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YSSP Report

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Optimal transmission infrastructure expansion planning to efficiently integrate renewable energy generation

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ABSTRACT

In the framework of developing greenhouse gas mitigation strategies, we propose an efficient modelling assessment for planning optimal transmission network expansion considering the market competition between the generation investors, while stimulating the further expansion of renewable energy sources. The proposed approach accounts for centralised and decentralised electricity industry structure considering the power market modelled as either perfect competition or Cournot oligopoly in the latter case. We apply the aforementioned modelling approach to implement an illustrative case study for the Northern European energy system.

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List of Abbreviations and Acronyms

Below is the description of abbreviations or acronyms used in the following text.

Abbreviations/Acronym	Description
CCT	Closed-Cycle Turbines
CERT	CO_2 Emission Reduction Target
EU	European Union
GHG	Greenhouse Gas
ISO	Independent System Operator
MPPDC	Mathematical Program with Primal and Dual Constraints
OCT	Open-Cycle Turbines
TSO	Transmission System Operator
VRES	Variable Renewable Energy Sources

1 Introduction

1.1 Background

Presently prevalent trends among the operations research community target the development of efficient strategies to replace the energy generation technologies with environmentally friendly and renewable alternatives. The tendency is caused by the steady increase in emissions of CO_2 and other greenhouse gases. As the main consequence, one can observe the increase of the global average temperature and the increase in ocean acidity by more than 30% since preindustrial times (Rau and Baird [2018]), among others effects such as reduction of the ice coverage, increased desertification, drought and wildfires.

Responding to these issues, several countries have paid significant attention to developing efficient solutions to mitigate emissions. As examples, the European Union (EU) set a 40% CO2 emission reduction target (CERT) by 2030 based on its 1990 greenhouse gas (GHG) emissions level, and South Korea established a national CERT to reduce its GHG emissions by 37% below its business-as-usual level by 2030 (Jeong et al. [2018]).

Although a considerable amount of renewable power has been installed in the past decade (wind, solar, and biomass represented 20.9% of the EU electricity mix in 2017 in comparison to 9.7% in 2010), the vast majority of the EU member countries are far from meeting these targets (Sandbag and Energiewende [2017]). Thus, significant variable renewable energy capacity will be built in the medium-term, requiring large-scale investments in infrastructure expansion and substantial planning efforts for its successful integration (van der Weijde and Hobbs [2012]). (Krishnan et al. [2016]) highlighted the importance of the investments in the transmission system in the context of renewable energy targets. However, existing transmission systems were not designed to cope with such levels of renewable penetration (Moreira et al. [2017]). Consequentially, renewable-driven expansion of the generation requires new approaches for transmission network planning.

1.2 Research objectives

The main objective of this research is to study the optimal transmission network expansion planning and its welfare effects, considering the market competition between the generation investors, while stimulating the further expansion of renewable energy sources.

The research activities comprise two main directions. Planning the development of energy systems usually involves analytical modelling based on mathematical optimisation (Zerrahn and Huppmann [2014]). Therefore, the first direction is the development of a comprehensive modelling assessment along the lines inspired by (Virasjoki et al. [2020]) where the authors proposed a bi-level model to study the optimal storage investment, in particular large-scale battery storage alternatives. The lower level depicts a power system operations model as either perfect competition or Cournot oligopoly. The upper level represents the investor that is either a welfare-maximiser or a profit-maximising standalone merchant. The proposed bi-level model expectedly focuses mainly on the detailed representation of the storage technologies. Hence, the authors do not consider the mechanisms for the renewable-driven generation motivation (e.g. the carbon taxes) involving the possibility for the generation capacity and transmission system expansion.

In this research, we have modified the aforementioned bi-level model to consider welfare-maximising transmission system operator (TSO) at the upper level making investments in transmission lines instead of storage investments. Concurrently, we accounted for the possibility for the producer companies to expand their conventional and VRES generation capacities. To facilitate renewable-driven generation expansion we have also introduced the carbon taxes. Additionally, the modelling approach considers investment budget limitations for each of the generation companies and the TSO to study the interaction between generation and transmission investors under different restrictive conditions. The new bi-level model more precisely represents the interaction between TSO and generators, ultimately allowing more realistic modelling of European market behaviour. The implementation of the bi-level model provides insights into how investments in transmission expansion are intertwined with generation companies' incentives and how competition among generators impacts optimal transmission planning. Following (Virasjoki et al. [2020]) to obtain a tractable alternative of the bi-level model we employed a reformulation technique that converts this bi-level problem into a mathematical programming problem with primal and dual constraints, rendering a quadratically constrained quadratic programming problem.

The second direction of this research aims at implementing an illustrative case study for the Northern European energy system. Nevertheless, while serving demonstrative purposes due to the data approximation it still poses evidence of the proposed methodological assessment efficiency providing insights on the interconnected decisions of TSO and generation investors. Therefore, the developed model can be potentially exploited as a supportive tool for modelling EU energy systems.

List of Nomenclature

Below is the description of all nomenclature used in the following text.

Symbol	Description
$n \in N$	Nodes
$s \in S$	Availability scenarios
$e \in E$	Conventional energy sources
$r \in R$	Variable renewable energy sources (VRES)
$i \in I$	Power producer companies
$t \in T$	Time periods

Table 1: Indices and sets

Symbol	Description	Units
T_t	Number of hours clustered for the time period $t \in T$	h
P_s	Probability of of the availability scenario $s \in S$	
$D^{slp}_{s,t,n}$	Slope of linear inverse demand function at scenario $s \in S$, node $n \in N$ in time period $t \in T$	€ / MWh^2
$D^{int}_{s,t,n}$	Intercept of linear inverse demand function at scenario $s \in S$, node $n \in N$ in time period $t \in T$	€ / MWh

