

LIFE CYCLE OPTIMIZATION OF POWER GENERATION AND TRANSMISSION EXPANSION PLANNING

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Abstract

This paper aims to quantify key life-cycle environmental impacts of a long-term energy system generation and transmission expansion planning (GTEP) that satisfy the load demand for Texas from 2020 to 2050. We also analyze the system behaviour with and without a carbon tax strategy. Besides, it is essential to evaluate how the inclusion of environmental constraints may influence the expansion and planning decisions. We propose an optimization model to achieve this goal that minimizes the system's net present cost. At the same time, we evaluate the system's impacts on global warming, fine particulate matter, ecotoxicity, land use, and mineral and fossil resources scarcity indicators. The model captures the complexity of the energy system by considering fluctuating and firm generators, transmission lines, battery charge/discharge, and ramping constraints. The non-taxed GTEP comes with a 31.6% economic saving compared to the taxed counterpart. Overall, in 2050, regardless of the tax strategy, the energy system comprises high shares of wind and solar generators. This shift is possible by judiciously transmitting power within the system and flexibly operating the fossil-based generators. At the same time, the taxed GTEP selects utility-scale batteries while requiring 24.1% higher transmission capacity than the non-taxed system. Furthermore, in 2050, the total capacity of the coal and natural gas units, mainly acting as backup reserves, will remain relatively the same as in 2020 while being integrated with CCS at significant levels in the taxed system. Our analysis highlights potential bottlenecks of the transition towards renewable sources, which increase ecotoxicity and mineral depletion. These burdens are lower in the non-taxed GTEP. Finally, the system reduces the remaining metrics significantly, while the taxed counterpart outperforms the non-taxed alternative.

Keywords

Life cycle assessment, Energy system, Expansion planning

Introduction

Today's global aim to achieve a low-carbon future, aligned with the Paris climate agreement (United Nations, 2016), calls for significant greenhouse gas emissions reductions. In turn, this stresses the energy systems' generation expansion planning and transmission expansion planning (GEP and TEP, respectively) to mitigate climate

change successfully, while avoiding shifting the damages to other ecological areas. Besides, the limiting factor to satisfying the load demand more sustainably might be the generation or transmission infrastructure in locations with high availability of renewables.

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GEP determines the most beneficial plan for the energy system (i.e., profit maximization), while TEP aims to facilitate the energy exchange optimally among producers and consumers (i.e., social welfare maximization). Therefore, even though they are interrelated, analyzing the GEP and TEP problems independently might lead to suboptimal solutions since, in such an approach, it is not possible to build new transmission or generating infrastructure respectively (Conejo et al., 2016).

Determining the location, size and type of power generation units (and transmission lines) for the long-term demand-supply has attracted significant interest (Conejo et al., 2016). GEP and TEP models are usually large-scale mixed-integer linear programming (MILP) problems with yearly investment-related decisions. At the same time, operating decisions require an hourly representation within the long term, which increases the model's complexity significantly, thus, making it computationally intractable. Therefore, it is often common to sacrifice modeling accuracy to achieve computational tractability. For instance, using clustered days reduces the model's variables leading to a simplified system representation. Another simplification could be using a transportation model, a DC approximation, or a different approach for the power flow instead of the most accurate AC representation (Moradi et al., 2016).

Within this general context, (Lara et al., 2018) investigated the cost-optimal and multi-regional GEP of a power system for the Electric Reliability Council of Texas (ERCOT) over a 30-year horizon. The authors proposed a nested Benders decomposition algorithm (Benders, 1962) to effectively tackle the large-scale MILP, while also using representative days for the system inputs. The decomposition algorithm allows including the investment decisions in a master problem and the operating decisions in one or several sub-problems. Cuts obtained from the sub-problems are introduced iteratively to the master problem, narrowing the search space until convergence is achieved. (Li et al., 2022) enlarged the GEP model Lara et al. (2018) developed to include the transmission network. In that work, the authors solved the generation and transmission expansion planning (GTEP) for a 20-year horizon using the Benders decomposition from CPLEX (Bonami et al., 2020).

