BILEVEL OPTIMIZATION OF ENERGY SYSTEM TRANSITION PATHWAYS CONSIDERING COMPETITION IN MARKETS

David Yang Shu[1,†], Christiane Reinert[2,†], Jacob Mannhardt[2], Ludger Leenders[1], Jannik Lüthje[3], Alexander Mitsos[3,4,5] and André Bardow[1,*]

[1] Energy & Process Systems Engineering, ETH Zurich, Switzerland
[2] Institute for Technical Thermodynamics, RWTH Aachen University, Germany
[3] Process Systems Engineering (AVT.SVT), RWTH Aachen University, Germany
[4] JARA-CSD, Aachen 52056, Germany
[5] Institute of Energy and Climate Research, Energy Systems Engineering (IEK-10), Forschungszentrum Jülich GmbH, Germany

Abstract

The energy system transition towards net-zero greenhouse gas emissions involves multiple decision makers. While greenhouse gas mitigation targets must be jointly achieved, the decision makers are primarily interested in minimizing their individual cost of energy supply. The competing interest of decision makers are commonly neglected in optimization models of the energy system transition. To overcome this shortcoming, we model the energy system transition as a multi-leader-single-follower game: In our model, individual decision makers develop investment strategies in shared electricity and carbon markets. We formulate the game as a bilevel optimization problem that reflects the multi-level nature of the decision-making process. We find an equilibrium solution to the multi-leader-single-follower game by applying the Gauss-Seidel method. Our case study of the European electricity system shows that the bilevel optimization problem results in a transition pathway with higher capacity expansion compared to a centralized approach. Further, the average market clearing price and the spread of locational market clearing prices are lower. As a result, overall costs are reduced when considering trading and carbon allowance costs on top of the investment and operating costs. Hence, considering competition and market behavior is vital in modeling the energy system transition.

Keywords

Nash equilibrium, Stackelberg game, mathematical optimization, mathematical problem with equilibrium constraints (MPEC), electricity market

Introduction

Multiple countries and international organizations intend to reach net-zero emissions before 2050, e.g., the European Union with the European Green Deal (European Commission, 2019). To steer the energy system transition towards affordable and low-carbon systems, energy system modeling is essential for policymakers. Typically, optimal transition pathways for the energy system are determined, minimizing cost while meeting environmental constraints such as greenhouse gas (GHG) emission limits.

Such energy system models often assume a central planner for capacity expansion and operation decisions (Savvidis et al., 2019). However, in reality, multiple decision makers determine the capacity expansion and follow individual, possibly conflicting interests.

[†] These authors contributed equally
[*] To whom all correspondence should be addressed

Furthermore, the production and subsequent transmission of power is determined on markets instead of by a central planner. Consequently, the central planner approach predicts an unrealistic behavior of decision makers and can underestimate social welfare costs (Panos et al., 2017) and miss environmental targets.

As an alternative to centralized optimization, the energy system transition including decision makers and markets, can be modeled as a multi-leader-single-follower game and formulated as a bilevel optimization problem: In the investigated game design, the decision makers act as competitive leaders making initial capacity expansion decisions to which the common electricity market reacts as a follower, considering environmental constraints.

Bilevel optimization has been applied to capacity expansion problems to model the interaction between decision makers and markets. However, bilevel optimization has only been applied to stylized energy systems (Kazempour et al., 2011; Taheri et al., 2017; Wogrin et al., 2013a; Wogrin et al., 2013b; Wogrin et al., 2020) or to case studies based on small real-world systems (Panos et al., 2017; Rocha et al., 2015) with few decision makers due to modeling complexity.

For example, Panos et al. (2017) consider investment decisions of countries at the upper level and strategic trading with market power in the common market at the lower level. In a case study, the authors demonstrate the impact of the market power on cost using a model limited to 5 decision makers and two timesteps. Rocha et al. (2015) model a cap-and-trade system, where 4 players optimize their capacity expansion under a cap-and-trade program in a 9-node network model of Northern Illinois. In their model, players choose between predefined capacity expansion plans. Wogrin et al. (2020) obtain substantial cost and capacity differences when comparing a centralized to a bilevel optimization in an illustrative example.

Hence, bilevel optimization is already applied to investigate competition between decision makers and market interactions in capacity expansion problems. However, the impact of competition and markets on energy system transition pathways has not been investigated in case studies on continental-scale energy systems.

