Impact of integrating societal factors on the accuracy of optimization-based electricity system modeling in 31 European countries

Xin Wen[1]*, Qin Alexander Crebas[1,2], Kenneth Bruninx[2], Evelina Trutnevyte[1]
[1] Renewable Energy Systems, Institute for Environmental Sciences (ISE), University of Geneva, Switzerland
[2] Policy and Management, Faculty of Technology, Delft University of Technology, The Netherlands
(* Corresponding author: 66 Boulevard Carl-Vogt, CH-1211 Geneva 4, Switzerland; +41 22 379 09 10; xin.wen@unige.ch)

Overview

To achieve net-zero emissions target by 2050, cost optimization-based energy system models are commonly used to generate national or global decarbonization pathways informed by techno-economic and environmental considerations. However, there are multiple retrospective studies showing that past transitions have not been in line with cost-optimal model solutions due to societal complexities (Morgan and Keith, 2008; Trutnevyte, 2016; Wen et al., 2022a). Existing models have thus been criticized for neglecting societal realities and producing practically infeasible scenarios (Geels et al., 2016; Schubert et al., 2015; Trutnevyte et al., 2019). At the same time, there are an increasing number of studies experimenting with integration of societal factors into models, such as public attitudes (Cotterman et al., 2021; Koecklin et al., 2021) or investment risks (Polzin et al., 2021), but few papers provide evaluative evidence (Fisch-Romito et al., 2024; Wen et al., 2023). In this study, we evaluate the performance of integrating various societal factors (EU climate policy, perceived seriousness of climate change in the public, and country-specific and technology-specific investment risks) into national-level optimization-based electricity systems models in 31 European countries. Through hindcasting in 1990–2019, we obtain evidence on how the integration of societal factors impacts model solutions and how these modelled pathways compare with real-world transitions in terms of past accuracy.

Methods

We integrate three societal factors in cost optimization-based electricity system models D-EXPANSE (Trutnevyte, 2016; Wen et al., 2022a) for 31 European countries (EU27, Iceland, Norway, Switzerland, and UK): *EU climate policy* (as emission targets), *Perceived seriousness of climate change in the public* (as acceptance of emission targets), and *Investment risks*. With these factors, wgenerate six model versions. The reference model version is the original *Techno-economic* model version that excludes societal factors, even exogenous emission targets and energy policies (Trutnevyte, 2016; Wen et al., 2022b). The *EU climate policy* model version includes the European emission targets in model as a proxy for EU climate policy (Delreux and Ohler, 2019), which means that additional emission constraints are set based on the European emission targets. For non-European countries like Iceland, Norway, Switzerland, and UK, we assume the same EU climate policy. The *Perceived seriousness of climate change* model version considers national public attitudes towards climate change according to the past survey data (European Commission, 2023). On top of the EU climate policy model version, here the national emission constraints are additionally adjusted with attitudes data in every country. The *Investment risks* model version considers investment risks, modelled by applying different country- and technology-specific weighted average costs of capital (WACC) instead of the uniform assumption from the reference model version (Polzin et al., 2021). *EU climate policy with investment risks* model version integrates both the EU climate policy and investment risks in each country. The *Perceived seriousness of climate change* model version combines all three societal factors by applying attitudes-adjusted emissions targets and modelling country- and technology-specific investment risks.

Second, we assess the accuracy of the generated national electricity system transition pathways by hindcasting in all these European countries in 1990 – 2019, using data from Jaxa-Rozen et al. (2022). We use the accuracy indicators of symmetric Mean Absolute Percentage Error (sMAPE) and Root Mean Squared Logarithmic Error (RMSLE) to evaluate the performance of the model regarding total CO_2 emissions, installed capacity and annual generation of each technology (Wen et al., 2022a).

Results

We first look into the impact of the integration of three societal factors of EU climate policy, perceived seriousness-adjusted climate policy, and investment risks on 35 quantities: CO_2 emissions, installed capacity and annual generation by technology (Figure 1). If we compare the performance of *Techno-economic* model version with other model versions, we find that there are 13 out of 31 countries (in green) that have better accuracy in *EU climate policy* model version. An evident accuracy improvement is observed in Portugal, followed by Austria, Sweden, Italy, Finland, and Luxembourg. For these 13 countries, also Croatia and Ireland, similar levels of improvements are seen under *Perceived seriousness-adjusted climate policy* model version. By observing the model versions *Investment risks, EU climate policy, and Perceived seriousness-adjusted climate policy*, we find that the inclusion of investment risks tends to increase the accuracy in 24 or 25 out of 31 countries, albeit sometimes very little. This indicates that the inclusion of investment risks on top of EU climate policy in general has still improved the hindcasting accuracy of electricity system transition modeling.

