SoftwareX 29 (2025) 101982

Contents lists available at ScienceDirect

SoftwareX

journal homepage: www.elsevier.com/locate/softx

HOPE: Holistic Optimization Program for Electricity

Shen Wang [a,b], Ziying Song [a,c], Mahdi Mehrtash [a,d,*], Benjamin F. Hobbs [a]

[a] Ralph O'Connor Sustainable Energy Institute, The Johns Hopkins University, Baltimore, MD 21218, USA
[b] Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[c] Department of Mechanical and Aerospace Engineering, University of California San Diego, San Diego, CA 92093, USA
[d] Department of Electrical and Biomedical Engineering, University of Nevada, Reno, Reno, NV 89557, USA

ARTICLE INFO

Keywords:
Power system planning
Capacity expansion planning
Production cost model
Open-source software
Power system optimization
Julia programming language

ABSTRACT

In this paper, we present a novel open-source electricity systems optimization tool, the Holistic Optimization Program for Electricity (HOPE), to assess emerging generation technology, inform policy design, and support planning. With a highly transparent, interpretable, and compact model design, HOPE easily allows user access and modification, serving its main goal to benefit users beyond engineer communities and facilitate collaboration across the science-policy boundary. By activating different modes, the current version of HOPE (v1.0) offers flexibility in serving as either a Generation and Transmission Expansion Planning tool (GTEP) or a Production Cost Modelling tool (PCM). It includes modelling features such as long-term resource investments, short-term system operations, and a detailed representation of policies across various levels of regulated institutions. This paper outlines the building blocks of the model and its software structure. Case study results from using HOPE for the state of Maryland as well as the Pennsylvania-New Jersey-Maryland (PJM) footprint are also provided.

Metadata

Nr	Code metadata description	*Please fill in this column*
C1	Current code version	V1.0
C2	Permanent link to code/ repository used for this code version	https://github.com/HOPE-Model-Project
C3	Permanent link to reproducible capsule	N/A
C4	Legal code license	MIT License (MIT)
C5	Code versioning system used	Git
C6	Software code languages, tools and services used	Julia, JuMP
C7	Compilation requirements, operating environments and dependencies	Julia packages: JuMP, DataFrame, CSV, XLSX, YAML, Clustering, Statistics (see the project's HOPE.jl file for details) Solvers: Cbc, Clp, HiGHS, SCIP, Gurobi, and CPLEX
C8	If available, link to developer documentation/manual	https://github.com/HOPE-Model-Project/dev/
C9	Support email for questions	mahdi.mehrtash@ieee.org, swang187@alumni.jh.edu

1. Motivation and significance

Power system optimization models are widely used by grid planners, scholars, and policymakers as an analytic tool to explore decision-making under the changing landscape of electricity systems and policy priorities. Since the 1950s, these models have been continuously developed to better represent the system under study [1]. In recent decades, the increasing complexity of clean power resources (e.g., variable renewable energy, storage, demand response programs) and the pressing challenge of decarbonization policy design (e.g., renewable portfolio standards, clean power requirements, cap-and-trade emission trading) have introduced new requirements for power system optimization model development beyond merely achieving a cost-effective and operable system. New modelling tools should be well designed to capture and simulate these emerging needs depending on their applications [2].

A number of past studies have focused on addressing the existing needs and gaps in the development of power system modelling tools [1, 3–8]. Recently, the development of power system optimization models has exhibited three main trends. First, there is an increasing trend towards having these tools open-source [9]. From 2016 to 2023, the number of established works on open-source energy system models grew

* Corresponding author.
E-mail address: mahdi.mehrtash@ieee.org (M. Mehrtash).

https://doi.org/10.1016/j.softx.2024.101982
Received 2 September 2024; Received in revised form 25 October 2024; Accepted 15 November 2024
Available online 21 November 2024

Table 1
Comparisons between features among several open-source power system modelling tools

Model	Capacity expansion planning	Unit commitment operation	Convertible between one/ two stage modelling**	Cross-jurisdictional policy interactions***	Temporal flexibility****	Extendable constraints by users	Modularized design of code	Programming language	Main targeted spatial level
OpenTEPES [12]*	√	√			√			Python	National/ Regional
OSeMOSYS [15]	√	√	√	√	√			Python	Global
GenX [16]	√	√			√		√	Julia	National/ Regional
EMPIRE [10]	√	√						Python	National/ Regional
LEGO [13]	√	√			√	√	√	GAMs	National/ Regional
Switch 2.0 [11]	√	√			√	√	√	Python	National/ Regional
HOPE	√	√	√	√	√	√	√	Julia	National/ Regional

Note:
* With a focus on transmission expansion planning.
** Capable of one-stage (i.e., long-term capacity planning or short-term operation) and two-stage optimizations (i.e., link the long-term and short-term optimization) upon users' choice.
*** Enable accurate representation of complicated policies interactions among different jurisdictional levels.
**** Specifically means the model being able to change temporal resolution in operational optimization, not just by selecting different planning/investment years in long-term capacity expansion optimization.