In this work, we formulate a bilevel optimization problem for the capacity expansion in the European energy system considering national decision makers that interact in a common electricity market with a GHG emission constraint. We further combine the Gauss-Seidel method with an efficient mixed-integer linear programming single-level reformulation to determine an equilibrium solution of the bilevel optimization problem. Our case study compares the European electricity system transition pathway resulting from our bilevel optimization problem to the common centralized optimization problem. In particular, we quantify the differences in costs and market clearing prices. We thus isolate the impact of competition and markets on the energy system transition of a continental-scale energy system.

Conceptual bilevel formulation & solution approach

The transition pathway of the multi-national energy system consists of consecutive investments of the decision makers within a transition horizon. Each decision process is modeled as a multi-leader-single-follower game. In the game setup, the investment decision makers are the leaders, and the energy market is the common follower determining the operation of the power plants. We assume that the leaders have perfect knowledge of the other players' strategies for their decision-making and are engaged in a noncooperative game for which we seek a Nash equilibrium (Facchinei and Kanzow, 2010).

Wogrin et al. (2020) provide an overview of solution methods and challenges in solving bilevel optimization problems in energy system modeling. In this contribution, we apply the Gauss-Seidel method to solve the multi-leader-single-follower game. We first divide the multi-leader-single-follower game into individual single-leader-single-follower Stackelberg games by assuming fixed investment strategies for all but one decision maker. The decision maker is assumed to have complete knowledge of the market behavior. Hence, in each investment period, we formulate the single-leader-single-follower problem as a bilevel optimization problem (Eqs. (1)-(6)) for each decision maker $\bar{n} \in \mathcal{N}$.

$$\min_{\boldsymbol{x}_{\bar{n}},\boldsymbol{y}} \quad C_{\bar{n}}^{\mathrm{tot}} = C_{\bar{n}}^{\mathrm{inv}}(\boldsymbol{x}_{\bar{n}}) + C_{\bar{n}}^{\mathrm{op}}(\boldsymbol{y}) + C_{\bar{n}}^{\mathrm{trade}}(\boldsymbol{y}, c_{n,t}^{\mathrm{el}}) + C_{\bar{n}}^{\mathrm{CO_2}}(\boldsymbol{y}, c^{\mathrm{E}}) \tag{1}$$

$$\text{s.t. } \boldsymbol{f}_{\bar{n}}(\boldsymbol{x}_{\bar{n}}) \leq \boldsymbol{0} \tag{2}$$

$$\boldsymbol{y} \in \arg\min_{\boldsymbol{y}'} \sum_{n \in \mathcal{N}} C_n^{\mathrm{op}}(\boldsymbol{y}') \tag{3}$$

$$\text{s.t. } P_{n,t}^{\mathrm{dem}} + P_{n,t}^{\mathrm{exp}} - P_{n,t}^{\mathrm{imp}} - P_{n,t}^{\mathrm{gen}} - P_{n,t}^{\mathrm{curt}} = 0 : c_{n,t}^{\mathrm{el}}, \quad \forall\, n \in \mathcal{N}, t \in \mathcal{T} \tag{4}$$

$$\sum_{n \in \mathcal{N}} E_n^{\mathrm{op}} \leq E^{\mathrm{op,max}} + E^{\mathrm{S}} : c^{\mathrm{E}} \tag{5}$$

$$\boldsymbol{g}(\boldsymbol{y}', \boldsymbol{x}_n) \leq \boldsymbol{0} \tag{6}$$

The objective function in the upper level (Eq. (1)) depends on both upper-level variables $\boldsymbol{x}_{\bar{n}}$ and lower level variables $\boldsymbol{y}$ and includes the investment cost $C_{\bar{n}}^{\mathrm{inv}}$, operating cost $C_{\bar{n}}^{\mathrm{op}}$, electricity trading cost $C_{\bar{n}}^{\mathrm{trade}}$, and the emission cost $C_{\bar{n}}^{\mathrm{CO_2}}$ of the considered decision maker $\bar{n}$.

The investment cost and operating costs in the upper-level objective depend on the investment decisions and the operation of the generation units of the considered decision maker $\bar{n}$. In addition, the objective includes trading and emission costs that depend on the electricity price $c_{n,t}^{\mathrm{el}}$ and the carbon allowance price c^{E} that are formed in the respective markets in the lower level.

