Joint Activity Scenarios and Modelling

Energy Supply System Optimization Baden Nord

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December 8, 2020

Supported by:

Schweizerische Eidgenossenschaft
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Chapter 1

Energy hub optimization Baden Nord

1.1 Introduction

This chapter summarizes the results of a project focused on the development of a strategic energy plan for the area of Baden Nord, Switzerland (Figure 1.1). The project took place in the context of a collaboration between Regionalwerke Baden (RWB) and the Urban Energy Systems Laboratory at Empa (Empa) in 2018-19.

The area of Baden Nord is undergoing a transition from primarily industrial use to more commercial and residential use. This transition is expected to usher in required changes to the site's energy system. In particular, Baden Nord will experience changes in energy demand patterns and renewable energy requirements. The aim of the project was to identify optimal technological scenarios for the energy system of Baden Nord, with a focus on the technical feasibility and costs of achieving different levels of sustainability performance for the area's energy supply. A range of different energy production and storage technologies for provision of heat, electricity and cooling were considered, with the aim to facilitate the identification of a suitable energy supply configuration, also considering potentially uncertain future developments.

While the results of this analysis are specific to the site of Baden Nord, the problem addressed is similar to that faced by many sites across Switzerland towards achieving the Energy Strategy 2050. The present analysis illustrates how the challenge to decarbonize local energy systems can be effectively addressed using optimization-based modelling methods, and in particular Empa's Ehub Tool software.

1.2 Methodology

For the above-defined analysis, the following methodology was followed:

1. Energy demand modelling was used to estimate the future multi-vector energy demand patterns for the area

2. Using the outputs of step 1, an optimization model was applied to identify a set of optimal energy supply solutions for the given site, representing different levels of sustainability performance.

Figure 1.1: Location of the study site, Baden Nord, Switzerland.

1.2.1 Energy demand modelling

RWB provided various datasets pertaining to the buildings and energy consumption in the study area, including residential, commercial and industrial buildings. Empa cleaned and enriched the datasets provided by RWB – including filtering of anomalous values and calculation of missing data points – to obtain a complete demand-side dataset for the analysis (Figure 1.2, left pane). Missing values were computed using clustering methods (principal components analysis followed by k-medoids on normalized values). Using an approach based on building archetypes, hourly building energy demand profiles were subsequently calculated using the urban energy simulation tool CESAR (Wang et al., 2018). A clustering analysis, using hierarchical clustering, was subsequently carried out to identify a set of representative demand days to be used for the energy supply optimization in the supply system optimization (Figure 1.3).

1.2.2 Energy hub optimization

The calculated energy demand profiles were used as inputs to a multi-energy supply system optimization, carried out using the energy hub approach (Geidl and Andersson, 2007) combined with a synthesis mathematical programming and machine learning techniques. Figure 1.4 shows the technologies, resources and energy demands included in the analysis. The development/execution of the energy hub optimization proceeded in 3 phases. The aggregated analysis in Phase 1 was used as a basis for those in Phases 2 and 3, which addressed uncertainty and spatial aspects, respectively – both defined by problem owners as relevant aspects to the development of the strategic energy plan.

Phase 1 – Aggregated analysis: An aggregated energy supply optimization of the site was implemented and executed, considering a wide range of possible energy supply technology options but ignoring the constraints and costs associated with potentially necessary thermal network connections within the site. The goal of this analysis was to determine the optimal energy supply options for the site as a whole, given the full range of available options. The analysis was carried out in an iterative manner (6 iterations), with the set of technologies considered and the various parameters

