A STANDARDIZED FRAMEWORK FOR A SYSTEMATIC SELECTION PROCESS OF ENERGY SYSTEM MODELS

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Overview

Energy is considered as the capacity to do work (Holden et al., 2021). An energy system is the process chain from the extraction of primary energy resources to production, transformation, transportation, distribution, and consumption by end-users to satisfy human demands for energy services such as cooking, lighting, heating, cooling, appliances, mobility, and others (International Institute for Applied Systems Analysis, 2012). Energy system models (ESMs) are computer algorithms that replicate actual energy systems by translating the system's components and flows into tractable mathematical equations, creating simplified images of real-life applications in an organized model structure. They are decision support tools that allow examining parts of or whole engineered systems through scenarios of hypothetical futures under specific conditions, such as the presence or absence of policy (Farzaneh, 2019). ESMs have been under development over six decades ago, with a history dating back to the 1960s (Spittler et al., 2019). During the 1970s in response to the threats posed by the 1973 Arab oil embargo, these modeling tools focused on decoupling energy markets dependency on certain types of fuels (i.e., oil and gas) to maintain energy security and avoid the adverse effects of national economic crises (Rath-Nagel & Voss, 1981). With the rise of climate change as a critical global issue in the 1990s, these tools evolved into the testing of adaptation and mitigation strategies for the abatement of greenhouse gas (GHG) emissions to limit the rise in global temperature levels (Lopion et al., 2018; Pfenninger et al., 2014). With the enactment of the Paris Agreement in 2016, ESMs proliferated rapidly owing to advancements in computational power and the availability of electronic data sources which revolutionized the modeling process (Plazas-Niño et al., 2022). The current surge of ESMs in the literature poses a challenge in the selection of appropriate modeling tool(s) for user specific needs. The consideration of suitable modeling tool(s) hinges on a multitude of factors such as the nature of the case study, research objectives, intended outcomes, computational and technical requirements, model fidelity, level of uncertainty, and availability of relevant resources (e.g., time, budget, people, skills, information and data including type, quantity, quality, and scale), among various others. Most studies using ESMs either follow an arbitrary selection or provide poor justifications such as minimal description of the general positive attributes of the selected tool(s) or citing prior usage in similar contexts as a form of justifying the choice. Such justifications may obscure bias favoring certain tool(s) over others for convenience or familiarity purposes than by suitability for the specific problem at hand. The argument here does not emphasize the search for a "perfect" or "ideal" tool(s) as perhaps one may not exist but rather identify the "right" or "representative" tool(s) that "best" matches the specific requirements of a modeling undertaking. Therefore, the objective of this study is to standardize the selection process of ESMs through the application of a comprehensive framework developed using expert elicitation. The framework streamlines a systematic assessment for ESMs with different properties, to guide researchers and practitioners towards a more informed decision-making process in selecting the most suitable tool(s) tailored to specific needs.

Methods

The approach adopted to develop the standarized framework involved (i) the definition of assessment criteria and then (ii) assigning weights to these criteria to undergo a systematic selection process for ESMs. The criteria definition was initially guided by outcomes gained from an extensive literature review of studies and applications employing ESMs. A consultation using experts' ratings followed to assign the weights to the defined criteria. Specifically, the main criteria and supporting sub-criteria were incorporated into a semi-quantitative survey, designed as an online questionnaire with various questions formats ranging from multiple choice to free-text responses. The survey was circulated to members of the Open Energy Modeling (openmod) initiative community for energy system modeling who provided prior consent to undertake the survey. Multiple stakeholders from nine different entities, including academia, research institutions, private companies, and non-governmental organizations across nine respective geographical origins, participated in the survey. These participants are model owners and developers representing a sample population with up-to-date and in-depth knowledge about ESMs. They were asked to rank the importance of the defined criteria based on a five-point Likert scale – (1.0) Very Unimportant, (2.0) Unimportant, (3.0) Neutral, (4.0) Important, (5.0) Very Important. They were also asked to validate the proposed criteria and suggest other relevant criteria to the selection of ESMs that may have not been considered initially and rank their importance respectively. This resulted in slight modifications to the original criteria based on collected inputs and feedback received by the experts via online discussions and dialogues. Accordingly, the relative weights for the final criteria were calculated by dividing the score of each criterion by the total score of all criteria summed together.

Results

A total of thirty well-defined main criteria, each detailed by several sub-criteria, were identified to resemble key properties pertinent to ESMs (Table 1). These assessment criteria feature both technical and non-technical attributes for an across-the-board analysis that extends beyond the scientific modeling aspect to include user specific needs. The "technical" criteria (n = 20) refer to the fixed and inherent built-in "modeling" capabilities primarily used for "characterization" purposes but can also be used to influence the choice of ESMs to some degree. Meanwhile, the "non-technical" criteria (n = 10) represent the additional generic "non-modeling" aspects defined explicitly for the "selection" component of the process. The relative weights assigned to each criterion resemble a prioritization scheme for the specifications deemed necessary to initiate the energy system modeling process based on insights from energy experts. The criteria are also mapped to the corresponding modeling stage in which each will be applied. The modeling process constitutes eight stages in order of (1) conceptualization, (2) data collection, (3) configuration, (4) calibration, (5) validation, (6) interpretation, (7) iteration, and (8) reporting.

