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Cost sensitivity analysis on Swiss energy transformation towards net-zero target

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Abstract:
Energy technology costs and fuel prices play a critical role in the energy transition towards carbon neutrality. Despite its straightforwardness in comparing standalone technologies, the widely-used levelized cost of energy (LCOE) is not able to estimate the activation condition for low-carbon technologies due to lack of systematic assessment of the complexities in energy systems. In this study, we analyzed the impact of energy cost uncertainties for the deployment of renewables and carbon capture technologies for Switzerland based upon Energyscope, a systematic energy planning platform optimizing both investment and operational strategies for electricity, heat, and mobility. The results show that carbon capture becomes competent to renewable technologies when its cost drops below approximately 70 USD/tCO2. Furthermore, synthetic natural gas (NG) is promising to substitute fossil NG when the import price of the latter rises to above 0.1 USD/kWh level. These discoveries can be helpful for long-term planning, especially in the context of increasing geopolitical concerns on energy supply security.

Keywords:
Energy system, Cost sensitivity, Long-term planning.

1. Introduction

The 2022 United Nations Climate Change Conference (COP27) in Egypt [1] highlights that the global energy crisis, in addition to the impact of climate change, are challenging the efforts to achieve energy security. It calls on the essence of increasing the renewables' share in the energy mix and encourages the continued efforts to phase out fossil fuels. As indicated by [2–4], a radical transformation of the energy sector is mandatory. However, such rapid transition is triggering a series of social-economic concerns, especially in terms of the transition cost, which is commonly regarded as capital-intensive [5–7]. For instance, IEA [7] claims that the investment into clean energy should at least be doubled and triple by 2030 in the announced pledges scenario and the net-zero emission scenario respectively, with respect to 2022 levels (i.e., USD 1.4 trillion).

With the decreasing trends of renewable costs in the last decades, as illustrated in Figure 1, it is likely that renewable costs have already dropped below, or might become competitive to fossil energies, depending on geographical and meteorological conditions (solar irradiation, wind speed etc.). However, it is very difficult to predict the energy costs. On one hand, IRENA [8] emphasizes that most renewable energy technologies benefit from learning-by-doing, thus allowing the decrease of their investment costs at the global scale over time. For instance, the global capacity-weighted average total installed cost of utility-scale solar PV and onshore wind projects in 2021 decreased by 81% and 35% respectively with respect to 2010 values. On the other hand, IEA [7] observed that highly unpredictable exogenous events, such as the Russo-Ukrainian war, may have dramatic consequences on the cost of energy technologies, especially resources, like natural gas (NG) in the case of the Ukrainian conflict. Thus, taking into account learning trends while accounting for uncertainty that may come from exogenous events is key for making plausible decisions in order to achieve energy transition towards carbon neutrality.

Across the current energy research, one common practice is using the Levelized Cost Of Energy (LCOE) [10–12] to compare the energy costs. LCOE is calculated by the ratio of the total cost (investment and operational costs) and total energy output during the lifetime of a technology. By definition, the LCOE metric focuses only on a standalone technology, which is not able to capture the synergies and conflicts occurring between energy technologies among the highly interconnected energy systems. As a result, the conclusion of

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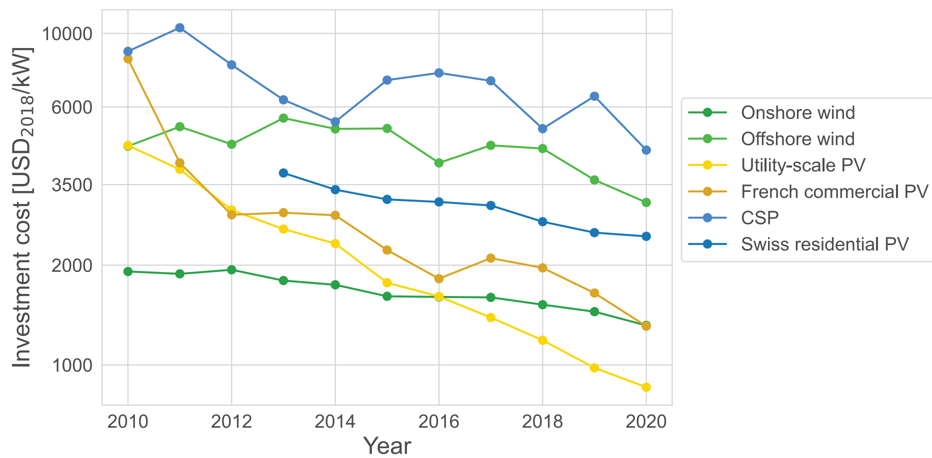

Figure 1: Historical cost trends for the main renewable energy technologies. Data taken from IRENA [9]. The costs are global-averaged data, except for the residential and commercial PV.

