The Techno-economic Transformation towards a Renewable Energy System

Developing and Applying Bottom-up Planning Models

vorgelegt von
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The Techno-economic Transformation towards a Renewable Energy System – Developing and Applying Bottom-up Planning Models

Scenarios are key tools for shaping the future of the energy system and rely on technically detailed bottom-up planning models for quantitative insights. As a result, successful transformation towards a renewable energy system implies that bottom-up planning models can adequately describe an energy system characterized by fluctuating renewables, energy storage and high levels of sector integration. Against this background, the dissertation advances methods for bottom-up planning and applies these methods to analyze scenarios of renewable energy systems. The dissertation is comprised of an original introduction in the first chapter and four subsequent chapters, each corresponding to a self-contained research paper.

The **first introductory chapter** transfers concepts from economic sociology to reflect on the social role of energy scenarios and derive implications for bottom-up planning models. Motivating the topic of the dissertation, these implications advocate for models that are open and transparent, seek to minimize bias, have relevance for public policy, and avoid needless complexity.

The **second chapter** evaluates if time-series reduction is adequate to use for bottom-up planning models of renewable energy systems. Due to their extensive temporal, spatial, and sectoral scope, macro-energy models commonly use a reduced time-series that is ought to preserve all key characteristics of the original time-series, but contains fewer elements, aiming for a favorable trade-off between complexity and accuracy.

The characteristics of energy systems with high shares of renewables put the use of reduced time-series into question. Unlike thermal generation, supply from wind and solar fluctuates and depends on energy storage to match generation with demand. If reduced time-series cannot adequately capture fluctuations and storage requirements, computed scenarios will either be sub-optimal or cannot fully satisfy demand.

For the analysis, the chapter combines different methods for deriving reduced time-series and for implementing them into bottom-up models. To evaluate different combinations of methods, a stylized bottom-up planning model is first solved with a reduced time-series and then run again with a full resolution, but capacities fixed to the values computed previously. Afterwards adequacy of the reduced time-series is measured based on the amount of lost load in the second step.

The results show that time-series reduction should be applied with caution when modeling renewable energy systems, because intermittency of renewables and dependency on seasonal storage adversely affect its accuracy. Depending on how reduced time-series are implemented, results are either biased towards short-term or long-term storage. The bias towards short-term storage causes considerable loss of load, but with a bias towards long-term storage, loss of load is small at the expense of overestimating system costs. In conclusion, the chapter proposes investigation of alternative methods to reduce computational complexity.

Following up on the previous conclusions, the **third chapter** introduces a novel graph-based formulation for bottom-up planning models. It aims at reducing computational complexity to mitigate dependence on time-series reduction when modeling high shares of renewables.

The formulation organizes sets of elements in rooted trees with multiple levels. For instance, the tree for time-steps will typically have years on the first and the subsequent time-steps within the year, likes days or hours, on the consecutive levels. Other sets organized in the same fashion include regions, energy carriers, and technologies.

As a result, temporal and spatial resolution can be varied per energy carrier, for instance modeling electricity hourly, but balancing supply and demand of gas daily. This achieves the temporal detail to capture fluctuations of wind and solar, but reduces the effort dedicated to other carriers and captures the inherent flexibility of large-scale infrastructures, like the gas grid.

To demonstrate feasibility of the presented formulation, an example model is created and solved at different temporal resolutions. Results show that limiting an hourly resolution to electricity and modeling other carriers daily or in four-hour blocks reduces computation time by about 70% but has negligible effects on system costs and installed capacities.

The graph-based formulation introduced in the previous chapter holds great benefits but is complex to implement. Therefore, the **fourth chapter** introduces *AnyMOD.jl*, a modeling framework implementing the graph-based formulation and automating the creation of models applying it.

Following the ideas proposed in the introduction, *AnyMOD.jl* promotes openness and accessibility. Besides the open-access publication of this chapter, a comprehensive online documentation and the commented code of the tool are publicly hosted on GitHub.

