Economic and Environmental Impacts of the Optimal Design of Sector-Coupling Energy Systems in Residential Districts

Themenbereich: Sektorkopplung und Flexibilität

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Motivation and Research Question

With increasing energy prices, growing demands and fluctuating renewable energy resources, designing energy systems to fulfill the energy demands of residential areas are becoming more challenging for decision-makers. Recent research has explored several solutions, mainly utilizing decentralized energy technologies and sector-coupling energy systems [1]. Nevertheless, optimization techniques are required to efficiently implement those solutions. Models for the design optimization of residential energy systems, which enable sector coupling, have been adequately researched [2]. Besides optimal planning, it is significant to understand the economic and environmental impacts of such energy systems in comparison to a typical energy system. Hence the question: how can those impacts be meaningfully analyzed and presented?

Methodology

The presented analysis is based on developing a multi-objective optimization model using a mixed-integer linear programming (MILP) approach. It aims to optimally select and dimension energy generation and storage technologies to cover a residential district's electricity and heat demands. The optimization is based on the minimization of total annual costs and total annual emissions. The cost-minimization function includes the annualized investment and operational costs, as well as the profits of exporting photovoltaic (PV) electricity. On the other hand, the emission-minimization function involves the CO2-equivalent emissions from importing electricity from the grid and burning gas. Since there is a trade-off between costs and emissions, the epsilon-constraint approach is implemented. In the first optimization run, the total costs are minimized without restricting the total emissions. Then, a new constraint is added to impose a limit on the total emissions, e.g., 95% of the emissions from the first run. The process is repeated until the optimization problem has no feasible solution.

In this model, the constraints describe the investment and operational limits of the considered technologies, including PV systems, combined heat and power units (CHP), heat pumps, gas boilers, battery storage and hot water storage. For the model development, python, the optimization library pyomo and oemof, a framework for modeling energy systems [3] have been utilized.

Results and Conclusion

In the presented case study, the design optimization is carried out to satisfy the electricity and heat demands of 12 residential buildings, clustered into three groups, in Bochum, Germany. To illustrate the impacts of sector coupling in this neighborhood, two instances of the optimization model are created; 'separated sectors' and 'coupled sectors.' The first one excludes any interaction between electricity and heat, while the second instance can include power-to-heat and co-generation units. Furthermore, it is possible to install rooftop PV systems in three different directions in a limited area. Figure 1 shows how both energy systems are structured. To perform the optimization, prices and emissions of electricity and gas, technologies' technical specifications and specific costs, historical weather data, as well as simulated load profiles of electricity and heat are inputted.

Using the solver Gurobi [4], a Pareto front between total costs and total emissions is created for each case, which can be seen in Figure 2. In the case of separated sectors, the best feasible reduction of total emissions is only 9%. On the contrary, it is possible to reduce the total emissions up to 25% by considering coupled sectors. Moreover, the second case leads to significantly higher cost savings, even at the minimum possible total emissions. This is mainly due to the possibility of utilizing PV in covering

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the heat demand when coupling the sectors and, hence, reducing the amount of imported gas, which is causing most of the emissions in both energy systems.

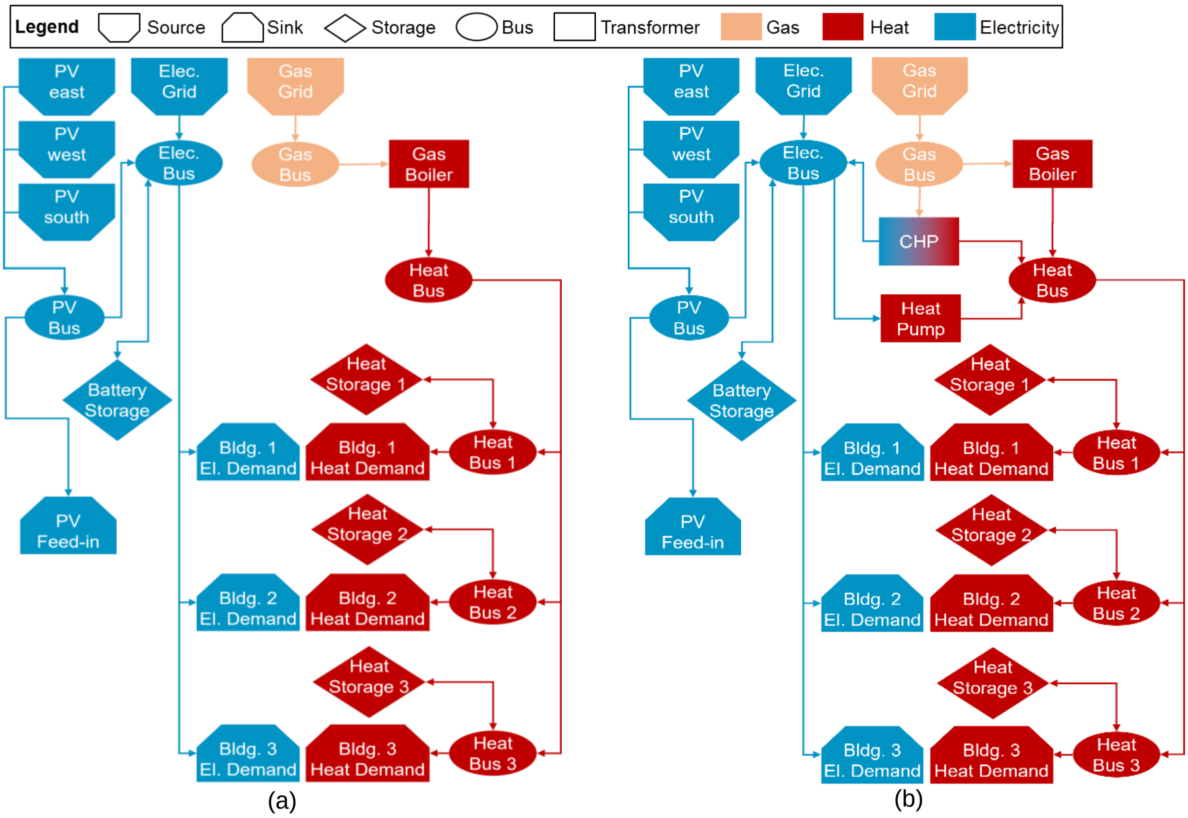

Figure 1: Considered energy systems in the cases of (a) separated sectors and (b) coupled sectors

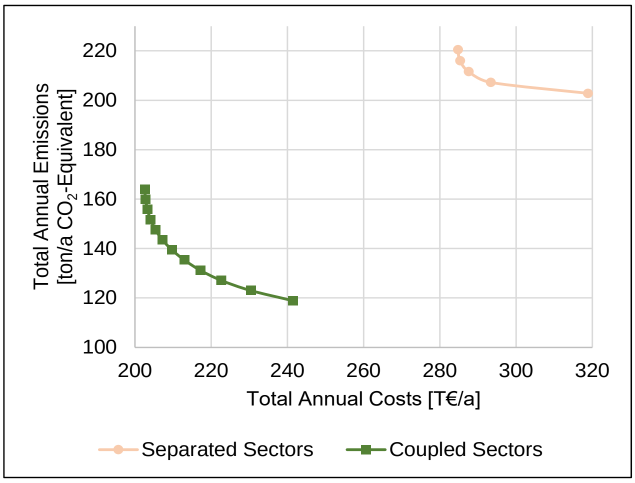

Figure 2: Costs-Emissions Pareto front for each case.

Literature

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