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A holistic view on sector coupling

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ABSTRACT

Sector coupling (SC) describes the concept of a purposeful connection and interaction of energy sectors to increase the flexibility of supply, demand, and storing. While SC is linked to research on smart energy system and locates itself in the research stream of 100% renewable energy systems, it currently focusses on counteracting challenges of temporal energy balancing induced by the intermittent feed-in of renewable energy sources. As regarding the coupling of grids, SC currently remains within classical energy grids. It does not exploit the coupled sectors' potential to its full extent and, hence, lacks a holistic view. To include this view, we call on the use of all grids from coupled sectors for spatial energy transportation, resulting in an infrastructural system. By using the different loss structures of coupled grids, we illustrate how a holistic view on SC minimizes transportation losses. We argue that SC should include all grids that transport whichever type of energy (e.g., even transportation or communication grids). Ultimately, we derive and discuss implications relevant for policy makers and research: We illustrate why regulation and market design should be aligned in a way that the resulting incentives within and across the different sectors support climate change goals.

1. Introduction

The growing share of intermittent renewable energy sources (RES) affects the stability of energy supply systems (Figueres et al., 2017; Markard, 2018), thereby leading to an increasing number of bottlenecks within the electricity grid, as well as increasing redispatch costs as part of congestion management (Lu et al., 2016; Plancke et al., 2016). While system operators used to build coal or nuclear power plants near locations of high energy demand to lower transmission costs (Dutton et al., 1974), today, locations for RES, especially wind farms or photovoltaic power stations, do not necessarily go along with locations of high energy demand (Brown et al., 2018; Krewitt and Nitsch, 2003). Since current efforts tend to counteract challenges of spatial energy transportation via cost-intensive electricity grid expansions (Alstone et al., 2015; Buijs et al., 2011), German system operators plan the construction of several high-voltage DC transmission lines between Germany's wind-intensive north and the energy-demanding south (Krewitt and Nitsch, 2003; Neuhoff et al., 2013). Hence, the increasing share of RES leads to spatial challenges (i.e. energy supply at the wrong location) and to temporal challenges (i.e. energy supply at the wrong time), while it requires an enhancement of loss minimizing, spatial energy transportation (Hansen et al., 2019a; Welder et al., 2018).

The concept of sector coupling (SC), under this term first discussed in the German-speaking region, receives increased international attention in recent academic literature (Bloess, 2019; Brown et al., 2018; Child et al., 2018; Maruf, 2019; Robinius et al., 2017). While SC locates itself in the research field of "100% renewable energy systems" (Hansen et al., 2019a; Lund and Mathiesen, 2009; Mathiesen et al., 2015), it encompasses the purposeful connection and interaction (i.e. coupling) of energy-demanding sectors (electricity, gas, heat, cooling, traffic, industry, buildings), including, for instance, the usage of power-to-gas technologies or gas-fired power plants (Lund et al., 2010; Mathiesen et al., 2015; Robinius et al., 2017). This mechanism requires the coupling of at least two sectors (e.g. electricity and gas). The concept of SC is also closely linked to the terms "smart energy systems" or "multi-energy systems" (Lund, 2018; Lund et al., 2016), as we elaborate in the following section.

The currently prevailing understanding of SC, however, focusses on counteracting temporal RES challenges (Robinius et al., 2017), while it does not encompass the dimension of spatial energy balancing

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comprehensively, which would mean to consider all grid infrastructures available. We, therefore, reflect that the current understanding of SC – which we hereinafter refer to as *inter-sectoral energy flow* – should only be considered as a subpart of a holistic SC. Since the ongoing challenges within energy supply systems require insights about the big picture (i.e. holistic solutions) (Hansen et al., 2019a; Kittner et al., 2017; Lund et al., 2017), we use the term *cross-sectoral energy flows* (i.e. the coupling of several sectors, thereby merging intra- and inter-sectoral energy flows) as a necessary building block of SC (Hansen et al., 2019a). As we deduce in the following, we understand SC as the multi-dimensional concept for governing cross-, inter- and intra-sectoral energy flows.

With this article, we underline the necessity of a holistic view on SC, thereby resulting in the inclusion of cross-sectoral energy flows. We illustrate how the integration of various grids (e.g. not only gas and heat but also streets and communication grids) may minimize losses of spatial energy transportation. We adopt the Traffic Assignment Problem (TAP), which is a modelling approach that is widely used in logistics (Roughgarden and Tardos, 2002). Based on technical losses, we take the physical and economic circumstances of the different grids into account to calculate the most efficient allocation of energy flows among coupled grids. Moreover, we derive and discuss wide-ranging implications that are relevant for policymaking and research; we also underline the important role of today's digital technologies (DT) for enabling efficient cross-sectoral energy flows (Hansen et al., 2019a).

2. Extending the boundaries of sector coupling

Among different (flexibility) options, research reflects the concept of SC as one of the most promising ones to deal with the intermittent feed-in of RES (Heffron et al., 2020; Robinius et al., 2017). Current research on SC mainly aims at counteracting the temporal challenges of an intermittent RES feed-in (Welder et al., 2018). Thus, it reflects two objectives: increasing flexibility of supply and demand (in terms of enabling the energy supply system to provide and consume different types of energy) and the application of storing technologies (Lund et al., 2010; Mathiesen et al., 2015; Robinius et al., 2017).

The German Association of Energy and Water Industries provides one of the most comprehensive understandings of current SC (Robinius et al., 2017): It reflects SC as the coupling of electricity, heat, and mobility, as well as the coupling of industrial processes and their respective infrastructures while increasing the flexibility of energy demand in the industrial, household and transport sectors. In reference to, and hence, also building on the research of Welder et al. (2018) and Hansen et al. (2019a), we find that existing research anticipates the above-introduced understanding of SC, but that scientific analyses and contributions often focus only on specific aspects, for example on specific countries, systems or technologies. While there are many review articles on SC and related concepts, we only give a brief overview on exemplary research in the following.

As already mentioned, the amount of research in the field of SC – and related concepts like "smart energy systems" or "multi-energy systems" – increased intensively within the last years (see, e.g., Mancarella (2014), Mathiesen et al. (2015), Lund et al. (2017), Lund (2018), or Guelpa et al. (2019), or Hansen et al. (2019a)). While the term smart energy systems has been used ambiguously and also for more specific components like the smart grid (Lund et al., 2017), the term multi-energy system has been used more consistently to describe the optimal interaction between different energy carriers (Gabrielli et al., 2018). In contrast to these all-embracing concepts, especially regarding the term multi-energy system, we use the term SC in order to more specifically describe the approach of adding sectors to the perception of energy systems which literature has not considered before. As a result, our proposed understanding of sector coupling may also enhance the scope of smart energy systems and multi-energy systems.