Furthermore, we examine the disaggregate error of each quantity across all countries to see the impact of highlighted societal factors on the model accuracy. For all the quantities, there are evident distinction between model versions with and without investment risks. The disaggregate errors (in Figure 2) show that compared to the *Techno-economic* model version, the accuracy (quantified by sMAPE) of CO_2 emissions has been improved or be almost the same, with one or multiple societal factors in 29 out of 31 countries, except in Cyprus and Norway, while the improvements in installed capacity and the annual generation depend on the country and technology.

For renewable technologies, there is no clear tendency of accuracy improvement with integrating EU climate policy only (such as onshore wind power in Figure 2), except for Austria and Portugal, where there is accuracy increase in biomass, onshore wind power and waste incineration deployment. The inclusion of investment risks has the most impact on waste incineration (with ten countries with higher accuracy and five countries lower accuracy), followed by biomass and onshore wind power. The waste incineration is often overestimated in the *Techno-economic* version (like in Bulgaria and Malta) than in the model versions with investment risks, where the incentive of its installation is restrained. For onshore wind power, the accuracy only decreases when investment risks are included in Greece and Ireland, since the installation for gas is favored over onshore wind power with more investment interests. The *Perceived seriousness-adjusted climate policy* versions have mostly the same results as *EU climate policy* versions, except for the annual generation for onshore wind power in Ireland. With co-evolution of EU climate policy (or perceived seriousness-adjusted climate policy) and investment risks, there is an accuracy increase (26%) regarding solar PV deployment in Cyprus. Otherwise, there is no accuracy improvement for solar PV and offshore wind power, and there is a slightly increase in biogas (within 12% in Italy, Norway, Portugal) and geothermal power deployment (within 10% in Iceland and Italy) across all the countries.

For low-carbon incumbent technologies, there are an increase or decrease of accuracy of annual generation for nuclear power in 15 out of 31 countries and for hydro dams in 9 countries (Figure 2). The inclusion of investment risks tends to improve the accuracy of the generation for nuclear power, especially in Latvia and the Netherlands. For combustion-based technologies (Figure 2), it is noticed that the accuracy of their annual generation is not always the same as the installed capacities (especially for gas and oil), unlike renewable technologies and low-carbon incumbent technologies. The accuracy of gas power generation tends to improve by including societal factors (in 16 countries, with seven countries being exceptions). Usually, the accuracy of gas power generation increases by including investment risks, making gas more competitive with nuclear power and hard coal, as seen in the real world. However, in France, the UK, Greece, Malta, Norway, and Slovenia, the opposite effect is observed. The accuracy of generation for oil mostly decreases, especially due to investment risks, although sometimes the accuracy of its installed capacity increases. The accuracy of brown coal is mostly increased, especially in Austria, under all the model versions with societal factors. For certain cases, including one or multiple societal factors lead to similar accuracy increases or decreases, such as generation for gas in Norway and Portugal, hard coal in Finland. and brown coal in Austria. On the other hand, the coevolution of multiple factors has a remarkable impact on the model. For example, in Sweden, the accuracy of gas generation improves only when multiple societal factors are considered, although this inclusion decreases the accuracy of hydro dam generation.

Conclusions

In this study, using hindcasting with electricity system model D-EXPANSE in 1990–2019, we investigated the impact of integrating societal factors into cost optimization-based electricity system modeling of transition pathways in 31 European countries. We found that there is no straightforward response of one or several societal factors always improving the hindcasting performance of the model. The results showed that the inclusion of societal factors can increase to some extent the performance of generated transition pathways. The national CO_2 emissions are more accurately modeled when incorporating any of the three societal factors compared to techno-economic modeling. Compared to the model versions with *EU climate policy* and *Perceived seriousness-adjusted climate polic*, the integration of investment risks makes an important impact on the modeled pathways and tends to improve the accuracy in many countries. The technology-disaggregated results demonstrate that with our societal factors included, the performance is improved for certain incumbent technologies like gas, brown coal, and nuclear power, but not necessarily for other technologies. This research provides valuable insights to inform modeling of societal factors in cost optimization-based bottom-up models.