The constraints in the upper level (Eq. (2)) represent the capacity expansion limits for the considered decision maker $\bar{n}$.

The objective of the electricity market (Eq. (3)) is the minimization of social welfare costs. Hence, the joint operating costs of all power plants for satisfying the inelastic electricity demands are minimized, assuming known investment strategies and plant availabilities of all decision makers $n \in \mathcal{N}$ (Eq. (3)).

The trading on the electricity market needs to satisfy the electricity demands. Hence, an energy balance equation is included (Eq. (4)), where the demand $P_{n,t}^{\mathrm{dem}}$ and the electricity exported to other decision makers $P_{n,t}^{\mathrm{exp}}$ need to equal the sum of generated electricity $P_{n,t}^{\mathrm{gen}}$, electricity imported from other decision makers $P_{n,t}^{\mathrm{imp}}$, and curtailed electricity demand $P_{n,t}^{\mathrm{curt}}$ for all decision makers $n \in \mathcal{N}$ in all considered time steps $t \in \mathcal{T}$. We assume zonal pricing of electricity with one bidding zone per decision maker. The dual variable corresponding to the energy balance is the locational market clearing price of electricity $c_{n,t}^{\mathrm{el}}$ and is considered in the trading cost of the leader's objective function. The curtailed electricity demand is a slack variable penalized heavily in the objective of the electricity market.

As emission trading enforces increasingly strict GHG emission limits, the GHG emissions of all countries are limited to a maximum value $E^{\mathrm{op,max}}$ (Eq. (5)). The slack variable E^{S} is heavily penalized in the operating costs of both upper and lower-level objectives. The dual variable corresponding to the GHG emission constraint is the carbon allowance price c^{E} and is also considered in the upper level when determining the carbon allowance cost of the leader.

Additional technical aspects of the energy system are modeled using lower-level constraints (Eq. (6)), including operating limits of generation units, and the DC-load-flow model for transmission (Overbye et al., 2004).

To solve problem (Eqs. (1)-(6)), the bilevel problem is first reformulated to a single-level mathematical problem with equilibrium constraints via strong duality. We linearize the bilinear terms resulting from the reformulation via binary expansion with 6 sampling points (Pereira et al., 2005), arriving at a mixed-integer linear program that can be solved using commercial solvers.

The Gauss-Seidel method is initialized using the solution of the centralized optimization. Then, we solve the bilevel optimization problem (Eqs. (1)-(6)) sequentially for each decision maker $n \in \mathcal{N}$ in the Gauss-Seidel method to obtain an equilibrium solution. After each iteration, the investment strategies of all other decision makers is updated with a damping factor until the investment strategies converge to a Nash equilibrium. The Gauss-Seidel method is not guaranteed to converge towards a Nash-equilibrium but is effective in the considered case study. However, the application of the Gauss-Seidel method to models with a larger number of players and higher model complexity is limited by computation time.

After the convergence of the investment strategies, the new capacities are added to the existing capacities of the decision makers. The multi-leader-single-follower game is repeated for the next investment period until the final investment period of the transition horizon is reached.

Case study: European energy system transition

Our case study investigates the impact of competition and markets in an optimization model of the European energy system transitioning to net-zero GHG emissions. We consider a transition horizon until 2050, starting from 2015 with investment decisions every 5 years. We select 2015 as the initial year due to the availability of data.

The case study includes the 21 countries in the Multi-Regional Coupling project (Gomez et al., 2019) that are also part of the European Union as decision makers , i.e., leaders. The countries are modeled as nodes connected by a transmission grid (Figure 1). The common electricity market with a shared GHG emission constraint is considered the follower in the bilevel optimization problem.

