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Benefits of a Multi-Energy Day-Ahead Market

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Abstract

Energy system integration can bring several benefits to energy systems, notably to those that are in transition to high shares of renewable energy. Strategies are needed to realize the theoretical benefits of this approach in practice. Therefore, this paper proposes the organization and mathematical formulation of a multi-carrier day-ahead market in which electricity, gas and heat are traded simultaneously. This market set-up is applied to a conceptual test case to identify how - compared to a reference set-up mimicking the current practice - the multi-carrier market is able to unlock the benefits of energy system integration. It is quantitatively shown that the multi-carrier market (1) eliminates the need for forecasts of prices on subsequent markets and the consequences of the related errors, (2) allows to use the flexibility available in one carrier to facilitate the balancing in another, e.g. using the flexibility of a heat system to help balance the electricity system, and (3) enables specific market outcomes, unachievable in a sequential set-up, which increase the optimality of the market outcome.

Keywords: Renewable energy, Flexibility, Power system planning, Power system operation, Electricity storage

1. Introduction

1.1. Energy system integration

Energy system integration is receiving increasing attention of both the scientific and regulatory community, evidenced e.g. by the call for integrated approaches in the European Commission's winter package [1]. This attention is driven in part by practical evolutions, such as the increasing deployment of heating networks and the cost evolutions of certain technologies; in part by the promises energy system integration holds for

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facilitating the realization of a competitive, low-carbon and secure energy supply. Such integration, realized by a multi-energy system approach – i.e. treating energy carriers simultaneously (e.g. electricity, heat and gas) and optimizing their interaction at a certain level (e.g. a neighborhood, city or country) [2] – can bring several benefits. The benefits of multi-energy systems and markets listed below come at the cost of increased market design and bidding complexity.

First, energy system integration can reduce greenhouse gas emissions. On the one hand this is achieved by increasing the flexibility in the energy system, which allows to increase the use of renewable energy sources; e.g. by linking electricity systems to heat [3] or gas systems [4], further unlocking the flexibility of any available storage in these systems. On the other hand this is done by reducing the overall use of energy; e.g. by using co- and trigeneration technologies [5] or by facilitating the use of waste heat [6].

Second, energy system integration can reduce the cost of supplying energy. In a first stage this can be done by increasing the utilization of assets, e.g. by increasing the use of the gas network to relieve the electricity network [7], or by increasing the efficiency of the whole energy system operation made possible by the increased flexibility mentioned just above [8]. In a second stage these effects can defer investments in network [9] and supply capacity [10], further reducing overall supply costs.

Third, energy system integration can increase energy system reliability. While increased subsystem interdependence could lead to cascaded failures [11], appropriate multi-energy operation can increase reliability through improved supply capacity planning [12], network capacity planning [13] and by a service rather than a commodity approach to energy supply [14] – take e.g. the case wherein a heating service is provided and heat demand can be met both via a heat network connection or via a heat pump; in case of a failure in the heat network, the heat service can still be provided by transporting energy over the electricity network and converting it locally into heat.

Finally, the evolution towards energy system integration is compatible with the evolution towards the sale of energy services rather than energy commodities, driven by the decreasing variable costs of supplying energy. Notably in the residential sector, consumers are less concerned with the specific energy carriers that are used to meet their demand for heating or cooling. Integrated energy systems are well suited to provide these services, while simultaneously providing the electricity to meet the electrical demand [15].

1.2. Multi-energy markets

Currently, most energy system integration research has looked at the operation and control of multi-energy systems [16], at times with a focus on mobilizing flexibility [17]; at their performance, e.g. in terms of reliability [14] or environmental aspects [18]; and at their design [10, 19]. Much less attention has gone to studying which market designs and policies would be needed to unlock the benefits of energy system integration shown in this research. Some authors have looked at certain aspects of market integration, notably the coupling of gas and electricity markets through the operation of gas-fired power plants [20, 21]. However, both papers still treat both markets separately and couple them through the development of integrated bidding strategies on a company level; i.e. by coordinating bids on spot markets to maximize profits. Other types of market integration – such as electricity-heat or -cold, gas-heat, etc. – have been studied much less. Moreover, many of today’s heating systems cannot even really be thought of as markets, as they are often operated by a single player. System operators are able to allow

certain new producers in their system (e.g. industrial waste heat), but consumers are not able to freely choose their heat supply/supplier. This approach clearly deviates from that of European electricity and gas markets, with their regulated network monopolies and liberalized supply side.

There is then a clear need for innovation in market design to promote co-ordination between multi-energy systems and realize the potential benefits outlined above. Therefore, the first contribution of this paper is to develop a fully-integrated market model for trading electricity, gas and heat. It proposes the principles for a multi-carrier day-ahead market in which the three energy carriers are traded simultaneously so that their interaction is optimized. The second contribution of this paper is to show how such an integrated market design is able to generate a more optimal outcome than the current sequential market organization. To do so, the proposed market model is applied to a conceptual test case which allows to trace in detail the mechanisms through which a multi-carrier market realizes its benefits. From this, the case for multi-carrier markets is argued.

The remainder of this paper is structured as follows. First, Section 2 discusses the methodology, i.e. the market organization, the market model, and the data and scenarios of the conceptual test case. Then, Section 3 presents the results of the test case, discussing both how benefits are generated through the use of an integrated market and how they are distributed among market participants. Finally, Section 4 concludes and gives policy recommendations.

2. Methodology and Data

This section starts by presenting the adopted market organization. This comprises all choices related to, among other things, timing of market clearing, order formats and geographical market scope, so as to effectively position the multi-carrier market in the energy system operational flow. Against the backdrop of this organization a day-ahead market model is proposed, i.e. the mathematical market clearing problem that is solved to maximize social welfare, including the new multi-carrier order types. Finally, the data is presented of the conceptual test system to which the market model is applied, as well as the set-up of the scenarios that are evaluated.

