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Abstract:
As global commitments to decarbonization intensify, energy-emission models are becoming increasingly vital for policymaking, offering data-driven insights to evaluate the feasibility and impact of climate strategies. These models help governments design evidence-based policies, assess mitigation pathways, and ensure alignment with national and international targets, such as the Paris Agreement and the EU Green Deal. Researchers often spend a lot of time considering their modelling choices to develop the best possible tools in terms of data-requirements, accuracy, computational demand, while there is always a 'debate' of complexity versus explicability and ready-to-use models for policymaking. Especially for energy-emissions models, given their increasing policy-relevance, and the need to provide insights fast for short-term policies (e.g. 2030, or 2050 net-zero goals), such considerations become increasingly pressing. In this paper, we present two different versions of the same energy-emissions model, and we run them for the same study area, planning horizon, and scenario analysis. The two versions differ only in how they approach complexity: Version1 is a more 'detailed', complex model, while Version2 is a 'simpler' and less data-hungry one. A set of evaluation criteria was then used to qualitatively compare these two versions, based on modelling- and policymaking-related considerations, debating modelers' and policymakers' expectations and preferences. We reflect on best modelling practices, discuss different goal-dependent approaches, providing useful guidance for modelers and policymakers.

Keywords: Energy-emissions modelling; Decarbonization pathways; Model development; LEAP; Models to policy.

1. Introduction

The combination of energy consumption and production processes, greenhouse gases (GHG) emissions, and other techno-economic factors, as systems, into single modelling tools has become a key consideration, aiming to inform the design of national decarbonization pathways (Timilsina et al., 2021). Such models are crucial in providing holistic and coherent views of the studied systems with direct policy implications, given the explicit net-zero commitments within national and international policy frameworks, such as the Paris Agreement and the EU Green Deal (Koundouri et al., 2024).

The main challenge in developing an energy-emissions model is accurately representing the energy system while ensuring (or handling) the availability of comprehensive and integrated data (Alamanos & Garcia, 2024). Defining the model's key components – such as energy demand, supply chains, socio-demographic assumptions, energy efficiencies and technologies, and associated emissions – and how they interact is a complex task requiring diverse expertise, and modelling experience to make decisions on the model-developing process (Koundouri et al., 2024). While extensive literature exists on applications of energy-emission models and the ways they can inform policies (Wietschel et al., 1997; Yang & Wang, 2023), guidance on model development and best practices for modelers are overlooked issues (Alamanos et al., 2020, 2021).

Comparative studies of energy-emissions models have been carried out, but in different contexts. For instance, most existing studies compare different models, reflecting on parameters that can affect more the economic and energy simulation outputs (Johansson et al., 2015; Yeh et al., 2016; Dekker et al., 2023). Also, an explorative comparison of 11 integrated assessment and energy system models was conducted by Henke et al. (2024), to highlight similarities and differences in energy-related outputs. Ruhnau et al. (2022) compared the uncertainty of five numerical power sector models using common input parameters, to discuss the potential model-related uncertainty ranges.

However, to our knowledge there is no study comparing the same model under different settings to balance different goals, aiming to provide insights for model-development. This is the aim of this paper, to fill this gap, by comparing two versions of the same model, representing different modelling philosophies, and reflecting on the most appropriate way to apply each case. We present and compare two versions of the Low Emissions Analysis Platform (LEAP) software (Heaps, 2022), simulating the efforts of Greece towards decarbonization by 2050. The two versions are identical in all their settings and assumptions, but consider different situations of data availability, explanatory depth scopes, and time constraints.

With this novel exercise, we expect to provide useful insights to both modelers and policymakers regarding model-development and expectations, depending on the context of their work.

2. Materials and Methods

Greece's energy sector, despite notable progress in renewable energy adoption, is currently relying primarily on fossil fuels, which account for a substantial portion of energy supply (Arampatzidis et al., 2025). The government has set ambitious commitments to reduce the total GHG emissions to net-zero by 2050. This is in line with the broader climate goals of the European Union, defining the Nationally Determined Contributions (NDC) under the Paris Agreement. Each Member State's National Energy and Climate Plan (NECP), as outlined in Regulation 2018/1999/EU on energy and climate action governance, sets out how each state can achieve these shared European climate targets. The Greek NECP (Greek Ministry of Energy and Environment, 2024) does so by proposing specific measures for each sector, aiming primarily to cleaner fuel mixes and improved energy efficiency. However, the progress in curbing GHG emissions so far is quite marginal (Arampatzidis et al., 2025).

The above situation instigated the current research, as the NECP for Greece was not explored through the lens of an energy-emission model. We used the LEAP software to simulate a Business-As-Usual (BAU) scenario (a do-nothing-situation, simply following the current trends as observed for the period 2000-2020) versus the Greek NECP. LEAP's ability to simulate different scenarios has been particularly useful in exploring future conditions and decarbonization pathways, so we explored what would be the best way to do that, by developing two versions of that BAU vs NECP model.

2.1. Description of Version1

Version1 is a complete simulation of the energy demand and supply sides. All sectors and feedstock fuels were simulated in detail, including all different uses and processes. Version1 was developed first, and at the time, it was the very first attempt to simulate the complete energy-emissions system of Greece as a whole. A key characteristic reflecting this ambitious effort, was the collection of multiple datasets for each sector and process, so the analysts get the best possible picture of every component of this system. This data-gathering exercise included datasets from different sources such as IEA (2023), Worldbank (2023), ELSTAT (2024), EUROSTAT (2024), NECP (2024).