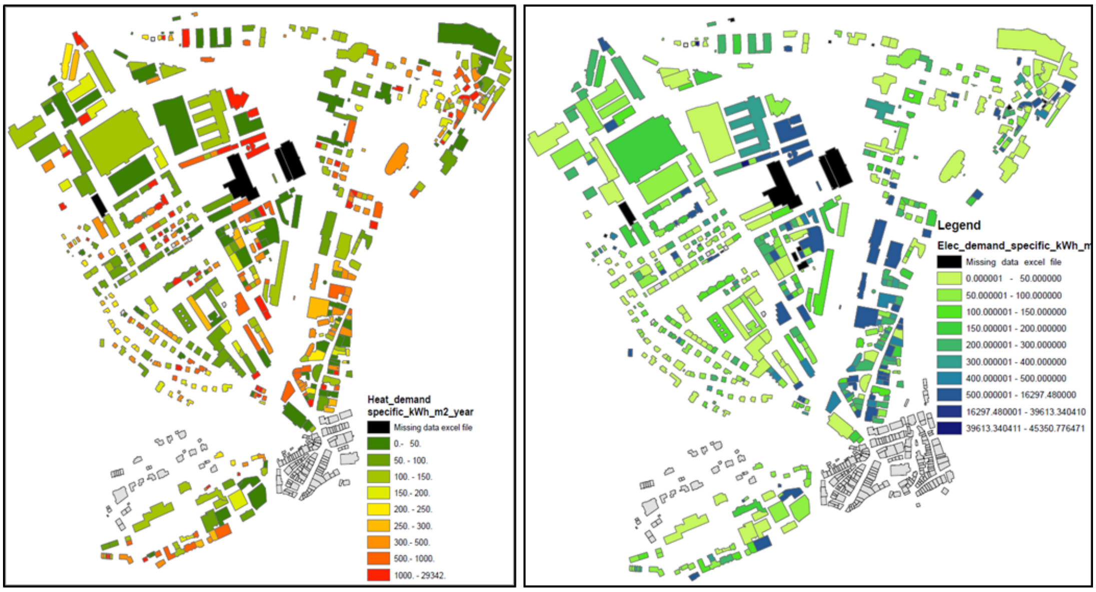


Figure 1.2: Heat map of estimated building heat demands (left pane) and electricity demands (right pane) in the study area.

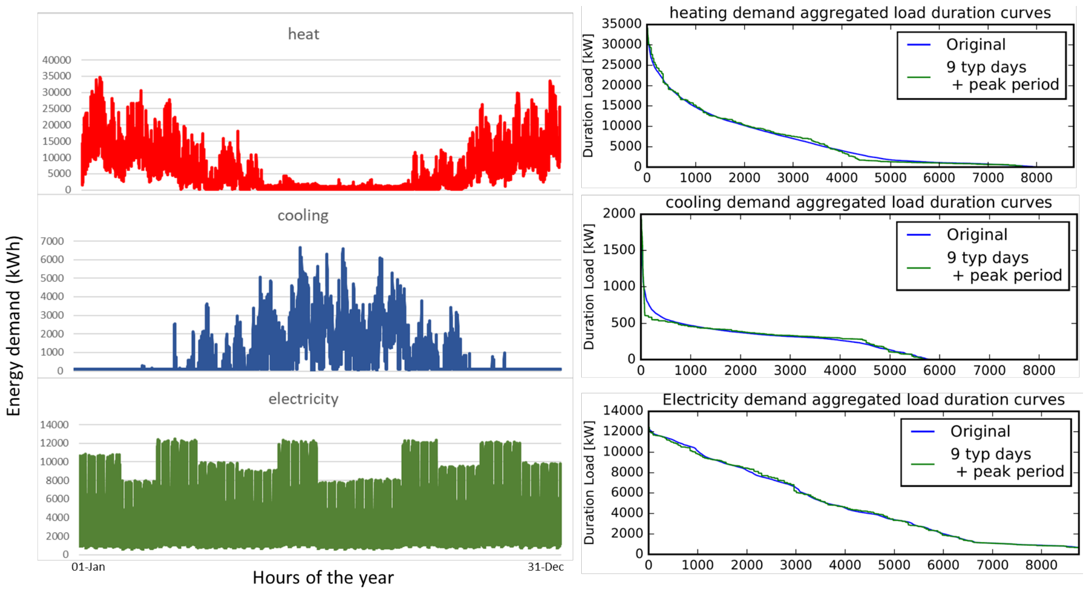


Figure 1.3: Simulated energy demand profiles for the site, for heating, electricity and cooling (left pane); and comparison of load duration curves of a reconstituted demand profile based on the selected representative days with those of the full-horizon demand profiles (right pane, x-axis values in hours).

