,i} = \{\hat{R}_0^{max,i}, \hat{R}_1^{max,i}, \hat{R}_2^{max,i}, \dots, \hat{R}_{23}^{max,i}\}$ where $\hat{R}^{min,i}$represents the hourly aggregated amount of energy needed to fulfil the EVs if charging has been delayed to the last possible moment and $\hat{R}^{max,i}$ if the charging starts as soon as possible. $\hat{N}^i = \{\hat{N}_0^i, \hat{N}_1^i, \hat{N}_2^i, \dots, \hat{N}_{23}^i\}$ represents the number of vehicles that is available at each hour.

Then, the following constraints ensure that each aggregator *i* purchases an appropriate electricity schedule given its forecasted energy.

$$\sum_{j=0}^{h} E_j^i \geq \sum_{j=0}^{h} \hat{R}_j^{min,i}, \forall h = 0,1,2, \dots, 23$$

$$\sum_{j=0}^{h} E_j^i \leq \sum_{j=0}^{h} \hat{R}_j^{max,i}, \forall h = 0,1,2, \dots, 23$$

$$\frac{E_h^i}{1hour} \leq \hat{N}_h^i Pmáx, \forall h = 0,1,2, \dots, 23$$

$$E_h^i \geq 0, \forall h = 0,1,2, \dots, 23$$

These constraints ensure that the energy is not bought too late or too early, that the purchased energy does not exceed the amount that the aggregator is able to charge (based on available EVs) and that the hourly energy quantities are nonnegative. These constraints are sufficient in scenarios where there is no network congestion, and the aggregators are able to purchase energy at will. However, network validation problems may impose additional constraints to aggregators located in congested buses. These may limit the energy available for purchase at a given hour, such as $E_h^i \leq Emax$ for some $Emax$ determined by the network validation algorithm.

The decentralized coordinated bidding algorithm used to solve the problem takes the form of a *global variable consensus* ADMM algorithm [13], and is based in [14]. The idea is that every aggregator solves a local optimization problem using *local variables* and, via a consensus step, where all the aggregators share their local variables and calculate joint *global variables*, these eventually converge to a *consensus* where every aggregator agrees on everybody's energy allocations [13].

The possibility for EVs participation in the market enabled by the described models will be complemented in MASCEM by several flexibility models already described in: (i) D4.1 [1], namely regarding the temporal shifting of EVs consumption; and (ii) D4.3 [2], concerning the spatial aggregation of EVs and other resources and the activation of flexibility with focus on the expected geographical location of EVs throughout the time.

4. Conclusion

This deliverable presented an overview of sectoral flexibility options identified in TradeRES as well as their existing and improved implementations in two agent-based models: AMIRIS and MASCEM.

AMIRIS already included implementations for residential heat pumps, coordinated by heat pump trading agents. Wholesale electricity prices are considered in order to shift the operation of heat pumps away from price peaks to phases of low electricity prices. Two different forms of thermal storage are implemented: Passive storage, where the structural thermal mass of buildings is used as storage, and active storage, where a thermal storage tank disconnects power consumption and heat demand.

MASCEM's existing sectoral flexibility implementations comprise two methods for studying the participation of EVs in electricity markets: 1) the representation of EVs individually as general MASCEM Buyer Agents, participating in local electricity markets, and 2) the representation of a set of EVs as an Aggregator Agent, participating in multiple markets at different scales, e.g. local, regional, continental.

AMIRIS' sectoral flexibility implementations will be enhanced by improving the representation of heat pumps and adding the representation of flexible EV charging. Time-variable electricity price components will be introduced in the heat pump representation, and an existing load-shift optimisation algorithm will be applied to data that represents the base load for charging a fleet of EVs and the flexibility of deviations from that base load.

MASCEM's capabilities to model the flexibility of EVs are being enhanced by refining and adapting potential business models in the context of distribution networks with high penetration of EVs. DR models shaped for EVs in a local market context are addressed, and the enhancement of the local market models to accommodate EVs transactions within MASCEM is being accomplished. Furthermore, a new model is being developed and integrated in MASCEM to enable the optimal coordinated bidding of multiple self-interested EV aggregators in wholesale electricity markets. The coordinated bidding model deeply relies on the active role of an aggregator entity, which accommodates the interaction between the individual EVs and the market itself. Such aggregators, in turn, have a strong need for using suitable aggregation models, such as the ones presented in Deliverable 4.3 [2] related to spatial flexibility options. There is, thereby, a rather straightforward connection between the sectoral flexibility models provided by EVs in MASCEM with the spatial flexibility options developed by the project, especially considering the variable location of EVs in the grid throughout the time. Studying such connections often requires applying some simplifications to the used models, hence options such as considering EVs as regular consumers from the market perspective, as done by MASCEM in its initial version, is expected to remain a valuable option for many of the studies that will be performed in the scope of Work Package 5.

The agent-based models require the representation of decision-making logic for different actors, which makes it difficult to include agents that consider also other energy sectors in their decision making. For this reason, the agent-based models in TradeRES are not able to capture all sector-coupling and energy conversion categories identified in TradeRES. Therefore, TradeRES project will also utilize optimization models (the focus in TradeRES

Work Package 2) to get a fuller picture and to provide sector coupling containing background data for the agent-based models. However, the existing and enhanced implementations in AMIRIS and MASCEM make it possible to assess certain sectoral flexibilities from agent perspective, such as tariffs that are best suited to align heat pump operation to the electricity markets. The implementations may also be further tuned according to the modelling needs identified in TradeRES Work Packages 3 and 5. Finally, the scenarios for future level of flexibility across different sectors and operational policies in different sectors and markets, affecting agents' behaviour, are defined together with TradeRES Work Packages 2 and 3.

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