Chair of Energy Systems
TUM School of Engineering and Design
Technical University of Munich

Planning Renewable Energy Systems at the District Scale using Mixed-Integer Linear Programming

Amedeo Ceruti[1], Benedikt Schweiger[1], Hartmut Spliethoff[1]

[1] Technical University of Munich, Chair of Energy Systems, Germany

Introduction

Heating is the largest end-use category of energy, accounting for around 50% of global final energy consumption [1]. In the European Union (EU), only 28% of the delivered residential heating was from renewable sources in 2019 [2]. New planning methods and tools capable to cope with high-shares of intermittent renewable energy sources are needed to speed up the transition to resilient, sustainable energy systems at the district level.

Methodology

Heat, power and cooling demands of the studied district are estimated from Level of Detail 2 (LoD2) Geographical Information System (GIS) data (**Figure 1**), which is pre-processed with the software FME [3]. Then, an age category is assigned to each building given the age distribution information provided by the Zensus2011 dataset [4]. A TABULA building type [5] is assigned to define building thermal properties. The obtained data is then used to compute heating, electricity and cooling demands with City Energy Analyst (CEA) [6].

A mixed-integer linear programming (MILP) problem is formulated (see model structure in **Figure 2**) with the given energy demands. The optimization objective is to minimize the system costs (**Eq. 1** and **2**). The optimization therefore selects optimal investment decision variables (C_{inv}, *first stage*) and operates a whole year (C_{op}, *second stage*).

$$\min \; C_{inv} + C_{op} \qquad (\mathbf{Eq.\,1})$$

$$C_{inv} = \sum_i [CRF_i \cdot (C_i \cdot G_i)] + C_{DHN} \cdot y \qquad (\mathbf{Eq.\,2})$$

To integrate price uncertainty in the optimization formulation, a two-stage stochastic programming (SP) formulation is used. To solve the generally intractable expectation function, it is approximated through S scenarios with a user-defined probability π_s (**Eq. 3**).

$$\min \; C_{inv} + \mathbb{E}\left[C_{op,s}\right] \;\rightarrow\; \min \; C_{inv} + \sum_{s \in S} (\pi_s \cdot C_{op,s}) \qquad (\mathbf{Eq.\,3})$$