Table 2: General parameters

Symbol	Description	Units
$M^e_{n,i}$	Annualised maintenance cost for conventional generation of the type $e \in E$ from the producer $i \in I$ at the node $n \in N$	€ / MWh
$C^e_{n,i}$	Operational cost for conventional generation of the type $e \in E$ from producer $i \in I$ the node $n \in N$	€ / MWh
$\overline{G}^e_{n,i}$	Installed generation capacity of the conventional generation of the type $e \in E$ from the producer $i \in I$ at the node $n \in N$	MW
$I^e_{n,i}$	Annualised capacity expansion investment cost for the conventional generation of the type $e \in E$ from the producer $i \in I$ at the node $n \in N$	€ / MW
$R^{up,e}_{n,i}$	Maximum ramp-up rate for the conventional generation of the type $e \in E$ at the node $n \in N$ from the producer $i \in I$	
$R^{down,e}_{n,i}$	Maximum ramp-down rate for the conventional generation of the type $e \in E$ at the node $n \in N$ from the producer $i \in I$	
$K^{E+}_{n,i}$	Capacity expansion investment budget for the conventional generation of the type $r \in R$ from the producer $i \in I$ at the node $n \in N$	€
D^e	Carbon tax for conventional generation of the type $e \in E$	€ / MWh

Table 3: Conventional generation parameters

Symbol	Description	Units
$M^r_{n,i}$	Annualised maintenance cost for VRES generation unit of the type $r \in R$ from the producer $i \in I$ at the node $n \in N$	€ / MWh
$\overline{G}^r_{n,i}$	Installed generation capacity of the VRES of the type $r \in R$ from the producer $i \in I$ at the node $n \in N$	MW
$A^r_{s,t,n}$	Availability factor for VRES type $r \in R$ at the time period $t \in T$ considering scenario $s \in S$ at the node $n \in N$	
$I^r_{n,i}$	Annualised capacity expansion investment cost for the VRES of the type $r \in R$ from the producer $i \in I$ at the node $n \in N$	€ / MW
$K^{R+}_{n,i}$	Capacity expansion investment budget for the VRES of the type $r \in R$ from the producer $i \in I$ at the node $n \in N$	€

Table 4: VRES generation parameters

Symbol	Description	Units
$\overline{L}_{n,m}$	Installed capacity at the line connecting nodes $n \in N$ and $m \in N$	MW
$M^l_{n,m}$	Annualised maintenance cost for transmission per line connecting node $n \in N$ to the node $m \in N$	€ / MW
$I^l_{n,m}$	Annualised capacity expansion investment cost for the line connecting node $n \in N$ to the node $m \in N$	€ / MW
$K^{l+}_{n,m}$	Capacity expansion investment budget for the line connecting node $n \in N$ to the node $m \in N$	€

Table 5: Transmission parameters

Symbol	Description	Units
$g^e_{s,t,n,i}$	Conventional generation of the type $e \in E$ at the node $n \in N$ by producer $i \in I$ considering scenario $s \in S$ and time period $t \in T$	MWh
$g^r_{s,t,n,i}$	VRES generation of the type $r \in R$ at the node $n \in N$ from producer $i \in I$ considering scenario $\in S$ and time period $t \in T$	MWh
$q_{s,t,n}$	Quantity of energy consumed at the node $n \in N$ considering scenario $s \in S$ during time period $t \in T$	MWh
$f_{s,t,n,m}$	Energy transferred from the node $n \in N$ to the node $m \in N$ considering scenario $s \in S$ and time period $t \in T$	MWh
$l^+_{n,m}$	Capacity added to the transmission line connecting nodes $n \in N$ and $m \in N$	MW
$\overline{g}^{e+}_{n,i}$	Generation capacity added to the conventional generation of the type $e \in E$ from the producer $i \in I$ at the node $n \in N$	MW
$\overline{g}^{r+}_{n,i}$	Generation capacity added to the VRES generation of the type $r \in R$ from the producer $i \in I$ at the node $n \in N$	MW

Table 6: Primal variables

Symbol	Description	Units
$\theta_{s,t,n}$	Shadow price on the power balance at node $n \in N$ considering scenario $s \in S$ during time period $t \in T$	€ / MWh
$\lambda^f_{s,t,n,m}$	Shadow price on the power flow primal feasibility constraint at node $n \in N$ considering scenario $s \in S$ during time period $t \in T$	€ / MW
$\beta^{f_1}_{s,t,n,m}$	Shadow price on the transmission capacity for the power flow from the node $n \in N$ to the node $m \in N$ considering scenario $s \in S$ during time period $t \in T$	€ / MW
$\beta^{f_2}_{s,t,n,m}$	Shadow price on the transmission capacity for the power flow from the node $n \in N$ to the node $m \in N$ considering scenario $s \in S$ during time period $t \in T$	€ / MW
$\beta^e_{s,t,n,i}$	Shadow price on conventional energy capacity of the type $e \in E$ from the producer $i \in I$ at node $n \in N$ considering scenario $s \in S$ during time period $t \in T$	€ / MWh
$\beta^r_{s,t,n,i}$	Shadow price on VRES capacity of the type $r \in R$ from the producer $i \in I$ at node $n \in N$ considering scenario $s \in S$ during time period $t \in T$	€ / MWh
$\beta^{up,e}_{s,t,n,i}$	Shadow price on the maximum ramp-up rate for the conventional generation of the type $e \in E$ at the node $n \in N$ from the producer $i \in I$ considering scenario $s \in S$ during time period $t \in T$	
$\beta^{down,e}_{s,t,n,i}$	Shadow price on the maximum ramp-down rate for the conventional generation of the type $e \in E$ at the node $n \in N$ from the producer $i \in I$ considering scenario $s \in S$ during time period $t \in T$	

Table 7: Dual variables

2 Models formulations

2.1 Assumptions

In the following models' formulations the TSO at the upper level makes decisions regarding the transmission lines capacity expansion to optimise the total welfare combining the producers and consumers surplus. The decisions $l^{+}_{n,m}$ are made in continuous sizes and limited by the budget available for each of the transmission lines $K^{L+}_{n,m}$. TSO is assumed not to charge the producer companies the transmission costs. Therefore, these costs are discarded in the models' formulations.

