An incentive scheme for storage investments to help reduce carbon emissions

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Abstract

Transmission companies (TRANSCOs) can be induced to act in a way that serves the public interest through incentive regulation. Here, we show how recently proposed schemes for network expansion can be adapted to support investments in grid-scale energy storage performed by TRANSCOs, while steering their decision-making process towards the environmental goal of reducing carbon emissions. A bilevel program has been developed to test the proposed mechanism, where the upper level represents a TRANSCO's investment decision problem subject to incentive regulation, whereas the lower level is a wholesale market clearing problem. Results based on actual data from the Italian day-ahead market show that the proposed approach can significantly help improve carbon abatement, reaching 190 kgCO2 per MWh of energy storage capacity deployed.

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1. Introduction

Transmission companies (TRANSCOs) can be subject to different incentive mechanisms and regulatory frameworks. In a centralised approach, an independent authority identifies system needs through cost-benefit analyses and informs TRANSCOs on how network capacity should be expanded. By contrast, in a merchant approach (Joskow & Tirole, 2005), a TRANSCO independently invest in network assets and is remunerated through transmission rights. One of the problems of the first approach is the asymmetry of information between the central planner and TRANSCOs, as the latter usually have better knowledge of technologies, market conditions and costs. By contrast, the merchant paradigm is subject to a significant conflict of interest, as TRANSCOs are private firms that pursue self-interests and, e.g., may withhold capacity to increase profit, while a central planner aims at public goals, such as the overall increase of social welfare. In addition, TRANSCOs usually are monopolistic firms, which makes the problem even more complex. An alternative approach to both centralised and merchant methods is *incentive regulation* (Vogelsang, 2020), in which a regulator tries to induce a monopolistic TRANSCO to use its superior information in a way that serves the public interest.

The concept of incentive regulation can be traced back to Loeb & Magat, (1979) and Vogelsang & Finsinger, (1979). The former proposed an approach where monopolistic utilities receive a subsidy equal to the consumer surplus generated by their investments. The drawback of this approach is that a regulator has to estimate the demand for public utility services. Instead, Vogelsang & Finsinger, (1979) suggested constraining the firm's pricing such that it would break even if it sold the same quantities of output of the previous period, converging to Ramsey prices over time (Ramsey, 1927). The drawback of this method is that it can be severely exposed to strategic cost manipulations by the firm. A step forward was the introduction of the concept of a two-part tariff (Hogan et al., 2010; Vogelsang, 1989, 2001), where the revenues of a monopolistic TRANSCO depend on both a regulated fixed fee and usage charges. Recently, Hesamzadeh et al., (2018) extended this approach by proposing the HRGV model, where the fixed fee is a function of the surplus that the investment creates, while the usage fee depends on the merchandising surplus. The strength of this approach is that it does not rely on subsidies and the surplus can be directly inferred from the market. However, as detailed in Section 2.1, the drawback of this scheme is that it hands the whole benefit created by the TRANSCO investments to the TRANSCO itself, leaving consumers and producers at their original benefit level, which might be considered unfair from a distributional perspective.

In this paper, we discuss a novel scheme, based on the HRGV model, to support grid-scale energy storage investments performed by TRANSCOs, while (i) trying to align their profit-driven self-interests with the public goal of reducing carbon emissions, and (ii) dealing with the fairness concern. The model is structured as a bilevel program, where the upper level represents a TRANSCO long-term investment problem subject to incentive regulation, whereas the lower level represents a wholesale market clearing performed by an independent system operator. Test cases based on actual data from the Italian day-ahead market show that the proposed approach can significantly help reduce carbon emissions.

2. Methodology

2.1. A brief review of the HRGV scheme

The HRGV model assumes the presence of a monopolistic TRANSCO that owns the transmission network and bears all investment costs. The TRANSCO's revenues are based on a two-part tariff scheme, with (i) a fixed fee subject to a regulatory constraint, and (ii) a usage fee equal to the merchandising surplus. Mathematically, the HRGV mechanism can be described through the following bilevel model:

$$\max_{\Phi_t, b} \sum_{t>0} \mathrm{M_t}(\mathrm{x_t^*}, \pi_t^*) + \Phi_t - \mathrm{I_t}(b) \qquad (1a)$$

s.t.

$$\Phi_t \le \Phi_{t-1} + \Delta \mathrm{V_t} \qquad \forall\, t \in T \qquad (1b)$$

$$(\mathrm{x_t^*}, \pi_t^*) = \arg \max_{\mathrm{x_t} \in \mathcal{X}_t(\mathrm{b})} \mathrm{U}_t - C_t \qquad \forall\, t \in T \qquad (1c)$$