Most GE(T)P problems focus on the power system's cost-optimal design (Gorenstein Dedecca et al., 2018; Lumbreras and Ramos, 2016). Notably, the studies mentioned in the previous paragraph consider the direct CO₂ emission of the system, and a carbon tax to integrate the climate action strategy into the modelled framework. Nonetheless, the life-cycle implications of the energy system investment and operation, and that of a carbon tax, remain unclear. Investment decisions have embodied life-cycle impacts through developing and constructing generators and transmission line networks. At the same time, operational decisions lead to impacts related to the consumption of fuels in the system, along with the direct release of CO₂ that could potentially be subject to taxation. The current study aims to investigate key life-cycle

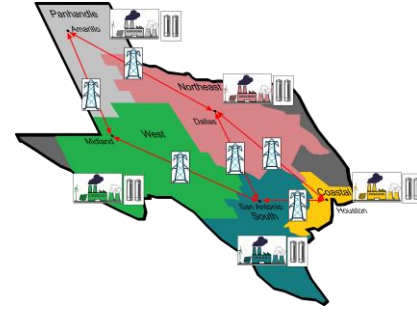


Figure 1. Representation of the system

indicators in the long-term GTEP problem for the ERCOT region, with and without a carbon tax, and evaluate the system's performance from 2020 to 2050.

Methodology

Generation and transmission expansion planning (GTEP)

To carry out our analysis, we developed an MILP model based on the work by Lara et al. (2018) and Li et al. (2022). We provide here only a concise representation of the problem, along with a brief description, due to space limitations, while a detailed MILP formulation can be found in the latter sources. The aim of our analysis is to determine the minimum net present cost design of an energy system (Eq. (1)) and evaluate its life-cycle impacts for satisfying the load demand of Texas from 2020 until 2050. The model is as follows,

$$OBJ = \min_{x,y} \sum_{n \in N} \sum_{l \in L} (c_n^T x_{n,l} + \sum_{d \in D_k} W_d f_n^T y_{n,l,d}) \quad (1)$$

s. t.

$$A_n x_{n,l} + B_n y_{n,l,d} \leq b_{n,l,d} \quad \forall n \in N, d \in D_k, l \in L \quad (1a)$$

$$C_{n-1} x_{n-1,l} + D_n x_{n,l} \leq g_{n,l} \quad n = 2, 3, \dots, |N|, l \in L \quad (1b)$$

$$x_{n,l} \in X, \quad \forall n \in N, l \in L, \quad (1c)$$

$$y_{n,l,d} \in Y, \quad \forall n \in N, d \in D_k, l \in L \quad (1d)$$

where the variable $x_{n,l}$ represents investment decisions at year n and location l , $y_{n,l,d}$ represents operating decisions corresponding to the representative day d in year n and location l , while W_d is the weight of the representative day d to make the operating and investment costs comparable.

Given are the years $n \in N$, representative days $d \in D_k$, and hours $h \in H$ of the time horizon. Given are also the locations $l \in L$, utility-battery systems $b \in B$, types of power generation units $u \in U$, and transmission lines connections $t \in T$. Namely, the generation units u consist of natural gas and coal power plants, with and without carbon capture and storage (CCS), wind onshore, solar photovoltaics (rooftop installations), and nuclear and biomass plants. Furthermore, the spatial space L is discretized into 5 regions, and we define 6 possible connections between them, as depicted in Figure 1. Moreover, the associated economic (NREL, 2021) and environmental data for installing and operating power

generators and storage technologies, along with historic hourly solar irradiation and wind speed, are given. Finally, we consider the time evolution (i) of the load demand for the system regions, (ii) for fuel costs, and (iii) for technology learning curves.

Eq. (1a) describes the operational decisions of each year n and each day d , hour h , and location l , i.e., generation, transmission, storage of power, and the unit's commitment. One example of **Eq. (1a)**, is the energy balance that aims to satisfy the demand of year n , day d , hour h , and location l , with the generators output plus the batteries discharge and power imports (by line t whose receiving end is location l) minus the batteries charge, power exports (by line t whose sending end is location l), and curtailment. However, unlike the more detailed work by Li et al. (2022), which represented the transmission network using a DC power flow model, we assume transmission losses as in Lara et al. (2018). Other examples of **Eq. (1a)** are constraints describing (i) the mode of the thermal generators, i.e., *on*, *starting up*, and *shutting down*, of which the shift is based on their ramping limits, (ii) spinning and quick startup reserves, and (iii) planning reserves to withstand the worst plausible operating condition (i.e., the annual peak load). **Eq. (1b)** are investment-related constraints, such as installing generation technologies and transmission lines between regions, purchasing utility batteries, and expanding capacity. Furthermore, as the demand dictates, the GTEP model follows a dynamic annual expansion approach. Finally, **Eq. (1b)** also describes the retirement or the operating life extension of units at the end of life.