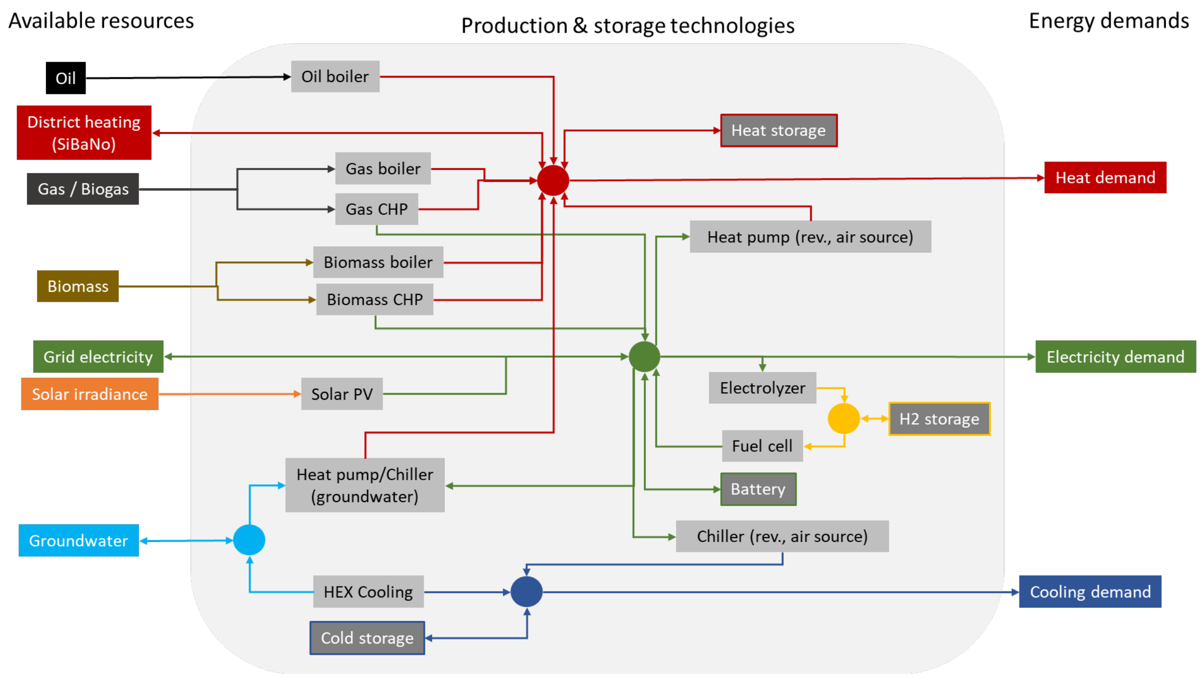


Figure 1.4: Energy hub diagram – production & storage technologies and energy pathways considered in the analysis.

constituting the analysis refined with each iteration based on discussions between RWB and Empa.

Phase 2 – Sensitivity analysis: A sensitivity analysis of the aggregated model was carried out, the goal of which was to determine the influence of different uncertain developments on the future optimal energy supply solution for the site. The parameters adjusted in the course of the sensitivity analysis are shown in Figure 1.9.

Phase 3 – Detailed analysis: A more detailed analysis of the site was carried out, encompassing a smaller set of supply technologies – reduced based on the results of phases 1 and 2 – but considering in more detail the thermal network options/structures for heating and cooling, and their respective costs.

For executing the analyses, Empa's *Ehub Tool* (Bollinger and Dorer, 2017) software was used. Given a specification of system options such as that illustrated in Figure 1.4, the Tool uses a synthesis of mathematical programming and machine learning to identify a "Pareto front" (Figure 1.5) of optimal energy supply solutions for a given site. The main inputs to the Tool include hourly heating, cooling and electricity demand profiles for the site, key technical and economic parameters of the energy production and storage technologies to be considered, and the prices and CO2 intensities of energy carriers imported to the site such as grid electricity, (bio)gas and oil. The main outputs of the Tool are the optimal energy production and storage technologies to be installed at the site, together with the optimal dispatch schedule and dimensioning of these technologies, and the cost and CO2 performance of the optimal systems.

