BUILD BACK BETTER? TRANSMISSION PLANNING IN AN IMPERFECTLY COMPETITIVE POWER SECTOR WITH ENVIRONMENTAL EXTERNALITIES

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Overview

Decarbonisation of the power sector necessitates increasing variable renewable energy (VRE) capacity adoption, such as wind and solar power. While VRE offers virtually emission-free power at no operating costs, it also introduces production intermittency, requiring effective variation management through storage, transmission, and demand-side resources. The Nordic countries possess flexible capacities, including hydro reservoirs, which positions them well to manage the sustainable-energy transition. Nevertheless, in a deregulated electricity industry, flexible producers may not align their incentives with society's interests (Tangerås and Mauritzen, 2018), given the enhanced leverage they may exploit in a future power system with expanded VRE output (Hassanzadeh Moghimi et al., 2023). To address this concern, we employ a bi-level optimisation framework for transmission planning that anticipates power companies' behaviour in a VRE-dominated power system. Our goal is to mitigate potential market imperfections and to develop policy insights that facilitate a welfare-enhancing transition by answering the following research questions:

- RQ1. In a future 2030 decarbonisation scenario, how should transmission planning in the Nordic region be adapted to attenuate the impact of market power?
- RQ2. If the cost of damage from CO_2 emissions is not fully reflected in the CO_2 price, then how are transmission capacities, generation adoption, and CO_2 emissions affected?

Methods

A Stackelberg leader-follower model, also known as a bi-level model, can be utilised to address various welfare-enhancing design problems, such as transmission expansion and policy targets. In our model, the upper-level problem is formulated to determine the transmission system operator's (TSO) optimal transmission-investment decisions. The lower-level problem is formulated as an open-loop Nash-Cournot equilibrium in investment and operations among profit-maximising firms and a surplus-maximising independent system operator (ISO). At the lower level, the firms determine generation-capacity investment and operations of their portfolios of hydro, thermal, and VRE assets, while the ISO controls consumption and power flows. The upper-level decision maker must anticipate the responses of lower-level decision makers when determining transmission investment (Baringo and Conejo, 2012; Maurovich-Horvat et al., 2015). By contrast, transmission-investment decisions are taken as given by the lower level. Moreover, the cost of damage from CO_2 emissions is included in the leader's objective function but may only be partially imposed on the followers, e.g., in the form of a CO_2 price (Barnett, 1980). Thus, there are two types of distortions, viz., the exercise of market power by firms and the environmental externalities, that potentially lead to conflicting incentives and necessitate countervailing transmission expansion to mitigate. To solve this, enumeration has been proposed as a solution, whereby the lower-level problem is solved for all possible combinations of transmission capacities.

Results

We utilise Nord Pool data from Hassanzadeh Moghimi et al. (2023) for our problem instances. As a benchmark, the social cost of damage from CO_2 emissions is assumed to be reflected fully by the CO_2 price imposed on the industry. Investments by firms in VRE generation technologies only are allowed. Based on a preliminary assessment of congestion, only 4 of the 18 transmission lines are prioritised for investment. Upgrades to capacities of either 400 MW or 800 MW are allowed.

In order to address our research questions, we implement the following scenarios:

- Base 2018 in which no capacity expansion is allowed and the CO_2 price is set to €15/t
- 2030C is the same as Base 2018 but with a CO_2 price of €100/t
- 2030CV is the same as 2030C but allows for generation expansion by firms in VRE capacity
- 2030CVT is the same as 2030CV but allows for transmission expansion

For each scenario, we conduct three cases:

- Perfect competition (PC), in which all firms are price takers
- Cournot oligopoly in thermal generation (COG), in which selected firms with large capacities, e.g., Vattenfall at SE3 and Fortum at FI, can withhold generation to manipulate prices
- Cournot oligopoly in reservoirs (COR), in which selected firms with strategic reservoirs, e.g., Vattenfall at SE1 and Statkraft at NO4, can exercise market power in hydro-reservoir generation to manipulate prices (their total nodal amount of net-hydro generation from reservoirs must be at least as much as under PC)

Given the 2018 installed capacities, the exercise of market power by large nuclear power plants under COG leads to a transfer of wealth from consumers to producers. In particular, relative to PC, Vattenfall enjoys a 71.57% increase in its surplus by withholding its nuclear output. The CO_2 emissions and electricity prices also increase under COG as fossil-fuelled plants are forced to operate more by making their capacity limits become binding. Under COR, welfare metrics are only mildly affected relative to PC. Nevertheless, Vattenfall can exert temporal arbitrage through its vast reservoirs by shifting water from peak to off-peak seasons. By doing so, it is able to boost its surplus by 11.59% compared to PC.

