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Electricity storage and transmission: Complements or substitutes?

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Abstract

Electricity from renewable sources often cannot be generated when and where it is needed. To deal with these temporal and spatial discrepancies, one frequently proposed approach is to expand storage capacities and transmission grids. It is often argued that the two technologies substitute each other, such that deploying one reduces the need for the other. Using a theoretical model, we show that storage capacities and transmission grids can also be complements if electricity system costs are minimized. We present the conditions that determine the kind of interdependence at specific storage locations: the characteristics of transmission congestion and the alignment of marginal generation costs between adjacent regions. By applying our theoretical insights to Italian power system data, we obtain empirical evidence that storage and transmission can act as either substitutes or complements. Planners of long-lasting and costly infrastructure can use the results to avoid design errors such as a misplacement of storage within the system.

Keywords: power grid, energy system, infrastructure planning, energy transition

JEL: C61, D24, L94, Q41, Q42

1 Introduction

Efforts to decarbonize the energy system lead to a significant increase in the renewable energy supply (RES), for instance, in the supply of wind and solar power (Mitchell 2016). Due to the fluctuating nature and decentralized production of many RES technologies, the real-time balancing of electricity demand and supply–both temporally and spatially–is a central challenge in the transformation of the energy system. This challenge can be addressed through a variety of system flexibility options. A prominent and widely discussed means of increasing flexibility is to increase the capacity of either electricity storage or transmission grids (e.g., The Economist 12 January 2017, Baidawi 31 November 2017, in The New York Times). Yet, there is no consensus among experts about the necessity of either, with some arguing that increased electricity storage would make most grid expansion obsolete, and others claiming the opposite (Schmid et al. 2017, Purvins et al. 2011).

Storage generally allows electrical energy to be shifted over time, whereas transmission systems allow energy to be shifted over distance. Although they both operate in different dimensions, the two technologies are not necessarily independent of one another but may exhibit different kinds of interdependencies. These are the focus of the present study. In the literature to date, some authors have claimed that the two substitute each other, while others have suggested that they act as complements. The former argue, for instance, that increasing storage capacity reduces network congestion (Denholm & Sioshansi 2009, MacDonald et al. 2016, Ghofrani et al. 2013, Abdurrahman et al. 2012, Xi & Sioshansi 2016). A real-world example supports this argument: American Electric Power (AEP) has deployed a 5 MW battery to mitigate congestion (Electricity Advisory Committee 2008). Others argue that optimal investment in storage is higher when additional transmission capacities are available (Haller et al. 2012). Furthermore, there are also ambiguous results on the kind of interdependencies that exist (Steinke et al. 2013, Brancucci Martinez-Anido & de Vries 2013, Zhou et al. 2014, Jamasb 2017). Factors cited in the literature as decisive for whether storage and transmission are complements are the share of RES in the system (Haller et al. 2012); the spatial distribution of supply, demand, and storage (Haller et al. 2012, Denholm & Sioshansi 2009, Ghofrani et al. 2013); the objective of the storage operation (Abdurrahman et al. 2012, Jamasb 2017); and volatility reduction of RES through its spatial aggregation through transmission (MacDonald et al. 2016).

Our study contributes to resolving these mixed findings. The theoretical model developed here provides clarity on the conditions that lead to storage and transmission being complements or substitutes[1]. The insights derived are highly relevant for current decision-making in the energy sector in general and in the field of energy policy in particular. While the expan-

[1] The literature defines (strategic) complements and substitutes in different ways (see, e.g., Hicks 1970, Bulow et al. 1985). Here, we employ the following: Assuming a cost-minimizing decision, we investigate whether a marginal increase in capacity of one of the technologies results in less (substitutes) or more (complements) optimal (i.e., cost-minimizing) capacity of the other. As an example, in the former case, an increased storage capacity decreases the need for network expansion and increases it in the latter.

sion of renewable energy generation has made rapid progress in recent years, the extension of the grid has been delayed in many countries, partially due to its low social acceptability, for instance, across the EU (Cohen et al. 2016) and in the USA (Cain & Nelson 2013). In addition, grid expansion requires large investments with long lead times. At the same time, the cost of storage is rapidly decreasing (Schmidt et al. 2017), and second-life batteries, e.g., from electric vehicles (cf. Neubauer & Pesaran 2011), could lead to an unexpected increase in available storage capacities. If the two options are substitutes, storage may be a (temporary) alternative to a constrained grid extension. Hence, deeper insights into the interdependence of the technologies are needed to enable the design of policies that will facilitate an efficient transition of the power system.

The remainder of this work is structured as follows. In Section 2, we present our two-region model, and in Section 3, we evaluate the optimal decisions for dispatch and capacity. We then derive a general condition for storage-transmission interdependence in Section 4 and specify the obtained insights for linear marginal generation cost (MGC) in Section 5.1 and two periods in Section 5.2. For the latter, we then derive discrete interdependencies for all feasible dispatch combinations. In Section 6, we discuss the model applicability and provide empirical evidence. Section 7 concludes.

2 Modelling approach

The ambiguous results in the literature to date indicate the limitations of empirical methods and large-scale numerical energy system models to comprehensively answer the research question at hand. In fact, most studies are confined to a specific parameter constellation represented by complex simulation models, such that the underlying drivers of the results are difficult to isolate.

We deploy an instructive cost-minimization model of a DC load flow power system that is analytically solved for two regions $i \in I$ and $I = \{1, 2\}$ as well as an arbitrary number of time slices $t \in T$. In addition to the variable descriptions given in the text, a comprehensive nomenclature is given in Appendix A. The minimal system costs are given by:

$$\min_{g_{i,t},l_t,s_{i,t},L,S_i} C = \sum_i \left[\sum_t c_i(g_{i,t}) + \psi S_i \right] + \gamma L, \tag{1}$$

subject to the local energy balance constraints

$$\forall t, i : R_{i,t} - g_{i,t} + s_{i,t} - \sigma l_t = 0, \text{ where } \sigma = \begin{cases} 1, & \text{for } i = 1, \\ -1, & \text{for } i = 2, \end{cases} \tag{2}$$

capacity constraints on transmission and storage

$$\forall t : |l_t| - L \leq 0, \tag{3}$$

$$\forall t, i : s^+_{i,t} + s^-_{i,t} - S_i \leq 0, \tag{4}$$

and balance of energy charged and discharged by the storage facilities

$$\forall i : \sum_t s^-_{i,t} - \eta \sum_t s^+_{i,t} = 0, \tag{5}$$

The optimization problem contains two stages of decision making, which reflect a sequential order: First, investment is possible in regional storage power capacities $S_i \geq 0$, which can be installed at unit costs ψ, and in transmission line capacity $L \geq 0$ at unit costs γ. Second, the dispatch decision concerns generation $g_{i,t} \geq 0$, which comes at generation costs $c_i(g_{i,t})$, storage charge $s^+_{i,t} \geq 0$, storage discharge $s^-_{i,t} \geq 0$, and transmission throughput l_t, and which has to satisfy the exogenous and inelastic residual demand $R_{i,t}$. A positive sign of l_t indicates that power is transmitted from region 2 to region 1, while a negative sign indicates the opposite power flow direction. For convenience, we write $c_{i,t} = c_i(g_{i,t})$ and marginal costs $c'_{i,t} = c'_i(g_{i,t})$. We assume that $c'_{i,t} > 0$ and $c''_{i,t} > 0$ (cf. Crampes & Moreaux 2010). Furthermore, we denote storage net charge as $s_{i,t} = s^+_{i,t} - s^-_{i,t}$ and its round-trip efficiency as $\eta < 1$.