Acknowledgements

The authors acknowledge funding of the Swiss National Science Foundation Eccellenza Grant for the project "Accuracy of long-range national energy projections" (Grant no. 186834, XW, ET).

Figures

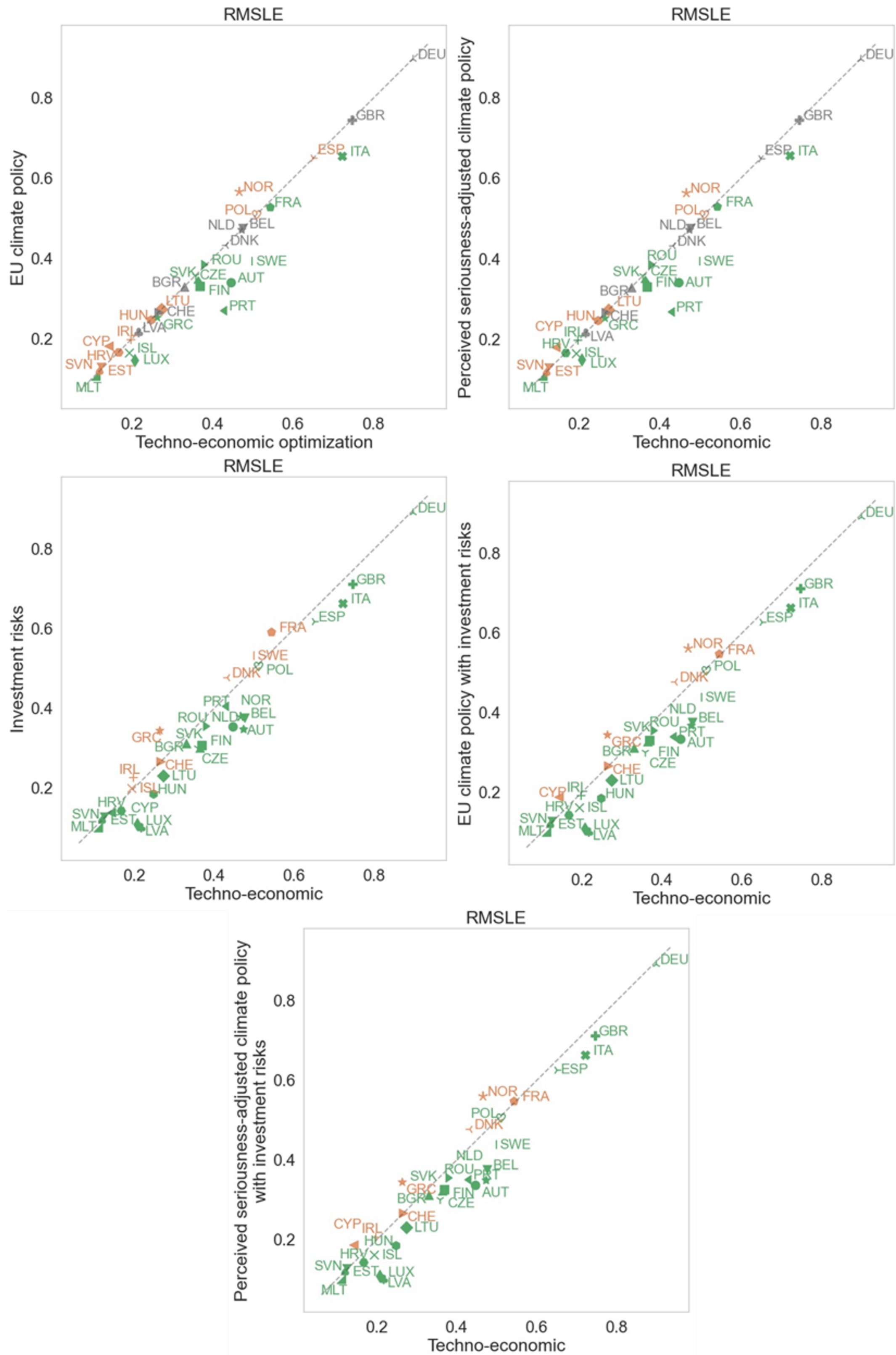

Figure 1*. The accuracy (quantified by RMSLE) of the model versions with societal factors compared to the Techno-economic model version. Five model versions are compared: EU climate policy, Perceived seriousness-adjusted climate policy, Investment risks, EU climate policy with investment risks, Perceived seriousness-adjusted climate policy with investment risks. Compared to the Techno-economic model version, countries in green show higher*

accuracy, countries in gray have the same performance and countries in orange have worse accuracy in the compared model version.