2.1. Market organization

The starting point for the multi-carrier market design is the current European electricity market design [22]. Moving from one to several traded carriers introduces several additional challenges for market design that are firstly related to the physical character of the carriers. For example, balancing supply and demand happens at different scales and over different time-frames for the different carriers, and over different networks. Moreover, certain technologies have one or more of the traded energy carriers both as in- and output, e.g. a heat pump or a gas-fired power plant. Special attention has to be given to how such technologies, referred to in this work as *multi-carrier technologies*, submit orders in a multi-carrier market, such that they are not confronted with technically infeasible market outcomes. Secondly, there are challenges related to the markets that have to be integrated themselves. For example, these markets currently have different trading times, which complicates market coupling, and very different levels of liquidity (compare

e.g. the day-ahead electricity and gas markets). Market integration would also impact the overall energy system operation, complicating the use of systems services, as e.g. a balancing action with a gas-fired power plant in the electricity system would impact the balance in the connected gas system. Finally, market integration will bring regulatory challenges, related to among other things non-discriminatory access – balancing the considerations related to orders from multi-carrier technologies with technology-neutral access, simplicity, fairness, confidentiality, metering and settlement, network expansion and management, and so on.

Considering these challenges, and aiming to unlock the benefits of energy system integration, a **simultaneous day-ahead multi-carrier energy exchange** is proposed. A **simultaneous** market uses a common time-step for all carrier supply-demand balances and clears them all at the same time. Consequently, in theory (i.e. all energy traded via the market, no market power, etc.) the interaction between the carriers can be arranged optimally. In a sequential market set-up (e.g. first heat, then electricity) outcomes of later markets have to be forecasted; this can lead to forecast errors, which are by design omitted in a simultaneous set-up. To make such a simultaneous design work, there needs to be a way to express inter-carrier dependencies when submitting orders. In short, the gain in optimality is made possible by a more complex ordering and clearing process. Nevertheless, an appropriate design of a set of multi-carrier order types, analogue to the time-related order types in [22], can limit this increase in complexity, as well as the amount of information that has to be shared, and ensures that the responsibility for technically feasible market outcomes is shared between market participants and operators. The **day-ahead** market stage is selected on the one hand because of its relevance (i.e. the high traded volumes compared to e.g. intra-day and system service markets), on the other hand because of the fact that it is close enough to real-time to capture part of the operational challenges and thus the value of e.g. flexibility exchanges across carriers. The **energy exchange** approach, rather than an energy pool approach, is chosen as it is the current approach in Europe. An energy pool approach would be more suited to capture all technical challenges of energy system integration, but would require far more information to be shared than is current practice. Here, the required additional technical information will be passed to the market operator through the multi-carrier order types, which will be presented further on.

This day-ahead market is fitted into the energy system operational flow as is presented in Figure 1. Market players submit their offers for all carriers at the same time to the multi-carrier market, after which this market is cleared and its outcome published; as is done currently in e.g. electricity markets. All Balancing Responsible Parties (BRPs) submit balanced portfolios based on the market outcome and possibly a set of Over The Counter contracts (OTCs) to the Transmission and Distribution System Operators (TSO, DSO). These can then, if needed, take corrective actions to ensure system stability. In the figure TSOs and DSOs are separate per carrier, but this flow would also work with integrated system operators. For the remainder of this paper the focus is limited to the second step of this process: the market clearing.

The market is built on the notion of **market areas**. Each market area is described by a geographical area and a traded carrier. Within each market area the supply and demand for that carrier must be balanced. Within each market area also network constraints could be checked. The notion of market areas further allows the use of different levels of spatial resolution, minimum order size, etc. per carrier. Take for example a heat pump

Figure 1: Day-ahead multi-carrier market time flow

located in a place that belongs to a nation-wide electricity market area and a local heat
 145 market area. This set-up allows to link the electricity demand orders and heat supply
 orders of the heat pump, while also allowing to tailor the lay-out of the market areas
 to the carrier-specific balancing challenge. Setting up these market areas then requires
 appropriately weighing such things as market volumes and liquidity, minimum order size,
 network limits, and so on. For the case study of this work the perspective of a European
 150 country is taken, with *national* electricity and gas market areas (i.e. a single balance per
 carrier) and *local* heat market areas (i.e. a multitude of balances). No minimum order
 size is considered, nor are network constraints checked.

2.2. Market model

Within this market organization, which either directly addresses the challenges out-
 155 lined earlier or is compatible with solutions for these challenges, a mathematical market
 clearing model is proposed. The goal of the model is to maximize social welfare, under-
 stood here simply as the sum of the consumer and producer surplus calculated in (4c).
 This is done by deciding on whether or not to accept the submitted *simple* orders i (i.e.
 supply and demand orders) and storage orders s , and to what extent to accept them.
 160 The orders are mathematically defined and explained in more detail later in this section.
 Therefore the welfare contributions of the simple and storage orders are summed (1).

$$\max \sum_{a \in \mathbb{A}} \sum_{t \in \mathbb{T}} \left(\sum_{i \in \mathbb{I}} w_{i,a,t} + \sum_{s \in \mathbb{S}} w_{s,a,t}^s \right), \quad (1)$$

where $a \in \mathbb{A}$ is the index of the area, $t \in \mathbb{T}$ is the index of time-step, $i \in \mathbb{I}$ is the index of a simple order, and $s \in \mathbb{S}$ of a storage order. In case of volume indeterminacy traded volumes are maximized; in case of price indeterminacy prices are put in the middle of the price of the marginal supply order and the willingness-to-pay of the marginal demand order. The social welfare maximization is subject to the market area balances, where supply and demand have to match for every time step t , given also the contributions from interconnection and storage (2). Quantity $Q_{i,a,t}$ is defined as positive for supply and negative for demand orders, and only non-zero for the area a and time-step(s) t linked to order i . Similarly charging quantity $Q_{s,a,t}^c$ and discharging quantity $Q_{s,a,t}^d$ are only non-zero for the area a linked to storage order s and for the and time-step(s) t during which the storage order can be used. Interconnection exchange $x_{a,b,t}$ is limited to the available interconnection capacity $X_{a,b}^{\text{cap}}$, see eq (3).

$$\sum_{i \in \mathbb{I}} u_i \cdot Q_{i,a,t} + \sum_{ai \in \mathbb{A}} x_{ai,a,t} - \sum_{ae \in \mathbb{A}} x_{a,ae,t} + \sum_{s \in \mathbb{S}} (u_{s,t}^c \cdot Q_{s,a,t}^c - u_{s,t}^d \cdot Q_{s,a,t}^d) = 0 \quad \forall a \in \mathbb{A}, t \in \mathbb{T} \quad (2)$$

$$x_{a,b,t} \leq X_{a,b}^{\text{cap}} \quad \forall a, b \in \mathbb{A}, t \in \mathbb{T}, \quad (3)$$

where $x_{ai,a,t}$ is import to the area a defined as import from all the neighbouring areas ai , and export $x_{a,ae,t}$ is defined as import from all the neighbouring areas ae .