Our theoretical approach has the advantage that we can generalize from currently available technologies and economic conditions. Thus, the model allows us to investigate the implications of both present and possible future costs (e.g., if storage becomes competitive at a large scale). To this end, however, we need to make some common abstractions from technical details such as the reduction to two regions (cf. Höffler & Wambach 2013, Oliver et al. 2014). However, each of the two regions may be interpreted as an aggregate of a network of multiple generation and load nodes connected via a single transmission line.

We follow Steffen & Weber (2013) in their assumptions about equal charge and discharge capacities as well as inelastic residual demand. Hence, we implicitly account for generation from renewable energies. Assuming an inelastic demand has the benefit that we can abstract from demand response programs and thereby isolate the pure effects of the transmission-storage interdependence. Instead of assuming that charging is a prerequisite for discharging, we impose an energy balance constraint on storage, i.e., storage has some initial energy level that must be restored eventually, and we ignore constraints on energy capacity (cf. Clack et al. 2015). Furthermore, we abstract from investment decisions in conventional generation capacity and assume perfect flexibility of generation (cf. Bertsch et al. 2016, Eisenack & Mier 2018, **?**).

3 Optimal dispatch and capacities

To obtain more insights and intuition about transmission and storage, in the following, we derive the optimal dispatch and capacity decisions. In Section 5, we will make direct use of the obtained conditions to specify our results about interdependence. We set up the Lagrangian for our optimization problem

$$\begin{aligned}\mathcal{L} = &\sum_{i\in I}\left[\sum_{t\in T} c_i(g_{i,t}) + \psi S_i\right] + \gamma L \\ &+ \sum_{i\in I, t\in T} \alpha_{i,t}(R_{i,t} - g_{i,t} + s_{i,t} + \sigma_i l_t) + \sum_{t\in T}\lambda_t(|l_t| - L) \\ &+ \sum_{i\in I, t\in T} \mu_{i,t}(s^+_{i,t} + s^-_{i,t} - S_i) + \sum_{i\in I}\xi_i(\sum_{t\in T} s^-_{i,t} - \eta\sum_{t\in T} s^+_{i,t}),\end{aligned} \tag{6}$$

where $\lambda_t, \mu_{i,t} \geq 0$ are the shadow prices for transmission capacity and storage capacity, $\alpha_{i,t}, \xi_i$ the ones for generation and stored electricity. Note that an explicit consideration of the two-stage structure is not necessary for a non-strategic cost minimization. Assuming strict non-negativity for generation, the Karush-Kuhn-Tucker conditions yield:

$$\forall i \in I, t \in T:$$

$$\frac{\partial\mathcal{L}}{\partial g_{i,t}} = c'_{i,t} - \alpha_{i,t} = 0 \quad \text{for } g_{i,t} > 0, \tag{7}$$

$$\frac{\partial\mathcal{L}}{\partial s^+_{i,t}} = c'_{i,t} + \mu_{i,t} - \eta\xi_i \geq 0, \quad s^+_{i,t} \geq 0, \quad \frac{\partial\mathcal{L}}{\partial s^+_{i,t}} s^+_{i,t} = 0, \tag{8}$$

$$\frac{\partial\mathcal{L}}{\partial s^-_{i,t}} = -c'_{i,t} + \mu_{i,t} + \xi_i \geq 0, \quad s^-_{i,t} \geq 0, \quad \frac{\partial\mathcal{L}}{\partial s^-_{i,t}} s^-_{i,t} = 0, \tag{9}$$

$$\forall t \in T: \frac{\partial\mathcal{L}}{\partial l_t} = \begin{cases} -c'_{1,t} + c'_{2,t} - \lambda_t = 0 & \text{for } l_t < 0, \\ -c'_{1,t} + c'_{2,t} + \lambda_t = 0 & \text{for } l_t \geq 0, \end{cases} \quad \frac{\partial\mathcal{L}}{\partial l_t} l_t = 0. \tag{10}$$

Under consideration of complementary slackness, for transmission, one of the following cases holds for each $t \in T$:

$$l_t = -L \quad \text{and} \quad c'_{1,t} \leq c'_{2,t}, \tag{11}$$

$$l_t \in (-L, L) \quad \text{and} \quad c'_{1,t} = c'_{2,t}, \tag{12}$$

$$l_t = L \quad \text{and} \quad c'_{1,t} \geq c'_{2,t}. \tag{13}$$

Hence, if flows are chosen optimally, at any point in time, transmission is either used below its capacity, with MGC equalized between the regions, or at its capacity limits (congestion), with a remaining spread of MGC depicted by the shadow prices (also cf. Bohn et al. 1984).

Now let us focus on optimal storage operation. Note that if strictly $s^+_{i,t} > 0, s^-_{i,t} > 0$, then complementary slackness of Eq. (8) and Eq. (9) implies $\xi_i = \frac{2\mu_{i,t}}{\eta - 1}$. Hence, the value of stored energy ξ_i has to be negative. Abstracting from negative values for power, i.e., $c'_{i,t} > 0$ we can conclude that storage will not charge and discharge simultaneously, i.e., $s^+_{i,t} s^-_{i,t} = 0$. Consequently, for each $i \in I, t \in T$, one of the following cases holds:

$$s^+_{i,t} = S_i,\ s^-_{i,t} = 0 \quad \text{and} \quad c'_{i,t} > \eta\xi_i, \tag{14}$$
$$s^+_{i,t} \in (0, S_i),\ s^-_{i,t} = 0 \quad \text{and} \quad c'_{i,t} = \eta\xi_i, \tag{15}$$
$$s^+_{i,t} = 0,\ s^-_{i,t} = 0 \quad \text{and} \quad \xi_i > c'_{i,t} > \eta\xi_i, \tag{16}$$
$$s^-_{i,t} \in (0, S_i),\ s^+_{i,t} = 0 \quad \text{and} \quad c'_{i,t} = \xi_i, \tag{17}$$
$$s^-_{i,t} = S_i,\ s^+_{i,t} = 0 \quad \text{and} \quad c'_{i,t} < \xi_i, \tag{18}$$

We can interpret these cases in the following way: For optimal storage operation, there are two specific MGC thresholds for each region. The higher threshold ξ_i depicts the minimum discharge cost, while the lower threshold $\eta\xi_i$ depicts the maximum charge cost. If MGC are between those two levels, storage is idle, as round-trip losses render void the benefits of any kind of operation. Otherwise, at times when MGC strictly exceed these thresholds, storage power plants operate at their maximum capacity. For dispatch, we thus derive the intuitive results that in general, the spread of MGC is reduced locally by transmission and temporally by storage (see Figure 1). Finally, we turn to the optimal capacity decisions. The Karush-Kuhn-Tucker conditions for optimal storage and transmission capacities are:

$$\frac{\partial \mathcal{L}}{\partial L} = \gamma - \sum_t \lambda_t \geq 0; \quad L \geq 0, \quad \frac{\partial \mathcal{L}}{\partial L} L = 0, \tag{19}$$
$$\forall i \in I : \frac{\partial \mathcal{L}}{\partial S_i} = \psi - \sum_t \mu_{i,t} \geq 0, \quad S_i \geq 0, \quad \frac{\partial \mathcal{L}}{\partial S_i} S_i = 0. \tag{20}$$