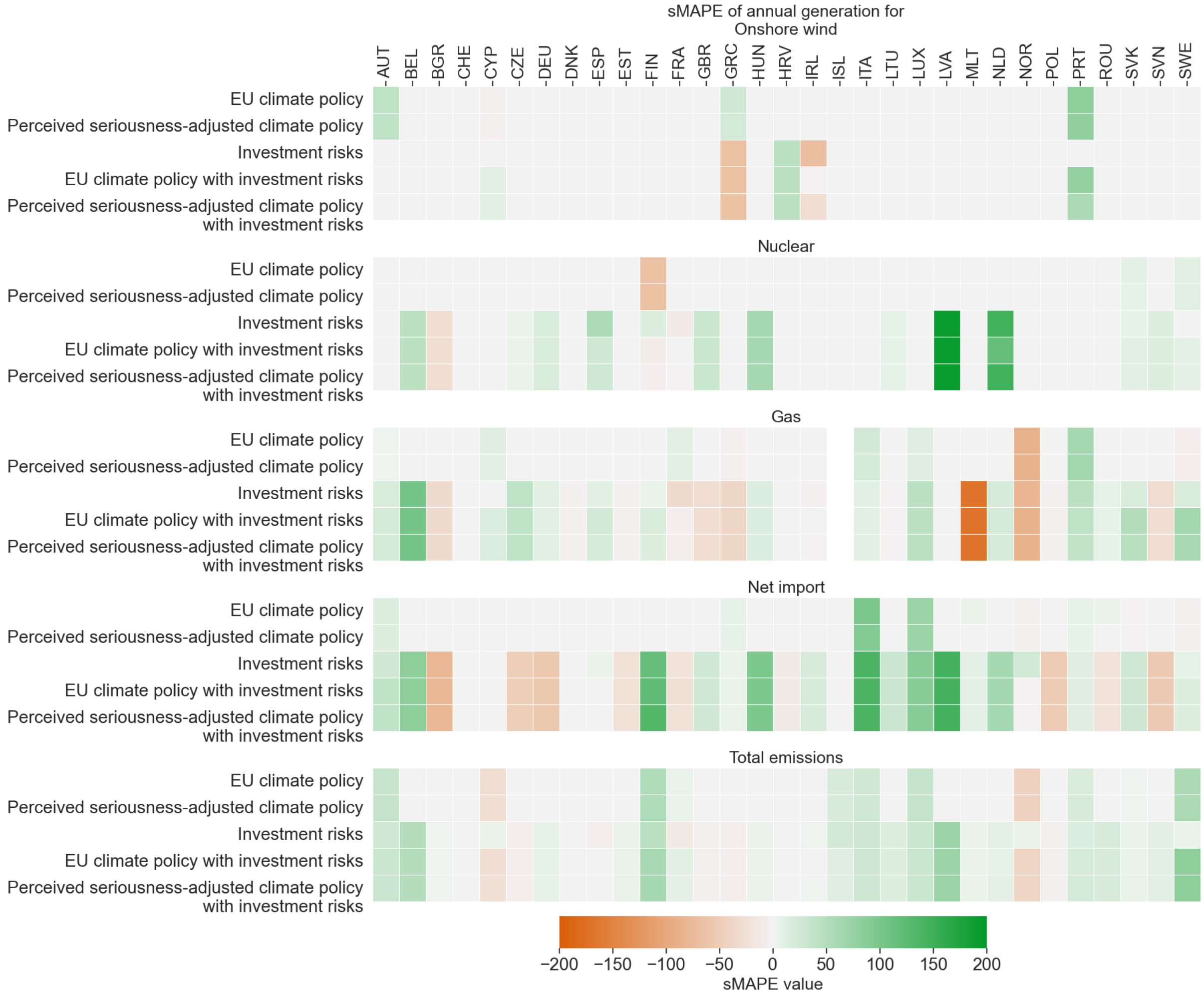

Figure 2*. The disaggregated accuracy (sMAPE) of estimating technology-specific generation of onshore wind, nuclear power, gas, net import, and total CO_2 emissions under the five model versions compared with the Techno-economic model version. The green color indicates a higher accuracy, gray color indicates the same performance and orange color indicates a worse performance.*