We quantify the system's environmental performance following the life cycle assessment principles, while avoiding directly constraining the energy system's impacts. Specifically, we do not impose any carbon neutrality target by 2050, aiming to describe rational decision-making based on cost minimization, which is the current norm in the literature in this kind of problems. However, we analyze the GTEP with two scenarios, one without a carbon tax, and one with a linearly increasing taxation of direct CO₂ emissions (0–350 \$ t⁻¹ for 2020 and 2050, respectively), where the latter indirectly affects the objective function.

Within this general context, and with a 16-days clustering approach for the system inputs (i.e., demand, solar and wind power generation) via hierarchical agglomerate clustering, the MILP model comprises 2,511,217 discrete and 3,776,700 continuous variables, while the number of equations is 9,272,535. We solved the model in GAMS 38.2, with the Benders implementation from CPLEX, on an Intel Core™ i7- 8700 machine at 3.20 GHz and 32 GB RAM, with a parallel search mode. The implementation of Benders decomposition requires the relaxation of the integrality constraints of the y_n variables, i.e., variables denoting the generators that are *on*, *starting up*, and *shutting down*. Therefore, the MILP size reduces to 11,377 discrete and 6,276,540 continuous variables, and because we apply Benders to the relaxed problem, we can only obtain a lower bound to the original problem.

Life cycle assessment

We analyze the energy system's performance by considering multiple functional units. Besides, the system expands annually from 2020 until 2050 to deliver a unique load demand. Therefore, the system's functional unit is to generate 1 MWh of power at each year until 2050.

Within this general context, we retrieved the life cycle inventories (LCIs) of fuels, utility inputs, construction, and operation of the power technologies from the ecoinvent database (Wernet et al., 2016). Furthermore, we retrieved from the literature the LCIs of the utility-battery storage units (Ellingsen et al., 2014) and the generation units with CCS (Iribarren et al., 2013; Petrakopoulou et al., 2015; Wildbolz, 2007).

A cradle-to-gate assessment is carried out using the global warming impact (GWI), fine particulate matter, ecotoxicity (terrestrial, freshwater, and marine), land use, mineral and fossil resources scarcity indicators of the ReCiPe 2016 Midpoint (H) methodology (Huijbregts et al., 2017). The GWI indicates the amount of kg of CO_{2eq} emitted to deliver the system function. In contrast, fine particulate matter refers to the kgs of organic and inorganic substances emitted with a diameter smaller than 2.5 μm (PM_{2.5}). The release of PM_{2.5} may cause human health damage, i.e., asthma, lung cancer, and respiratory diseases. The metric for land use indicates the equivalent space occupation expressed in m² of crop_{eq} y. Finally, the toxicity metrics indicate the kg of 1,4-dichlorobenzene equivalents (1,4DCB_{eq}) emitted, while the mineral and fossil resources scarcity indicate how many kg of equivalent copper, Cu_{eq}, and oil, Oil_{eq}, respectively, are required by the system.

Results

The GTEP model decisions

The model estimates the energy system's net present cost to be B\$ 238.2–313.4 for the non-taxed and taxed GTEP, respectively, obtained within a 0.5% optimality gap in 5.1–5.3 hours.

We observe that the generators capacity in 2020 highly depends on natural gas, coal, and wind units (**Figure 2**). Furthermore, the nuclear generator's capacity remains constant throughout the time horizon in both scenarios, while the model avoids biomass units due to higher costs. In the non-taxed GTEP, fossil-based generators persist instead of being phased out. In contrast, taxed GTEP leads to slow decommissioning rates of coal and natural gas generators between 2030 and 2037. Finally, their phase-out rate becomes significant after 2037, while generators with CCS replace them.