We denote the solutions to this equation system by L^*, S^*_i. If storage is installed at all in region i, then:

$$\psi = \sum_t \mu_{i,t} = \sum_{t \text{ with } s^+_{i,t} = S_i} (\eta\xi_i - c'_{i,t}) - \sum_{t \text{ with } s^-_{i,t} = S_i} (\xi_i - c'_{i,t}). \tag{21}$$

For transmission, we obtain the similar result that if there is transmission capacity at all,

$$\gamma = \sum_t \lambda_t = \sum_t |c'_{1,t} - c'_{2,t}|. \tag{22}$$

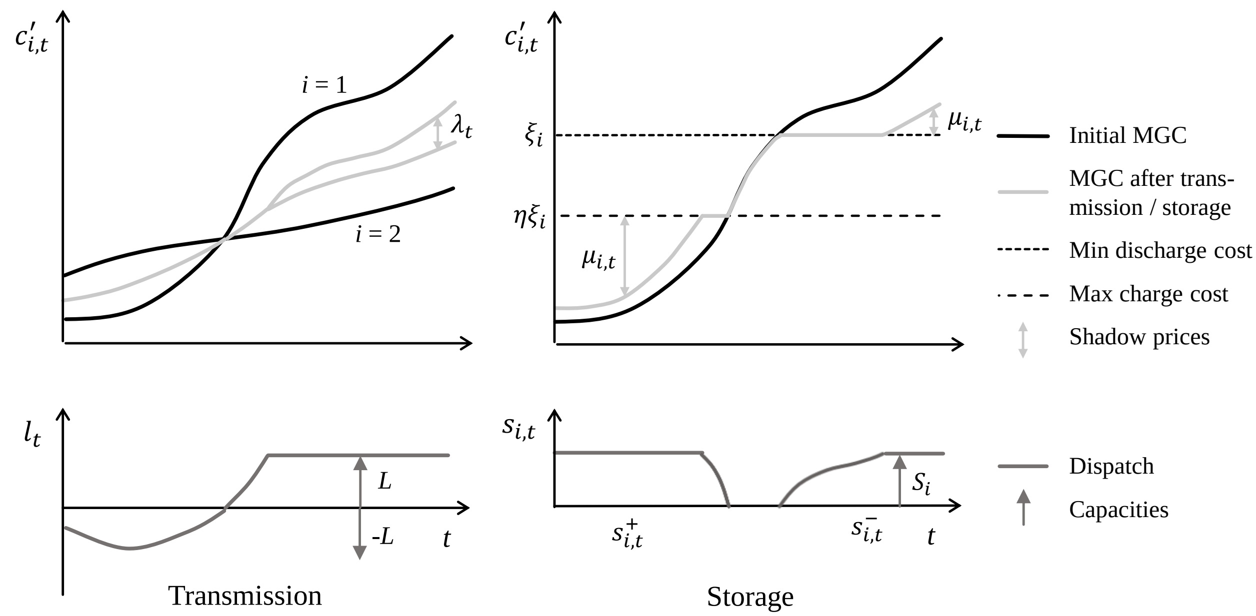

Figure 1: Optimal transmission flow and storage operation for exemplified MGC curves. Generally, both technologies cause MGC to converge. If operated at the capacity limit, shadow prices are the difference between regional MGC (transmission) or between the MGC and the respective charge/discharge threshold (storage).

It follows that if storage and transmission capacities are chosen optimally, the costs of additional capacity are in balance with the associated marginal reduction in dispatch costs, represented by the respective shadow prices. Thus, the sum of shadow prices across all time periods must be equal to the respective unit capacity costs. It follows the usual result that capacity constraints need to be binding at least once (cf. Steiner 1957). Otherwise, there would obviously be excess capacity, which cannot be optimal.

We summarize these findings in the following proposition.

Proposition 1. *Given the model described in Section 2, we find that optimally deployed and dispatched transmission and storage converge MGC in the local and temporal dimensions. Storage is idle if MGC are within a certain range. All capacities must operate at least once at their capacity limits, such that the cost of a marginal increase in capacity corresponds to the associated marginal dispatch cost savings.*

4 General complementarity and substitutability of storage and transmission

We are interested in how a marginal change in storage capacity affects the optimal choice (indicated by $*$) of transmission capacity. Hence, we need to evaluate $sgn(\mathrm{d}L^*/\mathrm{d}S_i)$ for all $i \in I$, which determines complementarity and substitutability of capacities. Note, however, that a reformulation of our successive argumentation would yield largely similar results for $sgn(\mathrm{d}S_i^*/\mathrm{d}L)$. We start by restating the optimization problem Eq. (1) to Eq. (5) in the following two-stage formulation with consecutive decisions on capacity and dispatch:

$$\min_L C = DC^*(L, S_1, S_2) + \psi \sum_{i \in I} S_i + \gamma L, \tag{23}$$

$$\text{s.t. } DC^*(L, S_1, S_2) = \min_{g_{i,t}, s_{i,t}, l_t} \sum_{i \in I, t \in T} c_{i,t}, \tag{24}$$

$$\text{s.t. Eq. 2} - \text{Eq. 5.} \tag{25}$$

In this formulation, storage capacities are exogenous and DC^* represents the minimal dispatch cost, such that generation must be at its optimal level $g_{i,t}^*$ for given capacities. The first-order condition for optimal transmission capacity becomes $\partial DC^*/\partial L = -\gamma$. The total differential then yields:

$$\frac{\mathrm{d}L^*}{\mathrm{d}S_j} = -\frac{\partial^2 DC^*/\partial S_j \partial L}{\partial^2 DC^*/\partial L^2}. \tag{26}$$

To obtain information on the kind of interdependence, we thus need to infer the signs of the second derivatives of DC^*. We assume that $\partial^2 DC^*/\partial L^2 \equiv DC_{LL}^* > 0$, i.e., decreasing cost savings for additional capacity. Later we prove this for the special cases of linear MGC (Section 5.1) and two periods (Section 5.2). Thus, if the cross-derivative $\partial^2 DC^*/\partial S_j \partial L$ is positive, an increase in storage capacity decreases the optimal transmission capacity and the two are substitutes, whereas for negative cross-derivatives, the two are complements[2]. This finding is formalized in the following proposition, which can be used to check for the kind of interdependence.

Proposition 2. *Electricity storage at node j complements optimally deployed transmission capacity if*

$$-\frac{\mathrm{d}L^*}{\mathrm{d}S_j} \propto \sum_{i \in I, t \in T} c''_{i,t} \frac{\mathrm{d}g_{i,t}^*}{\mathrm{d}L} \frac{\mathrm{d}g_{i,t}^*}{\mathrm{d}S_j} + c'_{i,t} \frac{\mathrm{d}^2 g_{i,t}^*}{\mathrm{d}L \mathrm{d}S_j} < 0, \tag{27}$$

[2]Assuming decreasing cost savings for additional storage capacity as well $DC_{S_j S_j}^* > 0$ allows for the same conclusion if storage capacities are optimally adjusted to exogenous transmission capacities.