For the present analysis, two optimization objectives are considered: life-cycle costs and operational CO2 emissions. Life-cycle costs encompass technology capital costs and maintenance costs, as well as energy costs in operation. Operational CO2 emissions include only those emissions incurred during the operational lifetime of the system (i.e. excluding embodied CO2). Each solution in the resulting Pareto front represents a different optimal supply solution with a different level of trade-off between cost minimization and CO2 emissions minimization. For each solution, the optimal set of supply technologies (including production and storage) is identified, together with the dimensioning of each, calculated based on a simulated hourly dispatching of technologies over a representative year.

The complete data basis for the present analysis is not provided with this report. Key assumptions underlying the analysis include:

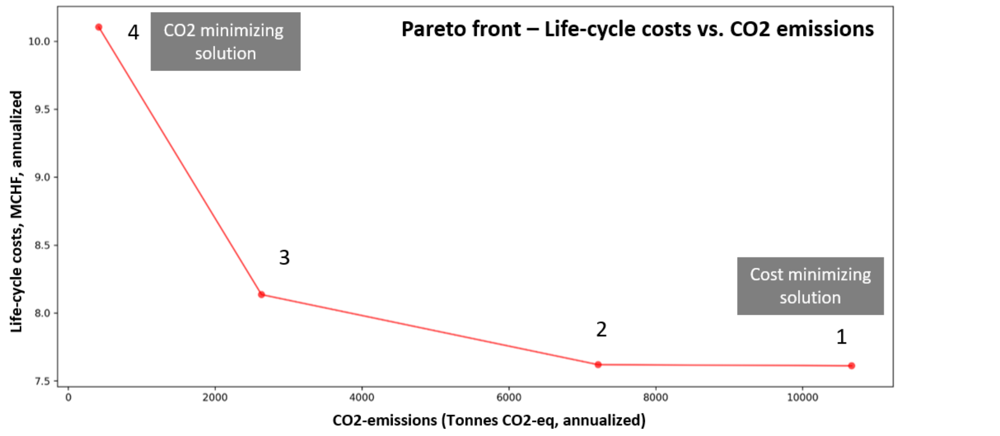
- Already existing on-site technologies for supply of heating and cooling are not considered in the analysis.
- Except for in phase 3 (Detailed analysis), thermal network costs and constraints are not considered in the analysis.
- It is assumed that groundwater temperatures are sufficient for direct provision of cooling.
- With the exception of minimum part-load operation constraints, detailed operational parameters of production technologies (e.g. ramping, minimum runtime, load-dependent efficiency) are not considered.
- The effect of outdoor temperature on air-source heat pump efficiency is not considered.

1.3 Results

1.3.1 Phase 1 – Aggregated analysis

The goal of the aggregated analysis was to determine the optimal energy supply options for the site as a whole, given the full range of available options. Key results from the aggregated analysis are illustrated in Figure 1.5. A pareto front consisting of 4 optimal solutions was identified, including a cost-minimizing solution (solution 1), an emissions minimizing solution (solution 4), and two intermediate solutions (solutions 2 & 3). Between the cost-minimizing solution and the CO2 minimizing solution, the life-cycle costs are increased by 33% and the CO2 emissions reduced by 96%. 75% of emissions reductions with respect to the cost-minimizing solution are achieved by solution 3, with an increase in life-cycle costs of only 7%.

Figure 1.6 shows the selected supply technologies for heating, cooling and electricity across the 4 optimal solutions for the aggregated analysis. In solutions 1 and 2, heat production is dominated by district heating and is complemented by an air-source heat pump / chiller (reversible). For solutions 3 and 4, heat production is dominated by a biomass-driven ORC (organic rankine cycle) boiler, again complemented by an air-source heat pump / chiller. In the CO2 minimizing solution, the system is further expanded with a groundwater heat pump / chiller system. Across all solutions, cooling demand is met by a combination of groundwater-based freecooling and air-source chiller.