at an average annual rate of 35%[1]. This openness greatly enhances the transparency of traditional "black box" models and increases the explanation of modelling assumptions, which benefits a wider range of users and audiences. Notable examples include EMPIRE [10], Switch 2.0 [11], OpenTEPES [12], LEGO [13], and GenX [14]. The second trend is increased modelling complexity, featuring higher temporospatial resolution and advanced technology representation within a single tool [7]. For example, LEGO is designed to perform comprehensive planning for power systems interacting with other sectors. The Switch 2.0 model emphasizes detailed modelling features related to renewable energy integration. GenX focuses on large-scale and long-term capacity expansion planning, considering short-term operational details at the same time. These tools typically feature a high level of flexibility, using block-wise module design to allow users to access and combine different functionalities (e.g., linear or integer decisions, unit commitment, policy choices, etc.) based on their specific needs [11,13]. On the other hand, modelling all aspects and details of a power system in an optimization-based framework will result in an intractable model. That is why the third trend is to focus on the careful modelling of system features directly relevant to a particular application while having sufficient but less detailed fidelity for the rest of the system [6]. Our proposed model, the Holistic Optimization Program for Electricity (HOPE), inherits the main flexibility features of the existing open-source power system models mentioned above. Additionally, HOPE improves existing models in three respects: (1) model/code interpretability, expandability, and transparency, (2) policy representation, and (3) holistic assessment. Table 1 briefly presents the main features and differences between HOPE and some other open-source power system modelling tools.

(1) Model/Code interpretability: Many comprehensive and flexible modelling tools are developer-friendly but are less user-friendly due to intricate and nested designs (i.e., LEGO, GenX). However, HOPE avoids the trade-off between highly modular blocks and complex coding requirements through its design. HOPE has a clear and concise model structure with a highly consistent format that aligns with mathematical formulations, making it easy to modify and extend. Each script in HOPE serves a single purpose or functionality. For example, "GTEP.jl" includes all the sets, parameters, and constraints required for planning optimization, ensuring the code flows smoothly like a storyline. This design facilitates easy navigation between code and formulations and simplifies the interpretation of the code. The tractable formulation and coded constraint structure enhance model transparency and interpretability. Consequently, HOPE gives many benefits to users who want to understand technical details or modify the model with new features based on their purposes.

(2) Policy representation: HOPE enhances policy representativeness by accounting for multi-level or cross-level regulatory landscapes, such as the coexistence of regulations and policies across multiple jurisdictions within a given power market. Many existing models typically address policy at a single level (e.g., a zone or state) by aggregating power resource information from multiple power system utilities or balancing authorities within a jurisdictional boundary, or vice versa, GenX, for example. However, discrepancies can arise as power balancing areas may not align with institutional boundaries, necessitating crude assumptions for allocating power resources across different jurisdictions. Recent studies highlight the need for greater policy realism and improved representation of subnational policy heterogeneity in engineering-economic optimization models [17], as well as in power market designs that simulate regulatory differences across jurisdictions [18]. HOPE offers a dual-layered institutional-jurisdictional framework that bridges the gap between upper-level policy directives and localized implementation strategies, or vice versa. For example, while carbon policies may operate at the state level, power markets or balancing authorities often transcend state boundaries, making it challenging to capture cross-jurisdictional interactions. By establishing a zone-state mapping, HOPE enables policymakers to more accurately capture the heterogeneous impacts of policies and their interactions with non-government regulators or institutions (e.g., power market system operators). This approach is practically valuable for policymakers seeking models that capture relevant characteristics for answering specific policy questions. This feature along with HOPE's interpretability and user-friendliness make it the best option for policymakers, who might not be experts in power system optimization and software development, to have hands-on experience for their state-level decision-making purposes.

(3) Holistic assessment: HOPE is designed to provide holistic

[1] This is calculated by searching key words "open-source power system model (with different combinations)" on SoftwareX and then sum the number of publications that matched per year.