The producer companies in the power market $i \in I$ invest in different types of conventional and VRES generation capacities, $e \in E$ and $r \in R$ respectfully, at each of the nodes $n \in N$. The decisions are guided by the producer companies budgets available for each of the nodes and conventional and VRES energy types, respectively $K^{E+}_{n,i}$ and $K^{R+}_{n,i}$. Producers can also own some capacities prior to the beginning of the planning. The producer companies act as either price-takers (perfect competition) or anticipate their production quantities to influence the market price (Cournot oligopoly) depending on the formulation.

The VRES availability is modelled via consideration of different seasonal scenarios $s \in S$ and assumptions on the percentage of the total VRES capacity available at each of the nodes considering each of the scenarios and time periods $t \in T$. This value is referred to as the availability factor and denoted as $A^{r}_{s,t,n}$ for each of the VRES types. Each of the scenarios is assumed to occur with some probability P_s such that $\sum_{s \in S} P_s = 1$.

2.2 Centralised planning: single-level formulation

Prior to decentralised market structure we present a single-level centralised planning alternative. In the single-level problem, the central planner aims at maximising social welfare by means of making both optimal transmission and generation capacity investments decisions along with deciding market operations. The single-level formulation is written as follows.

$$
\begin{aligned}
\max \sum_{n\in N} \Bigg(& \sum_{t\in T}\sum_{s\in S} P_s \Bigg[D^{int}_{s,t,n} q_{s,t,n} - \frac{1}{2} D^{slp}_{s,t,n} q^2_{s,t,n} \\
& - \sum_{i\in I}\sum_{e\in E} \left(\left[C^e_{n,i} + D^e \right] g^e_{s,t,n,i} \right) \Bigg] \\
& - \sum_{i\in I} \Bigg(\sum_{r\in R} \left[M^r_{n,i} \left(\overline{G}^r_{n,i} + \overline{g}^{r+}_{n,i} \right) + I^r_{n,i} \overline{g}^{r+}_{n,i} \right] \\
& + \sum_{e\in E} \left[M^e_{n,i} \left(\overline{G}^e_{n,i} + \overline{g}^{e+}_{n,i} \right) + I^e_{n,i} \overline{g}^{e+}_{n,i} \right] \Bigg) \\
& - \sum_{m\in N} \left[M^l_{n,m} \frac{1}{2} \left(\overline{L}_{n,m} + l^+_{n,m} \right) + \frac{1}{2} I^l_{n,m} l^+_{n,m} \right] \Bigg)
\end{aligned} \tag{1}
$$

s. t.

$$l^+_{n,m} - l^+_{m,n} = 0 \quad \forall n \in N, m \in N \tag{2}$$

$$I^l_{n,m} l^+_{n,m} - K^{L+}_{n,m} \leq 0 \quad \forall n \in N, m \in N \tag{3}$$

$$
\begin{aligned}
& q_{s,t,n} - \sum_{i\in I} \left[\sum_{e\in E} g^e_{s,t,n,i} + \sum_{r\in R} g^r_{s,t,n,i} \right] \\
& + \sum_{m\in N:m>n} f_{s,t,n,m} - \sum_{m\in N:m<n} f_{s,t,m,n} = 0 \quad \forall n \in N, t \in T, s \in S \quad (\theta_{s,t,n})
\end{aligned} \tag{4}
$$

$$f_{s,t,n,m,} - T_t \left(\overline{L}_{n,m} + l^+_{n,m} \right) \leq 0 \quad \forall n \in N, m \in N, t \in T, s \in S \quad (\beta^{f_1}_{s,t,n,m}) \tag{5}$$

$$- f_{s,t,n,m,} - T_t \left(\overline{L}_{n,m} + l^+_{n,m} \right) \leq 0 \quad \forall n \in N, m \in N, t \in T, s \in S \quad (\beta^{f_2}_{s,t,n,m}) \tag{6}$$

$$f_{s,t,n,m} = 0 \quad \forall n \in N, m \in N : m \leq n, t \in T, s \in S \quad (\lambda^f_{s,t,n,m}) \tag{7}$$

$$g^r_{s,t,n,i} - T_t A^r_{s,t,n} \left(\overline{G}^r_{n,i} + \overline{g}^{r+}_{n,i} \right) \leq 0 \quad \forall r \in R, n \in N, t \in T, s \in S, i \in I \quad (\beta^r_{s,t,n,i}) \tag{8}$$

$$\sum_{r\in R} I^r_{n,i} g^{r+}_{n,i} - K^{R+}_{n,i} \leq 0 \quad \forall n \in N, i \in I \quad (\beta^{R+}_{n,i}) \tag{9}$$

$$g^e_{s,t,n,i} - T_t \left(\overline{G}^e_{n,i} + \overline{g}^{e+}_{n,i} \right) \leq 0 \quad \forall e \in E, n \in N, t \in T, s \in S, i \in I \quad (\beta^c_{s,t,n,i}) \tag{10}$$

$$\sum_{e\in E} I^e_{n,i} g^{e+}_{n,i} - K^{E+}_{n,i} \leq 0 \quad \forall n \in N, i \in I \quad (\beta^{E+}_{n,i}) \tag{11}$$

$$g^e_{s,t,n,i} - g^e_{s,t-1,n,i} - T_t R^{up,e}_{n,i} \left(\overline{G}^e_{n,i} + \overline{g}^{e+}_{n.i} \right) \leq 0 \quad \forall e \in E, s \in S, t \in T, n \in N, i \in I \quad (\beta^{up,e}_{s,t,n,i}) \tag{12}$$

$$g^e_{s,t-1,n,i} - g^e_{s,t,n,i} - T_t R^{down,e}_{n,i} \left(\overline{G}^e_{n,i} + \overline{g}^{e+}_{n.i} \right) \leq 0 \quad \forall e \in E, s \in S, t \in T, n \in N, i \in I \quad (\beta^{down,e}_{s,t,n,i}) \tag{13}$$

$$q_{s,t,n} \geq 0 \quad \forall n \in N, t \in T, s \in S \tag{14}$$
$$g^{e}_{s,t,n,i} \geq 0 \quad \forall e \in E, n \in N, t \in T, s \in S, i \in I \tag{15}$$
$$g^{r}_{s,t,n,i} \geq 0 \quad \forall r \in R, n \in N, t \in T, s \in S, i \in I \tag{16}$$
$$\overline{g}^{e+}_{n,i} \geq 0 \quad \forall e \in E, n \in N, i \in I \tag{17}$$
$$\overline{g}^{r+}_{n,i} \geq 0 \quad \forall r \in R, n \in N, i \in I \tag{18}$$
$$l^{+}_{n,m} \geq 0 \quad \forall n \in N, m \in N \tag{19}$$