Concerning SC, research started to consider the coupling of the electricity sector and the gas resp. the heat sector to deal with the intermittent energy supply by RES (Böttger et al., 2014; Lund et al., 2010). Different power-to-gas resp. power-to-heat approaches enable the coupling of these two sectors: for an overview on these approaches, see Schiebahn et al. (2015) or Bloess et al. (2018). Over time, research started to reflect the coupling of the electricity and the transportation sector (Connolly and Mathiesen, 2014; Fridgen et al., 2016; Mathiesen et al., 2015). This approach is sometimes also referred to as vehicle-to-grid (Lund and Kempton, 2008; Mwasilu et al., 2014). Here, research reflects an increasing electrification of the transport sector by electric vehicles that may serve as consumers or storage of excess electricity (Geske and Schumann, 2018; Kahlen et al., 2018; Kempton and Tomić, 2005; Kester et al., 2018). Moreover, for example, Haupt et al. (2020) also consider so-called bidirectional charging, meaning that vehicles are also able to feed-in electricity back to the grid when needed. In the following, we consider energy flows between two coupled sectors that are enabled by power-to-X technologies as inter-sectoral energy flows. Based on these research streams, literature also considers the coupling of several sectors (multi-sector perspective), for example, the coupling of the electricity, the heat, and the transportation sector into one system (Bačeković and Østergaard, 2018; Dominković et al., 2016; Hansen et al., 2019b; Schiebahn et al., 2015). In this context, the review of Hansen et al. (2019a) finds that over 40% of studies on 100% RES systems include a multi-sector perspective.

With respect to this multi-sector perspective, recent literature introduces the term of cross-sectoral coupling (Hansen et al., 2019a; Lund, 2018; Lund et al., 2016) while Brown et al. (2018) link this term with the challenge of spatial energy transportation. This is in line with current research, underlining the need for SC to address holistic solutions (Hansen et al., 2019a) and the challenge of spatial energy transportation (Welder et al., 2018). So far, research exploits the potential of coupled sectors only to a limited extent: It reflects the transportation sector, for example, only as either source, sink, or storage for the electricity grid. However, in order to resolve the challenge of spatial energy transportation, research may also incorporate the grids of the coupled sectors; for the transportation sector, this would be, for example, streets or waterways. Indeed, research reflects the approach of using the grid of a coupled sector in some cases, but if so, the analyses remain within classic energy grids, such as the gas or heat grid (Lund, 2018; Robinius et al., 2018). In the following, we use the term cross-sectoral energy flow if several sectors and their grids are coupled, thereby merging intra- and inter-sectoral energy flows.

Applying a holistic view – including cross-sectoral coupling for spatial energy transportation – consequently leads to the reflection of all grids that transport energy in any form. We broaden the scope of the current perception of energy carriers and energy grids by including energy that is bound by its conversion to the consumer for its respective use: The power-to-product concept provides the idea of a purposeful usage of physical products as means of energy storage (Khripko et al., 2017; Schumm et al., 2018). Hence, we reflect grids that transport such products (i.e. supply chain networks or transportation grids, such as streets, waterways or railways) as additional grids that can transport energy (Watson et al., 2010). Extending this idea further to non-physical products (like digital commodities), we also reflect communication grids to be part of SC for the virtual transportation of energy as introduced by Fridgen et al. (2017): While energy consumption of data processing is on the rise (Jones, 2018) data centres connected via the internet can virtually transport energy by relocating the energy demand of (data) services (Fridgen et al., 2017). This potential is likely to increase due to an increasing usage of decentralised computing (e.g. in the upcoming fog or edge computing) (Shi et al., 2016).

The holistic view on SC provides an opportunity to establish new methods for minimizing losses or costs of spatial energy transportation by cross-sectoral energy flows, thereby leading to an enhanced definition of SC: Sector coupling is the multi-dimensional concept for governing cross-, inter-, and intra-sectoral energy flows of all grids that transport energy in any form, of energy transformation and storage, as well as for increasing the flexibility of energy supply and demand to tackle the challenges of a future energy supply system that is based on RES.

3. Modelling energy flows

For modelling energy flows, and later on efficiencies (cf. section 4), we adopt the TAP that research on logistics and routing optimization widely uses to calculate the most efficient allocation of (spatial) traffic flows (Sheffi, 1985). The TAP may be considered as a special case of the more general Multi-Commodity Flow Problem (LeBlanc et al., 1975). The simplest case applying the TAP is known as Pigou's example (Roughgarden, 2003), which illustrates a double edge parallel grid whose edges differ qualitatively, that is, the travel time a driver has to calculate, depends on the selected edge. The edges illustrate two streets that couple an origin node and a destination node. However, this take on the TAP can also be applied to research in other disciplines (Dafermos and Sparrow, 1969). We, therefore, use this concept to analyse the transport of energy without losing any explanatory power or validity by considering the loss minimization of spatial energy transportation. Our model aims at the minimization of total losses (i.e. the social optimum). This approach is referred to as a network with a central authority that determines flow patterns (here: cross-sectoral energy flows) (Dafermos and Sparrow, 1969).

We distinguish our work from the already existing energy and electricity system models by the objective of our model (Ringkjøb et al., 2018). give, for instance, a broad review of existing models for electricity and energy systems. Such models differ by methodology, temporal resolution, modelling horizon, geographical coverage and use different energy technologies in their scope (Ringkjøb et al., 2018). Still, these models have in common, that they aim to capture a variety of concurrent influencing factors (input) and to use optimization and simulation to create certain information as model output. Our model instead has the objective to only depict one specific aspect in the energy system, which concerns the spatial distribution of energy and to show the potential effects on transportation losses when multiple grids are considered for this purpose. While most of the existing models try to minimize system costs, we only refer to the technical minimization of energy losses, as the cost minimization depends on too many parameters and would, therefore, require a high number of simulation runs in order to derive generalizable results. Our model, however, may provide the input and impetus for more specified models and findings in the complex topic of SC. Thus, to deduce first insights of a holistic SC, we consider a simplistic setting (cf. Fig. 1). Our setting, therefore, encompasses four nodes (A, B, C, D), intra-sectoral energy flows ($\overline{AB}$ and $\overline{CD}$), inter-sectoral energy flows ($\overline{AC}$ and $\overline{BD}$) and cross-sectoral energy flows ($\overline{ABD}$ and $\overline{ACD}$).

In our setting, nodes A and C, as well as nodes B and D share the same geographical location. The two horizontal edges represent grid lines while bridging the spatial distance between locations I and II. By using grids of the particular sector, they enable spatial energy transportation. The differentiation of two nodes in the same location stems from energy conversion between sectors I and II (e.g. power-to-gas): The two vertical edges (i.e. $\overline{AC}$ and $\overline{BD}$) represent technical appliances for energy conversion by power-to-X technologies. Within the system boundaries of our setting, A represents an energy source that supplies a specific type of energy $(+E)$ (e.g. electricity) and D represents an energy sink $(-E)$ that demands another type of energy (e.g. gas). Furthermore, we consider one finite time step (*assumption I*).