”cheap” or ”expensive” based upon simply comparing LCOE may become unreliable in the field of long-term energy planning. For instance, even if the LCOE of a photovoltaic (PV) panel drops below a gas power plant, the system may still keep using the gas, taking into account additional costs for deploying the PV such as the storage (e.g. by battery) and backup technologies. More specifically, Hansen [13] compared the LCOE with Energy System Analysis (ESA) for assessing the cost of integrating an energy technology into an energy system by using the simulation model EnergyPLAN which accounts for systemic perspectives. The results show that the two methods lead to different energy technologies priorities and confirm that the LCOE method lacks to consider crucial systemic dimensions. Ueckerdt et al. [14] proposed a new version of LCOE, namely the Systemic LCOE, that considers both the integration and generation costs. The results show that integration costs may become within the same range as generation costs in the case of high wind shares, thus confirming the possible poor reliability of LCOE without having a systemic view. Consequently, it is important to apply system-level models with a holistic representation of the interactions of energy technologies, to analyze the impact of energy cost variation on the energy transition.

However, the majority of energy models are based upon cost-minimization, or profit maximization assumptions. As emphasized by Trutnevyte [15], costs are a key driver of the energy transition, but there are many others (e.g., social impacts) that may lead to non-rational decision. For instance, the electricity system transition of UK from 1990 to 2014 was not cost-optimized, by a 9-23% deviation according to Trutnevyte [15]. Nevertheless, cost-optimization models such as Energyscope [16] are needed, not for exactly predicting how the future energy system will look like, but as a systemic decision-making tool for generating a series of possible scenarios allowing for uncertainty analysis in order to evaluate potential trade-offs among heterogeneous pathways.

This work aims at unveiling the sensitivity of the future energy system as a function of the of the key energy technologies costs within their uncertainty ranges, while accounting for the interdependence between the different technologies. The sensitivity of the energy system is mainly reflected by the variation of annual energy output (in terms of GWh) for each technology. This paper is organized as below: Section 2 introduces the methodology of our study; Next, some preliminary results are presented and analyzed in Section 3; Finally, we summarize the major novelties of this work and possible future research direction in Section 4.

2. Methodology

2.1. Modelling framework

This research is conducted upon Energyscope, a bottom-up energy system model based on cost-optimization, designed for decision-making in the field of energy transition. It has been originated by Moret [16] as a so-called *snapshot* model. *Snapshots* describe an energy system at a given time mainly in terms of energy technologies installation [MW] and utilization [GWh/year] as well as the investment and operation costs that are associated to these. To generate those results, Energyscope is based on a Mixed-Integer Linear Programming (MILP) optimization problem, that is constituted by a set of energy conversion technologies (including

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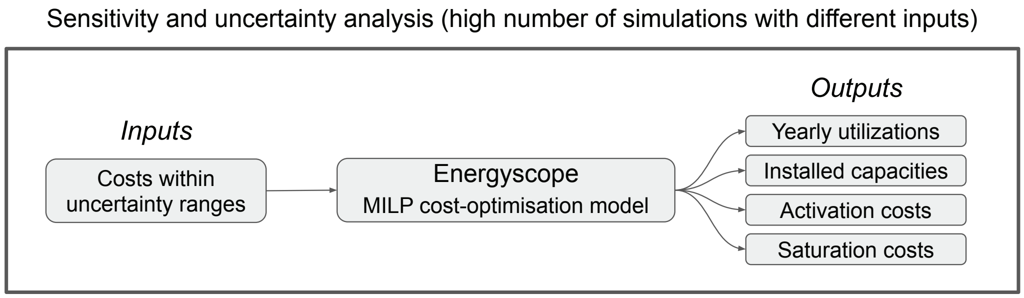

Figure 2: Scheme of the methodology

storage technologies), energy resources as well as the energy end-use demand (EUD). Each energy conversion technology is characterized according to a: 1) reference size [MW], 2) investment cost [USD/kW], 3) maintenance cost [USD/kW/year], 4) Global Warming Potential (GWP), 5) lifetime [year], 6) capacity factor [-], 7) minimum installed capacity [MW] and 8) maximum installed capacity [MW]. This model is working with a monthly granularity in order to account for time-dependent parameters (e.g., EUD, solar irradiation, wind power etc.) that are occurring over a year.