Constraint (4) ensures the balance between power consumption, generation and transmission. Constraints (5) and (6) define the transmission flows bounds and constraints (10) and (8) define the bounds for the conventional and VRES generation respectively. Inequalities (3), (11) and (9) represent the budget limitations for the capacity expansion investments regarding transmission lines, conventional and VRES generation accordingly. Equality (7) ensures the primal feasibility condition for the power transmission. Equality (2) guaranties the equivalence of the capacity expansion decisions for the transmission lines $n \rightarrow m$ and $m \rightarrow n$, $\forall n, m \in N$. Inequalities (12), (13) represent maximum ramping levels for conventional generation. The correspondent dual variables are written in brackets after each constraint. The omission of some dual variables implies the lack of their appearance in the dual problem formulation.

2.3 Decentralised planning: bi-level formulation

In contrast with the centralised planning formulation in the decentralised market structure the decision maker regarding transmission lines capacity expansion represented by TSO detaches to appear at the upper level only. Therefore, the decisions made at the upper level impact the lower level decisions regrading the generation levels and the generation capacity expansion constructing the bi-level problem.

2.3.1 Upper-level problem: Transmission lines capacity expansion

At the upper-level the TSO makes investments in the transmission lines capacities expansion to maximise the welfare and minimise the investment costs. The upper-level problem is, therefore, formulated as follows.

$$
\begin{aligned}
\max_{l^{+}_{n,m}} \sum_{n\in N} \Bigg(& \sum_{t\in T}\sum_{s\in S} P_s \Bigg[D^{int}_{s,t,n} q_{s,t,n} - \frac{1}{2} D^{slp}_{s,t,n} q^2_{s,t,n} \\
& - \sum_{i\in I}\sum_{e\in E} \left(\left[C^e_{n,i} + D^e \right] g^e_{s,t,n,i} \right) \Bigg] \\
& - \sum_{i\in I} \Bigg(\sum_{r\in R} \left[M^r_{n,i} \left(\overline{G}^r_{n,i} + \overline{g}^{r+}_{n,i} \right) + I^r_{n,i} \overline{g}^{r+}_{n,i} \right] \\
& + \sum_{e\in E} \left[M^e_{n,i} \left(\overline{G}^e_{n,i} + \overline{g}^{e+}_{n,i} \right) + I^e_{n,i} \overline{g}^{e+}_{n,i} \right] \Bigg) \\
& - \sum_{m\in N} \left[M^l_{n,m} \frac{1}{2} \left(\overline{L}_{n,m} + l^{+}_{n,m} \right) + \frac{1}{2} I^l_{n,m} l^{+}_{n,m} \right] \Bigg) \qquad (20)
\end{aligned}
$$

$$
\text{s. t.} \quad (2), (3), (19) \text{ and} \qquad (21)
$$

$$
g^e_{s,t,n,i}, g^r_{s,t,n,i}, q_{s,t,n}, f_{s,t,n,m}, \overline{g}^{e+}_{n,i}, \overline{g}^{r+}_{n,i} \in \text{ arg max}\{\text{single-level model}\}. \qquad (22)
$$

2.3.2 Lower-level problem: Power Market Operations

The lower-level problem depicts the power market operations where independent system operator (ISO) decides on the grid use. Concurrently, the generation companies suggest generation levels and make decisions regarding generation capacity expansion. The following model accounts for both perfect and imperfect competitions where the extended cost term (Virasjoki et al. [2020], Gabriel et al. [2013]) in the bold font appears when considering Cournot oligopoly settings of the market, i.e.,

$$
\begin{aligned}
\max \sum_{n\in N} \Bigg(& \sum_{t\in T}\sum_{s\in S} P_s \Bigg[D^{int}_{s,t,n} q_{s,t,n} - \frac{1}{2} D^{slp}_{s,t,n} q^2_{s,t,n} \\
& - \boldsymbol{\frac{1}{2} D^{slp}_{s,t,n} \sum_{i\in I} \left[\sum_{e\in E} g^e_{s,t,n,i} + \sum_{r\in R} g^r_{s,t,n,i} \right]^2} \\
& - \sum_{i\in I}\sum_{e\in E} \left(\left[C^e_{n,i} + D^e \right] g^e_{s,t,n,i} \right) \Bigg] \\
& - \sum_{i\in I} \Bigg(\sum_{r\in R} \left[M^r_{n,i} \left(\overline{G}^r_{n,i} + \overline{g}^{r+}_{n,i} \right) + I^r_{n,i} \overline{g}^{r+}_{n,i} \right] \\
& + \sum_{e\in E} \left[M^e_{n,i} \left(\overline{G}^e_{n,i} + \overline{g}^{e+}_{n,i} \right) + I^e_{n,i} \overline{g}^{e+}_{n,i} \right] \Bigg) \Bigg) \qquad (23)
\end{aligned}
$$

$$
\text{s. t.} \quad (4) - (18) \qquad (24)
$$

2.3.3 Mathematical program with primal and dual constraints (MPPDC) approach

Due to the lack of the off-the-shelf mathematical tools allowing to solve the suggested bi-level model (20), (21) - (23), (24) directly we suggest a single-level reformulation. Following (Virasjoki et al. [2020]) we rely on the MPPDC approach. The MPPDC reformulation combines upper level problem (20)-(21) objective function and respective constraints with the primal constraints, dual constraints and strong duality condition for the lower-level problem (23)-(24) rendering quadratically constrained quadratic programming model.