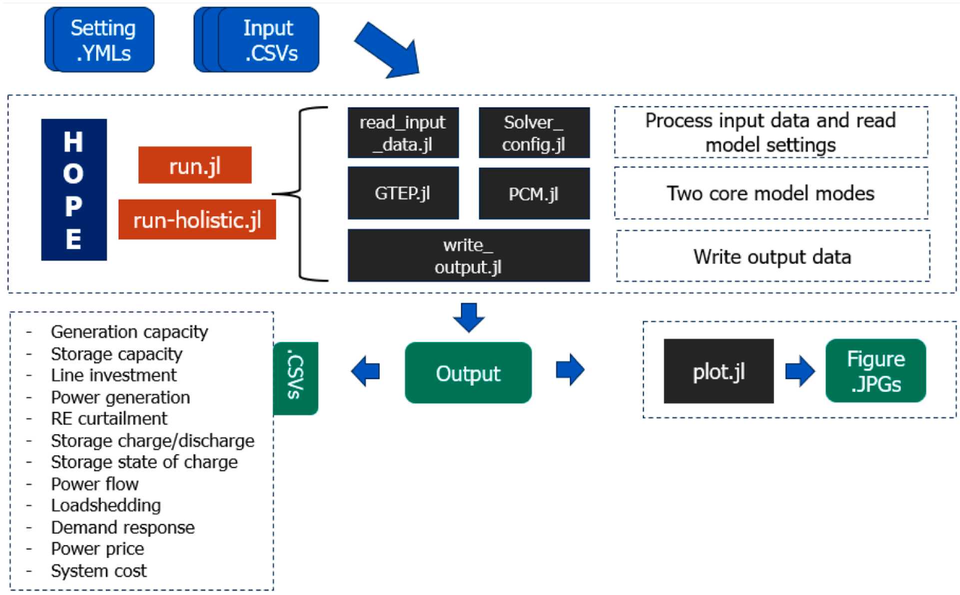


Fig. 1. Scripts flow chart of the HOPE model

simulation and analysis for planning and operating power systems under policies and regulations. The current version of HOPE includes both Generation & Transmission Expansion Planning (GTEP) and Production Cost Model (PCM) modes. "Holistic" in this context means that simulation results should be robust across different optimization modes which represents a long-term policy-driven system being operated feasibly with detailed physical constraints in the short term. For example, the planned future resource mix from the GTEP model should operate correctly in the PCM mode under reasonable assumptions. If GTEP results are infeasible or unreasonable in PCM (e.g., high value of loss-of-load when subjected to the more granular temporal or spatially resolved loads and system conditions that the PCM can represent), they can be set up together as a multi-stage model to dynamically re-solve the problem until the results are acceptable. This feature enables users to overcome computation burden when solving a larger system (e.g., national level) by setting GTEP in aggregate time blocks and reassessing operation feasibility in PCM mode with high temporal resolution. In another GTEP-PCM holistic run example, GTEP can capture long-term scenarios such as policies and economic drivers while PCM simulates operations driven by short-term uncertainty (e.g., renewable variability, prices variations, etc.) under these scenarios. In short, "holistic" in HOPE means that each part can be linked and optimized either alone or together at the user's choice to have a comprehensive understanding of the planned system. Thus, a key strength of the current HOPE and its ongoing development and improvement processes lies in their linkage between long-term and short-term dynamics through ongoing feedback and iterative improvement processes to represent policy and regulation.

The remainder of the paper is organized as follows. Section 2

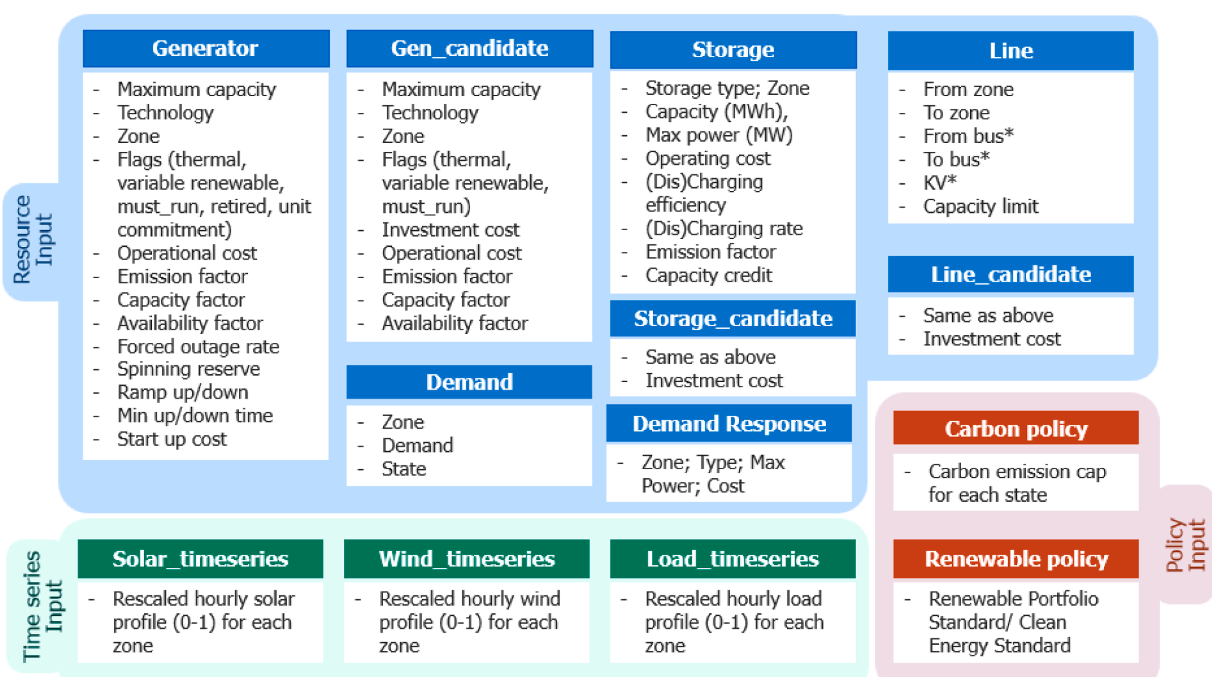


Fig. 2. Input data files of HOPE model

contains the software description, followed by illustrative examples in Section 3. Section 4 discusses HOPE's impact and future development plan.

2. Software description

2.1. Software architecture

HOPE is written in Julia language using JuMP - the mathematical optimization modelling tool embedded in Julia, and can be solved using several open-source or commercial solvers such as Cbc, Clp, HiGHS, SCIP, Gurobi, CPLEX, etc [19]. HOPE can be installed via a normal Julia project/package or download through the GitHub repository. On the HOPE GitHub main page, we provide installation instructions and the general steps for running a HOPE case study. In the "ModelCases" folder, we set up several test model examples with data and model configuration files to help users get started. The repository also contains detailed HOPE model documentation (i.e., model formulation, settings, and input data explanation) for users who are interested in modifying the model and customizing their own simulation features.

HOPE currently includes two modes of power system optimization, including GTEP and PCM. GTEP has been designed to support power resources capacity expansion planning, such as various power supply resources and transmission infrastructure, taking into account climate policies such as carbon emission limits and renewable portfolio standards (RPS). PCM focuses on the operational level of power system optimization, including unit commitment constraints and system operation at hourly time steps (could be modified to sub-hour operation based on users' needs). These two modes can be either running alone or linked together, testing operational ability after the capacity planning process.