Regarding renewables in the non-taxed GTEP model, we observe a slow deployment of wind and no investment towards solar for the first 5-year period of the time horizon. Subsequently, a gradual wind and solar expansion occurs until 2050 at an almost constant rate. On the other hand, in the taxed GTEP model, the wind generators' deployment

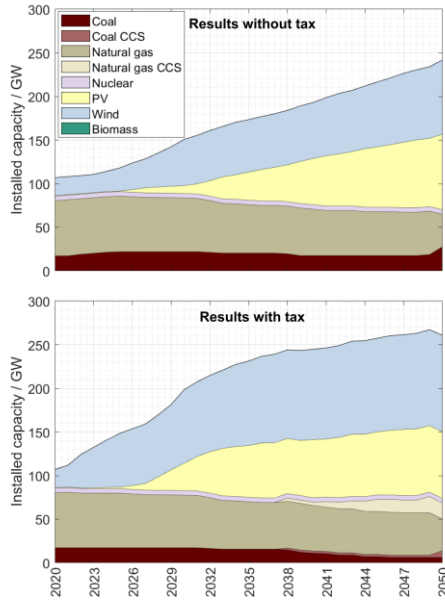


Figure 2. Aggregated capacity of installed generators in Texas per year

occurs at high rates in the first 10-year period, while installing solar generators is slower up until 2026. Subsequently, the addition rate of solar generators increases drastically until 2032, while their expansion is smaller for the remaining period. In 2050, we observe that the taxed GTEP has a 1.3-fold higher and 0.77-fold lower capacity of wind and solar generators, respectively, compared to the non-taxed counterpart.

Considering the expansion of the transmission lines (**Figure 3**), we observe a significant investment in the first 10 years in both scenarios due to the swift shift towards solar and wind generators. Connecting the generation and demand locations allows the fossil-based units to operate flexibly between *startup-on-shutdown* modes while the system exploits the cheaper, but fluctuating, renewables. The expansion begins with a few lines in 2020, leading to an installed capacity of 5.31–7.97 GW for the non-taxed and taxed GTEP, respectively. Since Panhandle has favourable conditions for harvesting wind power and low load demand (in 2010, Panhandle hosted only 1.7% of Texas's total population), the high transmission capacity through this connection is necessary. Hence, the expansion occurs predominantly between Panhandle- Northeast and West linkages (see **Figures 1** and **3**). The West-South link is also essential, leading to a transmission capacity of 15.94 GW in 2050 regardless of the taxation strategy. In contrast, the non-taxed GTEP avoids the Northeast-West connection entirely, while the taxed counterpart limits the investment to only one line installed in 2040. Overall, the total transmission capacity in 2050 amounts to 77.02–95.62 GW for the non-taxed and taxed GTEP, respectively.

Closing with the utility-scale batteries, we note that the non-taxed model avoids the use of energy storage. In contrast, the taxed counterpart acquired the first batteries in 2041 in Panhandle, Northeast, and West regions (180 MW). This decision is mainly driven by technology learning since

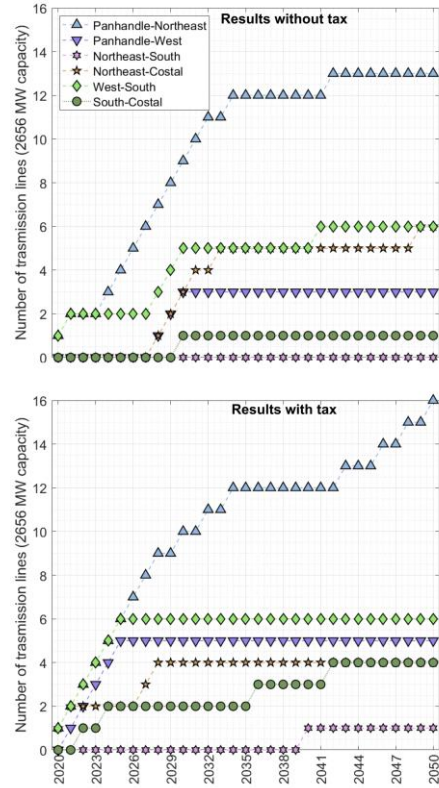


Figure 3. The number of transmission lines per region of Texas and year

their investment and operation become more competitive relative to additional transmission capacity. Finally, the South and Coastal regions will each obtain a battery in 2043, leading to a 300 MW storage capacity until 2050.