2.2.1. Simple orders

The simple orders are the building blocks of the market model. Based on these orders social welfare is calculated and cross-carrier constraints are formulated. A simple order is linked firstly to an ID i . This ID then links it to all its information. In the case of this implementation that is its sense (supply/demand), the market area a (e.g. a specific heat balance), the quantity $Q_{i,a,t}$, the two price points P_i^0 and P_i^1 , and the minimum acceptance fraction U_i^{min} . A simple order is also linked to a time step t through its quantity $Q_{i,a,t}$, which is only non-zero at specific time steps. Based on the sense of the order $Q_{i,a,t}$ is made into a positive (supply) or negative (demand) value. If the two price points are the same for a certain time step, the order becomes a step order; if not, it becomes a linear order with an increasing or decreasing price.

Furthermore, two variables are associated to each order: first, a binary acceptance variable z_i , and second, a continuous fraction variable u_i , which determines what share of the offered quantity $Q_{i,a,t}$ is accepted. This fraction variable can only have a positive value if the bid is accepted, as is expressed in (4a). A minimum can also be submitted for this acceptance fraction (4b). Finally, with these variables and parameters the contribution of the simple order to social welfare can be calculated (4c). The minus sign in front of both terms is due to the fact that $Q_{i,a,t}$ is negative for demand and positive for supply, while their contribution to total welfare has the opposite sign.

$$u_i \leq z_i \quad \forall i \in \mathbb{I} \quad (4a)$$

$$u_i \geq U_i^{\text{min}} \cdot z_i \quad \forall i \in \mathbb{I} \quad (4b)$$

$$w_{i,a,t} = -u_i^2 \cdot (P_i^1 - P_i^0) \cdot (Q_{i,a,t}/2) - u_i \cdot P_i^0 \cdot Q_{i,a,t} \quad \forall i \in \mathbb{I}, a \in \mathbb{A}, t \in \mathbb{T} \quad (4c)$$

2.2.2. Multi-carrier orders

To capture all relevant inter-carrier dependencies that might arise from bidding with multi-carrier technologies or with portfolios of diverse technologies, four multi-carrier order types are introduced. These order types still guarantee a technology-neutral character. All work by linking several simple orders in a specific way. A **linked** multi-carrier order block links simple orders to each other following the *parent-child* logic (5). It can be used, e.g., to impose that a second electricity supply order of a combined heat & power (CHP) installation could only be accepted if a first electricity supply order and a heat supply order have already been fully accepted. An **exclusive** multi-carrier order block links simple orders to each other through exclusivity in either acceptance (6) or acceptance fraction (7). It can be used, e.g., when the heat demand of a market participant that owns a heat pump and has a district heating connection can be satisfied directly from the heating network or by electric energy consumption. A **dependent** multi-carrier order block links simple orders to each other through their acceptance fraction, in that this fraction has to be the same for all orders in the block (8). It can be used, e.g., for multi-carrier technologies such as gas-fired power plants, where the gas input order then has to be accepted for the same fraction as the electricity output order. A **conversion** multi-carrier order block links simple orders to each other through a relaxed version of the dependent order type, imposing that the acceptance fraction of one order is limited by the acceptance fraction of another (9). It can be used, e.g., for multi-carrier technologies such as CHPs, where the highest fraction of the electricity and heat supply orders sets the fraction of the gas demand order. Note that all $R_{i,j}$ parameters are matrices with entries by default set to zero, that have a value of 1 if order i is linked to order j .

$$z_i \leq R_{i,j}^{\text{LO}} \cdot u_j \quad \forall i, j \in \mathbb{I} \quad (5)$$

$$z_i \leq 1 - \sum_{j \in \mathbb{I}} R_{i,j}^{\text{EO}} \cdot z_j \quad \forall i \in \mathbb{I} \quad (6)$$

$$u_i \leq 1 - \sum_{j \in \mathbb{I}} R_{i,j}^{\text{EO}} \cdot u_j \quad \forall i \in \mathbb{I} \quad (7)$$

$$u_i = R_{i,j}^{\text{DO}} \cdot u_j \quad \forall i, j \in \mathbb{I} \quad (8)$$

$$u_i \leq R_{i,j}^{\text{CO}} \cdot u_j \quad \forall i \in \mathbb{I} \quad (9)$$

These four multi-carrier order types, complemented with existing single-carrier order types (e.g. a minimum acceptance fraction), are able to capture the most important characteristics of multi-carrier technologies. They also give rise to a new kind of order pricing. Currently, the price of an order expresses how much a market participant is willing to pay for buying (or wants to receive for selling) a quantity of a carrier. In a simultaneously cleared multi-carrier market, however, the situation may occur where a market participant buys a quantity of a carrier (e.g. gas), converts it into another carrier (e.g. electricity), and sells the result in the same market. In this case the market player does not necessarily have a explicit willingness to pay for its input, nor a price it wants to receive for its output. Rather it is interested in the price spread between the carriers.

If this spread is sufficiently high to at least cover the conversion costs, then it wants the associated orders to be accepted. The prices of the associated orders would then reflect merely the conversion costs, not the variable costs in the traditional sense. While current market regulation may prohibit such pricing, it would be essential in a simultaneously cleared multi-carrier market to achieve maximal social welfare.

2.2.3. Storage orders

A special storage order is devised for the proposed multi-carrier market, namely one where the storage installation is offered to the market to be planned by the market operator in a welfare maximizing way. Therefore the storage operator communicates all required technical information (time steps on which it can be used, capacities $E_s^{\max}$, charging and discharging efficiencies η_s^c and η_s^d , etc.) and the costs for using the installation. For each storage order s two sets of equations are constructed: for charging and discharging. These impose for every time-step the same constraints as for the simple orders before. As this set-up is the same for charging and discharging, only the former is presented (10a)-(10c). An additional set of equations governs the energy level of the storage orders. The starting energy level is set through the parameter E_s^0 . To ensure that the storage is only used between the start and end time communicated by the storage owner, the quantities $Q_{s,a,t}^c$ and $Q_{s,a,t}^d$ are only non-zero between those times. (10f) replaces (10e) for the last time step. The equation (10g) limits the amount of storage by its storage capacity.