(and substitutes it if this expression is positive), assuming decreasing cost savings for additional transmission capacity, i.e., $DC^*_{LL} > 0$.

Proof. See Appendix B. □

For applications, the criterion Eq. (27) can be numerically evaluated if sufficient data are available. It has several general implications. First of all, storage and transmission are not necessarily always complements or substitutes–this depends on the parameters of the specific case. Second, the kind of interdependence may differ from one region to the next. This depends on both the MGC and the optimal adjustment of generation in response to changes in capacities. If the optimal generation is independent of one of the capacities at all times and in a given region (e.g., if there is always over-deployment of at least one technology), storage and transmission will be neither substitutes nor complements.

The first term in the sum represents direct effects of the capacities on the optimal generation. If these have opposite signs (particularly in regions and at times with steeply rising marginal costs), the direct effects imply complementarity. This is the case if expanding one technology increases optimal generation while expanding the other reduces it. If the direct effects have the same sign, substitutability between the two is implied. The second term in the sum represents indirect effects, i.e., how the deployment of one capacity influences the marginal effect of the other. Effects that depress each other make complements more likely, while mutual reinforcement makes substitutability more likely.

Consider, for example, a situation in which a transmission line is congested at peak load. If storage is expanded in the region with higher MGC, it could charge cheaply during off-peak periods and discharge during peak periods, leading, ceteris paribus, to lower generation in the peak load periods. If transmission is expanded, there is again less generation during peak load periods in the more expensive region due to transport from the cheaper to the more expensive region. Overall, this situation thus implies the same signs, and hence a positive product of the direct effects, and substitutability.

On the other hand, indirect effects occur due to endogenous changes in the cost structure induced by changing capacities. Transmission grid expansion together with increased storage capacities may, for instance, induce more charging during off-peak periods if costs are decreased. In this case, the indirect effect is positive and substitutability is implied.

It seems intuitive, then, that both technologies typically reduce the spread between MGC, so that the direct effects tend to have the same sign. It might therefore be expected that a substitution between storage and transmission capacities is more common. This might also hold in the more general case with indirect effects.

5 Complementarity and substitutability with model specifications

5.1 Linear marginal generation cost

By utilizing the optimal dispatch results and considering MGC that are linear in $g_{i,t}$, our finding from Proposition 2 utilizing the results for optimal dispatch (Proposition 1) can be specified as follows.

Proposition 3. *Electricity storage at node j complements optimally deployed transmission capacity if*

$$-\frac{\mathrm{d}L^*}{\mathrm{d}S_j} \propto \sum_{i \in I, t \in T} c''_{i,t} \frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} \frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}S_j} < 0, \tag{28}$$

(and substitutes it if this expression is positive), assuming linear MGC, i.e. $\forall i \in I, t \in T : c'''_{i,t} = 0$.

Proof. See Appendix C. □

Compared to the previous criterion Eq. (27) the cross-derivatives and hence the indirect effects vanish. Thus, the kind of interdependence can be immediately derived from the direct effects if MGC are linear. In Proposition 4, we show that Eq. (28) also holds for non-linear MGC if we consider two time periods. There might be further conditions that are also sufficient.

5.2 Two periods

We introduce the two time periods *peak* and *off-peak*, which we denote by π and ω, respectively (two-period approaches can also be found in Gravelle 1976, Sioshansi 2014). By doing so, we can also specify our findings on interdependency (Proposition 2) and utilize the results for optimal dispatch and capacity (Proposition 1) to obtain the following proposition.

Proposition 4. *If $|T| = 2$, then electricity storage at node j complements optimally deployed transmission capacity if*

$$\frac{\mathrm{d}L^*}{\mathrm{d}S_j} = \sum_{t \text{ if } l_t = L \vee l_t = -L} \frac{1}{1 + \sum_i c''_{i,t}/c''_{j,t}} \sigma_j \frac{\mathrm{d}l^*_t}{\mathrm{d}L} \frac{\mathrm{d}s^*_{j,t}}{\mathrm{d}S_j} < 0 \tag{29}$$

(and substitutes it if this expression is positive). Note that this does not require $c'''_{i,t} = 0$.

Proof. See Appendix D. □

Note that due to $c''_{i,t} > 0$, the first fraction to the right of the equals sign is always positive and can thus only influence the magnitude of the effect. For simplification purposes, let us denote this fraction by $\theta_{j,t}$. The kind of interdependence is determined by the consecutive terms, which depict the direct effects in a specified manner. In fact, the term now depends only on the reaction of optimal storage operation and transmission flow to a change in their own respective capacities. As in the case of linear MGC, the indirect effects vanish.

To be able to specifically evaluate Eq. (29), we need to insert the solutions for optimal transmission and storage dispatch Eq. (11)–Eq. (16). Even for two periods, there are several combinatorial possibilities to dispatch storage and transmission. Without a loss of generality, we denote the period and region with the highest MGC as period π (peak) and region 1, such that

$$\forall i, t : c'_{1,\pi} \geq c'_{i,t}. \tag{30}$$

Given this definition and assuming strictly positive storage and transmission capacities that are smaller than or equal to their optimum, the following proposition holds:

Proposition 5. *For two periods and regions, the feasible combinations of storage and transmission dispatch reduce to exactly seven cases, which are given in Table 1.*

Table 1: Feasible dispatch cases for two periods and two regions. Only discharge is shown for storage.

Case	$s^-_{1,\pi}$	$s^-_{2,\pi}$	$s^-_{2,\omega}$	l_π	l_ω
(i)	ηS_1	ηS_2		L	L
(ii)	ηS_1	ηS_2		L	$-L$
(iii)	ηS_1	ηS_2		L	$\in (-L, L)$
(iv)	ηS_1	ηS_2		$\in (-L, L)$	L
(v)	ηS_1		ηS_2	L	L
(vi)	ηS_1		ηS_2	L	$-L$
(vii)	ηS_1		ηS_2	L	$\in (-L, L)$

Proof. See Appendix E. □

Now let us look at the characteristics of these cases. For two periods, storage always charges at the capacity limit and discharges all available energy. Following Eq. (30), storage in region 1 always discharges in the peak period, but storage in region 2 may be discharging in the off-peak period if $c'_{2,\omega} > c'_{2,\pi}$. Then we speak of *negatively aligned* MGC (v-vii), and of *positively aligned* MGC if $c'_{2,\pi} > c'_{2,\omega}$ (i-iv). Transmission flow can be characterized by the timing of congestion (e.g., only during peak (iii,vii), only during off-peak (iv), or during both periods), as well as the congestion direction (e.g., bidirectional (ii,vi) or unidirectional (i,v)). Table 2 provides an overview of the case characteristics.

Table 2: All feasible optimal dispatch cases (i)-(vii) for two periods. Cases are characterized by the transmission flow (i.e., the occurring congestion) and the storage operation, which is determined by the alignment of MGC.