To facilitate access, *AnyMOD.jl* follows an easy-to-use principle and creates individual models solely from CSV files. As a result, analyzing inputs, running an existing model, or performing sensitivity analysis requires very little knowledge about the framework or programming. A deeper understanding of the framework enables users to create new models themselves and familiarity with the Julia language allows to add own features to a model. In addition, the tool includes elaborated features for plotting results, for example the energy flow diagram depicted in Fig. Figure 1.

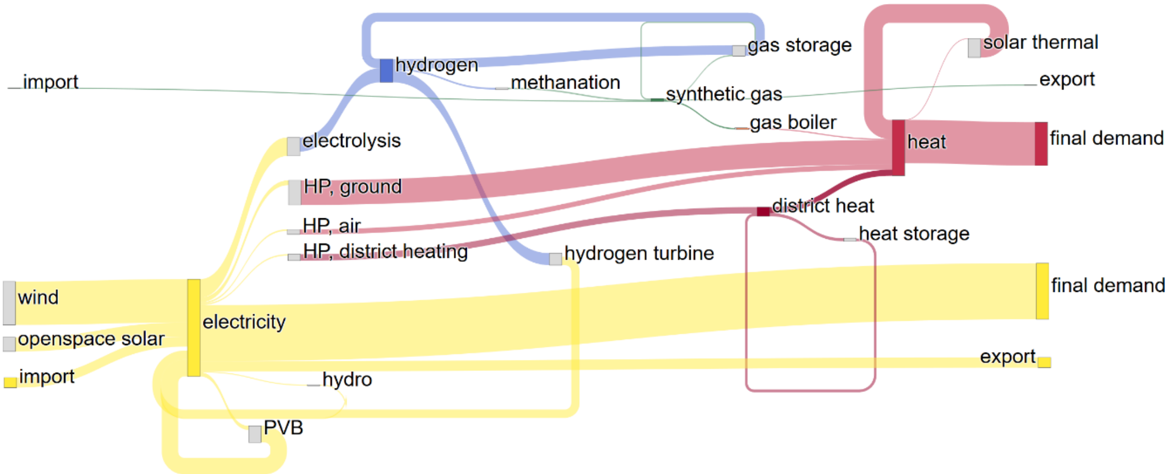


Figure 1: Exemplary Sankey diagram for a solved model of the power and heat sector

To enable modeling at large scope and detail, *AnyMOD.jl* makes additional efforts to increase the performance of creating and solving models. As a result, the model deployed in the second chapter is solved 80% faster when created with *AnyMOD.jl* compared to other frameworks but will provide the exact same results.

The **fifth chapter** applies the developed methods to evaluate the benefits of considering storage systems and different placement of renewables as substitutes for grid expansion. To analyze these benefits, a first-best scenario that simultaneously optimizes expansion of generation, storage, and the transmission grid is compared to several second-best scenarios.