Environmental performance

We start with the energy system's global warming impact (**Figure 4a**), which in 2020 amounted to 0.50–0.47 $\text{tCO}_{2\text{eq}} \text{MWh}^{-1}$ for the non-taxed and taxed GTEP, respectively, due to the capacity expansion from 2019. Notably, the 2020 values are close to the average U.S. system (Wernet et al., 2016). In the first 5-year period, the non-taxed GTEP does not significantly influence the GWI. We observe, however, a sharp dip in 2021 due to the installation of the first transmission lines that rebounds in 2022/23 because of natural gas and coal generators' expansion. Subsequently, the investment in wind and solar and additional transmission capacity decreases the GWI sharply between 2025–2030, attaining a value of 0.28 $\text{tCO}_{2\text{eq}} \text{MWh}^{-1}$. Further milder reductions follow until 2050, when the GWI equals 0.20 $\text{tCO}_{2\text{eq}} \text{MWh}^{-1}$. In contrast, in the taxed GTEP, the impact reduces sharply within the first 10-year period, when the GWI equals 0.10 $\text{tCO}_{2\text{eq}} \text{MWh}^{-1}$ (-78.7% relative to 2020). The main driver of these improvements is the same as in the non-taxed GTEP, along with the higher (i) share of renewables and (ii) flexibility of fossil-based units. Finally, the GWI decrease is milder for the remaining period and will become

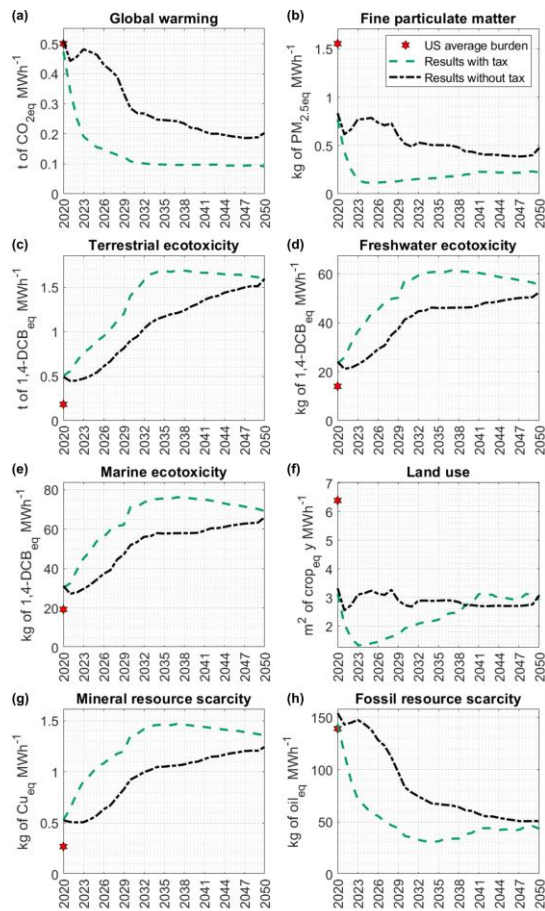


Figure 4. Environmental burdens for the GTEP problem in Texas

0.09 tCO_{2,eq} MWh⁻¹ in 2050.

Regarding particulate matter formation (Figure 4b), the impact in 2020 equals 0.83–0.76 kgPM_{2.5,eq} MWh⁻¹ for the non-taxed and taxed GTEP, respectively, almost half of the U.S. system's average. Notably, the particulates' release is always lower in the taxed GTEP compared to the non-taxed counterpart. Furthermore, the impact of the non-taxed GTEP system is not improving significantly for the first 5-year period, when their release equals 0.78 kgPM_{2.5,eq} MWh⁻¹. For the subsequent 5-year period, the burden reduces sharply, a 37.9% decrease relative to 2020, and then slowly becomes 0.48 kgPM_{2.5,eq} MWh⁻¹ in 2050. The taxed GTEP greatly eases the particulates' release by 2023 (-67.3% relative to 2020), while the impact increases slightly for the remaining period due to embodied burdens related to solar panels' supply chains, i.e., production, transportation, and installation. In 2050, the particulate matter formation of the system equals 0.22 kgPM_{2.5,eq} MWh⁻¹. The behaviour described above occurs since the expansion towards renewables, transmission, and the firm generators' shutdown can significantly reduce the particulates' release.