$$u_{s,t}^c \leq z_{s,t}^{s,c} \quad \forall s \in \mathbb{S}, t \in \mathbb{T} \quad (10a)$$

$$u_{s,t}^c \geq U_s^{c,\min} \cdot z_{s,t}^{s,c} \quad \forall s \in \mathbb{S}, t \in \mathbb{T} \quad (10b)$$

$$w_{i,a,t}^s = -(u_{s,t}^{s,c})^2 \cdot (P_s^{c,1} - P_s^{c,0}) \cdot (Q_{s,a,t}^c/2) - u_{s,t}^{s,c} \cdot P_s^{c,0} \cdot Q_{s,a,t}^c \quad \forall s \in \mathbb{S}, a \in \mathbb{A}, t \in \mathbb{T} \quad (10c)$$

$$e_{s,1} = E_s^0 \quad \forall s \in \mathbb{S} \quad (10d)$$

$$e_{s,t+1} = e_{s,t} + u_{s,t}^{s,c} \cdot Q_{s,a,t}^c \cdot \eta_s^c - u_{s,t}^{s,d} \cdot Q_{s,a,t}^d \cdot (1/\eta_s^d) \quad \forall s \in \mathbb{S}, t \in \mathbb{T} \quad (10e)$$

$$e_s^{\text{end}} = e_{s,t} + u_{s,t}^{s,c} \cdot Q_{s,a,t}^c \cdot \eta_s^c - u_{s,t}^{s,d} \cdot Q_{s,a,t}^d \cdot (1/\eta_s^d) \quad \forall s \in \mathbb{S} \quad (10f)$$

$$e_{s,t} \leq E_s^{\max} \quad \forall s \in \mathbb{S}, t \in \mathbb{T} \quad (10g)$$

2.3. Data

The market model is applied to a test system. While this system is based on realistic data, its main goal is not to accurately represent an existing system, but to be able to capture the benefits multi-energy approach. Therefore, on the one hand it considers several carriers – i.e. electricity, gas and heat – and several multi-energy technologies – e.g. heat pumps and gas turbines. On the other hand, it means that absolute numbers such as fuel costs are of secondary importance. Rather, it is the relative difference in results of the scenarios (discussed hereafter) that indicate the optimality of the multi-carrier market and illuminate how this market generates benefits.

As mentioned, the test system has a *national* electricity and gas market area, and *local* heat market areas. In practice there would indeed be numerous heat balances; for

the sake of traceability only one is considered here. This means that e.g. the benefits of heat system flexibility for electricity and gas markets are most likely underestimated. No interconnections are considered. Demand in the market areas comes from a time series of direct consumption and from the demand of the multi-carrier technologies; i.e. no demand response is considered, nor is price-sensitivity of demand. Once again, this could lead to an underestimation of the benefits of a multi-carrier market. Supply in the markets comes from multi-carrier technologies and a set of additional technologies. All demand and supply is assumed to pass through the market. Finally, it is assumed that there is electricity and thermal storage. Storage technologies participate in the markets through the storage orders.

For the **heat market**, demand is a time series derived from the gas demand for heating of a district of 200 households with a peak demand of 650 kW_{th}. Supply comes from a CHP installation, a heat pump (HP) and a gas boiler (GB) of each 200 kW_{th} output, and solar thermal panels with a total capacity of 300 kW (i.e. 100 households with a 3 kW installation). Storage comes from a generic thermal storage, with a charging and discharging power of 300 kW_{th}, a round-trip efficiency of $\eta^c = 90\%$ and 1500 kWh_{th} of energy storage. For the **electricity market**, demand and supply is that of the Belgian power system as reported by ELIA; the former being a time series, the latter a set of capacities. Storage, modeled after the Belgian pumped hydro storage, has a charging and discharging power of 1164 MW_{el}, a round-trip efficiency of $\eta^c = 75\%$ and 5 GWh_{el} of energy storage. Additionally, the CHP can supply electricity, and the HP can demand electricity. For the **gas market**, demand comes from the CHP and GB installation, and the gas-fired power plants. Gas supply consists of two supply orders: one priced at 26 €/MWh, one at twice that price. This set-up is meant to represent the tendency towards more short-term trading, and grasp the effect of changes in the merit order (i.e. being able or not to avoid the use of the more expensive gas source). No gas storage is considered (the second gas source can also be seen as a representation of the more expensive flexible gas balancing services). A full description of supply technologies is presented in Table 2. Negative capacities point to input, positive to output. Variable costs are expressed per capacity, per hour. To improve the traceability of the solutions (i.e. where costs come from) only fuel costs are considered.

Table 1: Capacity of supply technologies

	District [kW]				System [MW]							
	CHP	HP	GB	PV _h	Nuc.	Oth.	CCGT	OCGT	PV _e	Wind	GS ₁	GS ₂
Heat	200	200	200	300	-	-	-	-	-	-	-	-
El.	150	-67	-	-	5919	1202	3500	1051	2953	1961	-	-
Gas	-500	-	-300	-	-	-	-5833	-2695	-	-	8000	8000

2.4. Scenarios

Three scenarios are devised to identify how and which benefits a multi-carrier market generates: a reference, multi-carrier and control scenario. The difference between the first two allows to identify the full benefits of the multi-carrier approach; the difference between the last two allows to single out the effects not related to price forecast errors. In all scenarios all technologies offer their full capacity at marginal cost into the market,

Table 2: Fuel cost of supply technologies

	District [€/kWh]				System [€/MWh]						GS ₁	GS ₂
	CHP	HP	GB	PV _h	Nuc.	Oth.	CCGT	OCGT	PV _e	Wind		
Heat	0	0	0	0	-	-	-	-	-	-	-	-
El.	0	0	-	-	15	100	0	0	0	0	-	-
Gas	0	-	0	-	-	-	0	0	-	-	26	52

300 i.e. no strategic bidding behavior is considered. The scenarios are all evaluated for three weeks with hourly resolution (the first 168 hours of January, April and October of 2016).

2.4.1. Reference scenario

305 In the first scenario a sequential day-ahead market clearing is set up. First the day-ahead heat market is cleared, then the electricity, and finally the gas market. This specific sequence is chosen for the following reasons. Heat is cleared before electricity because of the lesser elasticity of heat demand compared to electricity demand. Gas is cleared after electricity to represent the move towards short-term gas trading, and to capture part of the balancing challenge in the gas system driven by the gas demand of the gas-fired power plants.