The primal constraints for the Problem (23)-(24) are (4)-(18). The dual constraints are written as follows where the terms in bold font only appear under Cournot oligopoly market settings.

$$-P_s\left(D^{int}_{s,t,n} - D^{slp}_{s,t,n} q_{s,t,n}\right) + \theta_{s,t,n} \geq 0 \quad (q_{s,t,n}), \quad \forall s,t,n \tag{25}$$

$$\theta_{s,t,n} - \theta_{s,t,m} + \beta^{f_1}_{s,t,n,m} - \beta^{f_2}_{s,t,n,m} = 0 \quad (f_{s,t,n,m}), \quad \forall s,t,n,m>n \tag{26}$$

$$\beta^{f_1}_{s,t,n,m} - \beta^{f_2}_{s,t,n,m} + \lambda^{f}_{s,t,n,m} = 0 \quad (f_{s,t,n,m}), \quad \forall s,t,n,m \leq n \tag{27}$$

$$\begin{aligned} &P_s\left(\mathbf{D^{slp}_{s,t,n}}\left[\sum_{\mathbf{e'\in E}} \mathbf{g^{e'}_{s,t,n,i}} + \sum_{\mathbf{r\in R}} \mathbf{g^{r}_{s,t,n,i}}\right] + C^e_{n,i} + D^e\right) - \theta_{s,t,n} \\ &+ \beta^e_{s,t,n,i} + \beta^{up,e}_{s,t,n,i} - \beta^{up,e}_{s,t+1,n,i} + \beta^{down,e}_{s,t+1,n,i} - \beta^{down,e}_{s,t,n,i} \geq 0 \quad (g^e_{s,t,n,i}) \quad \forall e,s,t,n,i \end{aligned} \tag{28}$$

$$P_s\left(\mathbf{D^{slp}_{s,t,n}}\left[\sum_{\mathbf{e\in E}} \mathbf{g^{e}_{s,t,n,i}} + \sum_{\mathbf{r'\in R}} \mathbf{g^{r'}_{s,t,n,i}}\right]\right) - \theta_{s,t,n} + \beta^r_{s,t,n,i} \geq 0 \quad (g^r_{s,t,n,i}) \quad \forall r,s,t,n,i \tag{29}$$

$$M^e_{n,i} + I^e_{n,i} - \sum_{s\in S}\sum_{t\in T} T^t \beta^e_{s,t,n,i} - \sum_{s\in S}\sum_{t\in T} T^t R^{up,e}_{n,i}\beta^{up,e}_{s,t,n,i} - \sum_{s\in S}\sum_{t\in T} T^t R^{down,e}_{n,i}\beta^{down,e}_{s,t,n,i} \geq 0 \quad (\overline{g}^{e,+}_{n,i}) \quad \forall e,n,i \tag{30}$$

$$M^r_{n,i} + I^r_{n,i} - \sum_{s\in S}\sum_{t\in T} T^t A^r_{s,t,n}\beta^r_{s,t,n,i} \geq 0 \quad (\overline{g}^{r,+}_{n,i}) \quad \forall r,n,i \tag{31}$$

Following (Virasjoki et al. [2020], Huppmann and Egerer [2015]), instead of a strong duality equality condition, we write weak duality inequality to provide for the convexity of the feasible area. Nevertheless, in case the solution satisfies primal and dual feasibility conditions it acts as equality. The weak duality condition is written as follows where, similarly to the dual constraints, the terms in bold font only appear under Cournot oligopoly market settings.

$$
\begin{aligned}
&\sum_{n\in N}\left(\sum_{t\in T}\sum_{s\in S}P_s\left[D^{int}_{s,t,n}q_{s,t,n}-\frac{1}{2}D^{slp}_{s,t,n}q^2_{s,t,n}\right.\right.\\
&-\boldsymbol{\frac{1}{2}\mathbf{D}^{slp}_{s,t,n}\sum_{i\in I}\left[\sum_{e\in E}\mathbf{g}^{e}_{s,t,n,i}+\sum_{r\in R}\mathbf{g}^{r}_{s,t,n,i}\right]^{2}}\\
&\left.-\sum_{i\in I}\sum_{e\in E}\left(\left[C^e_{n,i}+D^e\right]g^e_{s,t,n,i}\right)\right]\\
&-\sum_{i\in I}\left(\sum_{r\in R}\left[M^r_{n,i}\left(\overline{G}^r_{n,i}+\overline{g}^{r+}_{n,i}\right)+I^r_{n,i}\overline{g}^{r+}_{n,i}\right]\right.\\
&\left.\left.+\sum_{e\in E}\left[M^e_{n,i}\left(\overline{G}^e_{n,i}+\overline{g}^{e+}_{n,i}\right)+I^e_{n,i}\overline{g}^{e+}_{n,i}\right]\right)\right)\\
&\geq\\
&\sum_{n\in N}\sum_{t\in T}\sum_{s\in S}P_s\left[\frac{1}{2}D^{slp}_{s,t,n}\left(q^2_{s,t,n}+\sum_{\mathbf{i\in I}}\left[\sum_{\mathbf{e\in E}}\mathbf{g}^{\mathbf{e}}_{\mathbf{s,t,n,i}}+\sum_{\mathbf{r\in R}}\mathbf{g}^{\mathbf{r}}_{\mathbf{s,t,n,i}}\right]^{\mathbf{2}}\right)\right]\\
&+\sum_{s\in S}\sum_{t\in T}\sum_{n\in N}\sum_{m\in M}T_t\overline{L}_{n,m}\left(\beta^{f_1}_{s,t,n,m}+\beta^{f_2}_{s,t,n,m}\right)+\sum_{e\in E}\sum_{s\in S}\sum_{t\in T}\sum_{n\in N}\sum_{i\in I}T_t\overline{G}^e_{n,i}\beta^e_{s,t,n,i}\\
&\sum_{r\in R}\sum_{s\in S}\sum_{t\in T}\sum_{n\in N}\sum_{i\in I}T_tA^r_{s,t,n}\overline{G}^r_{n,i}\beta^r_{s,t,n,i}+\sum_{e\in E}\sum_{s\in S}\sum_{t\in T}\sum_{n\in N}\sum_{i\in I}T_tR^{up,e}_{n,i}\overline{G}^e_{n,i}\beta^{up,e}_{s,t,n,i}\\
&+\sum_{e\in E}\sum_{s\in S}\sum_{t\in T}\sum_{n\in N}\sum_{i\in I}T_tR^{down,e}_{n,i}\overline{G}^e_{n,i}\beta^{down,e}_{s,t,n,i} \qquad (32)
\end{aligned}
$$