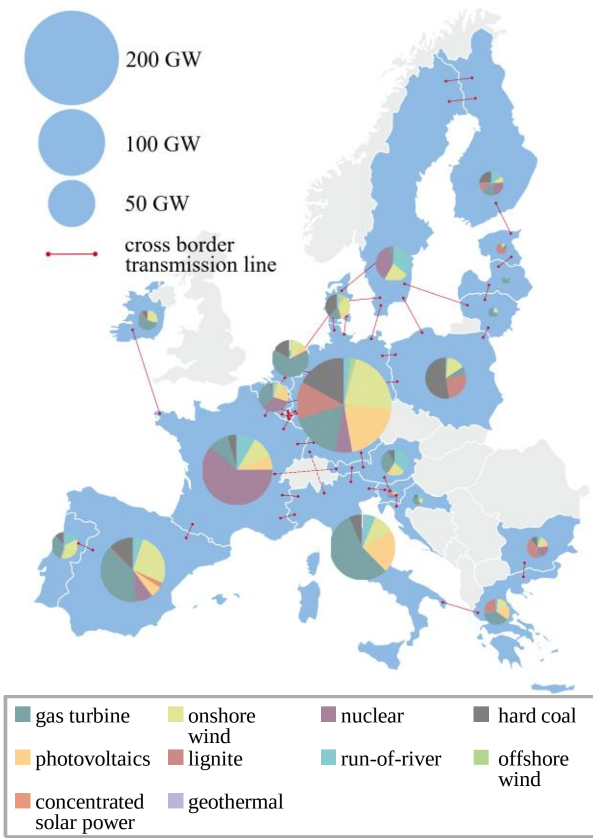

Figure 1: Existing generation capacities in the initial year of the transition pathway (2015) and cross-border transmission lines.

We model 10 electricity production technologies with country-specific capacity expansion limits. Further, we include existing capacities in the initial year of the transition pathway. As conventional energy converters, we include hard coal, lignite, natural gas, and nuclear power plants. As renewable energy converters, we include onshore and offshore wind, photovoltaics, concentrated solar power, run-of-river hydropower, and geothermal power plants. The inclusion of additional sectors of the energy system, such as heating and transport, could be investigated in future work to acknowledge the increasing sector coupling.

We formulate the bilevel and the centralized optimization problem, assuming the same cost and technical parameters. We thus isolate the impact of competition and the shared market on the transition pathway, which are considered in the bilevel optimization problem but neglected in the centralized optimization.

The cost and technical parameters are obtained from the sources below. The reference year of all sources is 2015, except for the electricity demand data by ENTSO-E, for which the most recent data from 2017 is selected:

- existing capacities in 2015 (Mantzos et al., 2018) and the respective construction years (European Commission, 2016; Mantzos et al., 2019)
- capacity expansion limits (Ruiz et al., 2019)
- capital and operational expenditures, fuel prices (European Commission, 2016; Mantzos et al., 2019)
- fossil power plant efficiencies (Eurostat, 2021)
- availability of volatile generators (Gonzalez Aparicio et al., 2017)
- net-transfer capacities for cross-border transmission (ENTSO-E, 2021).

To model operational GHG emissions, we apply the life-cycle assessment methodology (DIN EN ISO 14044:2018-05, 2018; DIN EN ISO 14040:2021-02, 2021). The operational GHG emissions are obtained from the life-cycle inventory database ecoinvent 3.7.124 APOS (Wernet et al., 2016), using the life-cycle inventories of Baumgärtner et al. (2021). As life-cycle impact assessment method, we employ Environmental Footprints 2.0 (Fazio et al., 2018).

To reduce computation time, we represent the annual time series using 10 typical time steps without temporal coupling. We determine the typical time steps using hierarchical clustering of the original time series (Kotzur et al., 2018).

Comparison of cost & market clearing price

The total cost (Eq (1)), including the annualized investment and operating costs and the trading and carbon allowance costs, are significantly lower for the bilevel optimization compared to the centralized optimization during the transition horizon (-8 % to -19 %) (Figure 2).

The bilevel objective of each country explicitly accounts for the trading and carbon allowance costs. However, trading and carbon allowance costs are neglected in the centralized optimization. For comparison with the bilevel optimization, we evaluate the trading and carbon allowance costs retrospectively by solving the bilevel optimization problem with upper-level variables fixed to the solution of the centralized optimization problem.

The total cost difference increases towards the end of the transition pathway and is dominated by trading costs (Figure 2). The total cost differs more due to a greater spread of locational market clearing prices and a higher average market clearing price in the centralized optimization compared to the bilevel optimization (Figure 3). On average, the European market clearing price is 40 % lower in the bilevel optimization than in the centralized optimization problem.