310 A strategy is then needed for the multi-energy technologies for dealing with this sequence. First, these technologies require a **forecast of the gas and electricity prices**. The gas price is forecasted at the cheaper price level (i.e. 26 €/MWh). The electricity price is "forecasted" by clearing the electricity market with the week-ahead forecast of demand and renewable generation (instead of the day-ahead forecast) and all supply and storage technologies except for those that also operate in the heat market (i.e. 315 the CHP and HP). Given that the capacity of these latter technologies is small compared to the size of the electricity market, the effect of leaving them out is negligible.

With these forecasts, **the orders for the day-ahead heat market are set up and the market is cleared**. The multi-carrier technologies set up their offers as follows. For each time-step, the CHP calculates its expected revenue from electricity sales (electric capacity times electricity price), then the expenses for gas (gas capacity times gas price), and finally the revenue it needs from the heat market to make up the difference. Similarly, the HP and GB calculate their expenses for electricity and gas respectively, and subsequently price their heat supply offers. Heat demand is priced at 325 3 000 €/MWh to express its inelasticity. The heat supply of the solar thermal panels is priced at 0 €/MWh. The heat storage is made available at no cost.

330 With the outcome of the heat market, **the orders for the day-ahead electricity market are set up and the market is cleared**. The CHP technology offers the electric capacity that corresponds with the heat capacity it has sold at 0 €/MWh (e.g. 40 % of heat capacity sold means 40 % of electric capacity offered at 0 €/MWh). Left-over capacity is offered at a price that covers the corresponding gas expenses. The HP submits an electricity demand bid at 3 000 €/MWh for the electricity it needs to produce the heat it has sold. The gas-fired power plants forecast their gas expenses at 26 €/MWh and price their electricity supply offers accordingly. Other supply technologies offer their capacity at marginal costs, storage is made available at no cost, and electricity demand 335 is also priced at 3 000 €/MWh.

Finally, with the outcome of the electricity market, **the orders for the day-ahead gas market are set up and the market is cleared**. All demand in this market comes from the multi-energy technologies. They all submit a demand offer at 3 000 €/MWh for the gas they need to produce the supply offers they have sold. Supply comes from the two supply orders described earlier; no storage is available in this market. This method for setting-up orders highlights that no strategic bidding is considered: no safety margins are integrated in the pricing of these orders to cover for possible errors in price forecasting or other elements.

2.4.2. Multi-carrier scenario

In the second scenario the simultaneous day-ahead multi-carrier market is cleared. Demand time series are again priced at 3 000 €/MWh, supply and storage technologies at marginal and no cost, respectively. The multi-carrier technologies offer their capacity using the multi-carrier order types. The CHP uses the conversion order type; the HP, GB and gas-fired power plants the dependent order type. The linked and exclusive order types are not required to set up this simple case, nor are they instrumental in demonstrating the added value of the multi-energy approach. Prices for all the related offers are set at 0 €/MWh, underlining once more that no strategic bidding is considered (i.e. all technologies are price takers). The clearing algorithm will perceive the cost of these offers given the other supply offers in the different balances which are linked to a non-zero price.

2.4.3. Control scenario

In the third and final scenario again the sequential market approach is used, but now instead of "forecasted" electricity and gas prices, the prices of the cleared multi-carrier market are used. These prices are obtained by exporting the dual variables of the balance equations of the multi-energy market clearing algorithm. To obtain these dual variables, the values of the binary variables of the original mixed integer problem are fixed, the problem is solved again as a linear problem, and the duals exported. The same sequence as described for the reference scenario is followed. To set-up the orders for the day-ahead heat market, the electricity and gas prices of the multi-energy market are used. To set-up the orders for the day-ahead electricity market, the outcome of this heat market (order acceptance and price) and the gas price of the multi-energy market are used. Finally, the orders for the day-ahead gas market are set up based on the outcomes of the heat and electricity markets. This scenario uncovers the added value of the multi-energy market that is not related to avoiding forecast errors.

3. Results and Discussion

3.1. Benefits of a day-ahead multi-carrier market

The theoretical benefits of the multi-carrier market should translate into an increase of social welfare, or for this test case in a decrease of the system supply cost. As only fuel costs are considered, this cost comes either from the use of the two gas supply orders or from the use of the Nuclear and Other technology. All other technologies either convert one of the traded carriers or have a zero marginal cost (i.e. the renewable energy sources).

Table 3 shows the supply cost for the evaluated weeks and scenarios. There is no supply cost related to the heat balance, as all heat comes from converting either electricity or gas, or from solar energy. Before continuing, a note on the magnitude of the cost differences. Given the set-up of the test case, they are small. The multi-carrier market creates benefits by changing order acceptance, due to the influence the different balances can have on one another. As mentioned, to be able to trace costs the amount of balances and technologies has been limited. Given the different order of magnitude of traded volumes in the electricity and heat balances (peaks of 14 GW and 650 kW, respectively) and the limited number of supply orders in the gas balance, the absolute impact is by design limited. However, the focus here is on understanding how this impact occurs, and from that extrapolate what could occur in more complex systems with more balances and technologies (market parties) where these effects would be magnified.

Table 3: Supply cost, absolute [M€] and relative [%]

	Ref	January MC	Ctrl	Ref	April MC	Ctrl	Ref	July MC	Ctrl
El.	14.92	15.02	16.12	14.92	14.92	14.92	14.92	14.92	14.92
Gas	20.59	20.37	19.65	23.48	23.37	23.46	16.95	16.95	16.95
Tot	35.50	35.39	35.77	38.40	38.29	38.39	31.87	31.87	31.87
El.	100	100.71	108.07	100	100	100	100	100	100
Gas	100	98.96	95.46	100	99.52	99.94	100	100	100
Tot	100	99.69	100.76	100	99.71	99.96	100	100	100

First, consider the results for **the first 168 hours of January**. The multi-carrier market reduces the system's supply cost by reducing gas expenses, which compensates increased electricity expenses. Looking at Table 4, it is seen that the cost decrease is the result of avoiding the use of the second, more expensive gas supply order. This is done partly by shifting the electricity supply towards the Other technology (variable cost: 100 €/MWh); partly by generating more electricity with the OCGT technology at times of lower demand, storing it and then discharging it during times of high demand. In the *Reference* scenario this doesn't happen as the OCGT's variable cost is expected to be 66.67 €/MWh at all times (given the constant gas price forecast of 26 €/MWh), because of which it continuously appears to be cheaper than the Other technology. This is a first mechanism through which multi-energy market is able to reduce system cost (or increase welfare): it eliminates the need for forecasting prices in other markets, thereby preventing the social welfare losses that can follow from the related errors. These errors do not only negatively impact total welfare, they can also lead to significant financial losses for the involved parties (see further).