Heat Demand Calculation

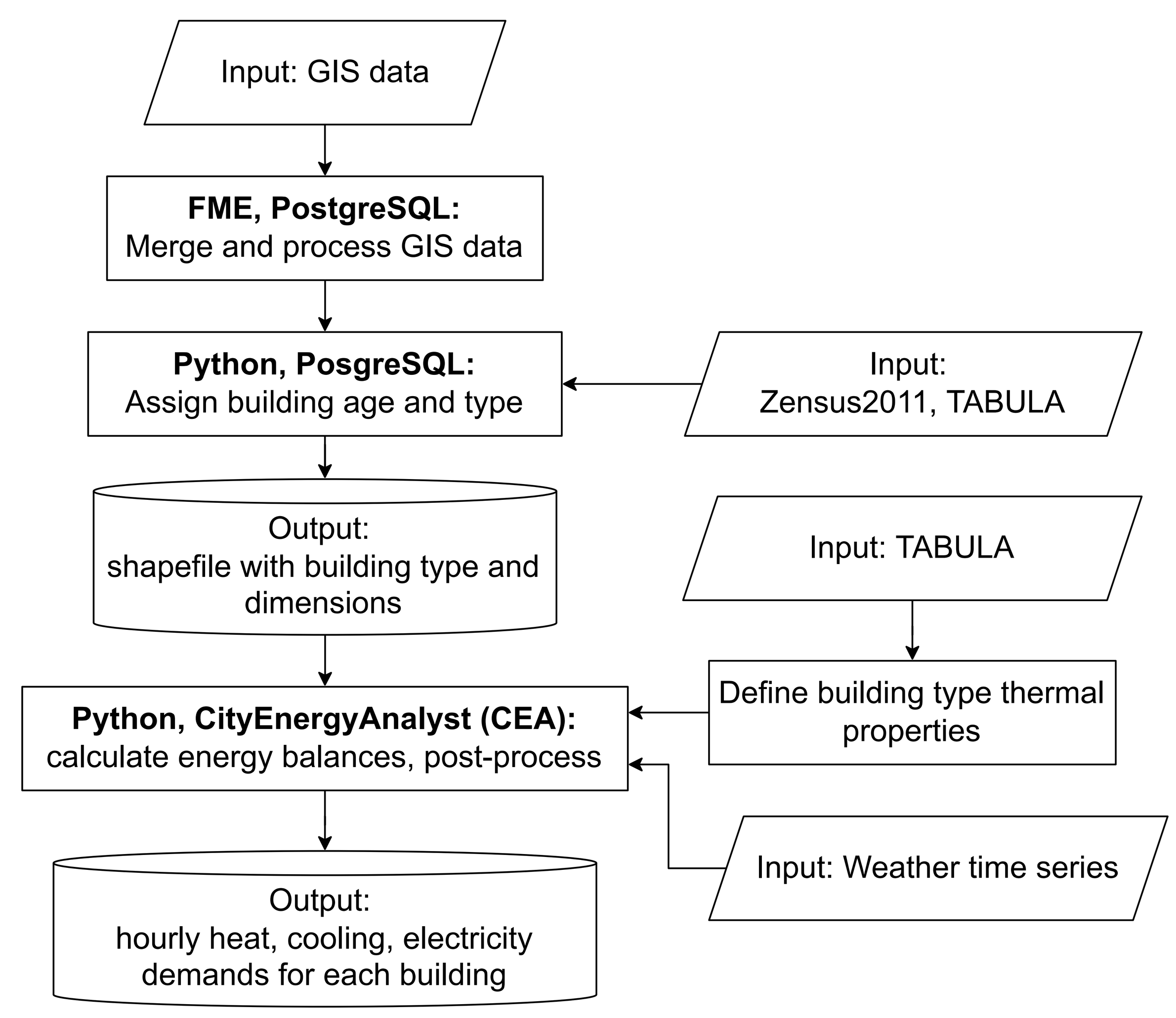

Figure 1. Simplified process to compute heat and electricity demands from GIS data.