In particular, Version1 includes the residential, agricultural, industrial, energy products, terrestrial transportation and aviation, maritime, and services sectors. The energy consumption (or demand in LEAP's terminology) of each sector consists of several components, expressing the different uses (see Table 1). Furthermore, the energy consumption of each use was parametrized, i.e. expressed through LEAP's Final Energy Demand Analysis method (Equation 1):

$$D_{sector,scenario,year} = AL_{sector,scenario,year} \cdot EI_{sector,scenario,year} \qquad (1)$$

This method suggests that the energy demand (D) has been calculated as the product of an activity level (AL) and an annual energy intensity (EI, energy use per unit of activity).

LEAP's energy supply models resources (representing the availability and characteristics of primary and secondary energy forms), and transformation processes (simulating how energy is converted, transmitted, and distributed through technologies like power plants, refineries, and grids) (Arampatzidis et al., 2025). The supply system ensures alignment with the per sector demand-side inputs and can simulate constraints, imports, exports, and system losses, offering detailed insights into energy flows. The detailed structure of the resources and energy production processes is also shown in Table 1.

The GHG emissions are then estimated automatically within LEAP, based on build-in emission coefficients of the IPCC's Fifth Assessment Report (IPCC, 2014) per sector, use and fuel type for the demand side, and per process for the supply side.

2.2. Description of Version2

After the successful simulation of the Greek energy-emissions system (Version1), there were some thoughts for potential improvements, such as:

- Avoid the detail in the input data, which leads to the use of data from multiple sources;
- Avoid the level of detail that can make the model complex for non-specialists;
- Time constraints that may apply when replicating this process (e.g. for another country or region);
- Relevance to policymakers and model explicability, in case there is the need to evaluate a certain scenario fast.

These are not necessarily weaknesses of Version1, but they are seen as potential shifts of focus, allowing us to cover other (or even more) modelling tasks.

These thoughts led to the development of Version2. The goal was to develop a model that could cover them, while maintaining a satisfactory performance in terms of accuracy and usefulness in scenario development. So, in response to the above bullet points, our goals for Version2 were to:

- Have a model with minimum data requirements, and from minimum number of different sources (e.g. ideally from one database);
- Reduce the level of detail of the sectoral simulation in a way that would also reduce the model's complexity;
- Reduce the time spent for model development, "standardizing" the procedure, and making it easily replicable. This would facilitate similar analyses, and enhance the reproducibility of the modelling approach;
- Make the model more easily explicable and usable to non-specialists and decision-makers, by keeping the focus on certain basic parameters (e.g. energy consumption per sector as a whole, a simpler categorization of key fuel types, etc.).

Of course, the level of detail is the main driving force for modelling time, easy reproducibility, and explicability. Reducing the detail while maintaining accuracy and insightfulness at an acceptable standard is a thoughtful process, and experience is crucial.

Version2 simulated the same sectors, but considered less energy uses (e.g. residential uses, industry types, transportation modes, etc.). Another key difference was that the energy consumption was not simulated according to Equation 1, but according to LEAP's Total Energy Demand method. That is, the total final energy consumption for each sector was used as a direct input in the model. Regarding the supply side, Version2 considered less fuel types than Version1. This was achieved by classifying Version1's fuel types into less categories that still capture their generation and use properties (see Table 1). This choice made the control over the demand-supply flows of fuels (namely, which fuel type covers each energy use) easier, reaching an energy balance faster (Figure 3).

The GHG emissions were estimated based on LEAP's build-in coefficients, exactly as in Version1. The only difference is that Version2 used more aggregated energy uses and fuel types than Version1.

2.3. Comparing the two versions

Table 1 is a summary of the main modelling decisions involved in the development of the two versions, comparatively. It describes what approach was used in each version, including their demand (each sector) and supply (fuel production) sides.

Table 1: Characteristics of the two model versions.

Simulated sectors/ parameters	Version1	Version2
Energy Demand		
Residential	**Method**: Final Energy Intensity Analysis **Activity Level**: Population divided into urban and rural. **Uses**: Space Heating, Space Cooling, Water Heating, Cooking, Lighting, Appliances	**Method**: Total Energy Demand **Uses**: Residential as a whole
Agriculture	**Method**: Final Energy Intensity Analysis **Activity Level**: Value added	**Method**: Total Energy Demand
Industry	**Method**: Final Energy Intensity Analysis **Activity Level**: Value added **Sub-sectors**: Food & Tobacco, Textiles & Leather, Wood & Wood Products, Paper Pulp & Printing, Chemicals, Rubber & Plastic, Non-Metallic (excluding cement), Basic Metals (excluding steel), Machinery, Transportation Equipment, Other Manufacturing, Mining, Construction, Cement, Steel	**Method**: Total Energy Demand **Sub-sectors**: Industry as a whole
Energy Products	**Method**: Final Energy Intensity Analysis **Activity Level**: Energy demand [ktoe] / Energy produced [ktoe] **Sub-sectors**: Hydrogen & Synthetic Fuels, Refined Petroleum Products, Natural Gas, Biomethane	**Method**: Total Energy Demand **Sub-sectors**: Energy Products as a whole
Aviation & Terrestrial Transportation	**Method**: Final Energy Intensity Analysis **Activity Level**: ktoe per Passenger-km **Sub-sectors**: Cars & Light Trucks, Freight Trucks, Motorcycles, Buses, Trains, Freight Trains, Domestic Airplanes	**Method**: Total Energy Demand **Sub-sectors**: Terrestrial Transportation, Aviation
Maritime	**Method**: Total Energy Demand **Sub-sectors**: Maritime as a whole	**Method**: Total Energy Demand **Sub-sectors**: Maritime as a whole
Services	**Method**: Total Energy Demand **Sub-sectors**: Services as a whole	**Method**: Total Energy Demand **Sub-sectors**: Services as a whole
Energy Supply (fuels' generation & transformation processes)		
Primary Resources	Solar, Hydro, Wind, Geothermal, Solid Waste, Biomass, Crude Oil, Lignite, Other Coal, Natural Gas	Renewables (includes: Solar, Hydro, Wind, Geothermal), Biomass (includes: Biomass, Solid Waste), Crude Oil, Coal (includes: Lignite, Other Coal), Natural Gas (includes: Natural Gas, CNG)
Secondary Resources	Electricity, Hydrogen, Synthetic Fuels, Heat, Biogas, Refinery Feedstocks, Diesel, Petroleum Coke, Fuel Oil, Kerosene, CNG, LPG, Gasoline, Other Petroleum Products	Electricity, Hydrogen, Synthetic Fuels, Heat, Biogas, Refinery Feedstocks, Petroleum Products (includes: Diesel, Petroleum Coke, Fuel Oil, Kerosene, LPG, Gasoline, Other Petroleum Products)
Transformation Processes	Transmission and distribution, synthetic fuel production, generation of hydrogen, electricity, heat, oil refining – with the associated losses	Transmission and distribution, synthetic fuel production, generation of hydrogen, electricity, heat, oil refining – with the associated losses
GHG Emissions		
Type of Pollutants	CO_2, CH_4, N_2O, PM2.5, Hydrofluorocarbons (HFCs),	CO_2, CH_4, N_2O, PM2.5, Hydrofluorocarbons (HFCs),

	Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), Black Carbon (BC), Organic Carbon (OC)	Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), Black Carbon (BC), Organic Carbon (OC)
Scenarios		
BAU	In both versions, the BAU refers to what LEAP requires as the model's "current accounts", namely the existing trends (a do-nothing situation). Practically, all the above parameters remain stable, except of those following the assumptions of the base-year according to the observed trends of the period 2000-2020 (e.g. population growth, demands for agricultural, industrial, and transportation services).	
NECP	The NECP assumes that each energy use will utilize a mix of cleaner fuels, which is also reflected in their generation and transformation side. It also assumes improvements in the energy efficiency of each sector, which is translated in reduced EIs. These mixes of fuels and EIs are explicitly expressed in the Greek NECP per sector, so the only difference between Version1 and Version2 is their application at a more (Version1) or less (Version2) aggregated model.	
Validation		
	For the current account, both energy consumption and fuel supply results were validated by cross-checking with data from multiple sources (ELSTAT, EUROSTAT, IEA, Worldbank).	For the current account, both energy consumption and fuel supply results were validated with data from a single source (EUROSTAT).

To make the comparison between the two versions possible, the following strategy was employed in this study:

- Both versions are set up in an annual time step, ensuring the same time-resolution;
- The same planning horizon was applied in both versions, which is the period 2022 (base-year) to 2050 (target-year);
- Both versions run under common scenarios (the BAU and the NECP), which are simulated with the exact same way in both versions (as also mentioned in Table 1), in order to perform a fair comparison between them.

Thus, the comparison of the two versions' results refers to the same conditions, in order to isolate and explore the differences due to the modelling approach followed in each case.

The views of 'modelers' and 'policymakers' from our team were also considered to make a qualitative comparison of these two versions, based on things that each one considers important.

3. RESULTS

3.1. Comparing numerical results

The desirable outputs of both versions are the energy consumption per sector along with the fuels needed to cover it, and the associated GHG emissions for all of these processes. Each version provides this set of results for the BAU and the NECP scenarios, by 2050 (Figures 1,2).

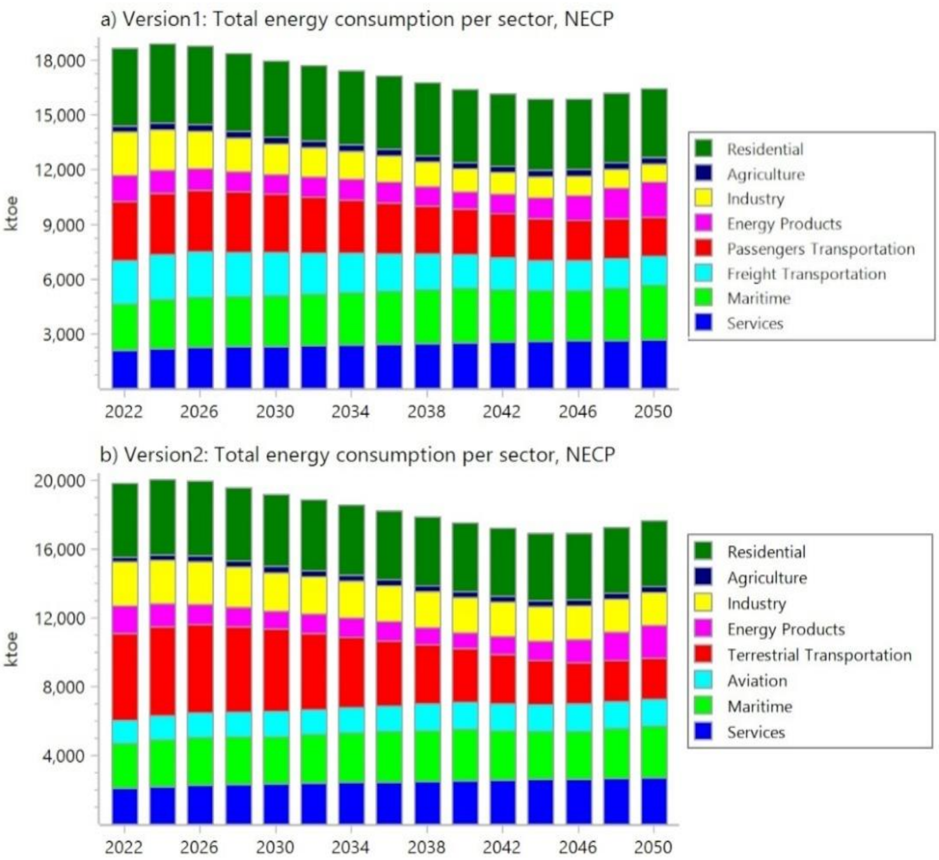

Figure 1: Total energy consumption per sector, under (a) Version1's NECP; (b) Version2's NECP.