The objective function of the upper-level problem (1a) maximises the profit of the TRANSCO, which depends on three components: (i) the merchandising surplus $\mathrm{M_t}$ (i.e. the difference between the amount paid by consumers and the one collected by generators); (ii) the fixed fee Φ_t; and (iii) the investment costs $\mathrm{I_t}(b)$. The term b represents the investment decisions. Constraint (1b) is the regulatory incentive cap, which limits the fee Φ_t at time t to the amount of the previous period Φ_{t-1} plus the change in surplus $\Delta \mathrm{V_t} = \mathrm{V_t} - \mathrm{V_{t-1}}$ of network users (i.e. consumers and generators). Note the trade-off between the merchandising surplus $\mathrm{M_t}$ and the fixed fee Φ_t. Indeed, withholding capacity to increase $\mathrm{M_t}$ (as a TRANSCO would do in a pure merchant approach), would likely decrease the user surplus $\Delta \mathrm{V_t}$ and, due to (1b), the fixed fee Φ_t.

The lower-level problem (1c) represents the market clearing performed by a market operator, which depends on consumer utilities U_t and generator costs C_t. The values $\mathrm{x_t^*}$ and π_t^* are the optimal dispatched quantities and clearing prices, respectively, where $\mathcal{X}_t(b)$ is the lower-level feasible set that depends on the upper-level TRANSCO investment decisions b.

The key property of the HRGV mechanism can be outlined as follows. First, note that the fixed fee Φ_t is maximised in the upper-level objective function (1a) and is constrained only by (1b). This means that (1b) is binding at the optimum, i.e. $\Phi_t = \Phi_{t-1} + \Delta \mathrm{V_t}$. By replacing this condition in (1a) and considering that $\Phi_0 = 0$ (as the fixed fee is necessarily zero before the scheme is introduced), the objective function can be reformulated as $\sum_{t>0}(\mathrm{W_t} - \mathrm{V_0})$, where $\mathrm{W_t}$ is the overall social welfare net of investment costs. This means that, given the initial consumer and generator surplus $\mathrm{V_0}$ at time zero, a monopolistic TRANSCO subject to the HRGV incentive regulation will aim at maximising the welfare in each period $t > 0$ (as in a centralised optimal planning problem), which is a desirable property from the point of view of a regulator. However, this scheme has a fundamental drawback. Indeed, it transfers all consumers and producers surplus increase due to the TRANSCO investment, i.e. $\Delta \mathrm{V_t}$ in (1b), to the TRANSCO itself through the new fixed fee $\Phi_t = \Phi_{t-1} + \Delta \mathrm{V_t}$, leaving consumers and producers at their initial benefit level $\mathrm{V_0}$. This means that consumers and producers do not harness any benefit from TRANSCO investments under the HRGV model.

2.2. An incentive scheme for energy storage investments

As outlined in the previous section, the HRGV model transfers all surplus ΔV_t created by an investment to the TRANSCO, which may raise significant fairness concerns. To overcome this problem, in (Xia et al., 2024) we propose to limit the amount transferred by a fraction k. That is, we modify the original HRGV model by replacing constraint (1b) with the condition:

$$\Phi_t \leq \Phi_{t-1} + k\Delta V_t$$

This means that consumers and producers can keep the amount $(1-k)\Delta V_t$ for themselves. The parameter k represents a lever that regulators could use to tune this scheme according to their policy objectives. Section 3.2 shows how it could be used to steer the TRANSCO investment decisions towards the public goal of reducing carbon emissions.

In this work, we focus on grid-scale energy storage investments performed by a TRANSCO, which an independent system operator then uses during the market clearing similarly to a network asset. Therefore, the following constraints on storage operations are included in the lower-level feasible set $\mathcal{X}_t$ in (1c). These include the bounds on charged p_t^{ch} and discharged p_t^{dis} power by the storage:

$$p_t^{ch} \leq \sum_i b_i \, p_i^{ch,max} \qquad \forall t \in T$$

$$p_t^{dis} \leq \sum_i b_i \, p_i^{dis,max} \qquad \forall t \in T$$

which depend on the TRANSCO investment decisions, represented by the binary variable b_i that is equal to one if the investment in the storage i is performed, and zero otherwise, with $\sum_i b_i = 1$. The energy e_t accumulated in the storage device depends on the level of the previous period e_{t-1}, and the power charged p_t^{ch} and discharged p_t^{dis}, that is:

$$e_t = e_{t-1} + \left(p_t^{ch}\sqrt{\eta} - \frac{p_t^{dis}}{\sqrt{\eta}}\right)\Delta_t \qquad \forall t \in T$$

where $\Delta_t = 1$ hour is the time interval, and η is the round-trip efficiency. The energy capacity is bounded by the minimum e_i^{min} and maximum e_i^{max} capacities, which depend on the selected investment b_i, that is:

$$\sum_i b_i \, e_i^{min} \leq e_t \leq \sum_i b_i \, e_i^{max} \qquad \forall t \in T$$