	Transmission congestion			
	Both periods unidirectional	Both periods bidirectional	Period π (peak)	Period ω (off-peak)
Positively aligned MGC	(i)	(ii)	(iii)	(iv)
Negatively aligned MGC	(v)	(vi)	(vii)	-

Interestingly, Eq. (29) can be temporally disaggregated. At any particular time and and in any region, it is only different from zero if the transmission is congested and if the storage operation depends on its own capacity. Hence, the kind of interdependence can be unambiguously determined if, during all times of congestion, the product of the direct effects has the same sign. If that is not the case, it may also depend on the magnitude of the direct effects, and $\theta_{j,t}$. For all cases, we present the solution to Eq. (29) in Table 3. We obtain that ambiguity occurs only if the transmission is unidirectionally congested during both peak and off-peak periods (i,v). In these cases, for instance, storage in region 1 has a substitutive effect during the peak period and a complementary effect during the off-peak period. For illustration purposes, Figure 2 depicts the MGC configurations as well as the regionally and temporally disaggregated direct effects for all two-period dispatch cases.

Unambiguous complementarity only exists if MGC are positively aligned (ii-iv). In this case, charge and discharge patterns are equivalent for storage facilities in both regions. Thus, storage in one region has a similar influence on MGC as transmission (e.g., discharging at the outlet of a congested line) while storage of the other region has an opposing effect (e.g., discharging at the inlet of the line). For instance, if congestion occurs during the peak period (iii), storage in region 1 substitutes, while storage in region 2 complements transmission, and vice versa for off-peak congestion (iv). Such a configuration does not occur, however, if MGC are negatively aligned. Here, storage operation is temporally opposing, and storage and transmission are predominantly substitutes (vi, vii).

Elaborating further on $\theta_{j,t}$, the fraction $\sum_i c''_{i,t}/c''_{j,t}$ depicts a relationship between cost function curvatures, which represent the change of marginal cost curves. If this is known or can be closely approximated, the otherwise indistinct cases (i,v) can also be evaluated unambiguously. Furthermore, the influence of storage capacity on optimal transmission deployment at

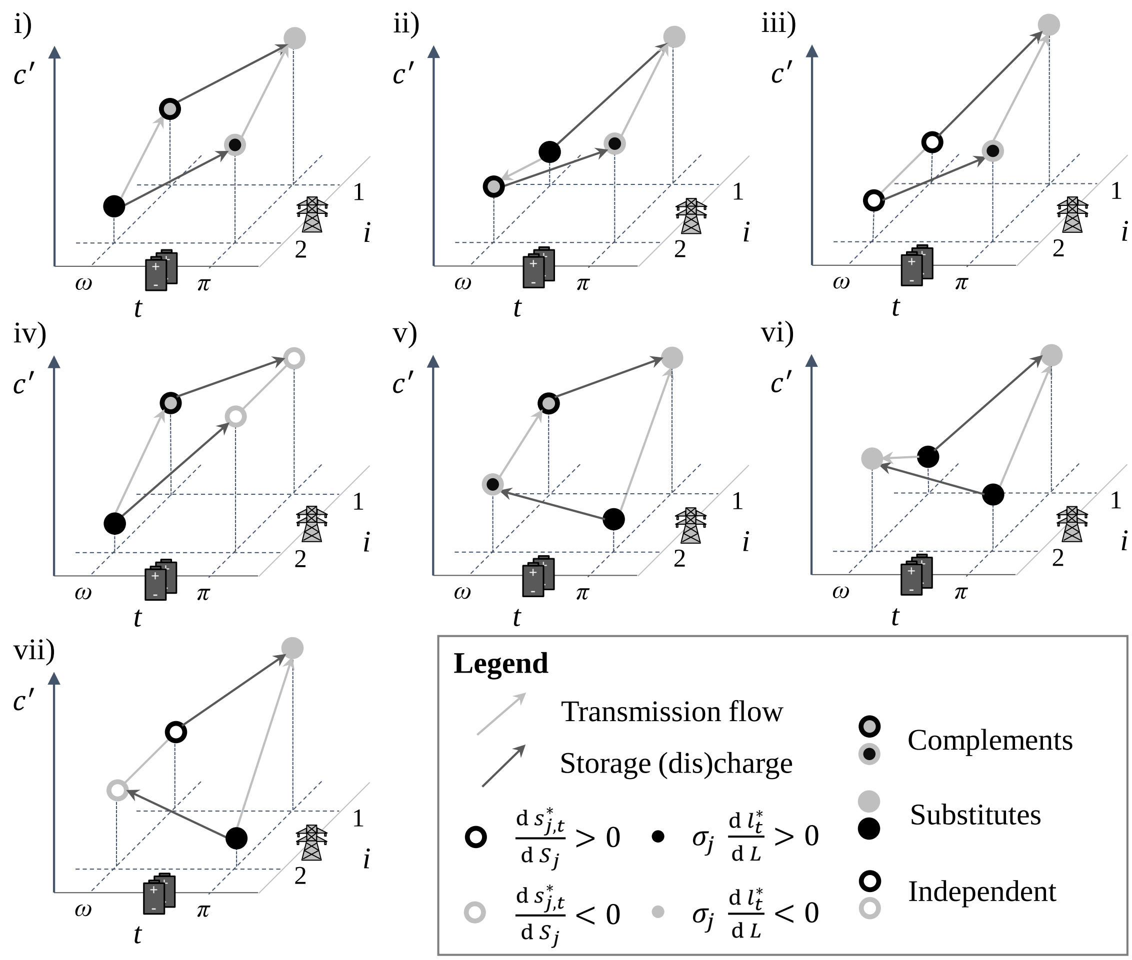

Figure 2: MGC configurations for the two-period dispatch cases. The direct effects of storage and transmission are represented by the outer and inner circle colors. The product of the effects implies the kind of interdependence: If the signs are the same, the two are substitutes, and if the signs are different, they are complements.

Table 3: Solution of Eq. (29) for the dispatch cases. Positive terms imply substitutability, negative terms complementarity of transmission and storage of a particular region.

	Storage at			
Case	Region 1		Region 2	
(i)	$\eta\theta_{1,\pi} - \theta_{1,\omega}$		$-\eta\theta_{2,\pi} + \theta_{2,\omega}$	
(ii)	$\eta\theta_{1,\pi} + \theta_{1,\omega}$	> 0	$-\eta\theta_{2,\pi} - \theta_{2,\omega}$	< 0
(iii)	$\eta\theta_{1,\pi}$	> 0	$-\eta\theta_{2,\pi}$	< 0
(iv)	$-\theta_{1,\omega}$	< 0	$\theta_{2,\omega}$	> 0
(v)	$\eta\theta_{1,\pi} - \theta_{1,\omega}$		$\theta_{2,\pi} - \eta\theta_{2,\omega}$	
(vi)	$\eta\theta_{1,\pi} + \theta_{1,\omega}$	> 0	$\theta_{2,\pi} + \eta\theta_{2,\omega}$	> 0
(vii)	$\eta\theta_{1,\pi}$	> 0	$\theta_{2,\pi}$	> 0

one particular point in time will be greater, the larger $c''_{i,t}$ is in the storage region compared to the other region.

Our last interesting finding involves the aggregate (not regional) interdependence of storage and transmission. For positively aligned MGC (i-iv), we see from Table 3 that the effects of the two regions are always exactly opposing. Hence, if generation cost curves in both regions are equivalent and MGC are linear ($\forall i, t : c'''_{i,t} = 0$), the effects cancel each other out and regionally aggregated storage capacity is independent of transmission.