Whereas other energy system models may be proprietary, computationally expensive and only integrating the electricity sector, Energyscope is open-source, has a small computation time (sec) due to its *snapshot* design and both models the electricity, heat and mobility sectors. Its short computation time allows to use this model for sensitivity and uncertainty analysis, which typically requires several thousands of iterations. The modelling of the entire energy system ensures that the interactions between the different energy sectors are taken into account in the results and thus in the decision-making process. The heat sector EUD is further divided between low temperature and high temperature heating needs, whereas the mobility sector EUD is divided between passenger mobility [Mpkm] (itself divided between public and private mobility) and freight mobility [Mtkm] (itself divided between road and rail freight).

The objective function of the MILP optimization problem to minimize is the system total cost, defined by Eq. 1, subject to mass and energy balances, as well as storage behaviours. The optimization variables (written in **bold**), and thus the output of the model, are the energy conversion technologies installed capacities [MW] and yearly productions [GWh/year], the centralised and decentralised heat supply shares, the public and private mobility shares as well as the freight rail and road shares. The complete optimization problem can be found in [16]. We added a modelling of carbon flows [17] by identifying carbon sources, carbon conversion technologies and carbon sinks. This is allowing to model a carbon circular economy within the context of a highly interconnected energy system due to increasing deployment of biomass and carbon capture, use and storage (CCUS) technologies.

$$\min \ \mathbf{C_{tot}} = \sum_{j \in TECH} (\mathbf{C_{inv}}(\mathbf{j}) \cdot \tau(j) + \mathbf{C_{maint}}(\mathbf{j})) + \sum_{i \in RES} \mathbf{C_{op}}(\mathbf{i}) \tag{1}$$

where:

$$\tau(j) = \frac{i_{rate}(1 + i_{rate})^{n(j)}}{(1 + i_{rate})^{n(j)} - 1} \tag{2}$$

$$\mathbf{C_{inv}}(\mathbf{j}) = c_{inv}(j) \cdot \mathbf{F}(\mathbf{j}) \tag{3}$$

$$\mathbf{C_{maint}}(\mathbf{j}) = c_{maint}(j) \cdot \mathbf{F}(\mathbf{j}) \tag{4}$$

$$\mathbf{C_{op}}(\mathbf{i}) = \sum_{t \in T} c_{op}(i,t) \mathbf{F_t}(\mathbf{i},\mathbf{t}) t_{op}(i) \tag{5}$$

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The above equations are mainly cost-relevant formulations. More detailed mathematical framework of Energyscope is available in [17, 18]. Next, we define scenarios and vary the model inputs, in order to analyze the corresponding variation of utilization of resources.

2.2. Scenario definition

Two scenarios are defined in this study, namely:

- Scenario (a): State-of-the-art, based upon the Swiss energy system in 2020. This implies all the model parameters and variables, including technology costs, fuel costs, installed capacities, and energy supply, are fixed with the real values in 2020. As the price of natural gas had a significant change before/after the Russia-Ukraine war, we conducted a specific sensitivity analysis on the utilization of natural gas as a function of natural gas cost.
- Scenario (b): Net-zero scenario, based upon the cost projection data (as of 2050) from a variety of sources, such as IEA [5–7] and IRENA [19–21] databases. Built on the future energy system, we perform Monte Carlo simulation in order to explore how robust a net-zero emission system is against cost uncertainty.

Based upon the definition of scenario (b), one interesting topic is to assess the competition between renewables and carbon capture: both are beneficial to realize the climate target, but which condition one might be more widely used compared to the other ? Furthermore, we analyze the simultaneous effects of both carbon capture cost and fuel price on the energy system.

3. Preliminary results

Figure 3 shows the results for scenario (a), illustrating the variation of natural gas utilization as a function of its price. It is observed that NG is not used anymore when the price rises above 90 USD/MWh; when the price drops below 50 USD/MWh (critical point), it begins to be largely used, probably replaced by a massive penetration of wind turbines, as reflected by the green line. In correspondence, the total cost of the energy system becomes almost invariant when NG cost is above the critical point.