3 Illustrative example

For the demonstration purpose, we have applied proposed modelling approach to study the Northern European energy market. It is essential to highlight that this case study only serves illustrative purposes implying that the outcome results and conclusions can not be directly employed when making decision policies for the Nordic energy market.

To fulfil the objective of the case study we constructed the centralised and decentralised planning models for the network comprising Finland, Norway and Sweden as nodes 1, 2 and 3 respectively. The decentralised model was implemented in two versions account for perfect and imperfect (Cournot oligopoly) competition market modelling.

All the models where designed using the Julia (version 1.3.1) language (Bezanson et al. [2017]) and solved using commercial solver Gurobi (Gurobi Optimization [2020] (version 9.0.0)). All the source code and data generated is openly available at the GitHub repository https://github.com/Nikita-Belyak/IIASA_TSEP.

3.1 Data

In the experimental settings, we considered one week as the timeline, which was divided into 14 time periods with an equal length of 12 hours implying $T_t = 12$ for $t = 1, \ldots, 14$. As the representative availability scenarios, we considered the second week of each of the years seasons to be the source for the scenario-dependent parameters constructing 4 scenarios in total.

As the VRES types, we considered wind onshore, wind offshore and solar energy. Regarding the conventional energy sources, we included biomass, nuclear, coal, closed-cycle turbines (CCT) and open-cycle turbines (OCT) gas energy.

The model accounts for two producers with different budget limits to participate in the market. Each of the producers was assumed to have zero generation capacity at each of the nodes prior to the beginning of the modelling time horizon. This assumption also spaned transmission lines capacities implying none of the transmission lines existing prior to the beginning of modelling.

As it has been highlighted, due to the illustrative purposes of the case study, some of the input data employed to feed the models has been approximated to provide representative output results. In particular, this concerns the intercept and slope of the linear inverse function denoted $D^{slp}_{s,t,n}$ and $D^{int}_{s,t,n}$, respectively. Following (Virasjoki et al. [2020]) data generation process for the illustrative example, $D^{slp}_{s,t,n}$ and $D^{int}_{s,t,n}$ were calculated as follows.

$$D^{slp}_{s,t,n} = \frac{\text{price}_{s,t,n}}{\text{demand elasticity} \times \text{demand}_{s,t,n}}$$

and

$$D^{int}_{s,t,n} = \text{price}_{s,t,n} + D^{slp}_{s,t,n} \times \text{demand}_{s,t,n}.$$

The demand elasticity parameter was arbitrary chosen to be 0.3. The $\text{price}_{s,t,n}$ values were obtained by averaging the 2018 year hourly-based day ahead prices provided by entso-e platform (Hirth et al. [2018]) for each time period and scenario.The $\text{demand}_{s,t,n}$ and $A^r_{s,t,n,}$ values were obtained by applying the same approach to the demand and VRES availability data provided by GlobalEnergyGIS (Mattsson et al. [2021]). Therefore, all the parameters $D^{slp}_{s,t,n} > 0,\ \forall s \in S, t \in T, n \in N$ render the inverse correlation between the quantity of energy consumed $q_{s,t,n}$ $\forall s \in S, t \in T, n \in N$ and price defined as $D^{int}_{s,t,n} - D^{slp}_{s,t,n} q_{s,t,n}$ e.g. the higher the quantity consumed the lower the price vaue and vice versa.

Another essential set of the input data falling into the approximation category is the GHG taxes denoted as D^e which were chosen arbitrary as presented in Table 8. Nevertheless, one can exploit emission factors to refine the GHG taxes values when considering the real case study.

Conventional energy type	D^e (node 1)	D^e (node 2)	D^e (node 3)
Biomass	10	10	10
Nuclear	20	20	20
Coal	10	10	10
Gas CCT	10	10	10
Gas OCT	20	20	20

Table 8: Carbon taxes (€ / MWh)

The rest of the parameters settings can be found at the GitHub repository (Belyak [2021]).

3.2 Results

To reflect the influence of the transmission lines investment decisions made at the upper level on the generation levels and capacity expansion decisions made at the lower level the solution results are provided considering two settings for the transmission capacity expansion budget defined per transmission line. In the first case, the budget limit was set to be 100000 € per line and in the second to 1000000 € per line.

Table 9 presents the optimal transmission lines capacity expansion decisions made under different budget limits and market settings. Tables 10, 11 and 12 demonstrate the optimal decisions regarding the VRES capacity expansion considering centralised planning, perfect competition and Cournot Oligopoly market settings accordingly. Respectfully, the optimal conventional energy expansion decisions suggested under central planning, perfect competition and Cournot oligopoly market structures illustrated by Tables 13, 14 and 15. Table 16 informs the values of the objective functions, total optimal transmission system, VRES and conventional energy generation capacity expansion along with the total VRES shares among the various energy sources capacities installed considering different market settings and transmission lines expansion budgets options.