Figure 1 shows the evolution of energy consumption in both versions under the NECP. Note that we omit the corresponding figures for BAU since i) energy consumption remains stable across all years in both versions; ii) BAU is not a realistic scenario/policy as it assumes that the current account will be perpetuated until the end of the planning period. Table 2, instead, provides some results for BAU, indicatively for year 2050, to facilitate comparisons with NECP for both versions. Figure 1 shows that the two versions exhibit a similar pattern regarding the energy consumption reduction under the NECP. The overall reduction is similar in Version1 and Version2 (11.8% and 11.1%, respectively). In both versions, the most dramatic decrease is observed in transportation (34.4% and 31.8% in passenger and freight transportation of Version1 respectively, and 52.9% in terrestrial transportation of Version2) under NECP. The seemingly large difference between the two versions can be explained by the increase (by 14%) of energy consumption in aviation, which is a separate category in Version2, but one of the sub-sectors of passenger transportation in Version1. The overall reduction of energy demand in terrestrial transportation is due to the projected development of alternative forms of mobility, such as micro-mobility (e.g. bicycle use) and active mobility, as well as the increased use of public transport. A significant decrease is also observed in industrial (30% in Version1 and 57% in Version2) and residential energy consumption (approximately 12% in each version) due to improvements in energy efficiency and Greece's shrinking population. Finally, an increase in energy demand is projected in services (approximately 28% in each version), agriculture (14.6% in Version1 and 25% in Version2) and energy products (35% in Version1 and 21% in Version2).

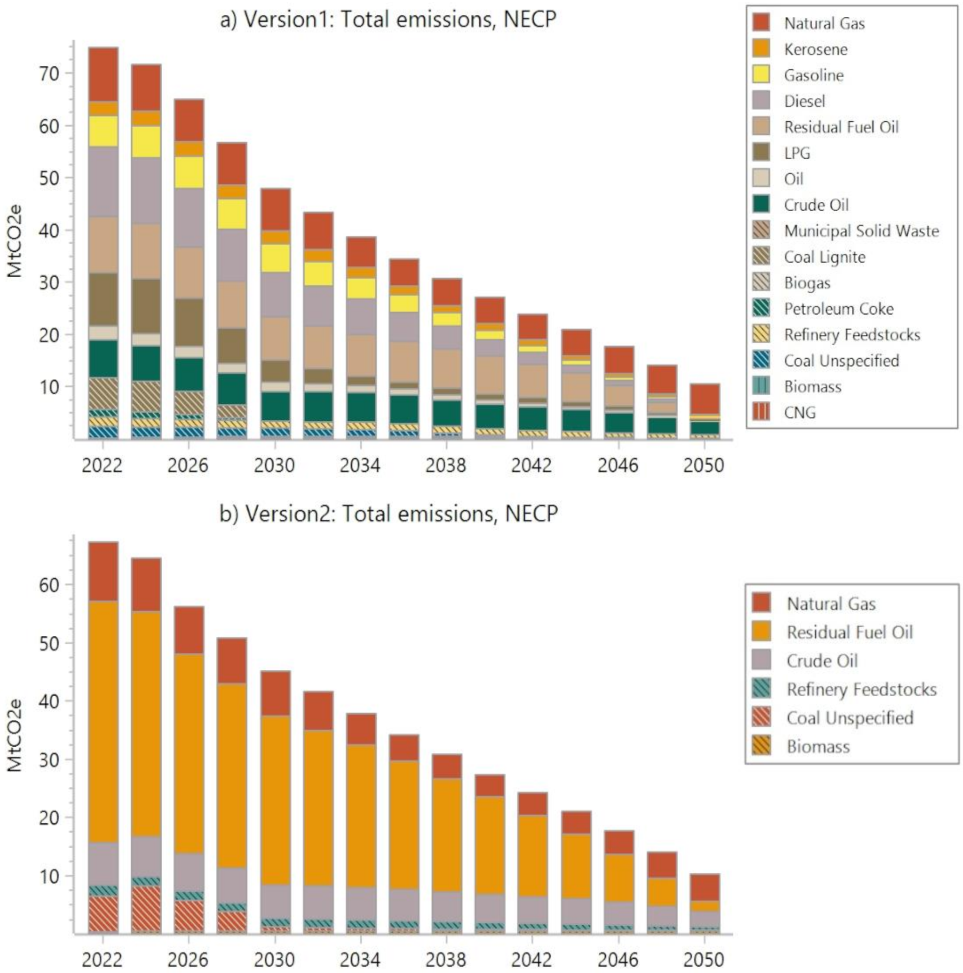

Figure 2: Total GHG emissions (100-Year GWP) per fuel for (a) Version1's NECP; (b) Version2's NECP.

Figure 2 shows the evolution of GHG emissions, calculated using the 100-year Global Warming Potential (GWP), in both versions under the NECP. For the same reasons as in Figure 1, we omit the corresponding figures for BAU; some indicative results are shown in Table 2 for year 2050. The implementation of the NECP leads to an 86% and 84.7% decrease of GHG emissions in Version1 and Version2, respectively. Despite this drastic reduction, Greece does not achieve complete decarbonisation under the NECP, as it reaches approximately 10.5 MtCO2e by 2050 in each version. The main reasons for the near-complete decarbonisation are: i) the operation of oil refineries which, despite facing a shrinking domestic demand, they keep their exports of petroleum products stable; ii) the fact that it is difficult to completely decarbonise sectors such as maritime and industry.