While the centralized optimization neglects trading costs, the bilevel optimization incentivizes countries to reduce trading costs as part of the objective function (Eq. (1)). Consequently, countries adjust their capacity expansion strategies to lower the need for costly electricity imports: In result, generation capacities in the bilevel optimization are 3 % higher than in the centralized optimization in 2050. Lower electricity imports also reduce grid congestion which further reduces the spread of market clearing prices and arbitrage.

The spread of average locational market clearing prices is lower in the bilevel optimization problem compared to the centralized optimization (Figure 3). The standard deviation of the countries' locational market clearing prices increases from 7.7 EUR/MWh to 55.7 EUR/MWh in the centralized optimization from 2015 to 2050. With the introduction of competition between countries in the bilevel optimization, the market clearing prices converge, resulting

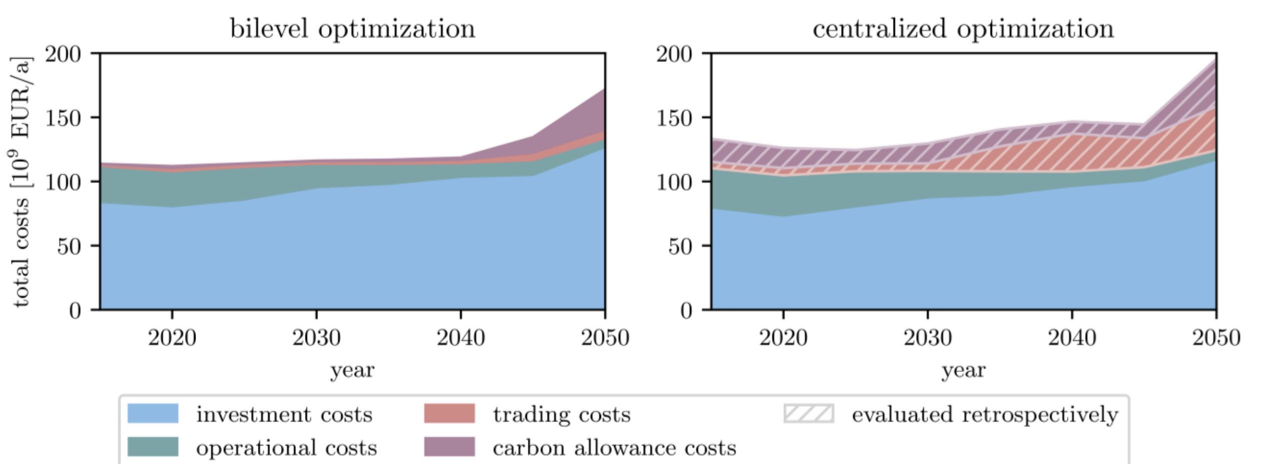

Figure 2: Total costs along the transition pathway for the bilevel optimization (left) and the centralized optimization (right). Trading and carbon allowance costs are not part of the objective function of the centralized optimization. For comparison, the trading and carbon allowance costs are evaluated retrospectively.

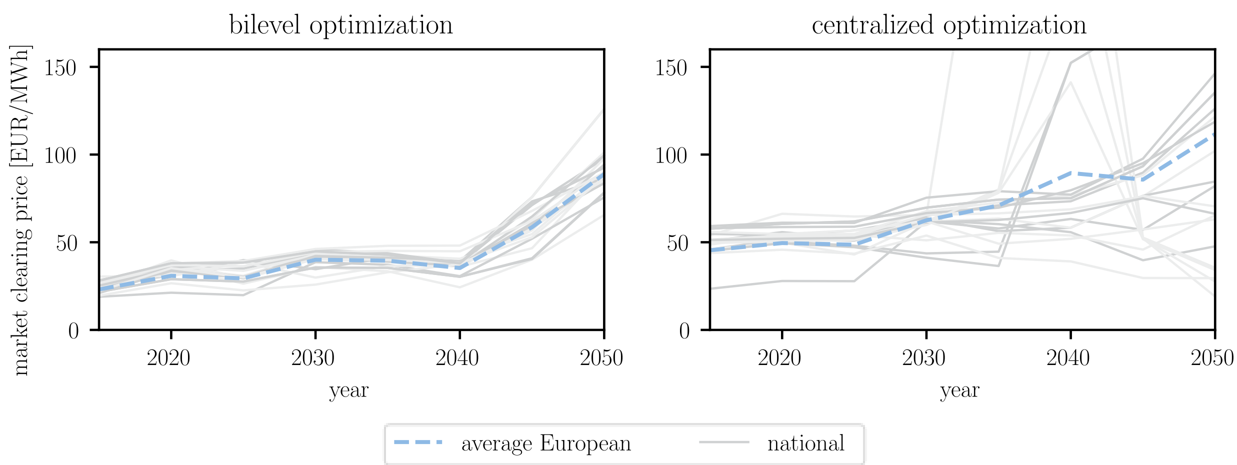

Figure 3: Average market clearing prices in Europe and individual countries for the bilevel optimization (left) and the centralized optimization (right). The average market clearing price in Europe is determined by weighting the national market clearing prices with national electricity demands.