Our model aims at minimizing losses of spatial energy transportation by cross-sectoral energy flows. Thus, we firstly analyse the losses of intra-sectoral (L_i or L_j) energy flows, as well as the losses of inter-sectoral energy flows (L_{ij}).

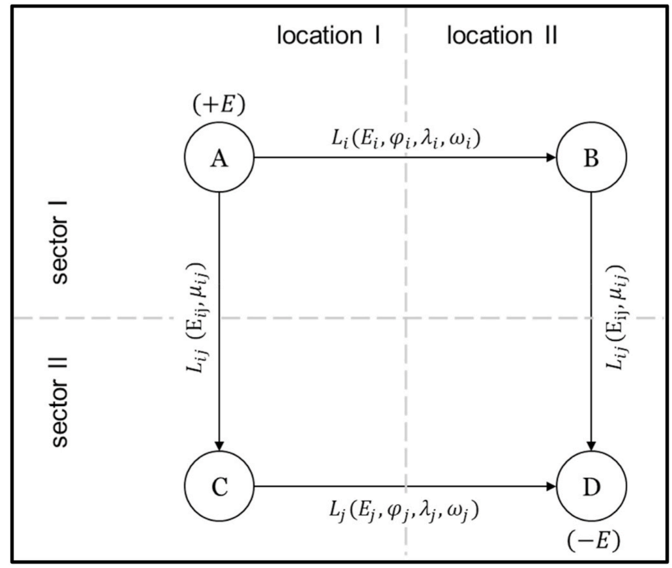

Fig. 1. General setting consisting of four nodes in two locations and two sectors; energy flows in sector I use grid i and energy flows in sector II use grid j. Losses of energy flows are provided by functions L_i, L_j, and L_{ij}.

3.1. Modelling intra- and inter-sectoral energy flows

For the purpose of our model, we describe losses of an intra-sectoral energy flow in grid (i) by a loss function ($L_i(E_i, \phi_i, \lambda_i, \omega_i)$) that is polynomial of second degree or lower (cf. equ. 1, *assumption II*). While L_i depends on the amount of energy transported (E_i) by grid (i), we define L_i as having a positive value for the defined domain of E_i (i.e. $E_i > 0$) (*assumption III*). Additionally, L_i depends on a set of factors: $\phi_i, \lambda_i, \omega_i$. While ϕ_i encompasses all quadratic dependencies and λ_i encompasses all linear dependencies (e.g. on distance and on operations or management costs), ω_i encompasses constant dependencies (e.g. investments) (Schaber et al., 2012). We generally describe losses in grids that are able to transport energy in equation (1):

$$L_i(E_i) = \phi_i E_i^2 + \lambda_i E_i + \omega_i \tag{1}$$

For the purpose of modelling intra-sectoral energy flows in our simplistic setting, we analyse essential dependencies of L_i on E_i (i.e. constant, linear and quadratic) by considering an electricity (e), gas (g), transportation (t), and communication grid (c).

In electricity and gas grids, physical formulae clearly encompass a quadratic dependency of L_i on E_i by $P = \rho * \frac{d}{A} * I^2$ as (technical) electrical power loss and $P = \frac{f*d}{A} * \frac{\rho}{2} * v^2$ as (technical) loss of pressure in a gas line (with specific loss factors (f) and (ρ), distance (d), and cross sectional area (A)). The (squared) energy intensity (I) reflects the amount of transported energy (E_e) in a certain time step in the electricity grid and the (squared) flow velocity (v) reflects the amount of transported energy (E_g) in a certain time step in the gas grid. Hence, according to the general formulation of $L_i(E_i)$ introduced by us, we define ϕ_e and ϕ_g, as well as λ_e and λ_g, to reflect $\rho * \frac{d}{A}$ or $\frac{f*d}{A} * \frac{\rho}{2}$, among others. ϕ_e and ϕ_g, as well as λ_e and λ_g have positive values.

For transporting energy or products by trucks on streets or by trains on railways (i.e. transportation grid, denoted by index t), or for transport via the internet (i.e. communication grid, denoted by index c), ϕ_t or ϕ_c are zero (Crainic, 2000; Fridgen et al., 2017; Gleick and Cooley, 2009). Furthermore, $\lambda_t > 0$ holds true, while we assume that the actual step-relation in transportation grids can be considered to be linear for large amounts of transported energy (*assumption IV*). We, furthermore, assume that λ_c is zero, because there is no significant impact of the transported quantity on technical losses in the internet (Fridgen et al.,

2017) (*assumption V*). Moreover, we assume that the following holds: $\lambda_c < \lambda_e < \lambda_g < \lambda_t$ (*assumption VI*). However, if there would be more complex structures of loss functions or dependencies of E_i on L_i, we would be able to apply the quadratic approximation according to Taylor's theorem.

For the purpose of our model (i.e. loss minimization by minimization problem), we consider marginal losses ($l_i(E_i)$). Hence, while we do not consider fixed costs or losses, we consider operational decisions (cf. Table 1):

$$l_i = \frac{\partial L_i}{\partial E_i} \tag{2}$$

According to our setting, the losses of inter-sectoral energy flows from grid *i* to grid *j* are provided by conversion losses ($L_{ij}(E_{ij}, \eta_{ij})$) with η_{ij} encompassing the energy conversion efficiency and ω_{ij} encompassing constant dependencies (*assumption VII*):

$$L_{ij} = E_{ij} * (1 - \eta_{ij}) + \omega_{ij} \tag{3}$$

While we note that the energy conversion efficiency (η_{ij}) may also be specific and may also depend on the amount of energy (E_{ij}), we assume η_{ij} to be constant for a certain energy range, which we reflect in the following (*assumption VIII*). Hence, the marginal loss of inter-sectoral energy flows $\left(\frac{\partial L_{ij}}{\partial E_{ij}}\right)$ is as follows: $l_{ij} = (1 - \eta_{ij})$.

3.2. Modelling cross-sectoral energy flows

Our modelling approach aims at a loss minimizing energy transportation by the loss minimizing allocation of cross-sectoral energy flows. Referring to Fig. 1, we introduce two paths ($p_1 = (ABD)$ and ($p_2 = (ACD)$) illustrating cross-sectoral energy flows, as well as the corresponding loss functions (L_{p_1} and L_{p_2}). p_1 (cf. equ. 4) and p_2 (cf. equ. 5) entail losses due to energy transportation (L_i and L_j) (i.e. intra-sectoral energy flows), as well as losses due to energy conversion L_{ij} (i.e. inter-sectoral energy flows):

$$L_{p_1}(E_i) = L_i(E_i) + L_{ij}(E_{ij}) = [\phi_i E_i^2 + \lambda_i E_i + \omega_i] + [(E_i - (\phi_i E_i^2 + \lambda_i E_i + \omega_i)) * (1 - \eta_{ij}) + \omega_{ij}] \tag{4}$$

$$L_{p_2}(E_i) = L_{ij}(E_{ij}) + L_j(E_j) = [(1 - E_i) * (1 - \eta_{ij}) + \omega_{ij}] + [(\phi_j((1 - E_i)*\eta_{ij})^2 + \lambda_j((1 - E_i) * \eta_{ij}) + \omega_j)] \tag{5}$$