Table 2: Comparing key outputs from the two versions.

Scenario	Energy consumption in 2050 [ktoe] Version1 | Version2	GHG emissions in 2050 [MtCO2e] Version1 | Version2	Energy imported in 2050 [ktoe] Version1 | Version2	Green fuels deployment in consumption in 2050 [in %] Version1 | Version2	Green fuels deployment in transformation in 2050 [in %] Version1 | Version2
BAU	18,909 | 19,821	77.5 | 74.7	33,952 | 33,732	27.1% | 26.1%	17.1% | 16.7%
NECP	16,464 | 17,614	10.5 | 10.3	15,421 | 12,787	85.6% | 83.7%	72.3% | 72.4%

The results presented in Table 2 are very encouraging for the two versions as they converge in all variables of interest by 2050. More specifically, only minor discrepancies are observed between the two versions in GHG emissions and green fuels deployment in both consumption and transformation by 2050. In contrast, the difference is larger in energy consumption, and thus in imported energy, but it remains still within a reasonable range.

It should be noted once again that the NECP scenario in Version1 was applied by a more detailed way, as more modelling components (e.g., energy uses, activity level, energy intensity, multiple types of fuels) were available, hence editable. Whereas in Version2 a more high-level approach was followed, suggesting total changes in consumption as a whole, according to the NECP's targets. In addition, there is a considerable difference in the need for input data between the detailed version (Version1) and the more aggregated version (Version2). This need is covered by a single data source (EUROSTAT, 2024) in Version2 compared to multiple sources (IEA, 2023; World Bank, 2023; ELSTAT, 2024; EUROSTAT, 2024) in Version1, which accounts for a non-negligible share of the observed differences between the two versions.

At this point, it should be noted that the different structure and degree of complexity between the two versions directly affects the validation process. On the one hand, using data from multiple databases (Version1) allows the modeller to cross-check the results with several sources. On the other hand, this entails data uncertainties from multiple sources. In contrast, Version2 uses data from a single database, which significantly reduces the validation effort, with the potential caveat of facing data uncertainty stemming from that single source. Overall, assuming that all data sources are accurate, validation of Version2 is sounder as it is directly controllable with minimum effort.

Despite those differences, under NECP both versions show a clear transition to cleaner fuels and an associated reduction in GHG emissions. Both versions also achieve an energy production-transformation-consumption balance throughout the simulation period. The energy balance in LEAP refers to a demand-supply 'mirror analysis', where the fuels produced can be used to feed the consumption, as exports, and a certain amount is imported. Figures 3a and 3b show all these flows, indicatively for 2050, for Version1 and Version2, respectively.