in an almost 4 times lower standard deviation of 14.2 EUR/MWh in 2050.

Centralized optimizations commonly choose the annualized investment and operating cost as the objective function. The centralized optimization underestimates the annualized investment and operating cost of the energy system transition as ideal cooperation is assumed between countries to satisfy electricity demands and meet global GHG emission limits. The underestimation increases with time, reaching a difference of -7 % compared to the bilevel optimization in 2050. Thus the centralized optimization neglects trading and carbon allowance costs in its objective and also underestimates annualized investment and operating costs compared to the bilevel optimization.

Conclusions

This contribution demonstrates the impact of modeling decision-making processes on optimized transition pathways of energy systems. We apply bilevel optimization to the transition planning of continental-scale energy systems to model multiple decision makers acting in a common electricity market with a GHG emission constraint as opposed to the common central-planner paradigm.

The multi-level decision-making in the energy system transition is modeled the energy system transition as a multi-leader-single-follower game. The multi-leader-single-follower game is solved by the Gauss-Seidel method. The resulting bilevel optimization problems are first reformulated to a single-level optimization problem via strong duality and then linearized using binary expansion to obtain a mixed-integer linear programming formulation.

We apply our method to a case study of the European electricity system transition. We compare costs and electricity prices resulting from the bilevel optimization and the commonly-used centralized optimization, which neglects markets and assumes perfect cooperation.

In our case study, the centralized optimization substantially underestimates annualized investment and operating cost (-7 %), which is a common objective function in centralized optimization. The annualized investment and operating cost is underestimated as the centralized optimization assumes perfect cooperation of all decision-makers and neglects markets. In addition, the total cost is lower in the bilevel optimization because it reflects the trading and carbon allowance costs on top of annualized investment and operating cost.

The bilevel optimization further yields an on average 40 % lower European market clearing price and an almost 4 times lower standard deviation of locational market clearing prices in 2050 compared to the centralized optimization. The lower market clearing prices are due to the introduction of competition between countries and their interaction in the electricity market. The competition and market interactions increase the overall generation capacity by 3 % until 2050.

The substantial impacts of market effects and competition between decision makers cannot be captured by the central-planner approach, which is commonly used in energy system transition planning. As both competition and market effects exist in real-life energy systems, our results underline the need to consider competitive, market-based decision-making in the modeling of the energy system transition.

Acknowledgments

DS has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 838031. CR received funding by SCI4climate.NRW (Grant-Nr. EFO 0001G). LL and AB acknowledge the funding by the Swiss Federal Office of Energy's SWEET programme as part of the project PATHFNDR. JL and AM gratefully acknowledge the financial support of the Kopernikus project SynErgie by the Federal Ministry of Education and Research (BMBF) and the project supervision by the project management organization Projektträger Jülich. Simulations were performed with computing resources granted by RWTH Aachen University under project thes1027 and rwth0882.

References

Baumgärtner N, Deutz S, Reinert C, Nolzen N, Kuepper LE, Hennen M, et al. Life-Cycle Assessment of Sector-Coupled National Energy Systems: Environmental Impacts of Electricity, Heat, and Transportation in Germany Till 2050. Front. Energy Res. 2021;9.

DIN Deutsches Institut für Normung e.V. DIN EN ISO 14044:2018-05: Beuth Verlag GmbH, 2018.

DIN Deutsches Institut für Normung e.V. DIN EN ISO 14040:2021-02: Beuth Verlag GmbH, 2021.

ENTSO-E. Ten-Year Network Development Plan 2020 – Main Report; 2021.

European Commission. POTEnCIA model description: version 0.9. Joint Research Centre. Institute for Prospective Technological Studies. Publications Office; 2016.