Cost category	*Cost minimizing solution* Solution 1	Solution 2	Solution 3	*CO2 minimizing solution* Solution 4
Investment costs	**Fr. 3,635,204**	**Fr. 3,884,161**	**Fr. 3,629,318**	**Fr. 4,513,473**
Energy costs	**Fr. 4,301,271**	**Fr. 4,287,156**	**Fr. 4,663,392**	**Fr. 5,842,397**
O&M costs	**Fr. 110,259**	**Fr. 104,408**	**Fr. 240,095**	**Fr. 343,402**
Income	**-Fr. 435,480**	**-Fr. 656,795**	**-Fr. 397,924**	**-Fr. 594,051**
Total costs	**Fr. 7,611,253**	**Fr. 7,618,929**	**Fr. 8,134,880**	**Fr. 10,105,221**

Figure 1.5: Pareto front for the aggregated analysis (top pane); and breakdown of costs per solution (bottom pane).

Heat production (kW)

Technology	*Cost minimizing solution* Solution 1	Solution 2	Solution 3	*CO2 minimizing solution* Solution 4
Biomass boiler ORC	0	0	22768	15961
Gas CHP	2188	0	0	0
Heat pump / chiller (air-source)	2717	4161	5517	8193
Heat pump / chiller (groundwater)	0	0	0	4153
District heating (SiBaNo)	32463	34649	0	0

Cooling production (kW)

Technology	*Cost minimizing solution* Solution 1	Solution 2	Solution 3	*CO2 minimizing solution* Solution 4
Heat pump / chiller (air-source)	2717	4161	5517	8193
Heat pump / chiller (groundwater)	0	0	0	2617
Freecooling (groundwater)	2500	2500	2500	2500

Electricity production (kW)

Technology	*Cost minimizing solution* Solution 1	Solution 2	Solution 3	*CO2 minimizing solution* Solution 4
Biomass boiler ORC	0	0	4208	2950
Gas CHP	2069	0	0	0
Solar PV (kWp)	13128	16071	13517	16201

Figure 1.6: Production technologies installed in each solution of the aggregated analysis and their respective sizing.

1.3.2 Phase 2 – Sensitivity analysis

The goal of the sensitivity analysis was to determine the influence of different uncertain developments on the future optimal energy supply solution for the site. Figures 1.7, 1.8 and 1.9, show the key results of the sensitivity analysis. In the course of the sensitivity analysis, 14 different scenarios were evaluated, each corresponding to a single parameter change in relation to the base case (aggregated analysis in phase 1). The purpose of these scenarios is to understand how the performance and technological composition of the optimal system changes under different conditions. Four categories of scenarios are evaluated:

- **Scenarios 1-8 – Energy prices:** Different assumed prices of energy resources, including gas, biogas, electricity and biomass.
- **Scenarios 9-10 – Energy demands:** Different assumed energy demand magnitudes for heating, cooling and electricity (+/-20% scaling of the default demand profiles).
- **Scenarios 11-12 – Technology prices:** Reduced prices for solar PV and batteries.
- **Scenarios 13-14 – Technology feasibility:** Different assumptions regarding the feasibility and constraints on the use of different technologies, in particular district heating and groundwater.

As illustrated in Figure 1.7, the largest relative changes in costs and CO2 emissions – compared to all other scenarios – are observed with increases or decreases of energy demand (heating, cooling and electricity) of +/-20%. Compared to other energy resources, changes in the price of electricity have the most significant effect on the cost performance of the system. Also visible in Figure 1.7, significant reductions in overall system costs are also observed with a reduction in the price of solar PV installations, attributable to the correspondingly reduced investment costs.

As illustrated in Figure 1.8, most scenarios resulted in moderate deviations in the technological composition of the optimal system with respect to the base case. For instance, increased/decreased prices of electricity resulted in less/more use of heat pumps. An increase/decrease in the price of gas results in less/more use of gas boilers and/or gas CHP. A significant change in the technological composition of the system (in comparison with the base scenario) is observed in scenario 13, with the district heating connection replaced by a combination of gas CHP, biomass boiler ORC and oil boilers.

1.3.3 Phase 3 – Detailed analysis

The goal of the detailed analysis was to identify the optimal supply technology locations and thermal network structures. Key assumptions are as follows:

- To limit the scope of the analysis, and given an interest in groundwater as a potential cooling source, the parameters of the analysis are set in accordance with scenario 14 of the sensitivity analysis, corresponding to an unlimited groundwater availability.
- The buildings in the site are divided into a set of 7 clusters, and possible thermal network links between these clusters are defined, with distance-dependent investment costs associated with the realization of each possible thermal network link.