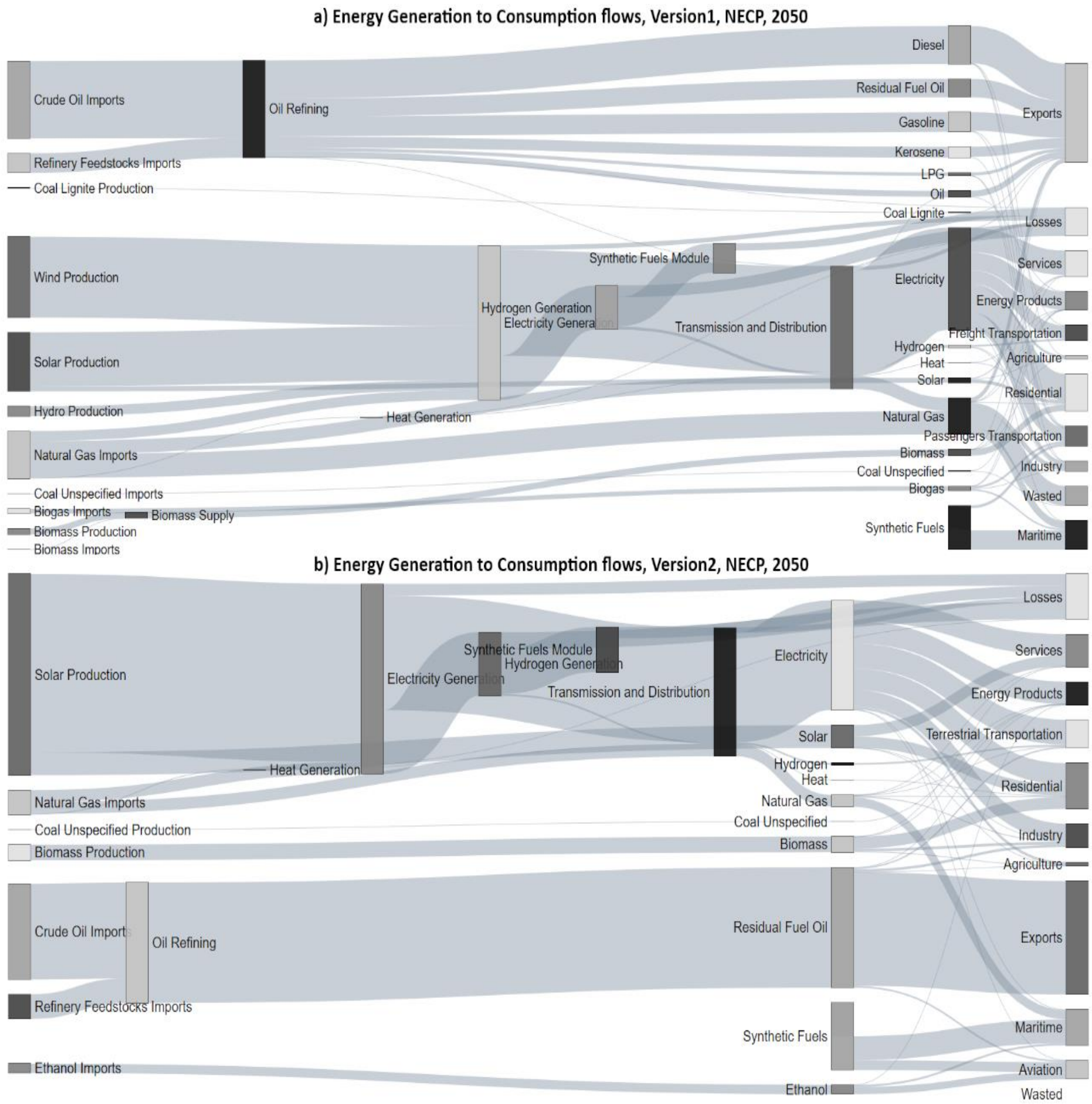

Figure 3: Sankey diagram for (a) Version1's NECP (2050); (b) Version2's NECP (2050).

3.2. Qualitative comparison

Both versions are representations of the energy systems' behaviour under a potential decarbonization pathway. They offer two different, alternative modelling approaches, each one with its own potential for policy input. Although there is literature on constructing relations among data, and software manuals can be quite detailed, the actual decision that a modeler should make while developing such models (e.g. parameter selection, function choice, variable definition, what can be omitted, etc.) is rare. It is the result of previous experiences, goals, data quality and availability, and personal preferences. Selecting between these two approaches is thus a debate between modelling and policy-relevant goals.

As mentioned, this qualitative comparison is a result of such a 'debate' between the members of this author team. Some of them have the role of modelers, involved in model-development processes and others are directly involved in policymaking processes, policy evaluation exercises, influencing decision-makers based on science-supported arguments. Such arguments result from data-driven models, so they have strong opinions on what is needed from such models. Thus, we believe

that in this paper, we can offer a quite spherical and representative overview of a modeler-versus-policymaker debate with useful insights for consideration.
To facilitate a qualitative comparison between Version1 and Version2, a feature table (Table 3) was developed, outlining relevant evaluation criteria from the authors' perspectives and the broader literature on model comparisons (Krause et al., 2005; Myung & Pitt, 2018; Alamanos et al., 2020). These features are considered important for the formulation and the usefulness/capabilities of any model's performance. A simple qualitative evaluation based on a strength (✓) / weakness (X) / equal (-) system was followed, as not all these features can be quantified.

Table 3: Comparing the two versions over qualitative features.

Comparison features	Version1	Version2
Model structure and complexity:		
Small number of input parameters required	X	✓
Ability to capture quantitative variables	-	-
Ability to capture qualitative variables	X	X
Detailed granularity in sectors/ sub-sectors representation	✓	X
Detailed level of disaggregation for different fuel types	✓	X
Simplicity (trade-off between detailed representation and usability)	X	✓
Data and validation:		
Small amount of input data	X	✓
Quality of input data	-	-
Time required for data gathering and preprocessing	X	✓
Plausibility and justification of assumptions	-	-
Reliability (validation potential, by comparing results with empirical data)	-	-
Policy relevance and usability:		
Stakeholders' involvement potential	-	-
Interpretability of input-output by non-experts	X	✓
Transparency	-	-
Flexibility for simulating different scenarios and policy evaluation runs	X	✓
Capacity to model specific (fine-resolution) scenarios and policy evaluation runs	✓	X
Speed of model development to obtain results	X	✓
Replicability / reproducibility in other regions	X	✓
Explicability without prior knowledge requirements of local (study area) context	X	✓
Ready-to-use results for high-level policy discussions	X	✓
Practical considerations:		
Total time required for structuring the model	X	✓
Connection with land-use models	-	-
Connection with water management models	✓	X
Connection with transportation-specific models	✓	X
Connection with economic (e.g. equilibrium) models	✓	X
Ease of model expansion (additional modules and variables)	X	✓
Computational efficiency (processing demand, run-time, bugs)	X	✓
Need for technical support and expertise to operate	-	-
Personal preference based on use-confidence:		
Preferred version by modelers	✓	X
Preferred version by policymakers	X	✓

Table 3 indicates that the two versions are quite competitive. If all comparison features are considered of equal weight (which is the assumption of this paper), then the high degree of competitiveness is a very interesting outcome. Overall, Version1 reached a score of 7/30 and Version2 14/30. It is worth noting that the two versions are even (-) across 8 features out of the total of 30 (so equal performance by 27%), while their differences account just for the 23% (7/30).

Regarding "model structure and complexity", and "practical considerations", the two versions are even, with a score of 2/6 each and 3/8 each, respectively. Data simplicity and policy relevance are the features that make the difference. In terms of "data and validation", Version2 prevails, scoring 2/5. As expected, Version2 is more "policy relevant and usable" (scored 6/9 versus 1/9 of Version1). As also expected, modelers prefer Version1 and policymakers prefer Version2. This preference indicates that certain features might actually be considered as more important than others, even at different stages of this modelling project.

4. DISCUSSION

The modelling process started from Version1, which contributed significantly to the understanding of the system and the role of each parameter. Thus, its development was a significantly longer process, involving some additional exploratory tasks to reach this understanding.

In particular, an extensive cross-checking exercise was carried out to ensure that the different datasets were consistent and accurate. As mentioned in section 2.1, collecting, validating and cross-checking multiple datasets for each sector and process helped the modelers understand the systems' components. This might sound simple or even redundant, but it is actually a goal for modelers, and quite important when starting a modelling process from scratch and an initial picture is needed. On the other hand, policymakers either ignore this process, or often take it for granted.