European Commission. The European Green Deal: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. COM/2019/640 final. Brussels: European Commission; 2019.

Eurostat. Supply, transformation and consumption of electricity: NRG_CB_E, 2021. https://ec.europa.eu/eurostat/databrowser/view/NRG_CB_E__custom_1230604/settings_1/table?lang=en (accessed August 21, 2021).

Facchinei F, Kanzow C. Generalized Nash Equilibrium Problems. Ann. Oper. Res. 2010;175(1):177–211.

Fazio S, Castellani V, Sala S, Schau E, Secchi M, Zampori L, et al. Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method: New models and differences with ILCD. JRC109369. Luxembourg: Publications Office of the European Union; 2018.

Gomez T, Herrero I, Rodilla P, Escobar R, Lanza S, La Fuente I de, et al. European Union Electricity Markets: Current Practice and Future View. IEEE Power and Energy Mag. 2019;17(1):20–31.

Gonzalez Aparicio I, Huld T, Careri F, Monforti-Ferrario F, Zucker A. EMHIRES dataset: Part II: Solar Power Generation: European Meteorological derived HIgh resolution RES generation time series for present and futures scenarios: Part II: PV generation using the PVGIS model. Luxembourg: Publications Office of the European Union; 2017.

Kazempour SJ, Conejo AJ, Ruiz C. Strategic Generation Investment Using a Complementarity Approach. IEEE Trans. Power Syst. 2011;26(2):940–8.

Kotzur L, Markewitz P, Robinius M, Stolten D. Impact of different time series aggregation methods on optimal energy system design. Renew. Energy 2018;117:474–87.

Mantzos L, Matei NA, Mulholland E, Rózsai M, Tamba M, Wiesenthal T. JRC-IDEES 2015: European Commission, Joint Research Centre (JRC), 2018. PID: http://data.europa.eu/89h/jrc-10110-10001.

Mantzos L, Wiesenthal T, Neuwahl F, Rózsai M. The POTEnCIA central scenario: An EU energy outlook to 2050. Luxembourg: Publications Office of the European Union; 2019.

Overbye TJ, Cheng X, Sun Y. A comparison of the AC and DC power flow models for LMP calculations. In: 37th Annual Hawaii International Conference on System Sciences, 2004. Proceedings of the; 08/01/2004 - 08/01/2004: Big Island, HI, USA: IEEE; 2004.

Panos E, Densing M, Schmedders K. Oligopolistic capacity expansion with subsequent market-bidding under transmission constraints (OCESM). Final Report 7.12.2017. Villigen PSI; 2017.

Pereira MV, Granville S, Fampa M, Dix R, Barroso LA. Strategic Bidding Under Uncertainty: A Binary Expansion Approach. IEEE Trans. Power Syst. 2005;20(1):180–8.

Rocha P, Das TK, Nanduri V, Botterud A. Impact of CO_2 cap-and-trade programs on restructured power markets with generation capacity investments. Int. J. Electr. Power Energy Syst. 2015;71:195–208.

Ruiz P, Nijs W, Tarvydas D, Sgobbi A, Zucker A, Pilli R, et al. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energy Strategy Rev. 2019;26:100379.

Savvidis G, Siala K, Weissbart C, Schmidt L, Borggrefe F, Kumar S, et al. The gap between energy policy challenges and model capabilities. Energy Policy 2019;125:503–20.

Taheri SS, Kazempour J, Seyedshenava S. Transmission expansion in an oligopoly considering generation investment equilibrium. Energy Econ. 2017;64:55–62.

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21(9):1218–30.

Wogrin S, Barquin J, Centeno E. Capacity Expansion Equilibria in Liberalized Electricity Markets: An EPEC Approach. IEEE Trans. Power Syst. 2013a;28(2):1531–9.

Wogrin S, Hobbs BF, Ralph D, Centeno E, Barquín J. Open versus closed loop capacity equilibria in electricity markets under perfect and oligopolistic competition. Math. Program. 2013b;140(2):295–322.

Wogrin S, Pineda S, Tejada-Arango DA. Applications of Bilevel Optimization in Energy and Electricity Markets. In: Dempe S, Zemkoho A, editors. Bilevel optimization: Advances and next challenges / Stephan Dempe, Alain Zemkoho, editors. Cham, Switzerland: Springer; 2020. p. 139–168.