MILP Formulation

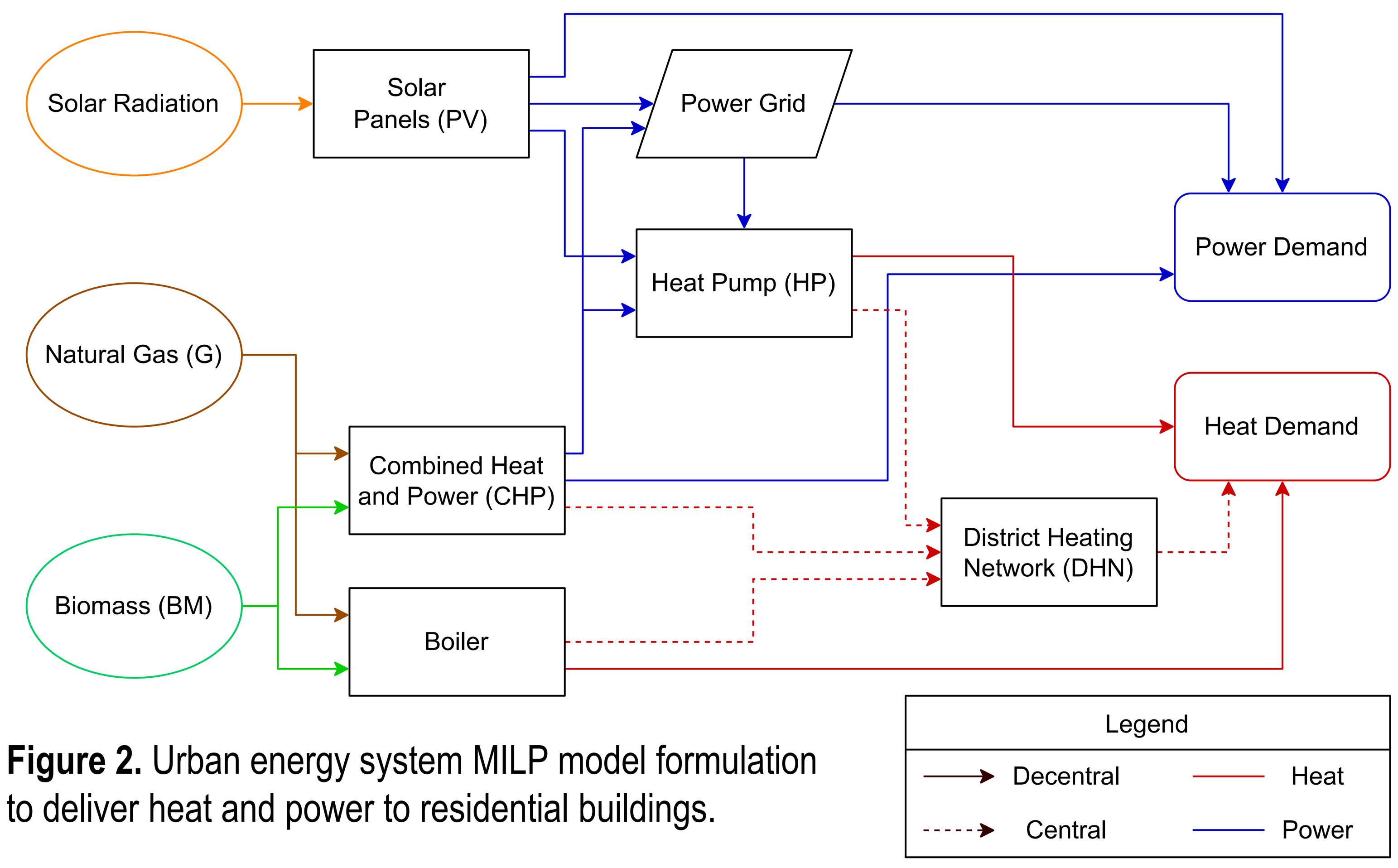

Figure 2. Urban energy system MILP model formulation to deliver heat and power to residential buildings.

Case Study

The developed method was applied to a town in southern Bavaria, Germany with around 300 residential buildings and the typical meteorological year (TMY) dataset of the closest meteorological station [7]. District heating network costs were obtained from THERMOS [8] and from sources [9-11] for commodity prices and technology life time. An internal rate of return of 8% was assumed. Four scenarios were computed as deterministic MILPs and two scenarios, “SP25” and “SP125”, as a two-stage SP (**Table 1**).

Table 1. Price assumptions for the calculated scenarios using MILP.

Scenario	Description	Natural Gas [€/MWh]	Wood Pellet [€/MWh]	CO_2 cost [€/t $CO_{2\,eq.}$]
BC	Base Case	16	39	25
S2	High CO_2 tax	16	39	125
S3	2022 prices	140	150	25
CO2	CO_2 minimization	140	150	-
SP25	Two-stage SP	[16, 140, 375]	[39, 150]	25
SP125	Two-stage SP	[16, 140, 375]	[39, 150]	125