As we reflect marginal losses for considering the loss minimizing allocation of cross-sectoral energy flows, we consider the following:

$$l_{p_1}(E_i) = \frac{\partial L_{p_1}(E_i)}{\partial E_i} = (l_i + (1 - l_i) * l_{ij}) \tag{6}$$

$$l_{p_2}(E_i) = \frac{\partial L_{p_2}(E_i)}{\partial E_i} = (-l_{ij} + (1 - l_{ij}) * l_j) \tag{7}$$

Moreover, we consider that energy flows can be limited due to capacity restrictions (π_i) within an edge (i): $\pi_i = \frac{max.\ capacity\ of\ the\ edge\ i}{total\ amount\ of\ energy\ supplied\ (+E)}$; $0 \leq \pi_i \leq 1$. This restriction can apply to any edge, for example, π_{ij} to edge (ij). By adopting this constraint to cross-sectoral energy flows, we derive the following restrictions for p_1 and p_2:

$$\pi_{p_1} = \min(\pi_i, \pi_{ij}) \tag{8}$$

$$\pi_{p_2} = \min(\pi_{ij}, \pi_j) \tag{9}$$

4. Minimizing losses of spatial energy transportation

In order to provide a general model that illustrates how cross-sectoral energy flows can minimize losses of spatial energy transportation, we adopt the TAP – a special case of the Multi-Commodity Flow Problem (LeBlanc et al., 1975) that research on logistics uses to calculate the most efficient allocation of (spatial) traffic flows (Roughgarden and Tardos, 2002; Sheffi, 1985).

4.1. Scenarios of a holistic understanding of sector coupling

We demonstrate two scenarios to illustrate possible cross-sectoral energy flows. Scenario 1 encompasses the coupling of an electricity grid with a transportation grid: Electricity is supplied in node A while energy in form of a product is demanded in node D. In line with Fig. 1, there are two paths: In p_1, production of the demanded product (i.e. energy conversion) occurs at location II while the required energy is transported via the electricity grid. In path p_2, energy conversion occurs at location I while p_2 transports the product via the transportation grid. l_{et} is constant and fixed for both paths. We analyse whether l_e and l_t intersect (note: we obviously consider that l_{et} decreases the amount of energy to be transported by grid t. However, we focus on the different loss function of grids in our analysis). If l_e and l_t intersect, it is loss minimizing to transport any additional amount of energy up to or above the intersection point via a coupled grid. We, therefore, show that l_e and l_t intersect: Two linear functions intersect at exactly one point when they are neither parallel nor identical in two-dimensional space. Thus, we firstly show that the marginal loss functions of scenario 1 are indeed linear (i.e. the proof of linearity $f(\sigma x) = \sigma f(x)$ must hold true):

$$Electricity\ grid:\ l_e(E_e y) = y * (2 * \phi_e * E_e + \lambda_e) = (y * 2 * \phi_e * E_e + y * \lambda_e)$$

$$Transportation\ grid:\ l_t(E_t y) = y * \lambda_t$$

The proof of intersection holds true if the functions have a different slope. Consequently, the following must hold true as well: $\frac{\partial l_e}{\partial E_e} \neq \frac{\partial l_t}{\partial E_t}$ and $\frac{\partial l_e}{\partial E_e} = 2 * \phi_e \neq 0 = \frac{\partial l_t}{\partial E_t}$. Since the proof of linearity holds for l_e and l_t, and since l_e and l_t have different slopes, the marginal loss functions intersect. According to assumptions IV and VI the intersection of l_e and l_t is within the first quadrant. The transport of energy beyond the intersection point via a transportation grid leads to increasing efficiencies.

The setting of scenario 2 is equivalent to scenario 1. Scenario 2 encompasses the coupling of an electricity grid with a communication grid. In line with assumption VI, $l_c < l_e$ (Fridgen et al., 2017) holds. Hence, the transportation of all energy via the communication grid minimizes losses in this case. However, the virtual transportation of energy via

Table 1
Marginal loss structures in exemplary grids of a holistic SC.

dependency of (L_i) on (E_i)	exemplary grid	loss functions (L_i)	marginal loss functions (l_i)
	energy grids		
quadratic	e.g. electricity grid	$L_e(E_e) = \phi_e E_e^2 + \lambda_e E_e + \omega_e$	$l_e(E_e) = 2*\phi_e*E_e + \lambda_e$
quadratic	e.g. gas grid	$L_g(E_g) = \phi_g E_g^2 + \lambda_g E_g + \omega_g$	$l_g(E_g) = 2*\phi_g*E_g + \lambda_g$
linear	transportation grids (e.g. streets)	$L_t(E_t) = \lambda_t E_t + \omega_t$	$l_t(E_t) = \lambda_t$
constant	communication grids (e.g. internet)	$L_c(E_c) = \omega_c$	$l_c(E_c) = \lambda_c = 0$

communication grids can only cover a small amount of overall energy transportation (Fridgen et al., 2017). Capacity restrictions play a key role in this example. According to equation (9), the capacity restriction of an energy transportation via the communication grid is defined as follows: $\pi_{p_2} = \min(\pi_{ec}, \pi_c)$.

4.2. Modelling loss minimizing allocations of cross-sectoral energy flows

In order to apply the principles of the TAP for calculating the loss minimizing allocation of cross-sectoral energy flows, we assume that our setting allows to regulate energy flows without any external interference (*assumption IX*). In line with the TAP, we consider a minimization problem. Here, α_i and α_j denote the share of energy transported via p_i and p_j (note: $0 \leq \alpha_i, \ \alpha_j \leq 1$, with $\alpha_{p_i} + \alpha_{p_j} = 1$).

$$\min\left(\alpha_{p_i} * L_{p_i} + \alpha_{p_j} * L_{p_j}\right) \ s.t. \ \alpha_{p_i} \leq \pi_{p_i} \tag{10}$$

$$\alpha_{p_j} \leq \pi_{p_j}$$

The solution of equation (10) as function of α_{p_i} or α_{p_j} provides the loss minimizing allocation of cross-sectoral energy flows for a scenario with two grids.

Our model for calculating the loss minimizing allocation of cross-sectoral energy flows also holds for scenarios with a coupling of n grids: It enables adding any additional path (i) as summand consisting of the product ($\alpha_{p_i} * L_{p_i}$). Equation (11) provides the loss minimizing allocation of cross-sectoral energy flows reflecting capacity restrictions (π_{p_i}) :

$$\min\left(\sum_{i=1}^{n}\left(\alpha_{p_i} * L_{p_i}\right)\right) \ s.t. \ \left(\alpha_{p_i}\right) \leq \pi_{p_i} \ , \ \sum_{i=1}^{n} \alpha_{p_i} = 1 \tag{11}$$

Fig. 2 illustrates an n-grid scenario with m-sectors.