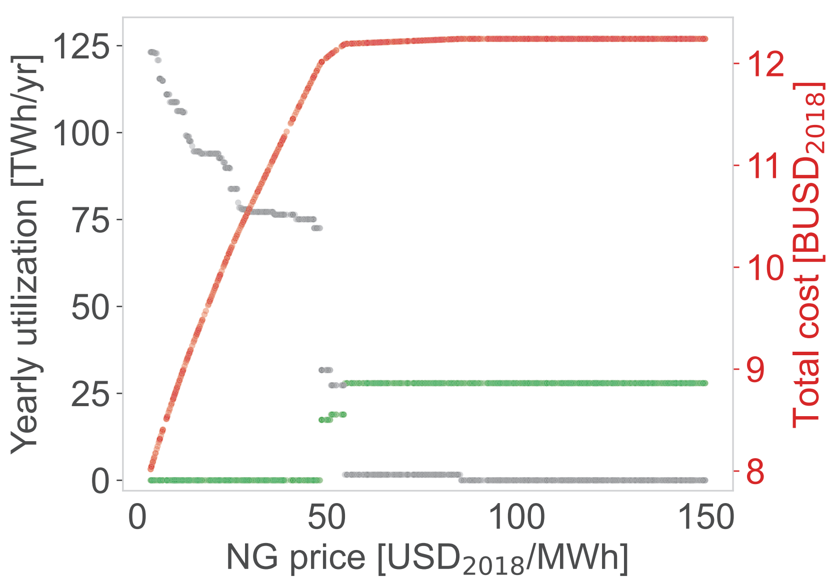
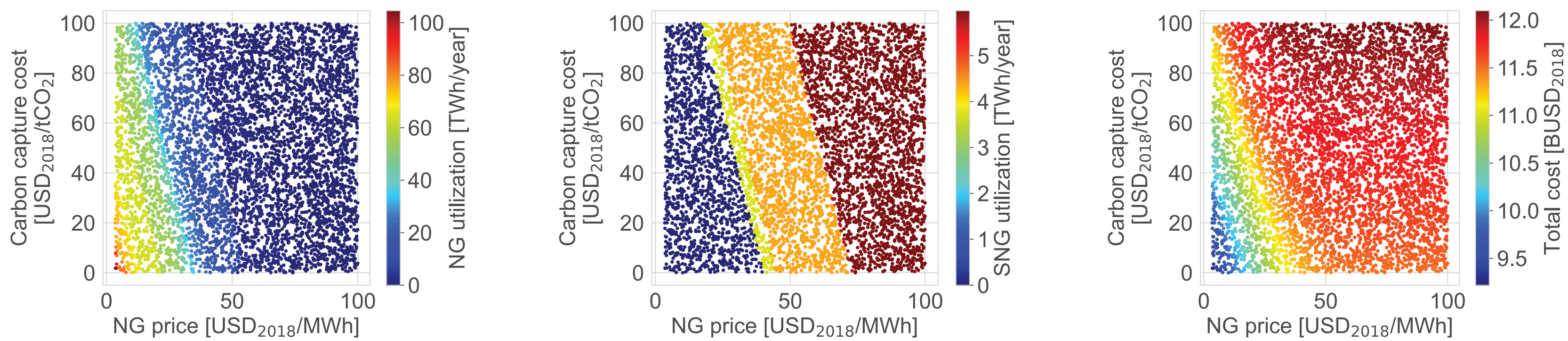


Figure 3: Sensitivity of natural gas consumption (grey dots), wind energy (green dots), and system total cost (red dots) as a function of NG price signal. Other costs are fixed to their 2020 values.

Furthermore, Fig. 4 reflects the impacts of NG price and carbon capture cost on the utilization of NG, Synthetic NG (SNG), and the total cost of the energy system in the net-zero scenario. From Fig. 4 (a), the utilization of natural gas is highly sensitive to the carbon capture cost when NG price remains low. In the most extreme case where the NG price is close to zero, the carbon capture cost has to be surpass 70 USD/tCO2 in order to maintain the NG utilization below 50 TWh/year. When the NG price stays the same as of 2020, i.e., around 30 USD/MWh, a carbon capture cost close to 100 USD/tCO2 can stop the utilization of NG. In practice, these results can be linked to carbon tax and thus conductive to defining effective energy measures.