Moreover, demand $0 \leq d_{t,k}$ and generation $0 \leq g_{t,k}$ of users k at time t are bounded by the maximum quantity $d_{t,k}^{max}$ and $g_{t,k}^{max}$, respectively, specified in their market bids, that is:

$$d_{t,k} \leq d_{t,k}^{max} \qquad [\varphi_{t,k}^{d} \geq 0] \qquad \forall t \in T, \forall k \in D$$

$$g_{t,k} \leq g_{t,k}^{max} \qquad [\varphi_{t,k}^{g} \geq 0] \qquad \forall t \in T, \forall k \in G$$

where the terms $\varphi_{t,k}^{d}$ and $\varphi_{t,k}^{g}$ in square brackets are dual variables. The lower-level objective function (1c) represents the welfare $\widetilde{W_t}$ of the market participants, i.e.:

$$\widetilde{W_t} = \sum_{\mathrm{k} \in \mathrm{D}} p_{t,k}^{d} d_{t,k} - \sum_{\mathrm{k} \in \mathrm{G}} p_{t,k}^{g} g_{t,k}$$

where $p_{t,k}^{d}$ and $p_{t,k}^{g}$ are the consumers' and producers' submitted bid prices. The time interval $\Delta_{\mathrm{t}} = 1$ has been omitted for ease of reading. Note that the consumers and producer surplus $\mathrm{V_t}$ at time t can be represented as (Biggar & Hesamzadeh, 2014; Savelli & Morstyn, 2021):

$$\mathrm{V_t} = \sum_{k \in D} d_{t,k}^{max} \varphi_{t,k}^{d} + \sum_{\mathrm{k} \in \mathrm{G}} g_{t,k}^{max} \varphi_{t,k}^{g}$$

Therefore, by definition, the merchandising surplus $\mathrm{M_t}$ in (1a) can be formulated as:

$$\mathrm{M_t} = \widetilde{W_t} - V_t = \sum_{\mathrm{k} \in \mathrm{D}} p_{t,k}^{d} d_{t,k} - \sum_{\mathrm{k} \in \mathrm{G}} p_{t,k}^{g} g_{t,k} - \left(\sum_{k \in D} d_{t,k}^{max} \varphi_{t,k}^{d} + \sum_{\mathrm{k} \in \mathrm{G}} g_{t,k}^{max} \varphi_{t,k}^{g} \right)$$

which is a linear relation. Consequently, by using standard primal-dual reformulation techniques (here omitted for ease of reading, but the interested reader is referred to (Savelli & Morstyn, 2021)), the bilevel model (1a)-(1c) can be rewritten as a single mixed-integer linear problem.

3. Results

3.1. Data and settings

This section reports the results obtained by using the model developed in Section 2.2, and the data of the Italian day-ahead market referring to the 1st of January 2023 and the 2nd of July 2022 to account for seasonality (GME, 2023). Each instance of the day-ahead market clearing problem involved ~70,000 bids, on average. For ease of computation, we considered two time periods, where $t = 0$ is the initial status with no investment, whereas at $t = 1$ the TRANSCO can decide to invest in grid-scale energy storage. The available devices are Li-ion batteries with a duration of either 2, 4, or 8 hours and rated power spanning from zero to 600 MW with 100 MW step increments. The storage can be located in any of the seven zones of the Italian day-ahead market represented in Figure 1. Storage parameters and investment costs have been collected from (Viswanathan et al., 2023).

Figure 1 The Italian day-ahead market zones.

3.2. The effect on surplus and carbon emissions

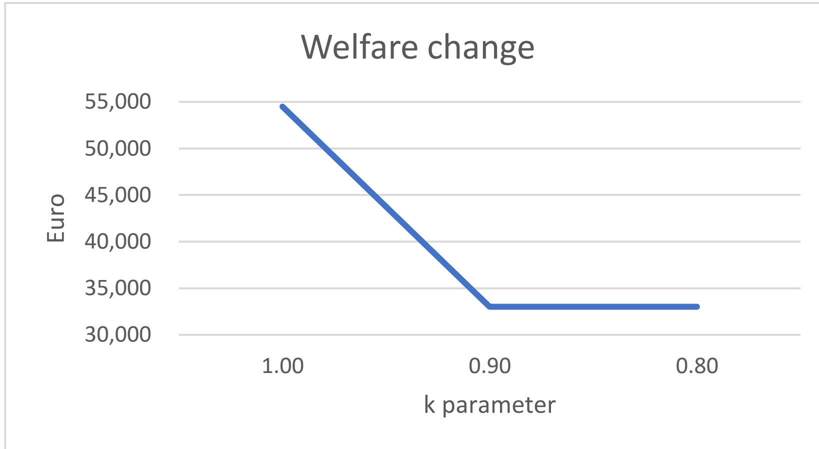

Figure 2 Social welfare change, w.r.t. the case with no investment, as a function of the parameter k.