Within an n-grid scenario, several cross-sectoral energy flows may occur. While the model we introduce is able to reflect real-world examples (i.e. a complex scenario with several grids and sectors that may not be symmetric (vertical and horizontal)), we illustrate one possible scenario via Fig. 2. In Fig. 2, the black solid lines illustrate actual energy flows and the black dotted lines illustrate possible energy flows. For instance, location II demands an amount of produced aluminium in node N_4. Aluminium production can either occur in location I ($\overline{N_1, N_3}$) and

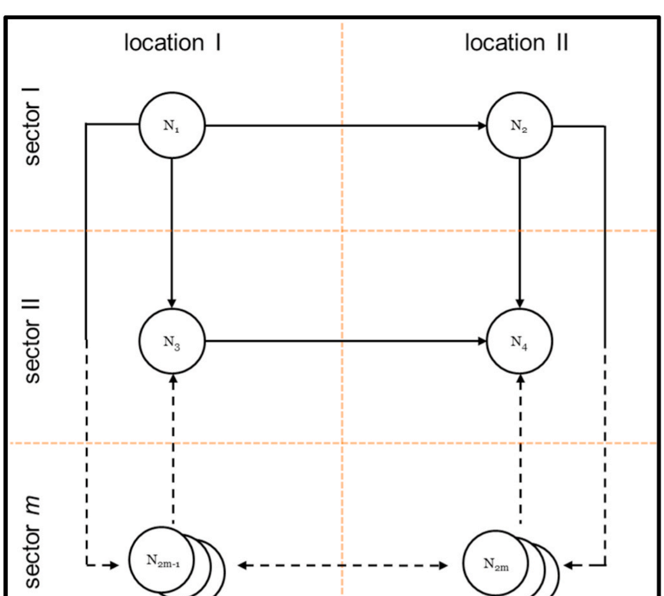

Fig. 2. Illustration of a scenario with n-grids of m-sectors.

aluminium is transported by a transportation grid ($\overline{N_3, N_4}$) to location II or production can also occur in location II ($\overline{N_2, N_4}$) while energy that is required for production is transported by an electricity grid ($\overline{N_1, N_2}$) to node N_2. Let $\overline{N_{2m-1}, N_{2m}}$ (e.g. sector III) be, for example, a communication grid with nodes N_{2m-1} *and* N_{2m} as data centres. While aluminium is produced in location II, data centres in sector m are able to transport energy demand (i.e. provide more energy) from location I to location II in order to avoid energy transport via sector I that may feature another loss function.

5. Discussion of a holistic understanding of sector coupling

From the holistic understanding of SC, several consequences derive. In the following, we introduce and discuss three exemplary consequences (C_1–C_3) that are relevant for both research and practice.

C_1: SC can minimize losses of a spatial energy transportation by reflecting cross-sectoral energy flows.

We illustrate the usage of different physical circumstances in grids to minimize losses of spatial energy transportation by reflecting cross-sectoral energy flows (cf. Fig. 3). According to assumption VI, Fig. 3 illustrates a loss minimizing allocation of cross-sectoral energy flows using four grids: The intersection points or capacity restrictions *(A, B, C)* determine the range of each section. Due to physical circumstances of the grids, a loss minimizing allocation of cross-sectoral energy flows may start with spatial energy transportation via the internet up to its capacity restriction, followed by the electricity and the gas grid, leading to transportation of any additional amount of energy by the streets grid. While there are conversion losses between the electricity, the gas, and the streets grids, we assume no losses between the internet and the electricity grid (*assumption X*). However, we strengthen the notion that the parameters of the different loss functions may differ from product to product.

For scenario 1, our analysis implies that energy transportation via an electricity grid up to the intersection point of l_e and l_g (cf. point B in Fig. 3) minimizes losses. Considering that there are losses in the case of cross-sectoral conversion, the actual shift between the electricity and the gas sector would take place for a higher amount of energy in point B'. The same applies for the conversion between the gas grid and the streets grid in point C, respectively C'. Beyond this intersection point, the spatial transportation of any additional amount of energy via a transportation grid minimizes losses. Consequently, the more energy-intensive the production of a demanded product is, the more relevant is spatial energy transportation via a transportation grid up to the point where no production plant would ever be opened at location 2, due to the plant's fixed costs. For scenario 2, assumptions V and VI defines that $l_c < l_e \ \forall E_c$. Consequently, there is no intersection point of l_e and l_c within the boundaries of our setting. Hence, starting spatial energy transportation via a communication grid up to its capacity restriction leads to increasing efficiencies. Even if the capacity of using communication grids for virtual spatial energy transportation is currently limited, its potential is likely to increase, due to both cloud computing (Fridgen et al., 2017) and decentralised fog computing (Bonomi et al., 2012). The additional consideration of η_{ij} would even increase the usage of p_2 in both scenarios, because η_{ij} decreases the amount of energy in p_2 that has to be spatially transported.

C_2: SC should include all grids that transport energy in any form.

Our proposed definition of SC leads to the consideration that all grids transporting energy in any form should be considered for comprehensive cross-sectoral energy flows. As illustrated in C_1, taking additional grids into consideration reduces losses of spatial energy transportation: Any additional grid provides the opportunity to increase the degrees of freedom of the minimization problem (cf. $0 \leq \alpha_i, \ \alpha_j \leq 1$). Hence, any additional grid should yield better results in the model. Thus, compared to grids encompassed by the previous understanding of SC (e.g. electricity, gas), the consideration of grids with a structurally different

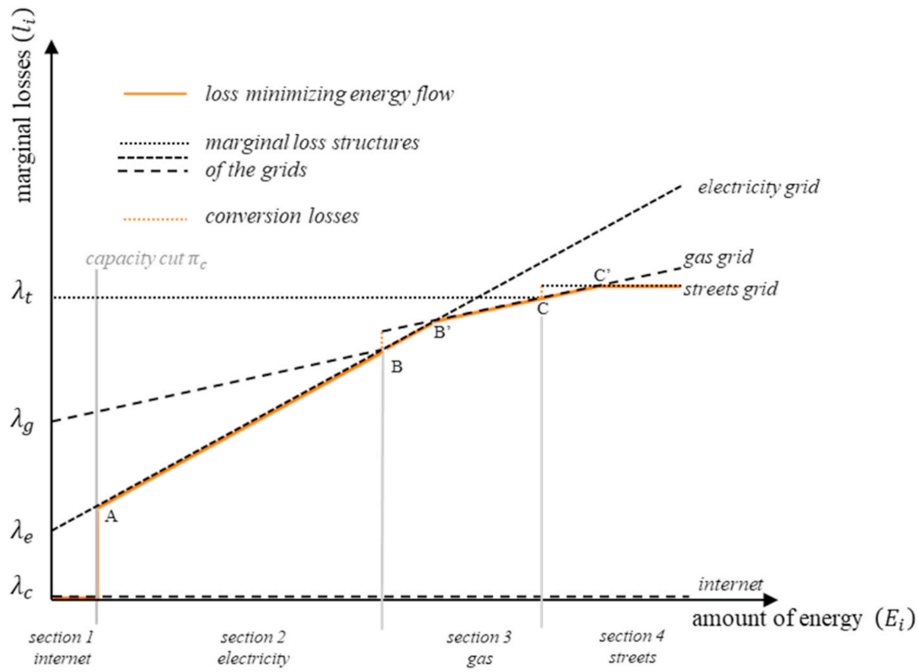

Fig. 3. Possible loss minimizing allocation.