We observe that in 2020 all toxicity-related metrics will perform slightly worse than the average U.S. system (Figure 4c-e). Regardless of taxation, terrestrial ecotoxicity worsens by 3.2-fold in 2050 compared to 2020. Similarly, freshwater and marine ecotoxicity increase 2.3-fold. At the

same time, the non-taxed GTEP impact is always lower than that of the taxed counterpart. Furthermore, these metrics follow a similar worsening trend until 2032 due to both scenarios' significant wind and solar expansion. Finally, the burden curves bend due to the slow-down of the capacity expansion (Figures 2-3) and the increase of the annual delivered load (impact per MWh).

Considering land use implications (Figure 4f), we observe that the 2020 requirement for both scenarios is almost half the average U.S. system. In the non-taxed GTEP, the land requirement remains relatively unchanged for the investigated horizon since minerals mining, manufacturing, and installing solar and wind generators substitute the burdens of operating fossil units. In contrast, investment and operational decisions highly influence the land needs for the taxed GTEP. Besides, the shutdown operation of fossil generators, and the shift to wind, almost halves the land requirements in the first 3-year period. Other works also highlight the high land implications of coal generators' (Stamford and Azapagic, 2012), where 99.3% of burdens arise from the mines and their associated infrastructure. In 2024, we observe that the expansion of solar units significantly influences this metric, even though the rooftop panels require less land than fossil-based plants. This increase in land use emerges due to embodied burdens for producing the metal for their manufacturing stage. At the same time, the energy system is affected considerably due to the high expansion. Moreover, the use of utility batteries after 2041, and thus, mining of rare earth elements, along with the installation of CCS-equipped generators, increases the impact significantly. In 2050, the impact becomes 2.93 m²_{cropeq} y MWh⁻¹, the same as the non-taxed GTEP for that year. Overall, the taxed GTEP will require less land than the non-taxed counterpart for the first 20-year period, while it shows a slightly higher intensity until 2050.

As expected, shifting towards renewables will significantly stress the mineral reserves (Figure 4g). In both scenarios, 2020's impact amounts to 0.53 kgCu_{eq} MWh⁻¹, slightly higher than the average U.S. system. Notably, all the investment and operating decisions select alternatives that tremendously stress this metric and follow the trend of the expanding renewables. In 2050, compared to 2020's system, minerals scarcity increases almost by 2.4- and 2.5-fold for the non-taxed and taxed GTEP, respectively. Again, similar to the toxicity metrics, the non-taxed GTEP will require substantially fewer minerals and metals resources than the taxed counterpart.

We close by analyzing the scarcity of fossil resources (Figure 4h), where the 2020's systems show a similar burden (0.15–0.14 tOil_{eq} MWh⁻¹ for the non-taxed and taxed GTEP, respectively) to the average U.S. system. For the first 5-year period, the non-taxed GTEP reduces the fossil resources use only slightly since it installs natural gas and coal generators. For the subsequent 5-year period, fossil consumption reduces significantly (-39.86% relative to 2020), decreasing further at a milder rate. In 2050, the impact will be reduced by almost 69.8% compared to 2020 regardless of the taxation strategy, due to the decoupling

from fossil resources to a large extent. Nonetheless, the taxed GTEP requires lower fossil resources than the non-taxed counterpart since it curbs the fossil resources use drastically within the first 10-year period (-77.68% relative to 2020).

Conclusions

This work has assessed the impact exerted on 8 midpoint environmental metrics for the integrated generation and transmission expansion planning problem of an energy system for Texas. Our analysis spans 2020 to 2050 for a design with and without a carbon tax strategy.