The HOPE model consists of several code scripts in the "src" folder. Each has a different function. The "read_input_data.jl" reads and process input data from user-defined spreadsheets (i.e., .xlsx or .csv files) and converts them into a data frame format that is ready to be called by model. The "GTEP.jl" and "PCM.jl" are the main model scripts for generation and transmission expansion planning model and production cost model, respectively. They use processed data to create predefined input sets, indices, and parameters, and build up a model case including decision variables, expressions, objectives, and constraints. Next, the "run.jl" or "run_holistic.jl" file calls the relevant scripts above and solves the case using the specified solver option. The "write_output.jl" file writes the solved results into different data frames as csv files. Fig 1 below shows the flow chart of different module scripts.

Each built-in or user-defined HOPE case is a single folder that contains input data and settings. The input data should be stored in Excel workbooks either in .csv or .xlsx format. In the built-in cases, there are nine .csv input files or a .xlsx with nine sheets to provide actual data. The difference between these two types of input files is that .csv files usually consume less memory than .xlsx files. Thus, if users have a large dataset, storing in .csv format will bring down computation effort significantly. The files used for input data are briefly described in Fig 2, and more details are in the online documentation. The setting folder contains two types of scripts - the solver-specific configurations and the HOPE model configuration. We provide a basic setting for each solver configuration in the corresponding "yml" file, i.e., "cbc_settings.yml" "gurobi_settings.yml", etc. The specific functionality of the solver can be adjusted by changing parameters in these "yml" files according to the solver's documentation. The "HOPE_model_settings.yml" supports case-level HOPE model configurations. For example, the users can set using a generation cluster or not, using binary investment decision or continuous investment, using or setting representative day, using unit commitment or not, using demand response or not, setting solver types, etc. See section 2.1.2 and online documentation for more details. Detailed step-by-step instructions on running example cases are also available on GitHub home pages.

2.2. Software functionalities

HOPE provides the freedom of switching between different optimization solvers. One can choose between Cbc, Clp, CPLEX, SCIP, HIGHS, or Gurobi, which are made compatible with HOPE and can be reached by changing solver names in "HOPE_model_settings.yml" file.

HOPE is highly flexible to be used in several ways. Users can easily switch on/off some functionalities by setting binary variables in setting files or input data files based on existing model formulations. To list a few: 1) HOPE provides multiple build-in flags to activate different constraints and model different assets such as thermal generators, variable renewable sources, retirement, must-run, unit commitment, flexible demand, etc. so that users have the freedom of switching them on or off for tailored situations; 2) Nodes (referred to as "zone" in the HOPE model) point to the smallest region of the system. A node (zone) can be a state, a county, or a transmission zone of a specific regional transmission organization (RTO), based on the user's preference; 3) Flexibility in time resolution. HOPE can take full hourly data for a year or hours within predefined representative days as input through the 'representative day" flag. Nonetheless, increasing time resolution can be computationally expensive. Thus, temporal resolution should be selected with caution; 4) HOPE offers the option to establish data clustering based on statistical methods, such as averaging. This is a useful step to reduce computational burden when working with extremely large datasets. By switching between binaries in model case setting scripts, clustering can be turned on for "generation technology", upon users' choice.

In addition, HOPE has two specifically built-in modules, namely "plot" and "debug" to facilitate users' experience. The Plot module has two parts, one can plot a stacked bar chart for existing and planning capacity based on input data and GTEP modelling results, respectively; another can plot a stacked line chart for existing and planning power flows based on input data and PCM modelling results, with chart type and color arrangement adjustable by users. The Debug module offers two methods, namely the "conflict method" and the "penalty relaxation method", which can be activated using flags. These methods are designed to identify model infeasibility, enabling the detection of infeasible solutions and reporting information about violated constraints.

3. Illustrative examples

In this section, we present two case studies to exemplify HOPE's ability. The first is a **clean energy scenario for the state of Maryland** for the period of 2022 to 2035. 2035 is also the target year for the Maryland government to achieve 100% clean energy [20]. Through long-term planning, chronological daily modelling, unit commitment, operating reserves, storage, RPS, and other customizability offered by HOPE, we can provide insights on feasible and sustainable transition pathways to a 100% clean electricity sector for Maryland as desired by policymakers and other stakeholders. The second is a **business-as-usual scenario for the Pennsylvania-New Jersey-Maryland (PJM) interconnection** as of 2035. The RPS is set to be 80% in Maryland and 20% for the rest of the states based on a PJM energy transition study in 2021 [21].

These case studies use openly available data collected from PJM [22], NREL Annual Technology Baseline [23], and the US Energy Information Administration [24], with data cleaning and processing beforehand. All input data used to produce examples are distributed alongside this paper in the HOPE's GitHub repository. The general assumptions include: 1) the same economic and technical parameters are used for the same type of technology (regardless of location); 2) storage can do between day arbitrage; 3) to maintain simplicity, we ignore physical transmission features, e.g., voltage angles, reactive power, etc.; 4) a 20% total growth in electricity demand towards 2035; 5) hourly resolution (for the Maryland case) and four representative weeks (for the PJM case) are used; and 6) the capacity of multiple generators in the

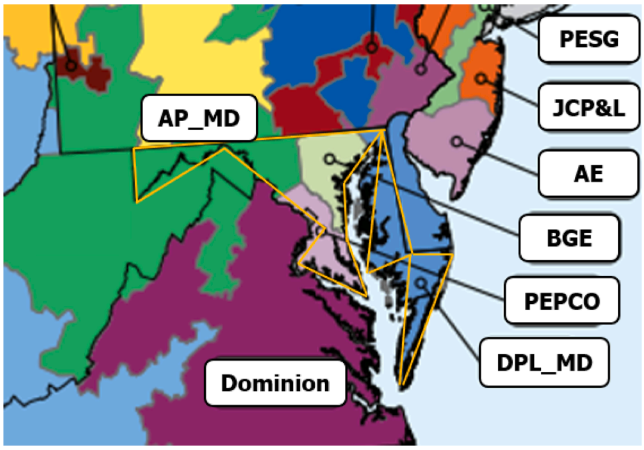


Fig. 3. Zones for Maryland case study

same technologies are aggregated to reduce computation complexity.