Results

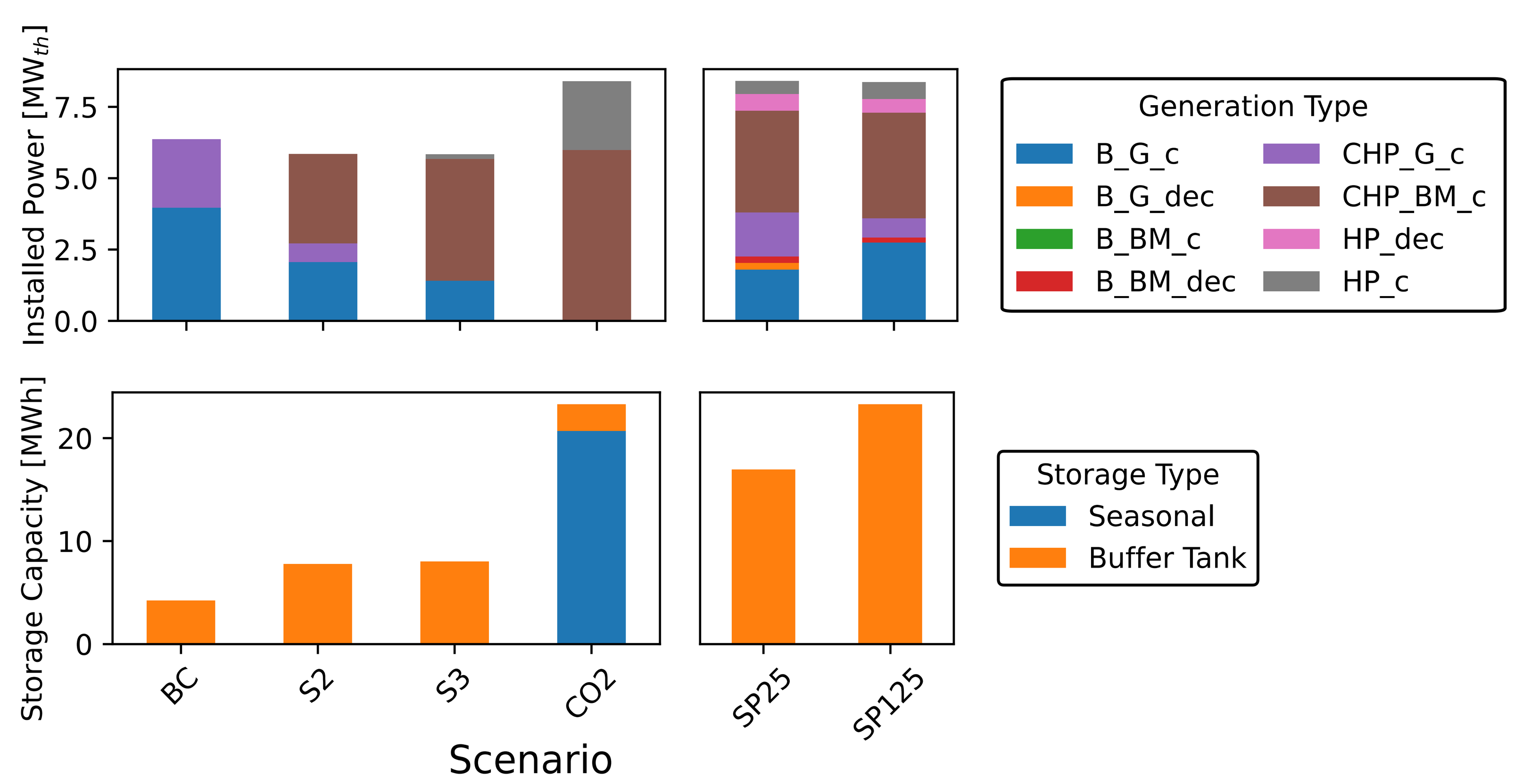

Figure 3. Thermal energy generation and storage results for deterministic MILP (“BC“, „S2“, S3“, „CO2“) and two-stage SP („SP25“ and „SP125“) optimization.

Technical University of Munich
TUM School of Engineering and Design
Chair of Energy Systems

Amedeo Ceruti, M. Sc.
amedeo.ceruti@tum.de
+ 49 89 289 16343

Research funded by:
Federal Ministry for Economic Affairs and Climate Action

[1] IEA. “Heating.” https://www.iea.org/reports/heating (accessed Nov. 4, 2022).
[2] Eurostat. “Energy consumption in households.” https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households (accessed Nov. 2, 2022).
[3] Safe Software, *FME* (2022). Surrey, Canada. Accessed: Nov. 2, 2022. [Online]. Available: https://www.safe.com/fme/
[4] Statistisches Bundesamt. “ZENSUS2011 - Bevölkerungs- und Wohnungszählung 2011.” https://www.zensus2011.de/DE/Home/home_node.html (accessed Nov. 2, 2022).
[5] T. Loga, B. Stein, and N. Diefenbach, “TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable,” *Energy and Buildings*, vol. 132, pp. 4–12, 2016, doi: 10.1016/j.enbuild.2016.06.094.
[6] J. A. Fonseca, T.-A. Nguyen, A. Schlueter, and F. Marechal, “City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts,” *Energy and Buildings*, vol. 113, pp. 202–226, 2016, doi: 10.1016/j.enbuild.2015.11.055.
[7] L. K. Lawrie and D. B. Crawley, “Development of global typical meteorological years (TMYx),” 2019. [Online]. Available: http://climate.onebuilding.org
[8] THERMOS project partners. “THERMOS (Thermal Energy Resource Modelling and OptimisationSystem) project.” https://www.thermos-project.eu/home/ (accessed Aug. 2, 2022).
[9] KEA Klimaschutz- und Energieagentur Baden-Württemberg GmbH. “Technikkatalog zur kommunalen Wärmeplanung in Baden-Württemberg.” https://www.kea-bw.de/waermewende/wissensportal/kommunale-waermeplanung/technikkatalog#c5088-content-5 (accessed Nov. 2, 2022).
[10] European Energy Exchange AG. “EEX Market Data.” https://www.eex.com/en/ (accessed Nov. 2, 2022).
[11] Deutsches Pelletinstitut GmbH. “DEPI - Pelletpreis/Wirtschaftlichkeit.” https://www.depi.de/pelletpreis-wirtschaftlichkeit (accessed Nov. 3, 2022).