





EnergyModelsX: Flexible Energy Systems Modelling with Multiple Dispatch

Lars Hellemo ^{1*}, Espen Flo Bødal ^{2*}, Sigmund Eggen Holm ^{2*}, Dimitri Pinel ^{2*}, and Julian Straus ^{2*}

1 SINTEF Industry, Postboks 4760 Torgarden, 7465 Trondheim 2 SINTEF Energy Research, Postboks 4761 Torgarden, 7465 Trondheim  Corresponding author * These authors contributed equally.

DOI: [10.21105/joss.06619](https://doi.org/10.21105/joss.06619)

Software

- [Review](#) 
- [Repository](#) 
- [Archive](#) 

Editor: [Oskar Laverny](#) 

Reviewers:

- [@odow](#)
- [@joshuaeh](#)

Submitted: 08 March 2024

Published: 13 May 2024

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

Summary

[EnergyModelsX](#) is a multi-nodal energy system modelling framework written in Julia ([Bezanson et al., 2017](#)), based on the mathematical programming DSL JuMP ([Lubin et al., 2023](#)). The framework is designed to be flexible and easy to extend, for instance all resources, both energy carriers and materials, may be defined by the user. Furthermore, [EnergyModelsX](#) follows a modular design to facilitate extensions through additional packages. [EnergyModelsX](#) was developed at the Norwegian research organization [SINTEF](#) at the institutes SINTEF Energi and SINTEF Industri. The framework consists of the package [EnergyModelsBase](#) and currently provides the following extensions: [EnergyModelsGeography](#), [EnergyModelsInvestments](#) and [EnergyModelsRenewableProducers](#).

See Bødal et al. ([2024](#)) for an example application of [EnergyModelsX](#).

Statement of need

The increasing share of renewable energy generation and importance of sector coupling increases the complexity of energy systems, and makes the modelling of these systems more challenging. To meet the demand of energy modelers, energy system models need ever increasing flexibility to analyse the energy systems of tomorrow ([Fodstad et al., 2022](#)). While large scale models like TIMES ([Loulou et al., 2016](#)) and GENeSYS-MOD ([Löffler et al., 2017](#)) are important for modelling large energy systems, they lack the potential for simple modifications in technology descriptions as well as simple incorporation of region specific constraints. [SpineOpt](#) ([Ihlemann et al., 2022](#)) offers the user with the flexibility, but the monolithic approach of including all functionality in a single package reduces the understandability of the code. [GenX](#) ([Jenkins et al., 2024](#)) and [Tulipa Energy Model](#) ([Tejada-Arango et al., 2024](#)) are other recent energy system models developed in Julia with similar goals to [EnergyModelsX](#), but with less focus on extensibility and alternative technology formulations.

[EnergyModelsX](#) is a modular energy-system modelling framework designed to give modelers a high level of flexibility. The time resolution is decoupled from the technology descriptions by the application of [TimeStruct](#) ([Flatberg & Hellemo, 2024](#)), facilitating the support of a wide range of time structures with different temporal resolution and to support operational uncertainty. The system is designed from the ground up to support multiple energy carriers, and the modeler may define resources, including energy carriers, materials and emissions freely. The base model is designed to allow extensions with extra functionality such as support for different spatial resolution or more detailed technology description, making the framework well suited to address the needs of modelling integrated energy systems with sector coupling.

State-of-the art modelling frameworks have several limitations; they are often built on proprietary

algebraic modelling languages with parameter-driven models and often start from a single energy-carrier. [EnergyModelsX](#) addresses these shortcomings by using the modern modelling framework JuMP with excellent performance characteristics. Modularity is achieved through Julia's multiple dispatch functionality, allowing extensions to build on the base package. The results can be made fully reproducible by using an open modelling language and the Julia package manager for simple reproducibility of analyses.

With a fast and flexible system, users and developers may iterate rapidly, develop new or modify existing functionalities to adjust analyses to their needs and run multiple sensitivity analyses with ease.