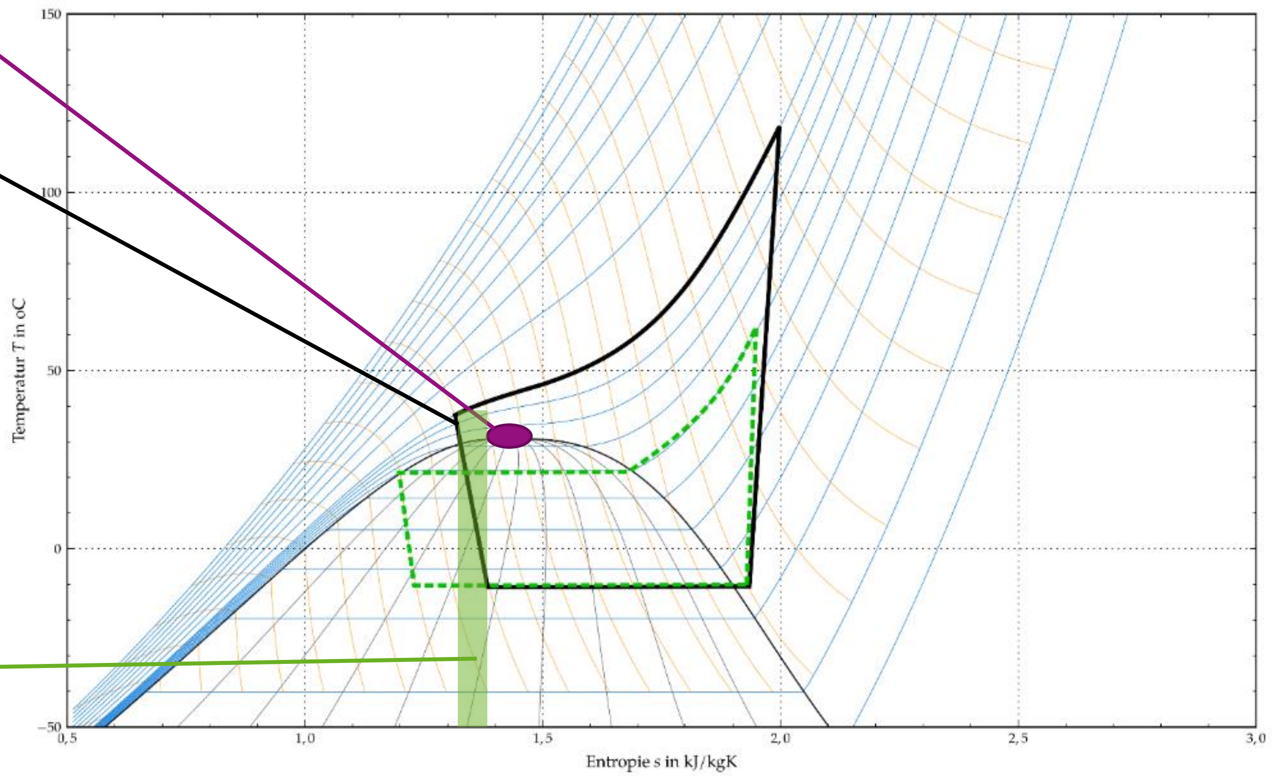
Analysis is focused on a renewable German power system but takes detailed account of sector integration and exchange with other countries. The applied model is based on the graph-based formulation for bottom-up planning models and applies an hourly resolution for electricity while hydrogen and synthetic gas are balanced daily. Assuming flexible charging, battery electric vehicles must cover their electricity demand across one day. Residential and process heat apply a four-hour resolution to account for the thermal inertia of buildings and load shifting potentials in the industry.

Results show that consideration of long-term storage as a substitute greatly decreases grid expansion and thus also system costs. At a 4.5 percent increase of system costs, storage can substitute grid expansion entirely. On the other hand, only small effects on grid expansion and system costs arise from short-term storage or placing renewables differently.

In conclusion, the model achieves a great spatial and sectoral scope, high temporal detail and a flexible representation of sector integration and provides results suggesting that modifications to the current policy framework could greatly reduce the need for grid expansion, even if sector integration doubles the demand for electricity. However, the chapter concludes that additional research with a different perspective is necessary to ensure the robustness of these findings, in particular more detailed models of grid operation.