A second effect that can be seen in Table 4 is the slight increase in gas boiler usage. In the *Reference* scenario, part of this demand comes when the first gas supply order is fully used. In the *Multi-carrier* scenario the boiler operates at other times to avoid the use of the second gas supply order, with the heat storage operating differently to maintain the balance. The associated efficiency losses mean that more heat needs to be produced. This is a second mechanism through which multi-energy market is able to reduce system cost: the clearing algorithm "observes" the flexibility available in the heat balance when clearing the gas balance, allowing it to avoid more expensive clearing

solutions. In other words: the flexibility of certain parts of the system can be mobilized to balance other parts of the system.

Table 4: Traded quantities in the first 168 hours of January

		District [MWh]				System [GWh]							GS ₁		GS ₂	
		CHP	HP	GB	PV _h	Nuc.	Oth.	CCGT	OCGT	PV _e	Wind					
Ref.	Heat	33.6	33.6	31.82	0.78	0	0	0	0	0	0	0	0	0		
	El.	25.2	-11.2	0	0	994.39	0	444.19	17.94	9.82	140.05	0	0	0		
	Gas	-84	0	-47.74	0	0	0	-740.32	-45.99	0	0	781.09	5.35	0		
MC	Heat	33.6	33.6	31.91	0.78	0	0	0	0	0	0	0	0	0		
	El.	25.2	-11.2	0	0	994.39	1.05	444.19	16.88	9.82	140.05	0	0	0		
	Gas	-84	0	-47.86	0	0	0	-740.32	-43.30	0	0	783.58	0	0		
Ctrl	Heat	33.6	33.6	31.91	0.78	0	0	0	0	0	0	0	0	0		
	El.	25.2	-11.2	0	0	994.39	12.04	444.19	5.89	9.82	140.05	0	0	0		
	Gas	-84	0	-47.86	0	0	0	-740.32	-15.11	0	0	755.28	0.28	0		

In the *Control* scenario the sequential markets use better price forecasts in an attempt to cancel the effect of the related errors. To achieve this, as mentioned, the dual variables of the multi-carrier market are used as price forecasts. However, in the hours in which the first gas supply order is fully used, the approach is slightly different. In these hours the gas balance's dual jumps to 39 €/MWh. Using the dual directly as the gas price forecast would mean that during these hours the OCGT and Other technology have the same variable cost, which would lead to random selections between the two. Reducing the gas price slightly in these hours would mean that OCGT technology is cheaper, which would result in practically the same outcome as in the *Reference* scenario. Both approaches would not be very informative, as these "prices" do not communicate anything about the limits of the first gas supply order. Therefore, the gas price is increased slightly in these hours so that the Other technology is slightly cheaper than the OCGT technology.

Using these price signals, the *Control* scenario has the highest supply cost of all scenarios. During the hours in which the first gas supply order is expected to be fully used, communicated via the high gas price, only the Other technology is used. In the *Multi-carrier* scenario, in contrast, the OCGT technology is used until the first gas supply order is fully used; only thereafter is the Other technology addressed (see Figure 2). Consequently, the Other technology is used much less than in the *Control* scenario, resulting in a lower supply cost. This reveals a third mechanism through which the multi-carrier market can reduce system cost: it allows for order acceptance that is practically almost impossible to achieve in sequential markets. By having information on in- and output costs and relations of multi-carrier technologies, and thus having (more) information on how different balances impact one another, the clearing algorithm can determine exactly which fraction of the submitted orders to accept for overall optimality. In sequential markets this would have to be achieved through more complex ordering – e.g., in the case of the OCGT technology the result could be approximated by offering a certain share of the capacity at low variable cost and the rest at a higher variable cost – but in real systems with numerous parties this would be highly prone to errors that could significantly impact optimality.

The cost increase in the *Control* scenario is further caused by the fact that the second gas supply order is used again. This happens in hour 83, close to hour 85 in which the gas price jumps to 39 €/MWh. Because of this price signal, in hour 85 the

Figure 2: Electricity outcome for the first 168 hours of January in the *Multi-carrier* scenario

electricity storage discharges more than in the *Multi-carrier* scenario, while the OCGT technology is used less. However, this is compensated by increasing the electricity supply (to charge the storage) in hour 83, an hour during which the gas price was expected to be only 26 €/MWh. As a result, total gas demand now exceeds the capacity of the first gas supply order in this hour. This example shows elements of the three mechanisms described above and can be summarized as such: by having better information, the multi-carrier market approach can generate more optimal market outcomes.

Table 5: Traded quantities in the first 168 hours of April

		District [MWh]				System [GWh]							
		CHP	HP	GB	PV _h	Nuc.	Oth.	CCGT	OCGT	PV _e	Wind	GS ₁	GS ₂
Ref.	Heat	11.28	25.86	0	1.04	0	0	0	0	0	0	0	0
	El.	8.46	-8.62	0	0	994.39	0	503.90	23.11	64.00	83.34	0	0
	Gas	-28.21	0	0	0	0	0	-839.83	-59.25	0	0	894.96	4.13
MC	Heat	12.31	24.72	0	1.04	0	0	0	0	0	0	0	0
	El.	9.23	-8.24	0	0	994.39	0	503.90	23.11	64.00	83.34	0	0
	Gas	-30.80	0	0	0	0	0	-839.83	-59.25	0	0	898.91	0
Ctrl	Heat	12.80	24.29	0	1.04	0	0	0	0	0	0	0	0
	El.	9.90	-8.10	0	0	994.39	0	503.90	23.11	64.00	83.34	0	0
	Gas	-32.00	0	0	0	0	0	-839.83	-59.25	0	0	895.53	3.57

The increased renewable output during the peak hours of the first 168 hours of April mean that the Other technology does not have to be used. Nevertheless, in the *Reference* scenario the second gas supply order is used again to provide input for the OCGT technology. In the *Multi-carrier* scenario this can again be avoided by using the electricity storage differently. Electricity balance outcomes are practically identical across market designs. The multi-carrier market clearing is limited in its impact because the improved information does not change which units are optimal to select. A greater diversity in electricity and/or gas supply would magnify the impact. In practice, e.g.,

many different CCGTs with differing characteristics (and owners) instead of one generic technology would lead to bigger changes in order acceptance. In the heat balance such changes do occur, driven by the rescheduling of the electricity storage. CHP electricity production is interesting from a system's perspective more often. Generating more value from electricity supply means that less value has to be generated from heat supply to cover gas demand costs. Consequently, it takes over part of the HP heat supply. Again, a greater number of heat balances (more significantly influencing electricity and gas balances) would have lead to greater effects.