Furthermore, various scenarios have been modelled within Version1 to explore how the different modelled components respond. For example, changes in fuel mixes, activity levels and energy intensities in line with key assumptions for decarbonization, according to the Shared Socio-economic Pathways (SSPs) were simulated. This is unpublished work, and it primarily served as an internal exercise to ensure that the model provides reasonable results compared to some expected behaviours (e.g. lower emissions in SSP1 versus SSP5, etc.). Also, it is crucial for modelers to familiarize with the software's settings, the way to change scenarios, and get them thinking of the most efficient way of modifying things within the model. This exercise is also particularly useful for indicating sensitive variables and aspects aimed at further improving the system, so it is a key experience-gaining process. Again, although this is important for modelers, policymakers pay very limited attention to these processes.

Version2 followed a more simplistic or aggregated approach, simulating less sub-sectors, considering their total energy demand. It is worth mentioning that policymakers did not consider some sectors at all, as they focus on large sectors that are important for many countries (not just Greece), seeking to generalize relations and findings. On the other hand, modelers were confident to proceed with this approach only because the detailed information on energy consumptions per sector was available, so LEAP's results could be validated over this data. With Version1 preceding, the expected changes when considering different scenarios, or even user-defined variations based on alternative technologies and efficiencies, make possible the direct change of the total consumption in Verison2's scenarios. This is a level of detail that policymakers might not want to assess, so if there is enough ground to justify this approach, it can provide satisfactory results quite fast.

Another important exercise to test the model's robustness is to input the data of one version, e.g. Version1, into Version2, to ensure the models provide the same results, no matter the different approach in their structure. This was also carried out, adding to Version2's soundness.

Regarding the supply side, having many different fuel types is a non-usable level of detail for policymakers and complicates things for modelers (to ensure the accurate energy demand-supply balance of many different types, making the model quite data-hungry). So, Version2's grouping of fuel types is a good balance between complexity and explicability, and in line with most official databases' categorization. The same applies also for the granularity of the GHG pollutants, where Version2 achieves a reasonable balance of simplicity and necessary detail

5. CONCLUDING REMARKS

This paper tried to enlighten some dilemmas that modelers may find when structuring energy-emission models, based on the authors' personal experiences in science-to-policy situations.

A parameter that could be depicted only indirectly in the comparison of Table 3, is the different scope of each version, which is crucial for the context of this work. In contrast with other studies, we did not compare different models as means to the same end. Instead, we compared two "good" performances of different approaches as pathways that can achieve different goals. Specifically, if the goal (either of the modelers or the policymakers) is:

- to understand the system and have an in-depth picture of how it behaves, then Version1 is recommended (data scrutiny and high level of granularity);
- to have sets of key results quickly to use them as evidence to a quite high-level discussion (often with limited time to engage in an in-depth analysis), then Version2 is recommended.

It should be also noted that Version1 does not "cancel" or revoke Version2, or vice versa. On the contrary, the 'weaknesses' of one version are remedied by the 'strengths' of the other. It would not be bad to have both versions as complementary tools; for example, Version1 would be ideal for policies targeting sectors and sub-sectors, while Version2 for national and regional policymaking.

From the modelers' perspective, perhaps a "Version1" approach is necessary to feel confident to develop a "Version2" and deliver it to policymakers. It allows modelers to be prepared for requests focusing on any possible parameter, while providing a usable and easily explicable, high-level tool. From the policymakers' perspective, things work in a much more aggregated and solution-oriented way. The focus is on a tool that can easily explain what should be done to achieve decarbonization targets by 2050: which sectors and fuels to target with specific interventions, and what would be the implementation trade-offs (e.g. emissions vs cost, clean energy vs additional investments in renewables, or land, etc.).

The experience of developing both versions while debating analytical depth with simplicity to cover policymakers' demands, leads to the conclusion that a right balance is needed. Version2 achieved this balance between accuracy and performance. While it addresses multiple sectors and the main fuels, it maintains a level of desirable explicability. We do not believe that it is a simplified approach, as it simulates multiple demand and supply aspects; however, it is a sufficiently simple approach. And whenever validation is possible to ensure the technical soundness, simplicity will be preferred as it is more likely to make clearer arguments and cut through high-level policy contexts.

Conflict of Interest Statement

Conflict of Interest – None.

Data Availability Statement

Data available after request from the authors.

Author Contribution Statement

Conceptualization, A.A., P.K., J.S. Methodology, I.A., S.D., A.A., Writing—original draft preparation, I.A., S.D., A.A., Writing—review and editing, I.A., S.D., A.A., P.K., J.S. All authors have read and agreed to the published version of the manuscript.

REFERENCES

Alamanos, A., & Garcia, J. A. (2024). Optimization Examples for Water Allocation, Energy, Carbon Emissions, and Costs. *Encyclopedia*, *4*(1), Article 1. https://doi.org/10.3390/encyclopedia4010022

Alamanos, A., Latinopoulos, D., Loukas, A., & Mylopoulos, N. (2020). Comparing Two Hydro-Economic Approaches for Multi-Objective Agricultural Water Resources Planning. *Water Resources Management*, *34*(14), 4511–4526. https://doi.org/10.1007/s11269-020-02690-6

Alamanos, A., Rolston, A., & Papaioannou, G. (2021). Development of a Decision Support System for Sustainable Environmental Management and Stakeholder Engagement. *Hydrology*, *8*(1), Article 1. https://doi.org/10.3390/hydrology8010040

Arampatzidis, I., Devves, S., Alamanos, A., Dellis, K., Christopher, D., & Koundouri, P. (2025). A model-based assessment of the Greek National Energy and Climate Plan under a water-energy-food-emissions nexus context. *EAERE*.

