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AdOpT-NET0: A technology-focused Python package for the optimization of multi-energy systems

Jan F. Wiegner [1¶], **Julia L. Tiggeloven** [1], **Luca Bertoni** [1], **Inge M. Ossentjuk** [1], **and Matteo Gazzani** [1¶]

1 Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, The Netherlands ¶ Corresponding author

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Summary

AdOpT-NET0 (Advanced Optimization Tool for Networks and Energy Technologies) is a software designed to optimize multi-energy systems via linear or mixed-integer linear programming. Energy system optimization models like AdOpT-NET0 are crucial in shaping the energy and material transition to a net-zero emission future. This transition involves various challenges such as the integration of renewable energy resources, the selection of optimal decarbonization technologies and overarching strategies, and the expansion or rollout of new networks (electricity, hydrogen, CO2). At the same time, the interplay of traditionally separated sectors (e.g., the residential, industrial, and power sectors) becomes increasingly important. The resulting systems are inherently complex and at times non-intuitive; not surprisingly, models to simulate and optimize such complex systems are of paramount importance for a successful transition to a net-0 society.

AdOpT-NET0 is a comprehensive tool to model and optimize a wide range of multi-energy systems from individual technologies to industrial clusters, regions, or multiple countries. In multi-energy systems, multiple energy and material carriers, conversion and storage technologies, as well as means of transport can interact. These systems are highly complex but also offer synergies to reduce costs and environmental impacts (Mancarella, 2014). Table 1 provides an overview of the covered dimensions of AdOpT-NET0, while Figures 1 and 2 show two examples of energy systems that can be modeled with the tool.

Table 1: Features of AdOpT-NET0. The feature list is based on the comprehensive review paper by Hoffmann et al. (2024).

Feature	AdOpT-NET0
Model Dimensions	
Commodities	Energy and/or material commodities possible
Space	Single node or multi-node systems with network constraints
Time	By default, hourly resolution (other resolutions possible)
Stochastic scenarios	Deterministic, Monte Carlo sampling possible
Transformation pathways	Perfect foresight, rolling horizon (planned for v1.0, not implemented yet)
Components	Modelling of sources/sinks, converters, electricity and material storage, and networks possible. Linear or mixed-integer-linear
Component Extensions	
Non-linear capacity expenditures	Piece-wise investment cost function possible
Technology dynamics	Constraining ramping, minimum part-load, minimum up-/down-time, maximum number of start-ups, slow start-ups/shut-downs possible

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Feature	AdOpT-NET0
Price elasticity of demand	Not implemented
Demand response	Possible with defining a storage component
Converter performance	Linear, piece-wise linear, technology-specific
Storage performance	Linear, piece-wise linear, technology-specific
Network performance	Linear or MILP, compression energy consumption for gas networks possible
Boundary conditions	
Technology potentials	Constraining maximum size of a technology possible
Regulations	Not implemented
System security and resource adequacy	Not implemented
Multi-criteria objectives	
Pareto fronts	ε-constraint method
Complexity handling	
Spatial aggregation	Not implemented
Technology aggregation	Not implemented
Temporal aggregation	Typical periods via k-means clustering, hierarchical time averaging
Investment paths	One-time investment
Model Implementation	
Language	Python
Translator	Pyomo
Solver	Multiple (solvers compatible with Pyomo)

The standard formulation of the model framework is a mixed integer linear program (MILP). Its implementation supports a wide range of spatial/temporal resolutions and technological details. AdOpT-NET0 can optimize both system design and technology operation variables, enabling the optimization of existing energy systems with expansions or additions (brownfield) and new systems without the constraints of existing installations (greenfield). A key feature of AdOpT-NET0 is its high level of technological detail, allowing for a comprehensive representation of individual technologies and their operational constraints. This detailed representation supports the exploration of technology integration into energy systems, enabling informed decision-making without limiting the scope of the analysis. Furthermore, several complexity reduction algorithms can be adopted to address infeasible computation times, including the use of design days for representing systems with seasonal storage (Gabrielli et al., 2018) and a time-hierarchical solution method for systems with a high penetration of renewables (Weimann & Gazzani, 2022).