The supply cost of the *Control* scenario now falls in between those of the other two scenarios. No use of the Other technology in the *Multi-carrier* scenario means that the dual variable of the gas balance stays at 26 €/MWh, which means that the *Control* scenario does not have improved information on gas balance dynamics. The improved information on electricity balance dynamics drives a shift from CHP to HP heat supply compared to the *Reference* scenario, but one that overshoots the optimal outcome of the *Multi-carrier* scenario. Because of this, and slightly different storage use, electricity market outcome changes negligibly, and gas market outcome changes such that slightly less of the second gas supply order is needed than in the *Reference* scenario.

Table 6: Traded quantities in the first 168 hours of July

	District [MWh]				System [GWh]							
	CHP	HP	GB	PV _h	Nuc.	Oth.	CCGT	OCGT	PV _e	Wind	GS ₁	GS ₂
Heat	0	3.05	0	8.35	0	0	0	0	0	0	0	0
El.	0	-1.02	0	0	994.39	0	391.26	0	87.60	80.24	0	0
Gas	0	0	0	0	0	0	-65.21	0	0	0	652.10	0

Outcomes across scenarios are identical for **the first 168 hours of July**. This shows the limits of the benefits of a multi-carrier market. Such a market generates benefits by changing order acceptance via improved information. In these 168 hours the improved information does not lead to different choices. The combination of HP, solar heat and storage always suffice to meet heat demand; the CCGT technology and storage meet electricity demand; and the first gas supply order never reaches its limits. In realistic systems, with much more orders, this situation is obviously very unlikely to occur.

Summarizing these results, it can be said that a multi-carrier market increases welfare compared to a sequential market when the improved information can be used to improve order acceptance. Three distinct drivers have been identified. First, a multi-carrier market eliminates the need for forecasting the prices of subsequent markets, and thus also the associated errors. Second, when balancing a specific carrier in a specific place, the clearing algorithm is aware of flexibility in other balances connected through multi-carrier technologies and can use this flexibility to facilitate balancing. This is a very useful quality, notably in systems with significant amounts of variable renewable energy sources. Third, it allows for order acceptance configurations that are almost impossible to realize in a sequential market set-up.

3.2. Distribution of multi-carrier market benefits

Once established how a multi-carrier market generates benefits, it should be analyzed how these benefits are distributed among the involved parties. On the one hand, **the**

500 **weighted average revenues of the multi-carrier and renewable technologies** are analyzed, which are calculated as follows. For the multi-carrier technologies, every time-step the bought and sold volumes of in- and output carriers are multiplied by their respective prices at that time step (i.e. the dual variables), and the whole is summed (outputs counting as revenues, inputs as expenses). For the renewable technologies sold volumes and respective prices are multiplied. These revenues per time-step are then
 505 summed over all time-steps, and finally divided by the total volume of bought inputs. On the other hand **the weighted average expenses of consumers** are analyzed, which are calculated as follows. For each carrier and every time-step the total demand volume is multiplied by the respective price. This expense per time-step is then summed over all time-steps, and finally divided by the total volume of demand. The results of
 510 these calculations are shown in Table 7.

In the *Reference* scenario, the GB and OCGT technologies have an average weighted revenue that is negative for **the first 168 hours of January**. Both units are almost always, when accepted, the marginal unit in the heat and electricity balances, respectively. Normally, marginal units would simply break even, but as they make price forecast errors
 515 they lose money, leading to negative average revenues, notably for the OCGT technology, which loses on average 17.7 € per MWh of gas it buys and converts into electricity.

Table 7: Weighted average revenues of multi-energy and renewable technologies and expenses of demand

		Revenue [€/MWh _{input}]							Expenses [€/MWh]		
		CHP	HP	GB	CCGT	OCGT	PV _e	Wind	Heat	El.	Gas
Jan.	Ref.	3.5	23.9	-0.6	3.1	-17.7	52.9	48.9	40.8	51.3	29.4
	MC	8.8	32.2	6.5	6.3	0	56.5	49.4	50.2	54.3	27.8
	Ctrl	9.7	32.2	7.1	7.5	-3.4	56.5	49.4	50.2	54.3	26.2
Apr.	Ref.	-3.4	7.3	0	4.1	-12.3	51.0	48.3	23.3	52.6	28.7
	MC	1.3	6.5	0	6.1	0	51.0	48.3	22.0	52.6	26
	Ctrl	-2.8	6.7	0	4.2	-11.1	51.0	48.3	22.0	52.6	28.4
Jul.	Ref.	0	-0.5	0	1.9	0	46.1	44.3	12.6	45.8	26
	MC	0	0	0	1.9	0	46.1	44.3	12.7	45.8	26
	Ctrl	0	0	0	1.9	0	46.1	44.3	12.7	45.8	26

In the *Multi-carrier* scenario these losses vanish. The OCGT technology breaks even, and the gas boiler is even able to generate positive revenue. This is mostly due to the increased heat price, which now reflects the impact that switching to the second gas
 520 supply order would have on the cost of supplying heat, instead of only reflecting the cost of balancing heat supply and demand. Consequently, average heat expenses increase significantly in this scenario. Average electricity expenses also increase, again due to influence of the gas balancing. The electricity price increase, which drives this expense increase, and is itself the result of reflecting the true cost of gas market balancing in the
 525 electricity market, has a positive impact on renewable energy revenues. Notably the PV_e technology benefits, as its output coincides with the moments when the gas supply is stressed. The average gas expenses decrease, but are above 26 €/MWh, even though the second gas supply order is not used. This is due to the gas price (i.e. dual) increasing to 39 €/MWh when the first gas supply order is fully used and the Other technology is
 530 needed to balance electricity demand and supply.

In the *Control* scenario revenues of heat supplying technologies increase even further. Here, again, the limited ability of the price signal to communicate information is seen. As the heat storage is now operated only to balance heat demand and supply, the CHP and GB technologies supply more of the heat during those hours in which the first gas supply order was almost at its limits in the *Multi-carrier* scenario. This results in higher revenues for these technologies, but leaves less cheap gas for the electricity supplying technologies, and leads to the use of the second gas supply order. Consequently, average OCGT revenues are again negative. Average heat and electricity expenses are the same as in the *Multi-carrier* scenario. Gas expenses, paradoxically, decrease. The dual now jumps to 52 €/MWh when the second gas supply order has to be used, and is 26 €/MWh otherwise – as in the *Reference* scenario. This effect is discussed further below.