dependency of losses on the amount of energy transported, is particularly interesting. In line with reality, our model implies that any clearly dominated grid may not be in operation (e.g. a decommissioned railway system). Of course, we reflect that the coupling of multiple grids results in smart, efficient control and governance mechanisms becoming increasingly important. In the same relevance as it applies to other energy flexibility options (Heffron et al., 2020; Körner et al., 2019), DT can be integrated into the system to ensure energy supply (Korkali et al., 2017) while serving as decision support for allocating cross-sectoral energy flows.

C_3: SC can reduce the planning of infrastructural (excess) capacities.

The currently prevailing, isolated planning (i.e. local optimization) of infrastructural capacities can lead to a misdimensioning of individual expansion projects (Buijs et al., 2011; Schaber et al., 2012). Based on the consideration of cross-sectoral energy flows, SC results in an integrative planning of expansion projects concerning all grids (i.e. overall optimization) – no matter to what extent SC is planned (e.g. at country, regional or city level). As mentioned above, the consideration of additional grids increases the degrees of freedom. This can reduce the cost-intensive misdimensioning of individual grids: In line with assumption VI and Fig. 3, SC may result, for example, in a decrease of the usage of the electricity grid, due to cross-sectoral energy flows. This reduces the necessity to expand the electricity grid (Lund, 2018; Lund et al., 2016). SC, furthermore, implies that considerations of spatial energy transportation should be increasingly integrated into location decisions of production plants, since energy transportation costs are of particular interest to the energy-intensive industry (cf. C_1).

6. Conclusion and policy implications

6.1. Policy implications

The proposed, holistic understanding of SC reduces the overall losses of spatial energy transportation by using transportation capacities best possible. Nevertheless, our perspective primarily presumes a technical perspective with a central control unit that is in charge for all energy flows in the coupled grids. In reality, this situation may apply for certain parts or levels of an electricity grid, like transmission or distribution system operators, who are in charge for spatially delimited electricity grids. Moreover, since the classical transportation grids (e.g. streets) have a different primary purpose than spatial energy transportation and may be organized on a more market-based shape than most electricity grids, a centralized coordination of cross-sectoral energy flows may not feasible in reality. As a result, the challenge for policy makers and regulation arises to establish a framework, that incentivizes a loss-minimizing energy transportation and the most efficient usage of grids.

Therefore, a respective framework needs to unify (subordinate) energy goals and economic incentives for individual actors in the complex network of energy grids. Here, energy goals describe the goals of or within an energy system on a national and transnational level to mitigate climate change (Bordoff, 2017). Regulation may therefore use, for example, the following instruments to implement a holistic understanding of SC in practice:

- Design of carbon dioxide fees and taxes in order to promote sustainable inter-sectoral energy flows and sustainable energy conversion technologies: For instance, the conversion of the primary energy source coal into electricity inherits higher carbon dioxide emissions per energy unit than a conversion from gas. Hence, an increase of fees or taxes for carbon dioxide would increase the competitive advantage of gas fired electricity generation. As a result, the path using the gas and electricity sector may be used to a higher degree than the path involving the coal and electricity sector.
- Design of fees for energy grid usage: As in most countries at least some energy grids are publicly owned, the design of fees for usage of these grids is another policy lever for direct incentives towards desired goals. Even if these grids are not publicly owned, there is strong regulation as can be seen, for example, in the case of electricity grids. Operating costs for these grids are usually reallocated to the users of the grid, while the calculation basis for grid feeds varies structurally among the grids: For instance, the amount of grid fees for electricity grid usage may depend on the total amount of energy consumed as well as the peak power (Woo et al., 2014), while fees for the usage of transportation grids (e.g. street tolls) often depend on the distance. Policy makers may take this aspect into account when designing grid fees, in order to promote the paths that spatially transport energy with least losses in alignment with energy goals.

- Governmental support programs for conversion technologies: Such support regimes like subsidies or funding of certain technologies may be another important lever. Depending on which sectors and technologies these programs focus on, efficiencies of inter-sectoral energy flows increase at certain points. This may lead to a change of the loss minimizing energy flow or path, that in turn influences grid usage and bottlenecks over all grids.

The challenge for policy makers is to orchestrate these instruments by designing incentivizing market mechanisms and – where necessary – support schemes in order to fulfil energy goals. A further challenge arises from the fact, that energy flows are not stopped by national borders (Brown et al., 2018). As there are different goals in the energy systems and different degrees of competition allowed, it is currently not feasible to build a consistent framework of incentives on a transnational level. Facing increasing efforts on climate change mitigation, also an increasing harmonization of energy policy and an international view on cross-sectoral energy flows is necessary.

Moreover, as we discuss that a holistic SC may minimize the losses of spatial energy transportation, policy makers may also notice that a holistic SC is able to reduce costs in infrastructural capacities (see C_3). While the isolated planning of infrastructural capacities can lead to a misdimensioning of grid expansion projects, our findings are in line with existing research (Lund et al., 2016): For example, Lund (2018) highlights detailed consequences on grid infrastructure when coupling the heat, the gas, and the electricity sector by a "smart energy systems pathway".

6.2. Conclusion, limitations, and future research

The previous view of research on grids used for spatial energy transportation with reference to SC often remains within classical energy grids, and hence, it does not exploit the coupled sectors' potential to its full extent. We, therefore, introduce cross-sectoral energy flows as way to provide new alternatives for spatial energy transportation by adopting all (coupled) grids that transport energy in any form (e.g. not only electricity and gas, but also transportation and communication grids). In order to illustrate the contribution of cross-sectoral energy flows to energy supply systems based on RES, we apply different loss structures in the coupled grids to a simplistic setting. Based on the TAP, we analyse if SC can minimize spatial energy transportation losses. Instead of trying to capture the entire energy system to a fully realistic extent, our research aims to introduce the specific aspect of using coupled grids for spatial energy transportation and to illustrate first implications. We then derive and discuss several consequences. Furthermore, we examine policy implications in particular (e.g. the considerable influence of grid fees on the loss minimizing energy flows). We find that a holistic SC is able to minimize losses of spatial energy transportation, and that is may also help to reduce costs of new grid capacities by cross-sectoral energy flows.