We split Maryland state into four PJM zones (BGE, PEPCO, DPL_MD, AP_MD) and two non-MD PJM zones (AP_non-MD, DPL_non-MD) based on our analysis of the PJM high-voltage transmission network in the mid-Atlantic region, enabling better policy interactions between the state level and the transmission zone level (Fig 3). In this way, renewable capacity deployment is better represented by accounting for operating interactions with neighboring PJM states. The case studies are solved with Gurobi® Optimizer version 11.0.1. on a server with Intel Core i7 12th Gen with 2.30 GHz and 32 GB of RAM.

From the capacity expansion and operation result of Maryland's 2035 clean scenario (shown in Figs 4 and 5), we can see that the incumbent coal and oil in the capacity mix will disappear in 2035. Solar PVs are deployed as the dominant new source in the future power system, accounting for 63% of the total installed new capacity. A large number of storage units are needed to reduce volatility brought by solar and wind and also enable certain levels of peak shaving. Gas plants can remain in the system to provide a source of flexibility to accommodate higher penetration of variable renewable energy sources after retrofitting with carbon capture and storage (CCS). Meanwhile, from the snapshot of the generation during a typical summer week in 2035, nuclear energy is envisaged as the baseload generation, and the peak load is mainly provided by solar plus storage. Also, HOPE has successfully captured the storage charging and discharging pattern – the charging action generally happens in the morning when there is plenty of solar generation while discharging is spread over different times – typically serving peak load hours) and when solar generation ramps down