Results for the **the first 168 hours of April** show similar tendencies: the "marginal" units turn a loss in the non-multi-carrier scenarios (electricity: OCGT, heat: CHP). Average heat expenses decrease in the multi-carrier set-up, as the clearing algorithm now more correctly assesses the value of the CHP for the electricity balance, which is higher than what is perceived in the *Reference* scenario. Electricity expenses are the same across scenarios. Consequently, renewable energy technologies revenues remain unchanged too. Gas expenses show the influence of the second gas supply order. As the Other technology is not used, gas expenses now simply reflect the cost of the first gas supply order. Results for the **the first 168 hours of July** see the marginal unit in the heat market (HP) turn a loss once again in the *Reference* scenario. Other results are the same across scenarios.

These results raise questions as to **how prices should be set in a multi-carrier market**. This analysis – i.e. with duals as prices – shows that prices can be set in a multi-carrier market such that all accepted orders result in at least a break even outcome. There are, however, several ways they could be set that would result in the same welfare, but distribute it differently among parties. Take, e.g., those hours in January when the first gas supply order is fully used *and* the Other technology has to be used to avoid using the second gas supply order. When using the dual variable as price, the price jumps to 39 €/MWh in these hours. This is the upper limit to the price, as a higher price would make the OCGT technology appear more expensive than the Other technology, which it is not. The lower limit to the price is the cost of the first gas supply order, i.e. 26 €/MWh. Between these limits there is price indeterminacy, with no straightforward way to resolve it. In a single-carrier market the price could be set somewhere between the cost of the marginal supply order and the willingness-to-pay of the marginal demand order. However, here the marginal demand order comes from a multi-carrier technology – the OCGT technology – which does not have an explicit willingness-to-pay, but rather works with the price spread between the gas and electricity balances. By setting the price at 39 €/MWh the OCGT technology operates at break even, and the first gas supply order takes all welfare. One might want to attempt to distribute this welfare more equally among the two parties by lowering the price. This would require calculating the impact of gas price changes on welfare generation for the gas supplier in the gas balance and for the OCGT technology in the gas and electricity balance. While straightforward for this small example, this could become complex in large systems.

575 4. Conclusions and Policy Implications

Throughout the literature, it is already indicated that energy system integration can bring numerous benefits for energy systems, notably those in transition towards renewable energy. This paper has shown that these benefits can be harnessed via a market approach. It has first presented a way to organize a multi-carrier day-ahead
 580 market, and then shown that this market effectively performs better than a set-up of sequential single-carrier markets. These benefits follow from the improved information available to the multi-carrier market, which allow to improve order acceptance through several mechanisms: (1) eliminating the need for price forecasting and the related errors, (2) using flexibility available in one balance to facilitate balancing in another, and (3)
 585 allowing for certain order acceptance configurations that can practically not be realized in a sequential set-up. Notably the first two mechanisms are of great interest for systems moving towards high shares of renewable energy. Additionally, the paper has shown that (the increases in) welfare can be distributed such that no accepted order loses money, e.g. through avoiding the financial losses related to price forecast errors in sequential markets.
 590 In a context where day-head energy prices will become more volatile for several reasons (increased renewable integration, more short-term gas trading, more heat systems, etc.), this market set-up can help market parties obtain more stable revenues, which in turn could boost much needed private investment in the energy system.

From these results, it can be recommended that policy-makers should push for the
 595 integration of heat and electricity markets, especially given the (expected) electrification of heat sector and increase in the number of heat systems. The mobilization of the flexibility of these systems can be achieved by first where possible having heat systems operated via a market approach, and then integrating these markets with existing electricity markets. Thermal flexibility can significantly facilitate the integration of variable
 600 renewable sources of electricity, and the proposed market approach can be an efficient way of enabling this. It can be expected that with increase of the size and number of heat systems, the need for a solid multi-carrier market organisation, along with the potential benefits of such markets, will increase. The results further show that integrating the gas market is in theory also something worth pushing for.

Implementing such an integrated market in real energy systems will pose several
 605 challenges. First, the number of bids would starkly increase, potentially leading to computational challenges. Nevertheless, these could be tackled through aggregation methods for bidding, e.g. on a heat system level, and will be eased over time as computation technology and techniques advance. Another challenge relates to the currently often low
 610 day-ahead gas market liquidity. In certain contexts an integration of all three carriers might then initially make less sense than simply integrating electricity and heat markets. This is especially true in a European context, where gas market liquidity varies significantly across member states, and where a common electricity market is the goal. Nevertheless, trends of increased short-term gas trading, and projected increased use of
 615 gas-fired power plants in light of energy transitions, might indicate that also this part of market integration could at some point become worth pursuing. Several market design challenges will also arise, some of which will strongly influence the acceptability of reform towards multi-carrier markets. Notably how prices should be set in a multi-carrier market will be a contentious issue, as this might involve the allocation of significant surpluses.
 620 Issues of market power abuse and strategic bidding would also need to be addressed,

especially in the smaller-volume heat markets. Finally, integrating markets will require coordination among system operators, for example in terms of corrective actions taken for reliability purposes.

In sum, multi-carrier markets can offer significant benefits in energy systems, notably those with significant shares of renewables, but these come at the cost of more complex market operations. Whether or not the former will outweigh the latter will depend on a range of factors, but with great renewable energy ambitions in many parts of the world, and rapidly developing information and communication technology, it might well be the case. What research needs to do now is figure out solutions for the challenges discussed above, and perform more detailed quantifications of the benefits of a multi-carrier market by studying a wider range of systems to account for the specific market characteristics and circumstances in different countries. A more detailed theoretical picture will help to determine whether the implementation of a day-ahead multi-energy market is also in practice the best way forward.

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Highlights - Benefits of a Multi-Energy Day-Ahead Market

1. Consistent multi energy market design solves many energy transition challenges.
2. Simultaneous clearing of different markets results in an increased social welfare.
3. Simultaneous clearing of different markets reduces the need for price forecasting.
4. A policy to facilitate integration of heat and electricity market is to be devised.
5. Measures to increase the liquidity on DA gas and heat markets should be brought.