However, since the implications that we deduce are based on the consideration of marginal losses, their explanatory power is limited to operational decisions. Grid losses and cross-sectoral conversion efficiencies have only been considered with a strongly simplified model. As a result, our simplistic setting only allows for an initial evaluation of SC's benefits. The opportunities of SC to which we draw attention may also lead to new analyses: In contrast to our social-optimum based model, future research can analyse SC under circumstances of the actors' selfish behaviour within energy supply systems (Roughgarden and Tardos, 2002). Future research can, in addition, strengthen analyses of structural risks within grid couplings, especially the interdependencies of controlling and controlled grids (Buldyrev et al., 2010; Korkali et al., 2017).

On that basis, research can examine purposeful controlling mechanisms using today's DT to ensure energy supply via cross-sectoral energy flows. Moreover, regulation (e.g. increased/decreased grid fees) determines a grid's usage for spatial energy transportation. Furthermore, future research may also analyse varying conversion efficiencies of the coupled grids with respect to the amount of energy being converted. While SC promotes grid coupling by targeting a simplified change of the grid used for spatial energy transportation, the competition between coupled grids increases. Research and especially policy makers may, therefore, consider a grid's or a conversion technology's contribution to overall energy goals (e.g. the decarbonisation of the energy supply system) when designing, as well as considering, grid regulation and incentive structures – going as far as net neutrality in communication grids (Cheng et al., 2011).

CRediT authorship contribution statement

Gilbert Fridgen: Supervision, Methodology, Writing - review & editing. **Robert Keller:** Conceptualization, Resources, Writing - review & editing. **Marc-Fabian Körner:** Conceptualization, Investigation, Project administration, Writing - original draft, Writing - review & editing. **Michael Schöpf:** Conceptualization, Investigation, Writing - original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alstone, P., Gershenson, D., Kammen, D.M., 2015. Decentralized energy systems for clean electricity access. Nat. Clim. Change 5 (4).

Bačeković, I., Østergaard, P.A., 2018. Local smart energy systems and cross-system integration. Energy 151, 812–825. https://doi.org/10.1016/j.energy.2018.03.098.

Bloess, A., 2019. Impacts of heat sector transformation on Germany's power system through increased use of power-to-heat. Appl. Energy 239, 560–580.

Bloess, A., Schill, W.-P., Zerrahn, A., 2018. Power-to-heat for renewable energy integration: a review of technologies, modeling approaches, and flexibility potentials. Appl. Energy 212, 1611–1626. https://doi.org/10.1016/j.apenergy.2017.12.073.

Bonomi, F., Milito, R., Zhu, J., Addepalli, S., 2012. Fog Computing and its Role in the Internet of Things. Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing.

Bordoff, J., 2017. Withdrawing from the Paris climate agreement hurts the US. Nat Energy 2 (9), 1–3.

Böttger, D., Götz, M., Lehr, N., Kondziella, H., Bruckner, T., 2014. Potential of the power-to-heat technology in district heating grids in Germany. Energy Procedia 46, 246–253.

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., Greiner, M., 2018. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 160.

Buijs, P., Bekaert, D., Cole, S., van Hertem, D., Belmans, R., 2011. Transmission investment problems in Europe: going beyond standard solutions. Energy Pol. 39 (3).

Buldyrev, S.V., Parshani, R., Paul, G., Stanley, H.E., Havlin, S., 2010. Catastrophic cascade of failures in interdependent networks. Nature 464 (7291).

Cheng, H.K., Bandyopadhyay, S., Guo, H., 2011. The debate on net neutrality: a policy perspective. Inf. Syst. Res. 22 (1).

Child, M., Koskinen, O., Linnanen, L., Breyer, C., 2018. Sustainability guardrails for energy scenarios of the global energy transition. Renew. Sustain. Energy Rev. 91, 321–334. https://doi.org/10.1016/j.rser.2018.03.079.

Connolly, D., Mathiesen, B.V., 2014. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int. J. Sustain. Energy Plann. Manag. 1, 7–28. https://doi.org/10.5278/ijsepm.2014.1.2, 2014.

Crainic, T.G., 2000. Service network design in freight transportation. Eur. J. Oper. Res. 122 (2).