Market settings	Centralised planning		Perfect competition		Cournot Oligopoly	
Budget (per line)	100K €	1M €	100K €	1M €	100K €	1M €
Transmission line						
Node 1 ↔ Node 2	1.46	1.46	172.12	1507.21	183.43	1539.98
Node 2 ↔ Node 3	7.68	7.68	410.90	3350.89	410.90	3357.07
Node 1 ↔ Node 3	5.92	5.92	296.67	2407.91	296.67	2545.27

Table 9: Transmission lines expansion decisions (MW) considering different budget limits per line and different market settings

Budget per line		100K €		1M €	
Producer		1	2	1	2
Node 1	Wind Onshore	1951.38	1374.11	2000.00	1325.49
	Wind Offshore	1533.01	922.70	1557.26	898.45
	Solar	0.00	0.00	0.00	0.00
Node 2	Wind Onshore	3496.11	1469.95	3530.32	1435.73
	Wind Offshore	2746.65	887.15	2756.80	877.00
	Solar	0.00	0.00	0.00	0.00
Node 3	Wind Onshore	3887.35	1480.04	3918.67	1448.73
	Wind Offshore	3061.83	883.11	3071.73	873.22
	Solar	0.00	0.00	0.00	0.00

Table 10: VRES generation expansion decisions (MW) under centralised planning market settings

Budget per line		100K €		1M €	
Producer		1	2	1	2
Node 1	Wind Onshore	8057.17	1009.94	369.61	400.10
	Wind Offshore	3789.19	403.94	14441.65	837.43
	Solar	1855.99	245.41	947.92	277.24
Node 2	Wind Onshore	8087.54	1014.84	378.34	399.11
	Wind Offshore	3821.90	405.04	14387.18	838.01
	Solar	1883.25	245.41	970.40	277.23
Node 3	Wind Onshore	2197.75	1187.34	0.00	0.00
	Wind Offshore	1648.83	538.71	0.00	0.00
	Solar	0.00	0.00	0.00	0.00

Table 11: VRES generation expansion decisions (MW) under perfect competition market settings

Budget (per line)		100K €		1M €	
Producer		1	2	1	2
Node 1	Wind Onshore	7357.27	217.14	4915.11	844.27
	Wind Onshore	3253.37	1375.90	5715.14	1236.83
	Solar	1726.93	84.58	2972.03	0.00
Node 2	Wind Onshore	7637.22	819.62	332.43	490.91
	Wind Onshore	3460.57	522.22	16611.97	1422.16
	Solar	1782.47	285.08	4.40	0.00
Node 3	Wind Onshore	1469.08	1457.82	0.00	0.00
	Wind Onshore	959.52	915.05	0.00	0.00
	Solar	0.00	0.00	0.00	0.00

Table 12: VRES generation expansion decisions (MW) under Cournot oligopoly market settings

Budget (per line)		100K €		1M €	
Producer		1	2	1	2
Node 1	Biomass	0.00	0.00	0.00	0.00
	Nuclear	0.00	0.00	0.00	0.00
	Coal	0.00	0.00	0.00	0.00
	Gas CCT	0.00	0.00	0.00	0.00
	Gas OCT	0.00	0.00	0.00	0.00
Node 2	Biomass	0.00	0.00	0.00	0.00
	Nuclear	0.00	0.00	0.00	0.00
	Coal	0.00	0.00	0.00	0.00
	Gas CCT	0.00	0.00	0.00	0.00
	Gas OCT	0.00	0.00	0.00	0.00
Node 3	Biomass	0.00	0.00	0.00	0.00
	Nuclear	0.00	0.00	0.00	0.00
	Coal	0.00	0.00	0.00	0.00
	Gas CCT	0.00	0.00	0.00	0.00
	Gas OCT	0.00	0.00	0.00	0.00

Table 13: Conventional generation expansion decisions (MW) under centralised planning market settings

Budget (per line)		100K €		1M €	
Producer		1	2	1	2
Node 1	Biomass	16.25	1.73	1.71	1.20
	Nuclear	11.83	0.98	0.99	0.65
	Coal	23.54	2.38	3.25	1.75
	Gas CCT	22.90	2.54	4.95	2.21
	Gas OCT	46.89	5.30	344.41	14.91
Node 2	Biomass	1.73	16.24	1.20	1.71
	Nuclear	0.98	11.81	0.65	0.99
	Coal	2.38	23.54	1.75	3.25
	Gas CCT	2.55	22.94	2.21	4.95
	Gas OCT	5.30	47.17	14.91	344.41
Node 3	Biomass	0.00	0.00	0.00	0.00
	Nuclear	0.00	0.00	0.00	0.00
	Coal	0.00	0.00	0.00	0.00
	Gas CCT	0.00	0.00	0.00	0.00
	Gas OCT	0.00	0.00	0.00	0.00

Table 14: Conventional generation expansion decisions (MW) under perfect competition market settings

Budget (per line)		100K €		1M €	
Producer		1	2	1	2
Node 1	Biomass	15.72	0.02	15.22	0.00
	Nuclear	12.00	0.01	11.72	0.00
	Coal	23.87	0.04	22.85	0.00
	Gas CCT	23.66	0.05	23.66	0.00
	Gas OCT	47.47	37.96	57.89	38.43
Node 2	Biomass	1.61	12.25	0.00	0.00
	Nuclear	1.08	8.26	0.00	0.00
	Coal	2.31	20.35	0.00	0.00
	Gas CCT	2.52	24.24	0.00	0.00
	Gas OCT	5.47	118.10	38.43	384.31
Node 3	Biomass	0.00	0.00	0.00	0.00
	Nuclear	0.00	0.00	0.00	0.00
	Coal	0.00	0.00	0.00	0.00
	Gas CCT	0.00	0.00	0.00	0.00
	Gas OCT	0.00	0.00	0.00	0.00

Table 15: Conventional generation expansion decisions (MW) under Cournot oligopoly market settings