Table 1: Summary matrix of the established main assessment criteria and their importance weights.

Category (Index)	Main Criteria*	Description	Weights (W_{index})	Modeling Stage
Technical (T01)	Scope and Function	Main purpose and analysis theme of the model	$W_{T01} = 0.034$	Conceptualization
Technical (T02)	Mathematical Formulation	Algorithms and governing equations used to represent the energy system	$W_{T02} = 0.037$	Conceptualization
Technical (T03)	Programming Language	Software language the model is developed in	$W_{T03} = 0.030$	Conceptualization
Technical (T04)	Analytical Approach	Computational technique used for model analysis	$W_{T04} = 0.033$	Conceptualization
Technical (T05)	Data Requirements	Types, quantities, and granularity of data needed to run the model	$W_{T05} = 0.034$	Data Collection
Technical (T06)	Geographical Boundary	Spatial areas covered by the model	$W_{T06} = 0.036$	Configuration and Calibration
Technical (T07)	Spatial Resolution	Level of detail in the model's spatial data	$W_{T07} = 0.036$	Configuration and Calibration
Technical (T08)	Temporal Resolution	Frequency at which time-dependent variables are modeled	$W_{T08} = 0.037$	Configuration and Calibration
Technical (T09)	Time Horizon	Period over which the model's projections are made	$W_{T09} = 0.033$	Configuration and Calibration
Technical (T10)	Time Step	Discrete time intervals used in calculations	$W_{T10} = 0.035$	Configuration and Calibration
Technical (T11)	Sector Coupling	Integration of different energy sectors within the model	$W_{T11} = 0.039$	Configuration and Calibration
Technical (T12)	Sustainability Metrics	Environmental, economic, and social analysis of the modeled energy system	$W_{T12} = 0.029$	Configuration and Calibration
Technical (T13)	SDGs Representation	Integration of the United Nations 17 goals, 169 targets, and 248 indicators	$W_{T13} = 0.025$	Configuration and Calibration
Technical (T14)	Technology Dynamics	Ability to account for technological changes in the model	$W_{T14} = 0.031$	Configuration and Calibration
Technical (T15)	Technology Coverage	Range of energy technologies included in the model	$W_{T15} = 0.033$	Configuration and Calibration
Technical (T16)	Commodity Coverage	Range of energy commodities included in the model	$W_{T16} = 0.032$	Configuration and Calibration
Technical (T17)	Emissions Accounting	Range of greenhouse gas emissions and air pollutants included in the model	$W_{T17} = 0.033$	Configuration and Calibration
Technical (T18)	Constraints Setting	Ability to define and apply restrictions or limits in the model	$W_{T18} = 0.030$	Configuration and Calibration
Technical (T19)	System Agility	Flexibility of the model to adapt to changing conditions over time	$W_{T19} = 0.040$	Configuration and Calibration
Technical (T20)	Uncertainty Analysis	Ability to evaluate uncertainty in inputs, parameters, or assumptions	$W_{T20} = 0.035$	Validation and Interpretation
Non-technical (N21)	Licensing and Accessibility	Model's availability and ease of access to users	$W_{N21} = 0.037$	Conceptualization
Non-technical (N22)	Model Age	How up-to-date the model's structure, assumptions, and data are	$W_{N22} = 0.022$	Conceptualization
Non-technical (N23)	Applicability	The user-base and target audience of the model	$W_{N23} = 0.030$	Conceptualization
Non-technical (N24)	Usability	Ease with which users can interact with the model	$W_{N24} = 0.032$	Conceptualization
Non-technical (N25)	Modularity and Interoperability	Model's ability to be modified or integrated with others	$W_{N25} = 0.034$	Conceptualization
Non-technical (N26)	Complexity	Level of detail and sophistication in the model's structure and processes	$W_{N26} = 0.028$	Conceptualization
Non-technical (N27)	Continuous Development	Extent to which the model is actively updated and improved over time	$W_{N27} = 0.035$	Iteration
Non-technical (N28)	Transparency	Openness of the model's design and assumptions	$W_{N28} = 0.037$	Iteration
Non-technical (N29)	Visualization	Model's ability to display results in a clear and understandable format	$W_{N29} = 0.033$	Reporting
Non-technical (N30)	Documentation	Quality of the model's instructions and explanatory materials	$W_{N30} = 0.039$	Reporting

**Each of these thirty main criteria is further divided into several supporting sub-criteria for the categorization of ESMs, which are not shown in this table due to space limitations.*

Conclusions

To conclude, this study developed a standardized framework to facilitate a systematic selection process for ESMs in prospective modeling endeavors. The framework is expected to improve consistency, reduce biases, and ensure that ESMs are chosen based on a clear set of criteria relevant to specific modeling goals, thus advancing energy system analyses and corresponding outcomes into more effective policy planning and formulation. Moving forward, the subsequent steps entail applying the developed framework following the shortlisting of multiple commonly used and broadly applicable ESMs. Data will be collected for these ESMs based on the assessment criteria provided in the framework. Multi-criteria decision-making (MCDM) will then be used to perform a comparative analysis where each ESM is evaluated against the others, and the scores for ESMs will be assigned taking into consideration the respective weights of each criterion. Finally, an uncertainty analysis will be conducted to verify the ranking of the ESMs according to the thirty identified criteria to arrive at the final selected tool(s) to use on a case study application.

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