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# EnergyModelsX: Flexible Energy Systems Modelling with Multiple Dispatch

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## 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 extentions 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.

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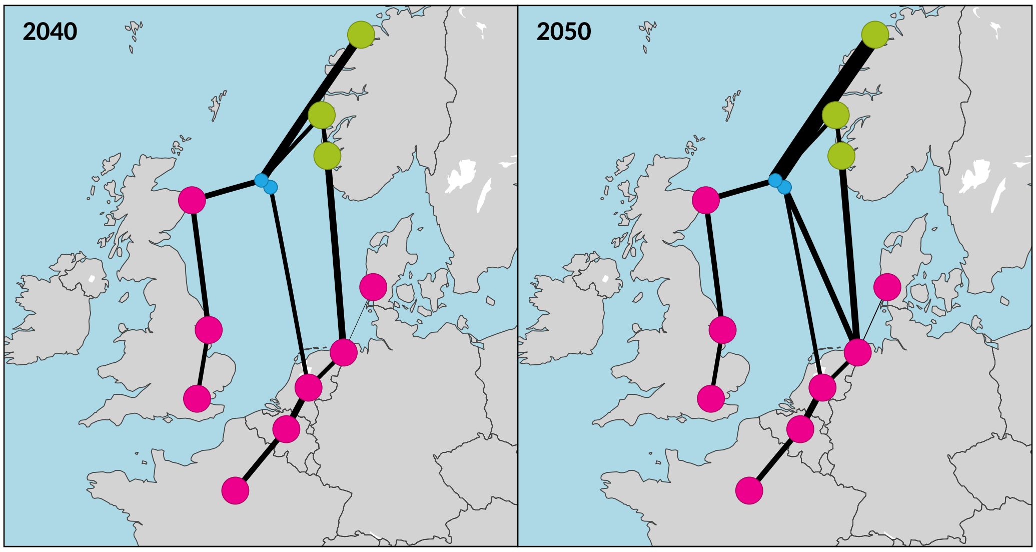
## Example application

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.




Export region with $H_2$ production from natural gas reforming with CCS and electrolysis
Routing region with potential to connect several pipeline
Import region with $H_2$ production from natural gas reforming with CCS and a $H_2$ demand
Hydrogen pipeline with width based on scale

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

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## 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