	Budget (per line)	
	100K €	1M €
Centralised planning		
Objective value (M€)	56.52	56.52
Transmission system expansion (MW)	15.07	15.07
VRES generation expansion (MW)	23693.40	23693.39
Conventional generation expansion (MW)	0.00	0.00
VRES share (%)	100.00	100.00
Perfect competition		
Objective value (M€)	26.88	33.39
Transmission system expansion (MW)	879.69	7266.01
VRES generation expansion (MW)	36392.25	34524.22
Conventional generation expansion (MW)	268.96	752.07
VRES share (%)	99.27	97.87
Cournot Oligopoly		
Objective value (M€)	26.71	32.75
Transmission system expansion (MW)	890.99	7442.32
VRES generation expansion (MW)	33323.83	34545.24
Conventional generation expansion (MW)	356.98	592.51
VRES share (%)	98.94	98.31

Table 16: Objective values, total transmission system, VRES and conventional generation capacity expansion and VRES share resulting from optimising the optimisation problems constructed considering different transmission lines expansion budget limits and market settings

As one can notice, the results suggest the highest welfare values when considering centralised planning. Additionally, such high welfare is achieved relying only on the VRES generation nearly completely satisfying local demand as the suggested transmission investments are essentially small and do not differ regardless of the transmission lines budget limits.

Another highlight indicated by the results is that the welfare declines when considering the Cournot oligopoly comparing to the perfect competition. However, increasing the budget defined per transmission line allows the increase in the welfare value for both market settings without the effect on the tendency defined in the sentence above.

Regarding the share of the VRES capacity expansion compared to the total energy capacity investment decisions made by all the producers at all the nodes, the results suggest a marginal decline by 0,3 per cent when considering Cournot oligopoly compared to the Perfect competition. An overall decline in this value can be observed for both decentralised market conditions when the transmission lines capacity expansion budget is increased. However, this decrease is less significant in the case of the Cournot oligopoly market structure reflecting the decline by only about 0,6 per cent compared to 1,4 per cent when the market is modelled as perfect competition.

Another noticeable highlight suggested by the results is a possible threshold in the investment budget defined per transmission line value. Until this value is reached the transmission capacity investment decisions do not demonstrate significant difference when considering perfect and Cournot competition as one can observe from the Table 9 and investment decisions made under 100K € budget per line.

4 Discussion and conclusions

In this study, we proposed a modelling framework allowing us to more profoundly understand the the role of the TSO supported by other renewable generation targeting policies (e.g. carbon taxes) in the VRES share increase strategies.

As the illustrative example suggests, given a centralised planning setting one can possibly expect the highest total welfare supported by only VRES generation while not strongly relying on the TSO decisions as most of the demand is suggested to be satisfied locally. Nevertheless, such power market settings hardly represent the majority of the present structures. Therefore, we also considered a framework where the producer companies compete to maximise individual revenues. Under such settings, the generation companies might act as either price takers forming a market modelled as perfect competition or anticipate the effect of their production quantities on the market prices representing the Cournot oligopoly market structure. Following the illustrative example results one can notice that the role of the TSO decisions under competitive market structure becomes more significant as the transmission lines expansion decisions not only affect the total welfare demonstrating a positive correlation between its value and the budget allocated per transmission line but also reflect reverse behaviour when considering the share of the VRES generation capacities among the energy sources. In addition, the outcome of the illustrative example suggests that the difference between the transmission lines capacities investment decisions comparing perfect and Cournot competition possibly becomes noticeable only once some investment budget value defined per line is exceeded.

Following the statements above, the proposed research plays a significant role in studying the optimal transmission network expansion planning and its welfare effects, considering different power market settings within the framework of GHG emissions reduction strategies. It can be also exploited when modelling small- and large-scale energy networks e.g. Nordics or the EU.

However, despite promising results, the proposed study still has a few shortcomings. The first one is associated with the limitations when considering the imperfect competing market modelled as the Cournot Oligopoly. While one does not observe any contradictions with such market settings in case the export quantities proposed by the producer companies do not exceed the transmission lines capacities when such a situation occurs the TSO would have to pause the market operations forcing the generation producers to reconsider their production decisions. Under such a scenario, the TSO behaviour does not allow Cournot competition but rather poses the centralised planning market structure. Nevertheless, even when such a situation occurs the optimal decisions are still made in favour of maximising total welfare. This has been suggested by a small toy case experiment we conducted and as we closely refer to (Virasjoki et al. [2020]) using identical Cournot oligoply formulation we have no reason yet to doubt the scaling of this assumption forming the proof by induction.

Another shortcoming is associated with the lack of consideration of the energy storage technologies in the power grid and consideration of the hydro-power as a VRES source. From the TSO perspective, the storage technologies could potentially facilitate market efficiency and, hence, social welfare increase (Schill and Kemfert [2011]). Expanding the proposed modelling assessment with hydro-power plants is essential when considering the grids with a high share of VRES generation, however, requires taking into account a significant number of additional constraints that other power plants types do not face (Stoll et al. [2017]). Both of the aforementioned modelling deficiencies are due to the time limits of the YSSP project.

A further drawback of the proposed modelling approach one can associate with modelling of the VRES availability rather than modelling uncertainty directly within time frames considered in the model e.g. stochastic programming. However, while arbitrary deciding on some weeks in the illustrative example to represent seasonal scenarios these can be also obtained using hierarchical clustering (Virasjoki et al. [2020]) to provide an efficient representation of the seasonal demand and VRES production.

Therefore, as one of the further steps in the proposed research one could consider the inclusion of hydro-power as one of the VRES types and involving energy storage technologies in the modelling process. Both enhancements will allow the closer representation of reality while taking into account the trade-off between computational tractability and detailed representation. Another possible direction could be to apply the proposed modelling assessment to the real case study. The latter would comprise designing clustering procedure to formulate the availability scenarios with profound data preprocessing. The latter in particular concerns the GHG taxes related data imposed in the model that is required to be refined following emission factors to closer represent the reality. Lastly, one could still conduct a thorough theoretical proof on the statement made regarding the Cournot oligopoly competition transforming into centralised planning maximising social welfare under the situation when suggested export exceeds decided transmission line capacity.

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