Supplementary Information

List of modeled countries and their country codes used for visualization: Austria (AUT), Belgium (BEL), Bulgaria (BGR), Croatia (HRV), Cyprus (CYP), Czechia (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), France (FRA), Greece (GRC), Hungary (HUN), Ireland (IRL), Iceland (ISL), Italy (ITA), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta (MLT), The Netherlands (NLD), Norway (NOR), Poland (POL), Portugal (PRT), Romania (ROU), Slovakia (SVK), Slovenia (SVN), Switzerland (CHE), Sweden (SWE), United Kingdom (GBR).

References

Cotterman, T., Small, M.J., Wilson, S., Abdulla, A., Wong-Parodi, G., 2021. Applying risk tolerance and socio-technical dynamics for more realistic energy transition pathways. Applied Energy 291, 116751. https://doi.org/10.1016/J.APENERGY.2021.116751

Delreux, T., Ohler, F., 2019. Climate Policy in European Union Politics, in: Oxford Research Encyclopedia of Politics. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228637.013.1097

European Commission, 2023. Climate change, Eurobarometer survey [WWW Document]. URL https://europa.eu/eurobarometer/surveys/detail/2954 (accessed 5.16.24).

Fisch-Romito, V., Jaxa-Rozen, M., Wen, X., Trutnevyte, E., 2024. Multi-country evidence on societal factors to include in energy transition modeling. Nature Energy.

Geels, F.W., Berkhout, F., Van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. Nature Climate Change 6, 576–583. https://doi.org/10.1038/nclimate2980

Jaxa-Rozen, M., Wen, X., Trutnevyte, E., 2022. Historic data of the national electricity system transitions in Europe in 1990–2019 for retrospective evaluation of models. Data in Brief 43, 108459. https://doi.org/10.1016/J.DIB.2022.108459

Koecklin, M.T., Longoria, G., Fitiwi, D.Z., DeCarolis, J.F., Curtis, J., 2021. Public acceptance of renewable electricity generation and transmission network developments: Insights from Ireland. Energy Policy 151, 112185. https://doi.org/10.1016/j.enpol.2021.112185

Morgan, M.G., Keith, D.W., 2008. Improving the way we think about projecting future energy use and emissions of carbon dioxide. Climatic Change 90, 189–215. https://doi.org/10.1007/s10584-008-9458-1

Polzin, F., Sanders, M., Steffen, B., Egli, F., Schmidt, T.S., Karkatsoulis, P., Fragkos, P., Paroussos, L., 2021. The effect of differentiating costs of capital by country and technology on the European energy transition. Climatic Change 167, 1–21. https://doi.org/10.1007/S10584-021-03163-4

Schubert, D.K.J., Thuß, S., Möst, D., 2015. Does political and social feasibility matter in energy scenarios? Energy Research & Social Science 7, 43–54. https://doi.org/10.1016/J.ERSS.2015.03.003

Trutnevyte, E., 2016. Does cost optimization approximate the real-world energy transition? Energy 106, 182–193. https://doi.org/10.1016/j.energy.2016.03.038

Trutnevyte, E., Hirt, L.F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O.Y., Pedde, S., van Vuuren, D.P., 2019. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. One Earth 1, 423–433. https://doi.org/10.1016/j.oneear.2019.12.002

Wen, X., Heinisch, V., Müller, J., Sasse, J.-P., Trutnevyte, E., 2023. Comparison of statistical and optimization models for projecting future PV installations at a sub-national scale. Energy 285, 129386. https://doi.org/10.1016/j.energy.2023.129386

Wen, X., Jaxa-Rozen, M., Trutnevyte, E., 2022a. Accuracy indicators for evaluating retrospective performance of energy system models. Applied Energy 325, 1–30. https://doi.org/10.1016/j.apenergy.2022.119906

Wen, X., Jaxa-Rozen, M., Trutnevyte, E., 2022b. Using Retrospective Modeling to Inform Choices in Developing Bottom-Up Electricity System Models, in: Mapping the Energy Future-Voyage in Uncharted Territory-, 43rd IAEE International Conference. International Association for Energy Economics.