Released packages of EnergyModelsX

As part of the initial release of [EnergyModelsX](#), the following packages and extensions are available:

EnergyModelsBase

[EnergyModelsBase](#) is the base model, providing an optimal dispatch model for operational analyses of local systems. Reference (linear) implementations are available for a set of different generic node types, including Source (only output), NetworkNode (input and output) and Sink (only input), as well as Availability nodes to serve as a connector, and Storage. EnergyModelsBase is designed to be extendable without changes to the core structure. It provides abstract types that may be extended by additional packages for more specific nodes such that more detailed technology modelling can be applied easily. This allows keeping the size of EnergyModelsBase to a minimum, reducing both the difficulty of understanding the modelling approach and the compilation time.

EnergyModelsGeography

[EnergyModelsGeography](#) extends EnergyModelsBase with modelling of geographical regions with transmission capacity between regions. Different modes of transmission are provided, allowing to model e.g. power transmission lines and pipelines. EnergyModelsGeography follows the same philosophy as EnergyModelsBase. Hence, users can easily develop new descriptions of transmission modes or special restrictions on regions.

EnergyModelsInvestments

To support capacity expansion models, [EnergyModelsInvestments](#) allows adding investment decisions to add or increase installed capacity for nodes. The investments can be modelled using a variety of investment modes, including discrete, continuous or semi-continuous. The modeler has full flexibility and may combine available investment modes as best fits the problem at hand, while EnergyModelsInvestments will make sure to only add the needed (binary) variables and constraints for each node or link.

EnergyModelsRenewableProduction

[EnergyModelsRenewableProducers](#) facilitates the modelling of renewable energy generation, both from non-dispatchable technologies such as wind power and PV and for hydropower with (pumped) storage. It also serves as an example for introducing new technology descriptions to EnergyModelsX and how to reuse constraints of the reference nodes.

Example application

To illustrate the usage of EnergyModelsX, consider the example of developing cost-effective hydrogen infrastructure for the North Sea Region. The example shows multiple regions with different technologies and different investment options available, including capacities for pipelines and production nodes. Pipeline costs take economies of scale into account, and the figure shows the pipeline capacities suggested by EnergyModelsX after solving with a standard MILP solver, given a set of costs and prices. See also Bødal et al. (2024) for a similar example.