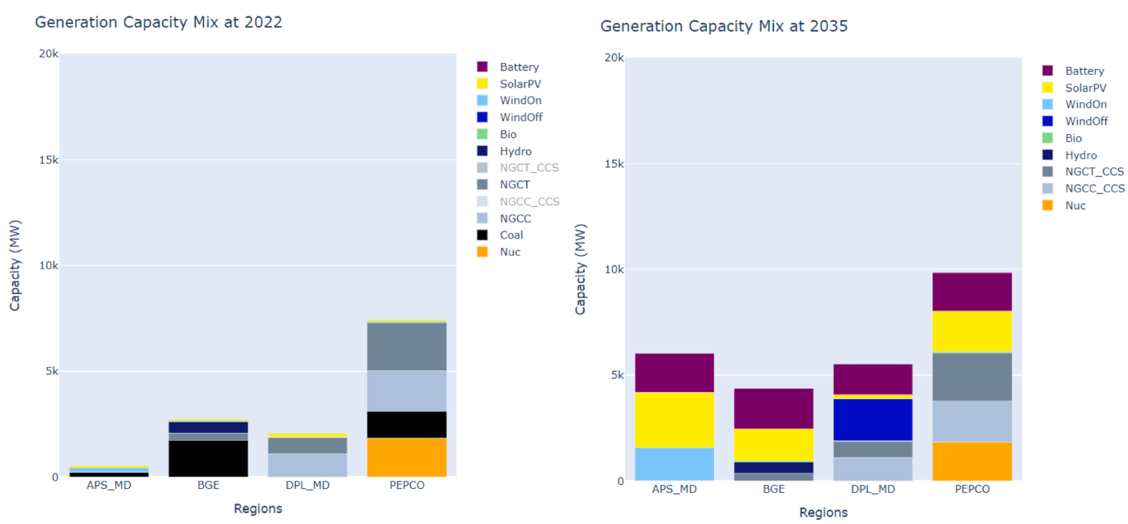


Fig. 4. Maryland case study results of capacity mix in 2022 and 2035

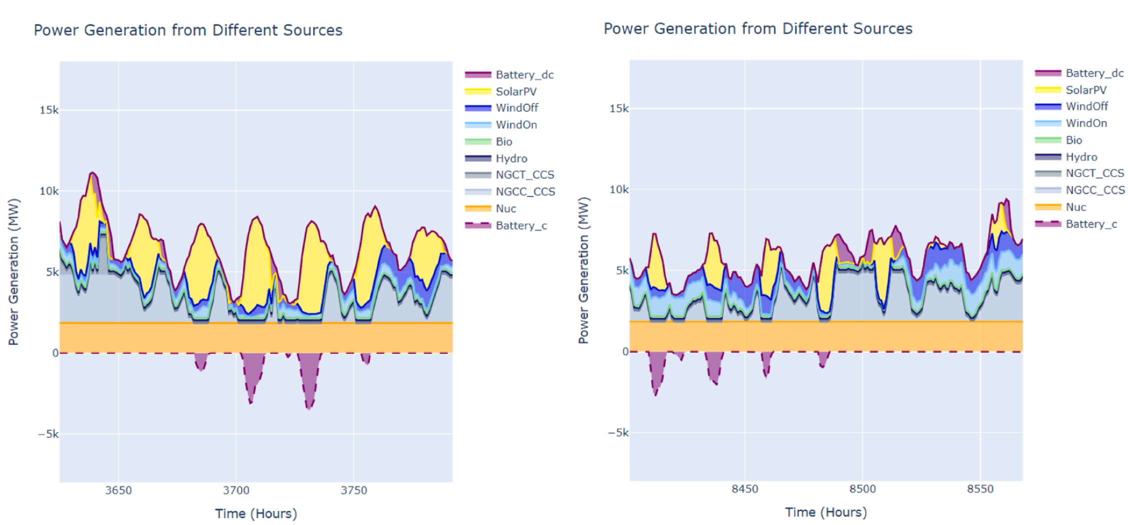
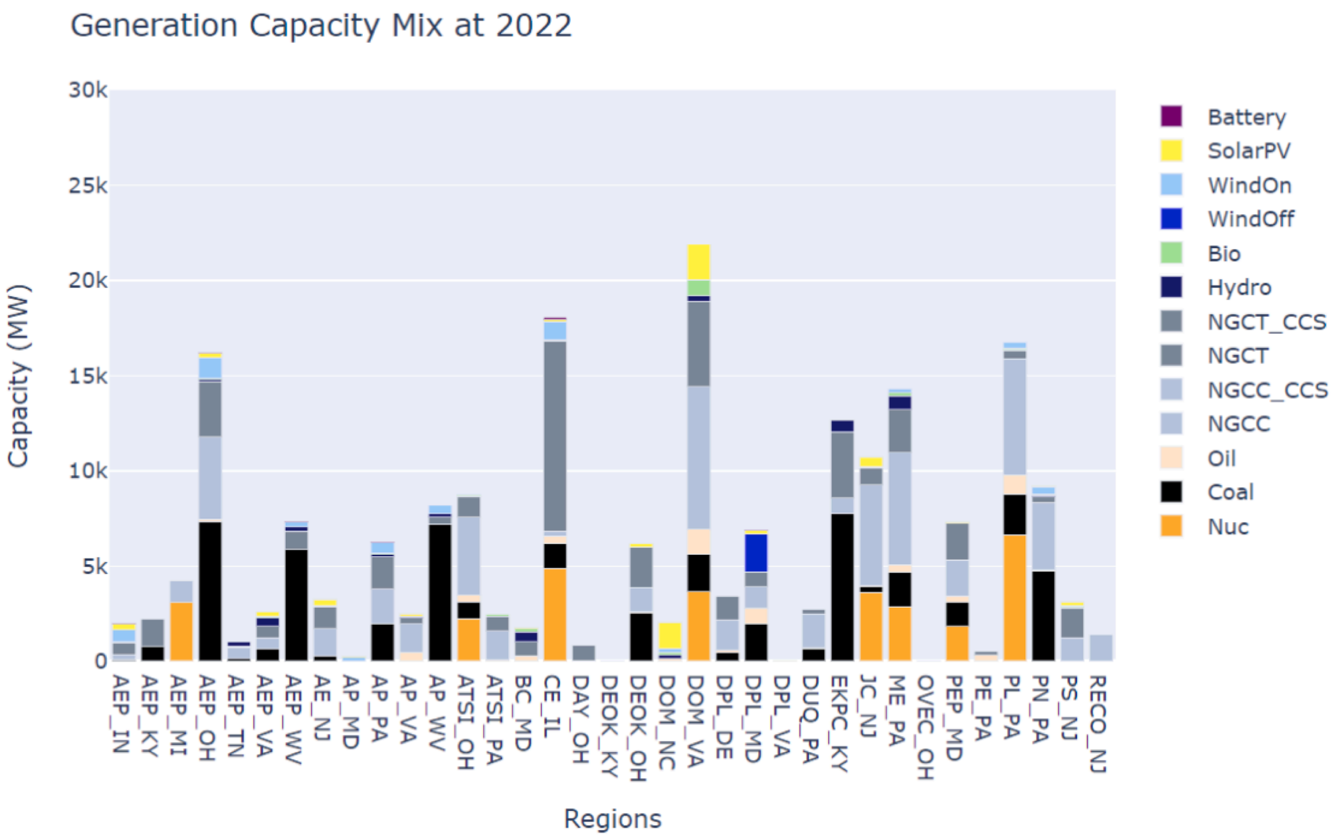


Fig. 5. Maryland case study results for generation of a typical summer (left) and winter (right) week