In 2030C, while the high CO_2 price has a minor impact on social welfare, it has more profound consequences for CO_2 emissions and welfare distribution. With higher CO_2 prices, emissions are reduced by over 80% in comparison with the Base 2018 scenario. As operations of fossil-fuelled units become more expensive, electricity prices increase, which leads to a welfare transfer from consumers to producers. In particular, Vattenfall's surplus under PC is more than twice its value in the Base 2018 scenario's PC case. However, the resulting curb in consumption limits Vattenfall's ability to exert market power under COG because it would have to withhold substantially more output to force fossil-fuelled plants to hit their capacity limits. Therefore, its surplus increases by 33.36% in moving from PC to COG. Likewise, strategic hydro reservoirs' room for manoeuvre is limited under COR as Vattenfall is able to bolster its surplus by only 0.23% through temporal arbitrage vis-à-vis PC.

Investment in VRE capacity in 2030CV increases welfare in all cases from the 2030C scenario. Adoption of wind capacity at FI reduces both electricity prices and CO_2 emissions. Consequently, relative to 2030C, consumer surplus increases and producer surplus decreases. However, under COG, withholding by nuclear plants incentivises more VRE adoption at FI and SE3, precisely where Vattenfall and Fortum have strategic assets. A response of this magnitude by price-taking fringe firms limits the extent of the increase in electricity prices from Cournot behaviour and curbs Vattenfall's ability to exert market power. Nevertheless, the subtler exercise of market power under COR actually proves relatively more potent here. In spite of substantial adopted VRE capacity, Vattenfall's producer surplus increases by 13.44% in moving from PC to COR. Hence, the leverage of strategic hydro reservoirs is enhanced in a future power system with endogenous VRE capacity expansion.

The 2030CVT indicates that transmission expansion has a modest impact on social welfare. However, there are more significant effects on the distribution of welfare. This is because the upgrade of the line between SE1 and FI improves access to SE1's hydro resources, leading to reduced adoption of VRE capacity at FI, slightly higher (lower) prices at SE1 (FI), a reduction in CO_2 emissions by almost 20%, and an increase in Vattenfall's surplus by 7.53% under PC from the corresponding 2030CV case. Under COG, the exertion of market power by nuclear plants at SE3 and FI induces a stronger reinforcement of the same line by the TSO. Interestingly, transmission expansion in the COG case increases VRE investment slightly compared to the corresponding case in the 2030CV scenario, which reduces CO_2 emissions by almost 25%. The combined generation and transmission expansion can mitigate the exercise of market power better in going from PC to COG, as Vattenfall's surplus increases by about seven percentage points less compared to the 2030CV scenario. In the COR case, it is best not to expand transmission capacity due to Vattenfall's strategic temporal arbitrage. This involves withholding water during fall and winter but having excess production during spring, which is partially offset by high wind availability at FI during the fall. FI's adoption of VRE capacity and Vattenfall's withholding of hydro generation at SE1 make it more of a net exporter during certain periods. Generation-capacity expansion at FI curbs the exercise of market power under COR, with Vattenfall's surplus increasing by 5.50% compared to 13.44% in the 2030CV scenario when moving from PC to COR.

Conclusions

The study highlights the significant effects of transmission expansion and strategic behaviour on CO_2 emissions and welfare distribution. In particular, we tackle RQ1 by demonstrating how the VRE capacity expansion decrease electricity prices and CO_2 emissions. Under full internalisation of the cost of damage from emissions, transmission expansion can also alleviate market power abuses but needs to be adapted to the type of strategic behaviour that is exhibited. Overall, the findings emphasise the importance of designing policies that promote competition and encourage investment in renewable energy while accounting for the strategic behaviour of market players. Ongoing work addresses RQ2, i.e., how transmission expansion should be modulated in case of incomplete pricing of the cost of damage from CO_2 emissions.

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