The first effect of varying the parameter k in (2) is that the location where the battery is deployed, as well as the rated power and duration chosen by the TRANSCO will change. Indeed, when k=1 the TRANSCO optimal decision is to invest in a 500 MW and 4 h duration storage located in Calabria (see Figure 1). In contrast, when k=0.90 the optimal decision is to invest in a 200 MW and 4 h duration battery located in Sardinia. Finally, if k=0.80, the TRANSCO selects a 200 MW and 4 h battery again, but it is deployed in Sicily. This directly affects the overall welfare, as shown in Figure 2. In detail, the figure reports the welfare change, net of investment costs, w.r.t. the base case with no investments. In both the cases with k=0.90 and k=0.80 the welfare is lower than when k=1. This is expected, as the latter represents the original HRGV mechanism, which induces the TRANSCO to maximise the social welfare (as reviewed in Section 2.1), but at the expense of handing all benefits from the investment to the TRANSCO itself. This means that consumers and producers do not receive any gain when k=1. By contrast, when the parameter k is reduced, they can keep the amount $(1-k)\Delta V_t$. This is highlighted in Figure 3, which reports on the left side the additional surplus for consumers and producers and, on the right side, the change in TRANSCO profits.

Figure 3 Change in consumer and producer surplus (left), and TRANSCO profit (right), as a function of the parameter k.

Finally, note from Figure 2 that the difference between the cases with k=0.90 and k=0.80 is negligible in terms of social welfare. Therefore, regulators basing their policy decisions only on welfare would consider the values k=0.90 and k=0.80 as equivalent, as they induce a different redistribution of wealth but without affecting its aggregate level. However, if we consider the effect that the presence of storage has on carbon emissions, reported in Figure 4, we observe that the case with k=0.90 (where the battery is deployed on the island of Sardinia), yields a significantly greater carbon abatement per MWh of energy capacity installed. This means that even though the cases with k=0.90 and k=0.80 can be considered equivalent in terms of social welfare, the value k=0.90 might be preferred, as it helps better reduce carbon emissions. By contrast, even though the value k=1 leads to the greatest welfare, it raises fairness concerns as the TRANSCO reaps all benefits and yields the lowest carbon abatement. Therefore, a regulator might select k=0.90 as the optimal policy parameter.

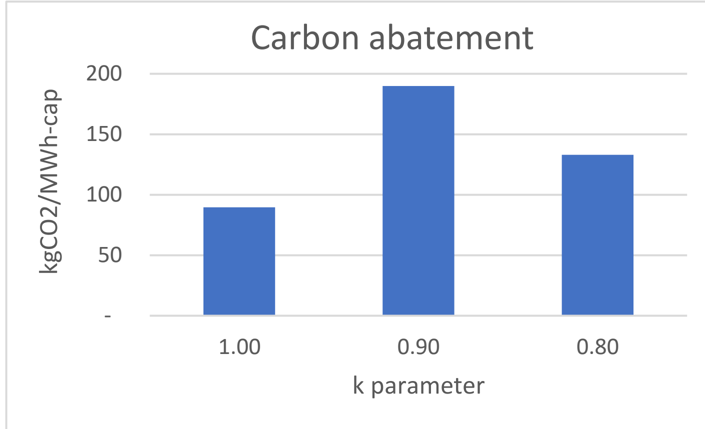

Figure 4 Carbon reduction (kgCO2) per MWh of energy storage capacity installed, as a function of the k parameter.

4. Conclusion

Incentive regulation can be an effective approach to steer the investment decision-making process of private transmission companies in a way that serves the public interest. This work discusses how this approach can be adapted to incentivise grid-scale energy storage investments. In particular, we show how the HRGV model can be refined to help reduce carbon emissions while addressing fairness concerns in benefit allocation. Results based on actual data from the Italian day-ahead market show that the proposed mechanism can help decrease emissions by up to 190 kgCO2 per MWh of storage capacity installed. These findings highlight the importance of adequately designing incentive schemes, where relatively minor changes, such as the introduction of the proposed tuning parameter, can lead to a significant beneficial impact.

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