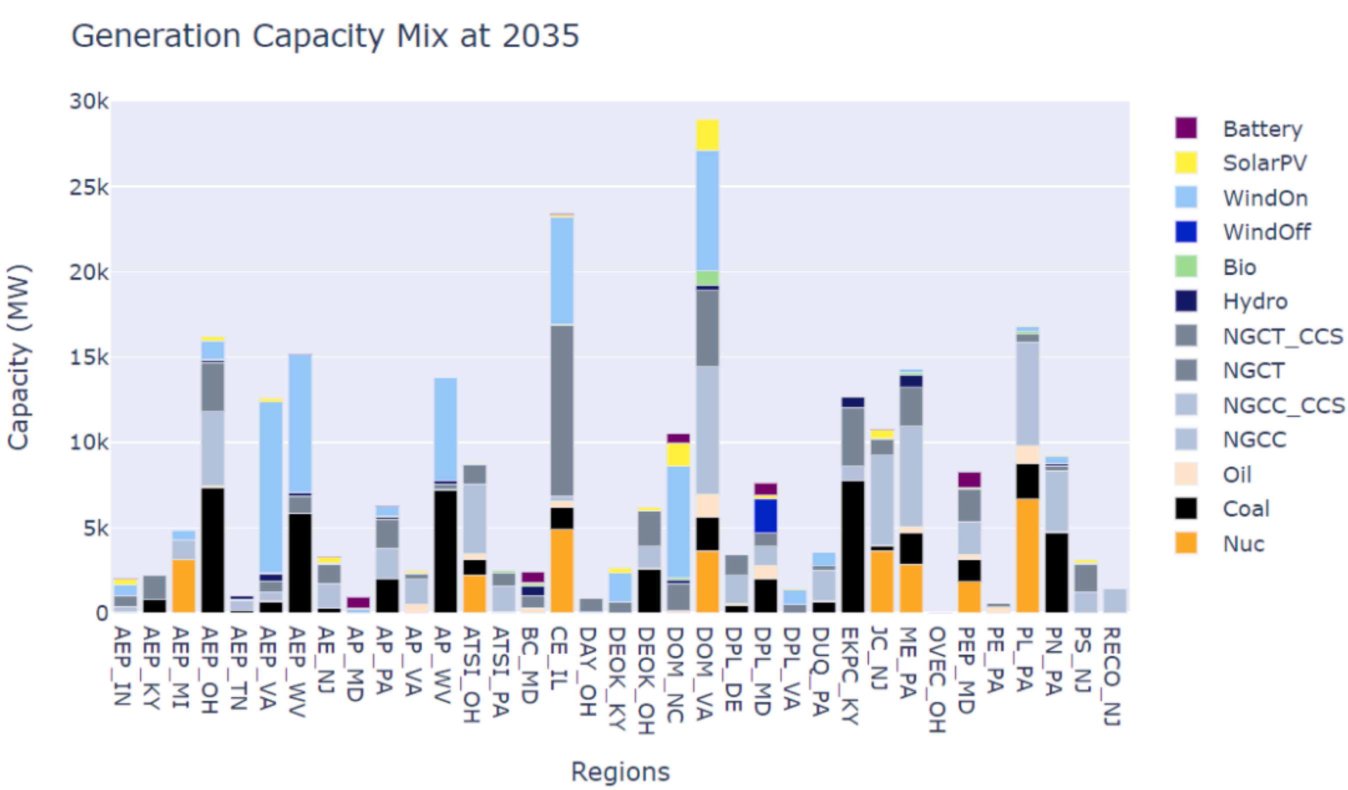


Fig. 6. PJM case study results of capacity mix in 2022 and 2035

quickly.

For the PJM study results shown in Fig. 6, it can be observed that a huge amount of onshore wind has been deployed for 2035 to serve most of the load growth (onshore wind land permit restriction not taken into consideration). Solar has minor expansion, probably due to its lower capacity factor compared to offshore wind despite its lower upfront investment cost, along with the relatively low RPS requirement (80% for Maryland and 20% for the rest of the PJM states). No coal or oil capacity is forced to close, and several CCS-installed gas plants as well as some storage units are newly built to accommodate new wind capacity.

4. Impact

HOPE is developed based on multiple previous research and modeling works. These include work on finding optimal system investments considering variable renewable energy's capacity credit [25], co-optimizing battery storage with transmission planning [26], planning power system investment in conflict-affected countries [27], as well as a new global solver for transmission expansion planning based on AC network representation [6], all of which have been developed building on classic capacity expansion planning model formulations [24]. With a newer lens added to previous work, HOPE aims to answer questions including but not limited to:

1. How much and in which technology states and independent system operators (e.g., PJM) should invest to reach their decarbonization targets?
2. What are the tradeoffs between implementing different decarbonization policies (carbon tax vs. cap-and-trade policy)?
3. What would be the hourly operation of the expanded system with respect to the carbon policies imposed?

HOPE opens avenues for exploring important energy transition questions for relevant stakeholders, especially policymakers. They can investigate policy implications of different transition pathways, shedding light on the effectiveness of various policy measures in achieving clean energy and decarbonization goals, such as fossil fuel retirement, CCS and storage deployment, potential impacts of data centers, nuclear phaseout, etc. Moreover, HOPE allows exploring the interplay between policy interventions, technological transitions, and their broader implications for energy sustainability. Notably, HOPE has been already adopted by state entities such as the Maryland Department of the Environment, demonstrating its suitability for a diverse range of users beyond the traditional engineering and academic community.

In future work, we plan to extend the modes of HOPE by adding an optimal power flow model (OPF) and a bilevel-market model for day-ahead and real-time electricity markets (DART). This will allow a holistic analysis of a power system from long-term planning to operation as well as a market perspective.

CRediT authorship contribution statement

Shen Wang: Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Conceptualization. **Ziying Song:** Writing – original draft, Methodology, Data curation. **Mahdi Mehrtash:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Benjamin F. Hobbs:** Conceptualization, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors gratefully acknowledge the State of Maryland (Maryland Environmental Service) for its financial support of the project, and the Maryland Department of the Environment and its stakeholders for valuable suggestions for the enhancement and usability of HOPE-MD. We also thank our colleagues at Johns Hopkins University for their collaboration and suggestions. The authors are solely responsible for any opinions and errors.

Appendix A. Supplementary material

Online link: https://github.com/HOPE-Model-Project

Data availability

No data was used for the research described in the article.