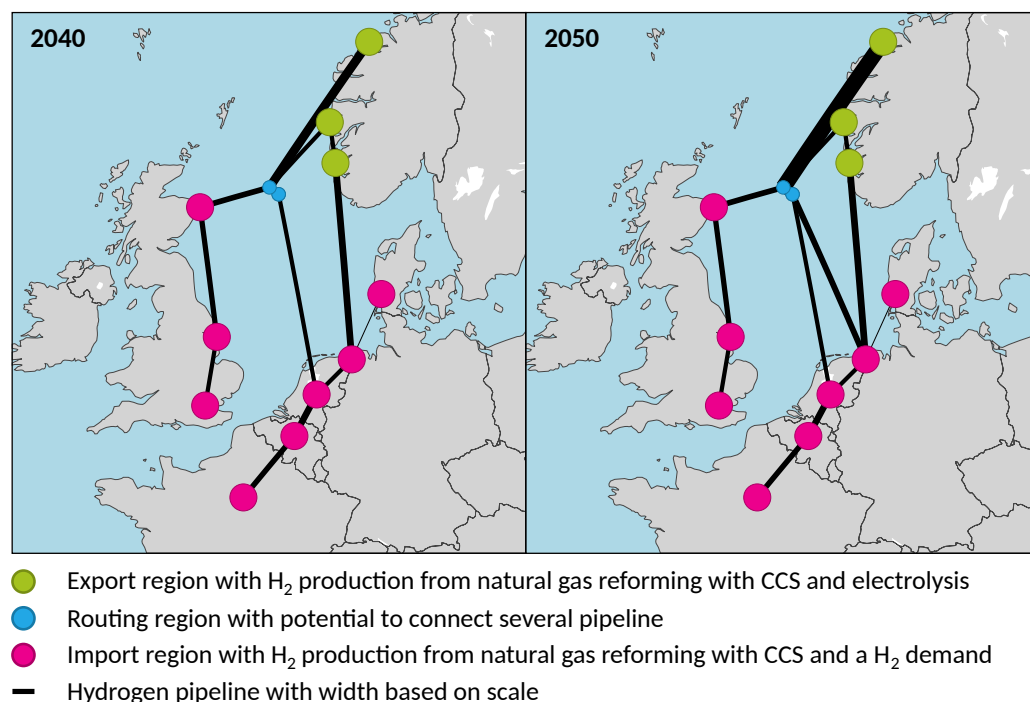


Figure 1: Example application: hydrogen infrastructure development in the North Sea region

Acknowledgements

The development of EnergyModelsX was funded by the Norwegian Research Council in the project [Clean Export](#), project number [308811](#). The authors gratefully acknowledge the financial support from the user partners: Å Energi, Air Liquide, Equinor Energy, Gassco, and Total OneTech.

References

- Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM Review*, 59(1), 65–98. <https://doi.org/10.1137/141000671>
- Bødal, E. F., Holm, S. E., Subramanian, A., Durakovic, G., Pinel, D., Hellemo, L., Ortiz, M. M., Knudsen, B. R., & Straus, J. (2024). Hydrogen for harvesting the potential of offshore wind: A north sea case study. *Applied Energy*, 357, 122484. <https://doi.org/10.1016/j.apenergy.2023.122484>
- Flatberg, T., & Hellemo, L. (2024). *TimeStruct.jl: Flexible time structures in optimization modelling*. Zenodo. <https://doi.org/10.5281/zenodo.10511399>

- Fodstad, M., Granado, P. C. del, Hellemo, L., Knudsen, B. R., Pisciella, P., Silvast, A., Bordin, C., Schmidt, S., & Straus, J. (2022). Next frontiers in energy system modelling: A review on challenges and the state of the art. *Renewable and Sustainable Energy Reviews*, 160, 112246. <https://doi.org/10.1016/j.rser.2022.112246>
- Ihlemann, M., Kouveliotis-Lysikatos, I., Huang, J., Dillon, J., O'Dwyer, C., Rasku, T., Marin, M., Poncelet, K., & Kiviluoma, J. (2022). SpineOpt: A flexible open-source energy system modelling framework. *Energy Strategy Reviews*, 43, 100902. <https://doi.org/10.1016/j.esr.2022.100902>
- Jenkins, J., Sepulveda, N., Mallapragada, D., Patankar, N., Schwartz, A., Schwartz, J., Chakrabarti, S., Xu, Q., Morris, J., & Sepulveda, N. (2024). *GenX*. Zenodo. <https://doi.org/10.5281/zenodo.10846069>
- Löffler, K., Hainsch, K., Burandt, T., Oei, P.-Y., Kemfert, C., & Von Hirschhausen, C. (2017). Designing a model for the global energy system—GENeSYS-MOD: An application of the open-source energy modeling system (OSeMOSYS). *Energies*, 10(10). <https://doi.org/10.3390/en10101468>
- Loulou, R., Goldstein, G., Kanudia, A., Lettila, A., & Remme, U. (2016). *Documentation for the TIMES model*. IEA Energy Technology Systems Analysis Programme.
- Lubin, M., Dowson, O., Dias Garcia, J., Huchette, J., Legat, B., & Vielma, J. P. (2023). JuMP 1.0: Recent improvements to a modeling language for mathematical optimization. *Mathematical Programming Computation*. <https://doi.org/10.1007/s12532-023-00239-3>
- Tejada-Arango, D., Morales-España, G., Clisby, L., Wang, N., Soares Siqueira, A., Ali, S., Soucasse, L., & Neustroev, G. (2024). *Tulipa energy model*. Zenodo. <https://doi.org/10.5281/zenodo.8363262>