We found that the proposed energy systems perform more sustainably in climate change, particulate matter, and fossil resources depletion metrics, while the burden is lower in the taxed model. Regarding land use, the non-taxed GTEP exerts similar behavior throughout the time horizon. In contrast, for the first 20 years, the taxed counterpart requires less land per MWh, while it shows a slightly higher impact than 2020 for the remaining years. Notably, environmental burdens related to ecotoxicity and minerals depletion worsen significantly due to trade-offs at the heart of the selected technologies, higher in the taxed scenario. These observations could be valid in any location with energy mixes yet to be decarbonized, such as ERCOT, which still relies heavily on fossil resources. Therefore, the feasibility of any long-term GTEP should be aligned with the availability of land and mineral resources. At the same time, further efforts should be carried out to avoid harming the quality of terrestrial and marine life by expanding via the emerging renewable transition.

For future studies, the investigation of, (i) the Pareto frontier for the GTEP, (ii) an expanded model including negative emission units (e.g., bioenergy with CCS), (iii) a carbon neutrality pledge by 2050, and (iv) uncertainty (for the (a) demand growth, (b) investment and operating costs, (c) environmental burdens, (d) carbon tax, and (e) non-periodic renewables availability), merit further investigation. All the above could shed further light on the economic and environmental trade-offs.

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References

Benders, J.F., 1962. Partitioning procedures for solving mixed-variables programming problems. *Numer. Math.* 4, 238–252.

Bonami, P., Salvagnin, D., Tramontani, A., 2020. Implementing automatic Benders decomposition in a modern MIP solver, in: *International Conference on Integer Programming and Combinatorial Optimization*. Springer, pp. 78–90.

Conejo, A.J., Baringo, L., Kazempour, S.J., Siddiqui, A.S., 2016. *Investment in electricity generation and transmission*, Cham Zug, Switzerland: Springer International Publishing. Springer.

Ellingsen, L.A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., Strømman, A.H., 2014. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *J. Ind. Ecol.* 18, 113–124.

Gorenstein Dedecca, J., Lumbresas, S., Ramos, A., Hakvoort, R.A., Herder, P.M., 2018. Expansion planning of the North Sea offshore grid: Simulation of integrated governance constraints. *Energy Econ.* 72, 376–392.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* 22, 138–147.

Iribarren, D., Petrakopoulou, F., Dufour, J., 2013. Environmental and thermodynamic evaluation of CO₂ capture, transport and storage with and without enhanced resource recovery. *Energy* 50, 477–485.

Lara, C.L., Mallapragada, D.S., Papageorgiou, D.J., Venkatesh, A., Grossmann, I.E., 2018. Deterministic electric power infrastructure planning: Mixed-integer programming model and nested decomposition algorithm. *Eur. J. Oper. Res.* 271, 1037–1054.

Li, C., Conejo, A.J., Liu, P., Omell, B.P., Siirola, J.D., Grossmann, I.E., 2022. Mixed-integer linear programming models and algorithms for generation and transmission expansion planning of power systems. *Eur. J. Oper. Res.* 297, 1071–1082.

Lumbresas, S., Ramos, A., 2016. The new challenges to transmission expansion planning. Survey of recent practice and literature review. *Electr. Power Syst. Res.* 134, 19–29.

Moradi, M., Abdi, H., Lumbresas, S., Ramos, A., Karimi, S., 2016. Transmission Expansion Planning in the presence of wind farms with a mixed AC and DC power flow model using an Imperialist Competitive Algorithm. *Electr. Power Syst. Res.* 140, 493–506.

Petrakopoulou, F., Iribarren, D., Dufour, J., 2015. Life-cycle performance of natural gas power plants with pre-combustion CO₂ capture. *Greenh. Gases Sci. Technol.* 5, 268–276.

Stamford, L., Azapagic, A., 2012. Life cycle sustainability assessment of electricity options for the UK. *Int. J. Energy Res.* 36, 1263–1290.

United Nations, 2016. *Framework Convention on Climate Change (UNFCCC), Paris Agreement*.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-ruiiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 3, 1218–1230.

Wildbolz, C., 2007. *Life cycle assessment of selected technologies for CO₂ transport and sequestration*. Swiss Federal Institute of Technology Zurich.