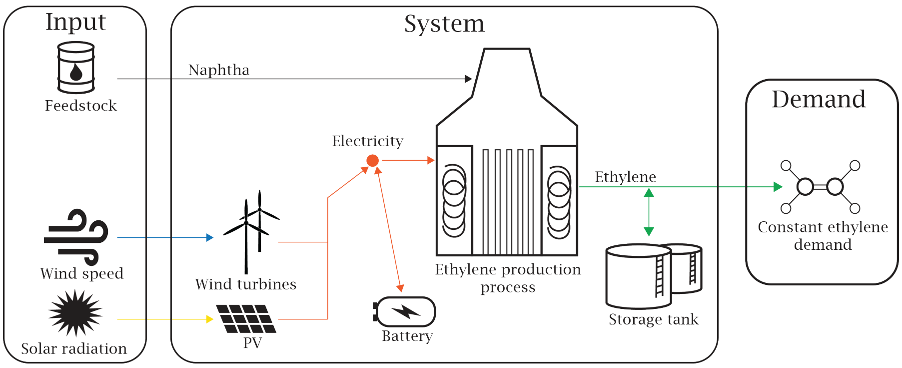

Figure 1: A possible application of AdOpT-NET0 with a single node studying ethylene production with an electric cracker relying on variable renewable energy sources (from Tiggeloven et al., 2023)

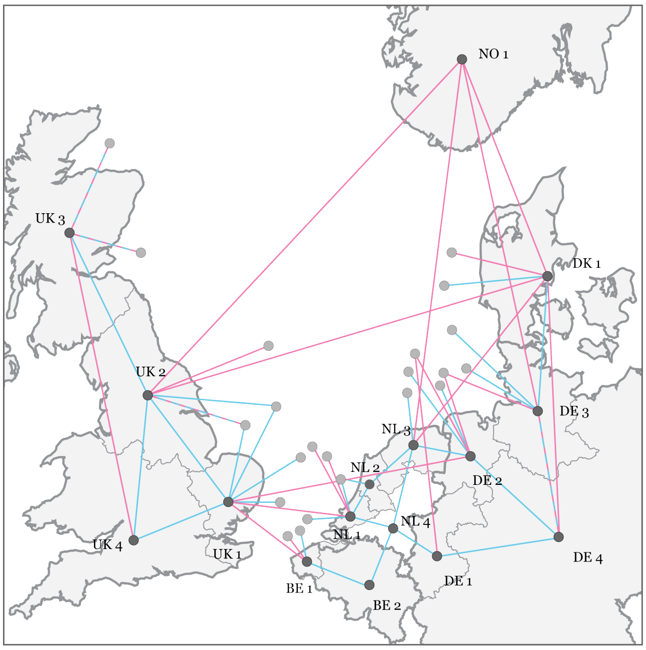

Figure 2: A possible application of AdOpT-NET0 with multiple nodes and networks studying the integration of large-scale offshore wind in the North Sea region (adapted from Wiegner et al., forthcoming)

The tool was developed to assist researchers and students interested in energy system modeling. It combines 5+ years of research and is inspired by a closed-source MATLAB version of the model. It also relies on open-source packages, mainly Pyomo, pvlib, and tsam (Anderson et al., 2023; Bynum et al., 2021; Hoffmann et al., 2022). Multiple detailed technology models, time aggregation methods, solving heuristics, and general improvements were added to form the present Python package that is further developed. AdOpT-NET0 also comes with a web-based visualization platform to provide a quick yet deep understanding of the model results to make informed decisions to advance towards a net-zero future.

Statement of need

Traditionally, models in the energy sector fall into two separate categories: (1) highly complex non-linear process or power system models with limited consideration of inter-temporal dynamics, and (2) low complexity, mostly linear, energy system models with simplified technology performances. AdOpT-NET0 bridges this methodological divide by providing a robust framework capable of modeling the complex behavior of energy and industrial technologies embedded within broader energy systems. As such, AdOpT-NET0 may be useful to both researchers tackling policy-related questions on national or international energy systems and to researchers aiming at understanding how detailed process models interact with an ever-complex energy system.

The dual capability of AdOpT-NET0 enables both the detailed representation of technology-specific behaviors and the spatial and temporal dynamics of (large-scale) energy systems, offering additional functionalities over existing models (Hoffmann et al., 2024). As such, AdOpT-NET0 includes advanced, scientifically validated technology models that are based on detailed, non-linear process models. These models capture a range of relevant energy and industrial processes, including direct air capture and carbon capture systems (Weimann et al., 2023; Wiegner et al., 2022), heat pumps (Ruhnau et al., 2019; Xu et al., 2022), gas turbine models across varied capacities (Weimann et al., 2019), underground hydrogen storage, (Gabrielli et al., 2020) and electric naphtha cracking (Tiggeloven et al., 2023). The model has been used in two forthcoming papers to model energy system integration pathways in the North Sea region (Wiegner et al., forthcoming) and to optimize emission reduction in an ammonia-ethylene chemical cluster (Tiggeloven et al., 2025). Additionally, it includes the possibility to model operational constraints of conversion technologies such as ramping rates, minimum uptime, minimum downtime, the maximum number of start-ups, or standby power (Morales-España et al., 2017).

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