Figure 4 (b) and (c) serve as supplementary of (a), showing the substitution of NG by SNG and the variation of the total cost of the energy system respectively. When the natural gas cost rises above 45 USD/MWh in the condition of zero carbon capture cost, SNG becomes competitive to NG. A high carbon capture (100 USD/tCO2) cost can even further halve the NG cost for activating SNG facilities. Finally, Fig 4 (c) reflects the corresponding maximal variation of the energy system cost is within $[-10\%, 20\%]$ range assuming the NG price staying the level 2020 and no carbon capture technologies.



(a) NG

(b) SNG

(c) Total cost

Figure 4: Sensitivity of NG and SNG utilization as well as total cost as a function of both carbon capture cost and NG price. Other costs are fixed to their 2050 value.

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4. Conclusion

This study performed sensitivity analyses on the impact of cost on the energy transition, allowing for quantifying the activation cost and saturation cost for different energy technologies and resources. All the results are obtained from a system-level model instead of simply comparing the LCOE, thus improving their plausibility. We believe these results can be easily understood by policy makers and other energy stakeholders, thus contributing to rational decision making, in particular for enacting energy policies.

This paper is dedicated to sharing our research idea. A complete paper with detailed data and more results are in preparation.

References

[1] COP27, "Climate Change Conference." https://cop27.eg/#/, 2022.

[2] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, and C. Breyer, "Radical transformation pathway towards sustainable electricity via evolutionary steps," *Nature Communications*, vol. 10, p. 1077, Mar. 2019.

[3] J. Markard, F. W. Geels, and R. Raven, "Challenges in the acceleration of sustainability transitions," *Environmental Research Letters*, vol. 15, p. 081001, Aug. 2020.

[4] M. M. Vanegas Cantarero, "Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries," *Energy Research & Social Science*, vol. 70, p. 101716, Dec. 2020.

[5] IRENA, "World Energy Transitions Outlook 2022: 1.5℃ Pathway," p. 352, 2022.

[6] IEA, "The cost of capital in clean energy transitions," 2021.

[7] IEA, "World Energy Outlook 2022," p. 524, 2022.

[8] IRENA, "Renewable Power Generation Costs in 2021," p. 204, 2022.

[9] IRENA, "Renewable Power Generation Costs 2020," tech. rep., 2021.

[10] G. Glenk, R. Meier, and S. Reichelstein, "Cost Dynamics of Clean Energy Technologies," *Schmalenbach Journal of Business Research*, vol. 73, pp. 179–206, June 2021.

[11] G. R. Timilsina, "Are renewable energy technologies cost competitive for electricity generation?," *Renewable Energy*, vol. 180, pp. 658–672, Dec. 2021.

[12] M. Ligus, "An analysis of competitiveness and potential of renewable energy technologies in poland," *Energy & Environment*, vol. 26, no. 8, pp. 1247–1269, 2015.

[13] K. Hansen, "Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs," *Energy Strategy Reviews*, vol. 24, pp. 68–82, Apr. 2019.

[14] F. Ueckerdt, L. Hirth, G. Luderer, and O. Edenhofer, "System LCOE: What are the costs of variable renewables?," *Energy*, vol. 63, pp. 61–75, Dec. 2013.

[15] E. Trutnevyte, "Does cost optimization approximate the real-world energy transition?," *Energy*, vol. 106, pp. 182–193, July 2016.

[16] S. Moret, *Strategic Energy Planning under Uncertainty*. PhD thesis, EPFL, 2017.

[17] X. Li, T. Damartzis, Z. Stadler, S. Moret, B. Meier, M. Friedl, and F. Maréchal, "Decarbonization in Complex Energy Systems: A Study on the Feasibility of Carbon Neutrality for Switzerland in 2050," *Frontiers in Energy Research*, vol. 8, p. 549615, Nov. 2020.

[18] S. Moret, V. Codina Gironès, M. Bierlaire, and F. Maréchal, "Characterization of input uncertainties in strategic energy planning models," *Applied Energy*, vol. 202, pp. 597–617, Sept. 2017.

[19] IRENA, "Electricity storage and renewables: Costs and markets to 2030," tech. rep., 2030.

[20] IRENA, "Renewable Power Generation Costs 2020," tech. rep., 2020.

[21] IRENA, "Renewable solutions in end-uses: Heat pump costs and markets," p. 57, 2022.

https://doi.org/10.52202/069564-0174