Dafermos, S.C., Sparrow, F.T., 1969. The traffic assignment problem for a general network. J. Res. Natl. Bur. Stand. B 73 (2).
Dominković, D.F., Bačeković, I., Ćosić, B., Krajačić, G., Pukšec, T., Duić, N., Markovska, N., 2016. Zero carbon energy system of south East Europe in 2050. Appl. Energy 184, 1517–1528. https://doi.org/10.1016/j.apenergy.2016.03.046.
Dutton, R., Hinman, G., Millham, C.B., 1974. The optimal location of nuclear-power facilities in the Pacific northwest. Oper. Res. 22 (3).
Figueres, C., Schellnhuber, H.J., Whiteman, G., Rockström, J., Hobley, A., Rahmstorf, S., 2017. Three years to safeguard our climate. Nat. News 546 (7660).
Fridgen, G., Keller, R., Thimmel, M., Wederhake, L., 2017. Shifting load through space: the economics of spatial demand side management using distributed data centers. Energy Pol. 109.
Fridgen, G., König, C., Häfner, L., Sachs, T., 2016. Providing utility to utilities: the value of information systems enabled flexibility in electricity consumption. J. Assoc. Inf. Syst. Online 17 (8).
Gabrielli, P., Gazzani, M., Martelli, E., Mazzotti, M., 2018. Optimal design of multi-energy systems with seasonal storage. Appl. Energy 219, 408–424.
Geske, J., Schumann, D., 2018. Willing to participate in vehicle-to-grid (V2G)? Why not! Energy Pol. 120, 392–401. https://doi.org/10.1016/j.enpol.2018.05.004.
Gleick, P.H., Cooley, H.S., 2009. Energy implications of bottled water. Environ. Res. Lett. 4 (1), 14009.
Guelpa, E., Bischi, A., Verda, V., Chertkov, M., Lund, H., 2019. Towards future infrastructures for sustainable multi-energy systems: a review. Energy 184, 2–21. https://doi.org/10.1016/j.energy.2019.05.057.
Hansen, K., Breyer, C., Lund, H., 2019a. Status and perspectives on 100% renewable energy systems. Energy 175, 471–480. https://doi.org/10.1016/j.energy.2019.03.092.
Hansen, K., Mathiesen, B.V., Skov, I.R., 2019b. Full energy system transition towards 100% renewable energy in Germany in 2050. Renew. Sustain. Energy Rev. 102, 1–13. https://doi.org/10.1016/J.RSER.2018.11.038.
Haupt, L., Schöpf, M., Wederhake, L., Weibelzahl, M., 2020. The influence of electric vehicle charging strategies on the sizing of electrical energy storage systems in charging hub microgrids. Appl. Energy 273, 115231. https://doi.org/10.1016/j.apenergy.2020.115231.
Heffron, R., Körner, M.-F., Wagner, J., Weibelzahl, M., Fridgen, G., 2020. Industrial demand-side flexibility: a key element of a just energy transition and industrial development. Appl. Energy 269, 115026. https://doi.org/10.1016/j.apenergy.2020.115026.
Jones, N., 2018. How to stop data centres from gobbling up the world's electricity. Nature 561 (7722).
Kahlen, M.T., Ketter, W., van Dalen, J., 2018. Electric vehicle virtual power plant dilemma: grid balancing versus customer mobility. Prod. Oper. Manag. 27 (11), 2054–2070.
Kempton, W., Tomić, J., 2005. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J. Power Sources 144 (1), 280–294. https://doi.org/10.1016/j.jpowsour.2004.12.022.
Kester, J., Noel, L., Zarazua de Rubens, G., Sovacool, B.K., 2018. Promoting Vehicle to Grid (V2G) in the Nordic region: expert advice on policy mechanisms for accelerated diffusion. Energy Pol. 116, 422–432. https://doi.org/10.1016/j.enpol.2018.02.024.
Khripko, D., Morioka, S.N., Evans, S., Hesselbach, J., de Carvalho, M.M., 2017. Demand side management within industry: a case study for sustainable business models. Procedia Manuf. 8.
Kittner, N., Lill, F., Kammen, D.M., 2017. Energy storage deployment and innovation for the clean energy transition. Nat. Energy 2 (9).
Korkali, M., Veneman, J.G., Tivnan, B.F., Bagrow, J.P., Hines, P.D.H., 2017. Reducing cascading failure risk by increasing infrastructure network interdependence. Sci. Rep. 7.
Körner, M.-F., Bauer, D., Keller, R., Rösch, M., Schlereth, A., Simon, P., Bauernhansl, T., Fridgen, G., Reinhart, G., 2019. Extending the automation pyramid for industrial demand response. Procedia CIRP 81.
Krewitt, W., Nitsch, J., 2003. The potential for electricity generation from on-shore wind energy under the constraints of nature conservation: a case study for two regions in Germany. Renew. Energy 28 (10).
LeBlanc, L.J., Morlok, E.K., Pierskalla, W.P., 1975. An efficient approach to solving the road network equilibrium traffic assignment problem. Transport. Res. 9 (5).
Lu, X., McElroy, M.B., Peng, W., Liu, S., Nielsen, C.P., Wang, H., 2016. Challenges faced by China compared with the US in developing wind power. Nat. Energy 1 (6).
Lund, H., 2018. Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 151, 94–102. https://doi.org/10.1016/j.energy.2018.03.010.
Lund, H., Kempton, W., 2008. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Pol. 36 (9).
Lund, H., Mathiesen, B.V., 2009. Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050. Energy 34 (5), 524–531.
Lund, H., Möller, B., Mathiesen, B.V., Dyrelund, A., 2010. The role of district heating in future renewable energy systems. Energy 35 (3).
Lund, H., Østergaard, P.A., Connolly, D., Mathiesen, B.V., 2017. Smart energy and smart energy systems. Energy 137.
Lund, H., Østergaard, P.A., Connolly, D., Ridjan, I., Mathiesen, B.V., Hvelplund, F., Thellufsen, J.Z., Sorknæs, P., 2016. Energy Storage and Smart Energy Systems. Int. J. Sustain. Energy Plann. Manag. 11, 3–14. https://doi.org/10.5278/ijsepm.2016.11.2, 2016.
Mancarella, P., 2014. MES (Multi-Energy Systems): an overview of concepts and evaluation models. Energy 65.
Markard, J., 2018. The next phase of the energy transition and its implications for research and policy. Nat. Energy 3 (8).
Maruf, M.N.I., 2019. Sector coupling in the north sea region—a review on the energy system modelling perspective. Energies 12 (22), 4298. https://doi.org/10.3390/en12224298.
Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P.A., Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K., Hvelplund, F.K., 2015. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl. Energy 145.
Mwasilu, F., Justo, J.J., Kim, E.-K., Do, T.D., Jung, J.-W., 2014. Electric vehicles and smart grid interaction: a review on vehicle to grid and renewable energy sources integration. Renew. Sustain. Energy Rev. 34, 501–516. https://doi.org/10.1016/j.rser.2014.03.031.
Neuhoff, K., Bach, S., Diekmann, J., Beznoska, M., El-Laboudy, T., 2013. Distributional effects of energy transition: impacts of renewable electricity support in Germany. Econ. Energy Environ. Pol. 2.
Plancke, G., Jonghe, C. de, Belmans, R., 2016. The implications of two German price zones in a European-wide context. European Energy Market (EEM), 2016. In: 13th International Conference on the IEEE.
Ringkjøb, H.-K., Haugan, P.M., Solbrekke, I.M., 2018. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew. Sustain. Energy Rev. 96, 440–459. https://doi.org/10.1016/j.rser.2018.08.002.
Robinius, M., Otto, A., Heuser, P., Welder, L., Syranidis, K., Ryberg, D., Grube, T., Markewitz, P., Peters, R., Stolten, D., 2017. Linking the power and transport sectors - Part 1: the principle of sector coupling. Energies 10 (7).
Robinius, M., Raje, T., Nykamp, S., Rott, T., Müller, M., Grube, T., Katzenbach, B., Küppers, S., Stolten, D., 2018. Power-to-Gas: electrolyzers as an alternative to network expansion–An example from a distribution system operator. Appl. Energy 210.
Roughgarden, T., 2003. The price of anarchy is independent of the network topology. J. Comput. Syst. Sci. 67 (2).
Roughgarden, T., Tardos, É., 2002. How bad is selfish routing? J. ACM 49 (2).
Schaber, K., Steinke, F., Mühlich, P., Hamacher, T., 2012. Parametric study of variable renewable energy integration in Europe: advantages and costs of transmission grid extensions. Energy Pol. 42.
Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., Stolten, D., 2015. Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany. Int. J. Hydrogen Energy 40 (12), 4285–4294. https://doi.org/10.1016/j.ijhydene.2015.01.123.
Schumm, G., Philipp, M., Schlosser, F., Hesselbach, J., Walmsley, T.G., Atkins, M.J., 2018. Hybrid heating system for increased energy efficiency and flexible control of low temperature heat. Energy Effic. 11 (5).
Sheffi, Y., 1985. Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Traffic Engineering Control. Prentice-Hall.
Shi, W., Cao, J., Zhang, Q., Li, Y., Xu, L., 2016. Edge computing: vision and challenges. IEEE Internet Things J. 3 (5).
Watson, R.T., Boudreau, M.-C., Chen, A.J., 2010. Information systems and environmentally sustainable development: energy informatics and new directions for the IS community. MIS Q. 34 (1).
Welder, L., Ryberg, D.S., Kotzur, L., Grube, T., Robinius, M., Stolten, D., 2018. Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy 158, 1130–1149. https://doi.org/10.1016/j.energy.2018.05.059.
Woo, C.K., Sreedharan, P., Hargreaves, J., Kahrl, F., Wang, J., Horowitz, I., 2014. A review of electricity product differentiation. Appl. Energy 114, 262–272.