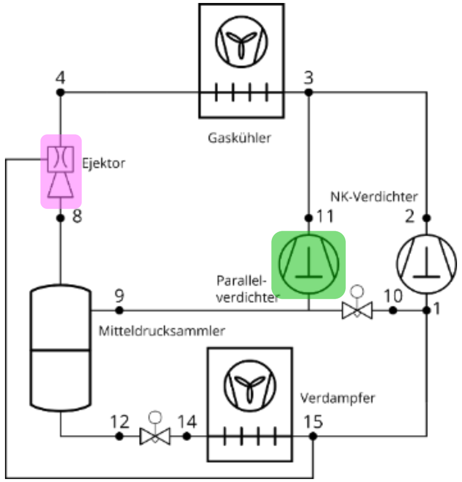
Thermodynamik von CO_2

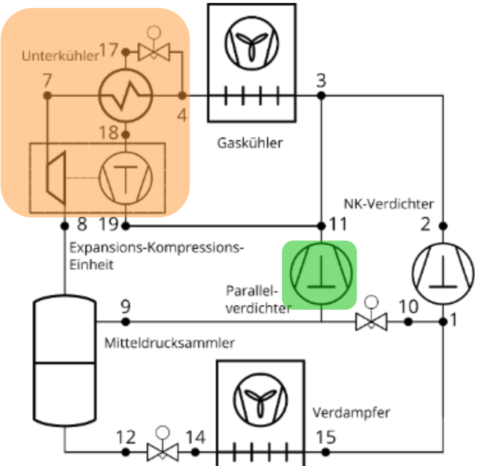
- Kritische Temperatur $t_{crit} \approx 31°C$
- Transkritischer Prozess bei Umgebungstemperaturen $t_a > 25\,°C$
- Dabei Effizienzeinbußen
- Kreislaufverbesserungen möglich, z.B. Rückgewinnung von Expansionsarbeit

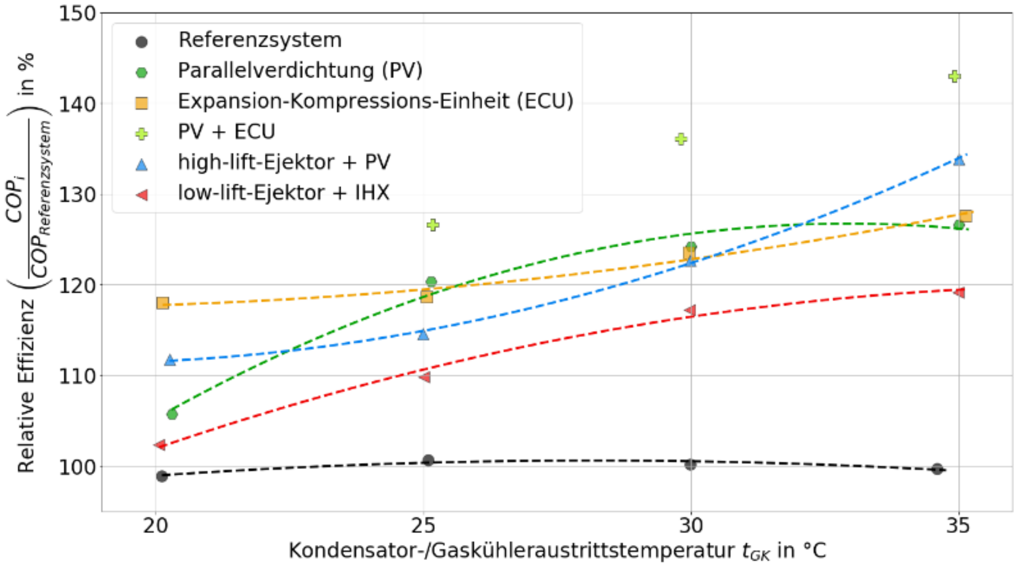


Effizienzsteigernde Maßnahmen für CO_2-Kälteanlagen

- Rückgewinnung von Expansionsarbeit mit Expandern oder Ejektoren
- Economization (Open-Flash-Economizer mit Parallelverdichter, interner Unterkühler mit Expansions-Kompressions-Maschine)
- Identifikation optimaler Systeme und adaptierte Regelung zur Effizienzsteigerung und Energieeinsparung







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Modellgestützte Optimierung für hocheffiziente CO_2-Kälteanlagen

- Numerische Berechnung des Anlagenverhaltens und des Jahresprofils anhand Klimadaten ausgewählter Orte
  - ➢ Jahresenergiebedarf
  - ➢ Einsparpotentiale
- Experimentelle Validierung an speziell umgerüsteter Versuchsanlage