6 Model applicability and empirical evidence

6.1 General

In the following, we discuss the general applicability of our model approach and provide some supporting evidence from an empirical example. While our approach is not appropriate to evaluate minor loop-flow-induced congestion, it is well suited to consider structural congestion on regional interconnectors. Additionally, it is applicable for dispatchable flows on, e.g., phase-shifter-controlled border connections or long-distance HVDC lines (IEA 2016). For an empirical application, it is convenient to apply the more specific Eq. (29) from the two-period case rather than the more general Eq. (27). By doing so, we can deduce the kind of interdependency directly from Table 3 without the need for much data, given that a two-period case can represent the real-world setup. Even though this neglects indirect effects and the influence of transmission capacity change on storage operation, it is reasonable to assume that storage operation is primarily affected by storage capacity (this holds, e.g., if the round-trip efficiency is high). We thus conjecture that the two-period approach can be applied appropriately to multi-period setups.

6.2 Evidence from Italian price data

To illustrate the applicability of our model, we analyse Italian regional day-ahead electricity price data for one year (11/2016-10/2017) provided online by [data] Gestore dei Mercati Energetici S.p.A (2017), and focus on the price relations between the bidding zones Northern Italy (NO) and Central-Northern Italy (CN), Central-Southern Italy (CS) and Sardinia (SA), as well as Central-Southern Italy and Southern Italy (SU). We assume that the obtained price data depict the temporal and regional MGC. When prices in the connected regions deviate, we can conclude that congestion occurs. Comparing price pairs during congestion with the mean prices of both regions allows us to determine peak and off-peak congestion, to match the data to the theoretical two-period dispatch cases, and to obtain the kind of interdependence between storage and transmission in the case at hand. Related price data scatter plots and descriptive statistics are given in Figure 3 and Appendix F.

The transmission between NO and CN is congested bidirectionally at about 7 % of all times with a power flow from CN to NO and 5 % in the opposite direction. In the former congestion case, prices are predominantly above the total mean, while in the latter, they are below. In addition, there exists a mostly positive alignment of regional prices, resembling the dispatch case (ii), characterized by bidirectional congestion. Hence, our model suggests that storage in NO substitutes, while storage in CN complements the transmission capacities between the two regions. The intuition is that in CN, charging during off-peak as well as discharging during peak times increases the regional price spread, while storage operation in NO reduces it. Higher (lower) price differentials, in turn, raise (reduce) the economic viability of interconnectors.

Transmission between regions CS and SA is congested at about 1 % of all times, resembling case (iv). Our model thus suggests that additional storage at CS would complement the interconnector of these regions, whereas storage at SA would substitute it. Between CS and SU, congestion occurs at around 11 % of all times. Prices in CS are always higher than in SU, and during congestion, both prices are generally either higher or lower than the mean, which indicates a positive alignment between them. These empirical findings resemble case (i), where during peak as well as off-peak times, the flow from SU to CS is congested. Hence, no clear conclusion about the complementarity of storage and transmission can be drawn from our model. In CS, storage substitutes transmission during peak times and complements it at off-peak times (and vice versa in SU). As we observe a substantially higher congestion mean price in CS relative to the mean of all times, which indicates congestion at predominantly peak times, substitutability of storage in CS and complementarity of storage in SU is implied.

In addition to the insight that storage on either end of a transmission line may induce different kinds of interdependence (cases ii-iv), we thus also find empirical evidence that storage in a single region can complement one transmission line and substitute another, which is the case for storage in CS and the lines to SA and SU. Such phenomena may occur if the congestion characteristics imply different dispatch cases for the two lines. As a consequence, no general statements about the kind if interdependence can be made, and it is crucial to determine which particular pair of capacities is being analysed.

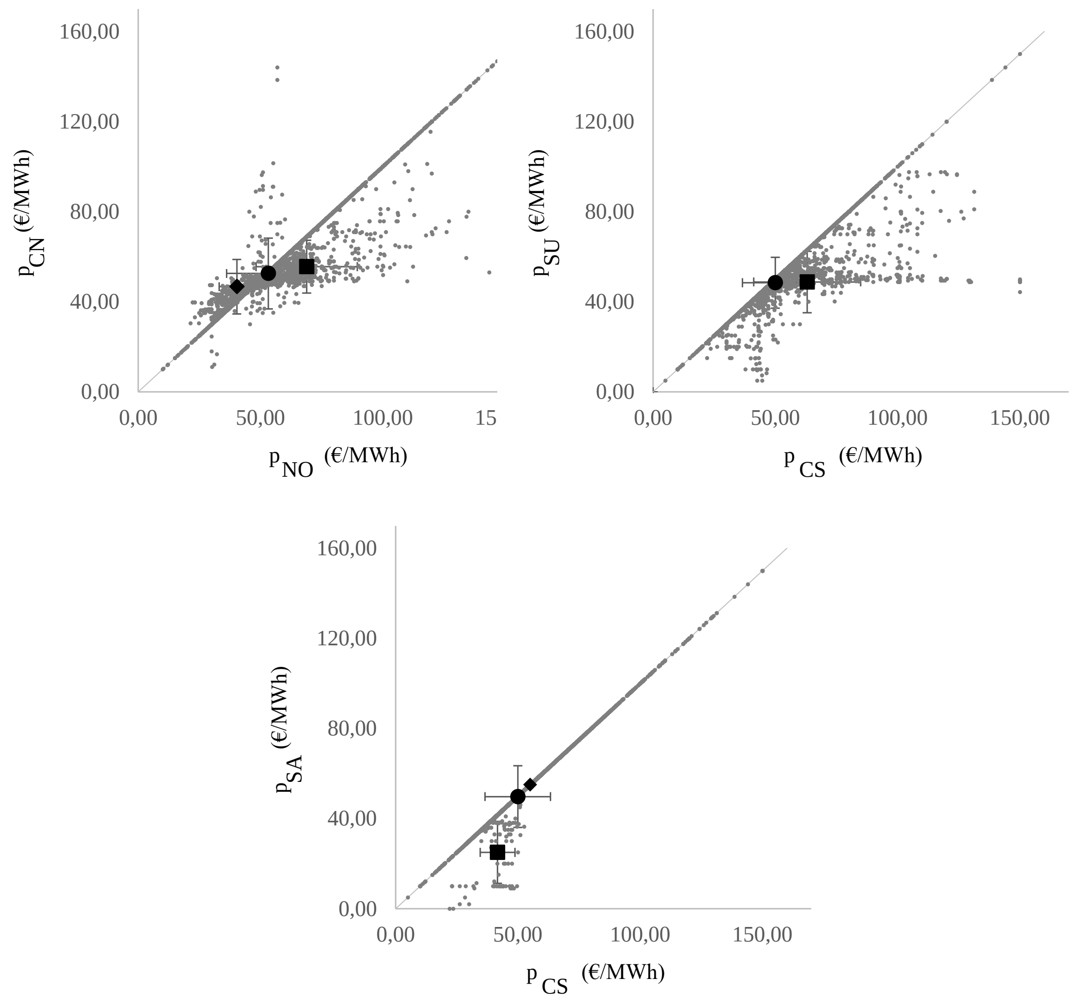

Figure 3: Day-ahead electricity price relation between adjacent Italian price zones. The diagonal indicates equal prices in both regions. Data points off the diagonal imply price differentials due to congestion. Bold points depict mean values (see Table 4) off all data points (●) as well as for unidirectional congestion (■, ♦). Data source: [data] Gestore dei Mercati Energetici S.p.A (2017).