Dekker, M. M., Daioglou, V., Pietzcker, R., Rodrigues, R., de Boer, H.-S., Dalla Longa, F., Drouet, L., Emmerling, J., Fattahi, A., Fotiou, T., Fragkos, P., Fricko, O., Gusheva, E., Harmsen, M., Huppmann, D., Kannavou, M., Krey, V., Lombardi, F., Luderer, G., … van Vuuren, D. (2023). Identifying energy model fingerprints in mitigation scenarios. *Nature Energy*, *8*(12), 1395–1404. https://doi.org/10.1038/s41560-023-01399-1

ELSTAT. (2024). *Main Page ELSTAT - the Hellenic Statistical Authority*. https://www.statistics.gr/en/home/

EUROSTAT. (2024). *Energy balances*. https://ec.europa.eu/eurostat/web/energy/database/additional-data#Energy%20balances

Greek Ministry of Energy and Environment. (2024). *National Energy and Climate Plan (NECP)*. Greek Ministry of Energy and Environment. https://ypen.gov.gr/energeia/esek/

Heaps, C. G. (2022). *LEAP: The Low Emissions Analysis Platform* (Version 2024.1.1.15) [Computer software]. Stockholm Environment Institute. https://leap.sei.org

Henke, H., Dekker, M., Lombardi, F., Pietzcker, R., Fragkos, P., Zakeri, B., Rodrigues, R., Sitarz, J., Emmerling, J., Fattahi, A., Dalla Longa, F., Tatarewicz, I., Fotiou, T., Lewarski, M., Huppmann, D., Kavvadias, K., van der Zwaan, B., & Usher, W. (2024). Comparing energy system optimization models and integrated assessment models: Relevance for energy policy advice. *Open Research Europe*, *3*, 69. https://doi.org/10.12688/openreseurope.15590.2

IEA. (2023). *Energy Policy Review: Greece 2023*. https://www.iea.org/reports/greece-2023

IPCC. (2014). *Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Draft conclusions proposed by the Chair.* https://unfccc.int/documents/8496?gad_source=1&gclid=Cj0KCQiAi_G5BhDXARIsAN5SX7qZkQc1UmZZswcJBJbVJ8oMBbQwb7LCsAc2BeLvTy4wit5eIgCllREaAm5EEALw_wcB

Johansson, D. J. A., Lucas, P. L., Weitzel, M., Ahlgren, E. O., Bazaz, A. B., Chen, W., den Elzen, M. G. J., Ghosh, J., Grahn, M., Liang, Q.-M., Peterson, S., Pradhan, B. K., van Ruijven, B. J., Shukla, P. R., van Vuuren, D. P., & Wei, Y.-M. (2015). Multi-model comparison of the economic and energy implications for China and India in an international climate regime. *Mitigation and Adaptation Strategies for Global Change*, *20*(8), 1335–1359. https://doi.org/10.1007/s11027-014-9549-4

Koundouri, P., Alamanos, A., Devves, S., Landis, C., & Dellis, K. (2024). Innovations for Holistic and Sustainable Transitions. *Energies*, *17*(20), Article 20. https://doi.org/10.3390/en17205184

Koundouri, P., Alamanos, A., Plataniotis, A., Stavridis, C., Perifanos, K., & Devves, S. (2024). Assessing the sustainability of the European Green Deal and its interlin kages with the SDGs. *Npj Climate Action*, *3*(1), 23. https://doi.org/10.1038/s44168-024-00104-6

Krause, P., Boyle, D. P., & Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, *5*, 89–97. https://doi.org/10.5194/adgeo-5-89-2005

Myung, J. I., & Pitt, M. A. (2018). Model Comparison in Psychology. In *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience* (pp. 1–34). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119170174.epcn503

Ruhnau, O., Bucksteeg, M., Ritter, D., Schmitz, R., Böttger, D., Koch, M., Pöstges, A., Wiedmann, M., & Hirth, L. (2022). Why electricity market models yield different results: Carbon pricing in a model-comparison experiment. *Renewable and Sustainable Energy Reviews*, *153*, 111701. https://doi.org/10.1016/j.rser.2021.111701

Timilsina, G. R., Pang, J., & Xi, Y. (2021). Enhancing the quality of climate policy analysis in China: Linking bottom-up and top-down models. *Renewable and Sustainable Energy Reviews*, *151*, 111551. https://doi.org/10.1016/j.rser.2021.111551

Wietschel, M., Fichtner, W., & Rentz, O. (1997). Integration of price-depending demand reactions in an optimising energy emission model for the development of CO2-mitigation strategies. *European Journal of Operational Research*, *102*(3), 432–444. https://doi.org/10.1016/S0377-2217(97)00209-9

World Bank. (2023). *Urban-Rural Population Growth*. https://data.worldbank.org/indicator/SP.RUR.TOTL.ZG?locations=EU

Yang, F., & Wang, C. (2023). Clean energy, emission trading policy, and CO2 emissions: Evidence from China. *Energy & Environment*, *34*(5), 1657–1673. https://doi.org/10.1177/0958305X221094581

Yeh, S., Yang, C., Gibbs, M., Roland-Holst, D., Greenblatt, J., Mahone, A., Wei, D., Brinkman, G., Cunningham, J., Eggert, A., Haley, B., Hart, E., & Williams, J. (2016). A modeling comparison of deep greenhouse gas emissions reduction scenarios by 2030 in California. *Energy Strategy Reviews*, *13–14*, 169–180. https://doi.org/10.1016/j.esr.2016.10.001