References

[1] Foley AM, Ó Gallachóir BP, Hur J, Baldick R, McKeogh EJ. A strategic review of electricity systems models. Energy 2010;35(12):4522–30. https://doi.org/10.1016/j.energy.2010.03.057.
[2] Lopion P, Markewitz P, Robinius M, Stolten D. A review of current challenges and trends in energy systems modeling. Renew Sustain Ener Rev 2018;96:156–66. https://doi.org/10.1016/j.rser.2018.07.045.
[3] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Ener Rev 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.
[4] Oberle S, Elsland R. Are open access models able to assess today's energy scenarios? Ener Strat Rev 2019;26:100396. https://doi.org/10.1016/j.esr.2019.100396.
[5] Chang M, et al. Trends in tools and approaches for modelling the energy transition. Appl Ener 2021;290:116731. https://doi.org/10.1016/j.apenergy.2021.116731.
[6] Mehrtash M, Cao Y. A new global solver for transmission expansion planning with AC network model. IEEE Transac Pow Sys 2022;37(1):282–93. https://doi.org/10.1109/TPWRS.2021.3086085. Jan.
[7] Mehrtash Mahdi, Hobbs Benjamin F, Mahroo Reza. Necessity of joint resource and transmission expansion planning in presence of system and policy uncertainties. IEEE Conf Pub 2024. Accessed: Jun. 13[Online]. Available, https://ieeexplore.ieee.org/abstract/document/10078637.
[8] Hoffmann Maximilian, et al. A review of mixed-integer linear formulations for framework-based energy system models. Adv Appl Energ 2024:100190.
[9] Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I. The importance of open data and software: is energy research lagging behind? Ener Pol 2017;101:211–5. https://doi.org/10.1016/j.enpol.2016.11.046.
[10] Backe S, Skar C, del Granado PC, Turgut O, Tomasgard A. EMPIRE: an open-source model based on multi-horizon programming for energy transition analyses. SoftwareX 2022;17:100877. https://doi.org/10.1016/j.softx.2021.100877.
[11] Johnston J, Henriquez-Auba R, Maluenda B, Fripp M. Switch 2.0: A modern platform for planning high-renewable power systems. SoftwareX 2019;10:100251. https://doi.org/10.1016/j.softx.2019.100251.
[12] Ramos A, Alvarez EF, Lumbreras S. OpenTEPES: open-source transmission and generation expansion planning. SoftwareX 2022;18:101070. https://doi.org/10.1016/j.softx.2022.101070.
[13] Wogrin S, Tejada-Arango DA, Gaugl R, Klatzer T, Bachhiesl U. LEGO: the open-source low-carbon expansion generation optimization model. SoftwareX 2022;19:101141. https://doi.org/10.1016/j.softx.2022.101141.
[14] J. D. Jenkins and N. A. Sepulveda, "Enhanced decision support for a changing electricity landscape: the genx configurable electricity resource capacity expansion model," MIT Ener Init, Working Paper, 2017. Accessed: Apr. 09, 2024. [Online]. Available: https://dspace.mit.edu/handle/1721.1/130589.
[15] Barnes T, Shivakumar A, Brinkerink M, Niet T. OSeMOSYS Global, an open-source, open data global electricity system model generator. Sci Data 2022;9(1):623. https://doi.org/10.1038/s41597-022-01737-0.
[16] MIT Energy Initiative and Princeton University ZERO lab, "GenX: a configurable power system capacity expansion model for studying low-carbon energy futures n. d." [Online]. Available: https://github.com/GenXProject/GenX.
[17] Davidson MR, Filatova T, Peng W, Verbeek L, Kucuksayacigil F. Simulating institutional heterogeneity in sustainability science. Proc Nat Acad Sci 2024;121(8):e2215674121. https://doi.org/10.1073/pnas.2215674121.
[18] Levin Todd, Frew Bethany, Moreira Alexandre, Ela Erik, Mehrtash Mahdi, Silverman Abe, Botterud Audun, Zhou Zhi, Guo Nongchao, Heleno Miguel, Schoppe Ryan, Hytowitz Robin, Hobbs Benjamin. Research priorities and opportunities in U.S. wholesale electricity markets: market design under deep decarbonization. Argonne Nat Lab 2024. Accessed: Oct. 23, 2024. [Online]. Available, https://www.anl.gov/argonne-scientific-publications/pub/188537.
[19] "JuMP," Julia Documentation. [Online]. Available: https://jump.dev/.
[20] C. B. Staff, "Gov. Moore announces Maryland's commitment 100% clean energy by 2035 - CBS Baltimore." Accessed: May 10, 2024. [Online]. Available: https://www.

cbsnews.com/baltimore/news/governor-moore-announces-maryland-commitment-100-clean-energy-by-2035/.
[21] "PJM - Ensuring a Reliable Energy Transition." Accessed: Jun. 11, 2024. [Online]. Available: https://www2.pjm.com/about-pjm/ensuring-a-reliable-energy-transition.
[22] "Data Miner 2," PJM. [Online]. Available: https://dataminer2.pjm.com/list.
[23] "2021 Electricity ATB Technologies and Data Overview," NREL. Accessed: Jun. 03, 2024. [Online]. Available: https://atb.nrel.gov/electricity/2021/index.
[24] EIA, "Form EIA-860 detailed data with previous form data." Accessed: Jun. 03, 2024. [Online]. Available: https://www.eia.gov/electricity/data/eia860/.
[25] Wang S, Zheng N, Bothwell CD, Xu Q, Kasina S, Hobbs BF. Crediting variable renewable energy and energy storage in capacity markets: effects of unit commitment and storage operation. IEEE Transac Pow Sys 2022;37(1):617–28. https://doi.org/10.1109/TPWRS.2021.3094408. Jan.
[26] Xu Q, Hobbs BF. Transmission planning and co-optimization with market-based generation and storage investment. In: Hesamzadeh MR, Rosellón J, Vogelsang I, editors. Transmission Network Investment in Liberalized Power Markets. Cham: Springer International Publishing; 2020. p. 201–36. https://doi.org/10.1007/978-3-030-47929-9_7.
[27] Spyrou E, Hobbs BF, Bazilian MD, Chattopadhyay D. Planning power systems in fragile and conflict-affected states. Nat Ener 2019;4(4):300–10. https://doi.org/10.1038/s41560-019-0346-x.