7 Conclusion and outlook

Despite the rise in public interest and increased number of pilot projects in recent years using storage to cope with transmission challenges, scientific literature on the true nature of the interdependence of storage and transmission is still scarce. Often, the substitutability of transmission by storage is even assumed without rigorous analysis. This can lead to the conclusion that recent transmission network challenges simply solve themselves once sufficient storage capacity is being constructed.

Our study highlights the need for sensitivity towards the complex interdependence of the electricity grid and storage. The results obtained here show that storage and transmission are not generally substitutes or complements, but that their kind of interdependence differs between regions. Hence, an increased availability of storage may imply a higher transmission requirement. This may occur if loads between regions are positively aligned or if, more generally, the direct effects of storage and transmission on generation have different signs. In addition to the storage location, the timing of and flow direction during transmission congestion as well as the alignment of MGC are found to be key factors in determining the kind of interdependence. Furthermore, if storage capacities are deployed in two adjacent regions with similar and positively aligned cost structures, they are likely to exert opposing effects on the connecting transmission line, such that the overall effect on transmission is small.

The two-period model can be successfully applied to empirical price data to derive initial indications as to the effects of additional storage capacity on transmission requirements. However, the more general equation we provided here may also be utilized if comprehensive data are available. The insights derived may be used for future infrastructure planning and in considering various options for the development of power systems. Future research should attempt to validate our findings with a more complex empirical analysis, i.e., by evaluating the impact of complex networks and additional arrangement options for storage. Of further interest are second-best approaches that take into account different storage operation objectives and regulatory aspects such as incentives for a storage operation that benefits the system. Enhancing our understanding of spatio-temporal phenomena will improve the integration of renewable energies and thus help to guide a more efficient transition towards a resilient low-carbon society.

Appendix A Nomenclature

$t \in T$	Time index
$\pi,\ \omega$	Two-period time indices for peak and off-peak
$i \in I = \{1, 2\}$	Region index
$g_{i,t}$	Generation (net of storage and transmission, kW)
$s_{i,t} = s^+_{i,t} - s^-_{i,t}$	Net storage operation (charge minus discharge, kW)
l_t	Transmission flow at time t, $l_t > 0$ for flow from region 1 to 2 (kW)
S_i	Storage power capacity (kW)
L	Transmission capacity (kW)
C	Electricity system cost ($)
DC	Dispatch cost ($)
c_i	Generation cost functions (€)
ψ	Unit costs for storage power capacity (€/kW)
γ	Unit costs for transmission capacity (€/kW)
$R_{i,t}$	Residual load (kW)
η	Storage round-trip efficiency

Appendix B Proof of Proposition 2

From Eq. (24) we obtain the derivatives

$$\frac{\partial DC^*}{\partial S_j} = \sum_{i\in I, t\in T} c'_{i,t}(g^*_{i,t})\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}S_j}, \tag{31}$$

$$\frac{\partial DC^*}{\partial L} = \sum_{i\in I, t\in T} c'_{i,t}(g^*_{i,t})\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L}, \tag{32}$$

$$\frac{\partial^2 DC^*}{\partial L^2} = \sum_{i\in I, t\in T} c''_{i,t}\left(\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L}\right)^2 + c'_{i,t}\frac{\mathrm{d}^2 g^*_{i,t}}{\mathrm{d}L^2}, \tag{33}$$

$$\frac{\partial^2 DC^*}{\partial L \partial S_j} = \sum_{i\in I, t\in T} c''_{i,t}\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L}\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}S_j} + c'_{i,t}\frac{\mathrm{d}^2 g^*_{i,t}}{\mathrm{d}L\mathrm{d}S_j}. \tag{34}$$

Eq. (34) together with Eq. (26) yields the relation we want to show.

Appendix C Proof of Proposition 3

If MGC are linear, i.e., $c_{i,t}''' = 0$, the second derivative with respect to the capacities vanishes in Eq. (33) and Eq. (34) due to the following argument. The optimal dispatch decision is determined from the KKT conditions Eq. (2) – Eq. (5), Eq. (11) – Eq. (18). This equation system, which determines all dispatch decision variables, is generally linear, except Eq. (12), Eq. (15), and Eq. (17). Yet, for linear MGC, the latter three equations also become linear. If re-arranged, this right-hand-side vector of the equation system has, inter alia, the capacities L, S_1, S_2 as coefficients. Thus, the solution of the equation systems depends linearly on the capacities, so the second derivatives vanish. Furthermore, for Eq. (33) the remaining quadratic term thus induces $DC^*_{LL} \geq 0$. However, it can only be $DC^*_{LL} = 0$ if the optimal generation is independent of the transmission capacity. In this case, storage and transmission capacities are also independent and we can ignore this case for our analysis, reducing our focus to $DC^*_{LL} > 0$. Thus Eq. (26) can be rewritten as Eq. (28).

Appendix D Proof of Proposition 4

First, determine how $s^*_{i,t}$ depends on capacities. Due to $T = \{\pi, \omega\}$, we have $\forall i \in I$: $s^+_{i,\omega} = S_i, s^-_{i,\pi} = \eta S_i$ or $s^+_{i,\pi} = S_i, s^-_{i,\omega} = \eta S_i$. Thus, obviously $\forall i \neq j$: $\frac{\mathrm{d}s^*_{i,t}}{\mathrm{d}S_j} = 0$ and $\frac{\mathrm{d}s^*_{i,t}}{\mathrm{d}L} = 0$ and $\frac{\mathrm{d}s^*_{j,t}}{\mathrm{d}S_j} \in \{1, \eta\}$. Now let us turn to the derivatives of l^*_t. In cases in which transmission is constrained by capacity, $l^*_t = L$ or $l^*_t = -L$, with obvious derivatives. In the other cases with $l^*_t \in (-L, L)$, MGC are identical in both regions, resulting in the equation $c_1'(R_{1,t} + s^*_{1,t} - \sigma_1 l^*_t) = c_2'(R_{2,t} + s^*_{2,t} - \sigma_2 l^*_t)$. This can be rearranged such that l^*_t is a function of $R_{i,t}, S_i, \eta$, but not of L. Thus, for $l_t \in (-L, L)$: $\frac{\mathrm{d}l_t}{\mathrm{d}L} = 0$. As one consequence, we can write each $g^*_{i,t} = R_{i,t} + s^*_{i,t} - \sigma l^*_t$ alternatively as an additive separable function of S_i, S_j, L, which results in $\frac{\mathrm{d}^2 g^*_{i,t}}{\mathrm{d}L \mathrm{d}S_j} = 0$. Furthermore, we can simplify:

$$\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} = \frac{\mathrm{d}s^*_{i,t}}{\mathrm{d}L} - \sigma \frac{\mathrm{d}l^*_t}{\mathrm{d}L} = \begin{cases} -\sigma, & \text{if } l^*_t = L, \\ \sigma, & \text{if } l^*_t = -L, \\ 0, & \text{if } l^*_t \in (-L, L), \end{cases} \tag{35}$$

this directly yields

$$DC^*_{LL} = \sum_{i \in I, t \in T} c''_{i,t} \left(\frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} \right)^2 = \sum_{i \in I, t \text{ if } l_t = L \vee l_t = -L} c''_{i,t}, \tag{36}$$

so that $DC^*_{LL} > 0$.

We can now rewrite Eq. (29) with vanishing cross-derivatives and distinguish terms by the cases for optimal flow:

$$-\frac{\mathrm{d}L^*}{\mathrm{d}S_j} = \frac{1}{\sum\limits_{i,t \text{ if } l_t = L \vee l_t = -L} c''_{i,t}} \Bigg(- \sum_{i,t \text{ if } l_t = L} c''_{i,t} \frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} \sigma \frac{\mathrm{d}L^*}{\mathrm{d}S_j} - \sum_{i,t \text{ if } l_t = -L} c''_{i,t} \frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} \sigma \frac{\mathrm{d}(-L^*)}{\mathrm{d}S_j} - \sum_{i,t \text{ if } l_t = \in(-L,L)} c''_{i,t} \frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} \sigma \frac{\mathrm{d}l^*_t}{\mathrm{d}S_j} + \sum_{i,t} c''_{i,t} \frac{\mathrm{d}g^*_{i,t}}{\mathrm{d}L} \frac{\mathrm{d}s^*_{i,t}}{\mathrm{d}S_j} \Bigg). \tag{37}$$

Making use of Eq. (35), this simplifies to:

$$-\frac{\mathrm{d}L^*}{\mathrm{d}S_j} = \frac{1}{\sum\limits_{i,t \text{ if } l_t = L \vee l_t = -L} c''_{i,t}} \Bigg(\sum_{t \text{ if } l_t = L} \sigma^2 c''_{j,t} \frac{\mathrm{d}L^*}{\mathrm{d}S_j} + \sum_{t \text{ if } l_t = -L} \sigma^2 c''_{j,t} \frac{\mathrm{d}L^*}{\mathrm{d}S_j} - \sum_{t \text{ if } l_t = L \vee l_t = -L} c''_{j,t} \sigma \frac{\mathrm{d}l^*_t}{\mathrm{d}L} \frac{\mathrm{d}s^*_{j,t}}{\mathrm{d}S_j} \Bigg). \tag{38}$$

Since the sums over t for $l_t = L$ and $l_t = -L$ are equivalent, we can rearrange and solve for $\frac{\mathrm{d}L^*}{\mathrm{d}S_j}$ to obtain

$$\frac{\mathrm{d}L^*}{\mathrm{d}S_j} = \sum_{t \text{ if } l_t = L \vee l_t = -L} \frac{1}{1 + \sum_i c''_{i,t}/c''_{j,t}} \sigma_j \frac{\mathrm{d}l^*_t}{\mathrm{d}L} \frac{\mathrm{d}s^*_{j,t}}{\mathrm{d}S_j}, \tag{39}$$

the relation we want to show.

Appendix E Proof of Proposition 5

From the optimal storage operation, it follows that storage charges at the capacity limit during the period of the lower price. Since we consider only two periods and $\eta < 1$, it cannot reach the capacity limit while discharging. For region 1 it follows from Eq. (30) that $s^-_{1,\pi} = \eta S_1, s^+_{1,\omega} = S_1$. However, the charge and discharge timing is less straightforward for region 2, because the period of higher MGC is not determined. Hence, we can have $s^-_{2,\pi} = \eta S_2, s^+_{2,\omega} = S_2$, i.e., a discharge at π, or $s^-_{2,\omega} = \eta S_2, s^+_{2,\pi} = S_2$, i.e., a discharge at ω.

Thus, we obtain two possible cases with respect to optimal storage dispatch. For the former, it means that marginal costs between regions are positively, for the latter negatively aligned ($c'_{2,\pi} > c'_{2,\omega}$ or $c'_{2,\pi} < c'_{2,\omega}$). Note that for the marginal case $c'_{i,\pi} = c'_{i,\omega}$, optimally no storage capacity would be deployed, such that $S_i = 0$ and $\forall t : s^*_{i,t} = 0$. We can therefore ignore this case.

We now turn our attention to the transmission flow. From Eq. (11)– Eq. (13) we know that there are three possible flows for each time period and hence nine combinatorial solutions. Yet, optimality excludes a flow from a region with higher to one with lower MGC, and hence $l_\pi \neq -L$. Furthermore, we have shown above that the capacity must be binding at least once. We can thus drop the combination $l_\pi \in (-L, L), l_\omega \in (-L, L)$. Also, if the transmission is uncongested for $t = \pi$, region 1 is not clearly defined from Eq. (30) because MGC are the same in both regions. Again, without loss of generality, we can define region 1 such that $l_\omega = L$. By doing so we omit the case of $l_\pi \in (-L, L), l_\omega = -L$, which is equal to the case $l_\pi \in (-L, L), l_\omega = L$ with a reverse region definition. Four cases remain with respect to optimal flow: $l_\pi = L$ together with $l_\omega = L$ or $l_\omega \in (-L, L)$ or $l_\omega = -L$ and $l_\pi \in (-L, L)$ with $l_\omega = L$.

Finally, we can combine two cases for storage operation and four cases for transmission flow. Yet, one of the eight combinations can still be excluded. In fact, $l_\pi \in (-L, L)$ implies that $c'_{1,\pi} = c'_{2,\pi} \geq c'_{2,\omega}$. Hence, an optimally operated storage facility can only charge at $t = \omega$ and discharge at $t = \pi$, such that the flow $l_\pi \in (-L, L)$ is not feasible with storage operation $s^-_{2,\omega} = \eta S_2, s^+_{2,\pi} = S_2$. This leaves us with the seven dispatch cases given in Table 1.

Appendix F Descriptive statistics for Italian regional prices

Table 4: Mean day-ahead prices (p_i) and standard deviations (sd) (€ /MWh) for Italian regions North (NO), Central North (CN), Central South (CS), South (SU), and Sardinia (SA). Values are computed for all hours of one year (11/2016-10/2017) and for hours with transmission congestion, i.e., $p_1 \neq p_2$. Data source: [data] Gestore dei Mercati Energetici S.p.A (2017).

Regions i	All			$p_1 > p_2$			$p_2 > p_1$		
	N	$p_1 \pm sd$	$p_2 \pm sd$	N	$p_1 \pm sd$	$p_2 \pm sd$	N	$p_1 \pm sd$	$p_2 \pm sd$
1–NO, 2–CN	8760	53,22 ± 17,01	52,56 ± 15,74	653	68,91 ± 20,69	55,6 ± 11,7	461	40,33 ± 7,21	46,7 ± 12,07
1–CS, 2–SU	8760	49,97 ± 13,38	48,44 ± 11,28	944	63,02 ± 21,85	48,81 ± 13,66	0		
1–CS, 2–SA	8760	49,97 ± 13,38	49,78 ± 13,67	100	41,67 ± 7,1	25 ± 13,75	1	55	55,08

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