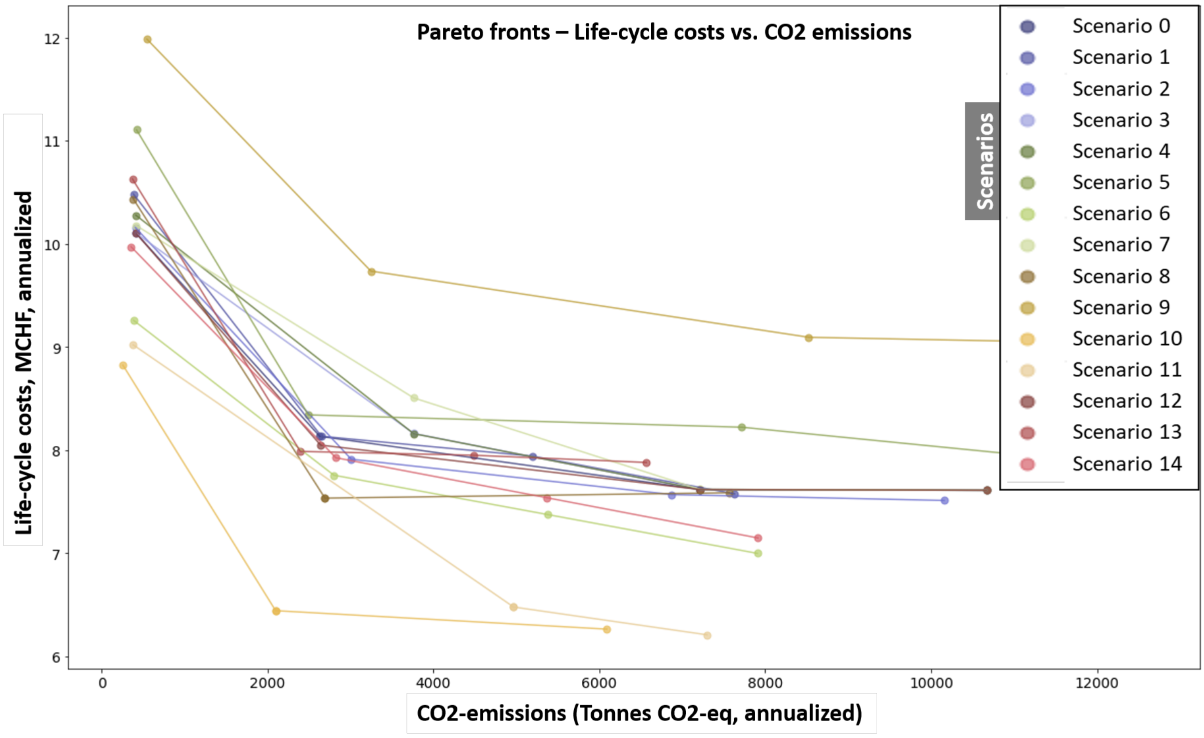


Figure 1.7: Pareto fronts for the different scenarios of the sensitivity analysis. See Figure 1.9 for an explanation of the scenarios.

- The heating, cooling and electricity demands within each cluster are determined by the properties of the buildings within the cluster, with the largest demands present in cluster 1.
- It is assumed that a groundwater source is available only at cluster 7.

In the course of the analysis, the optimizer selects which thermal links for heating and cooling should be realized and at which clusters the different supply technologies should be located. Figure 1.10 shows the results for the cost-minimizing solution. In terms of heating, the results closely mimic those of the cost-minimizing solution of the aggregated analysis, with the heating provided by a combination of district heating and gas CHP. The location of the gas CHP is selected by the optimizer to be at cluster 1 – the cluster with the highest demands. A district heating network fed by these sources spans all hubs in the site, with a main axis connecting the district heating source with cluster 1, and additional pipes extending to the other nodes. For cooling, a groundwater-based freecooling solution is selected, with a cooling network connecting the groundwater source (cluster 7), cluster 5 and cluster 1, which by far has the largest cooling demand of any of the clusters.

1.4 Conclusions

The following conclusions may be drawn from the results of this analysis, informed by the 3 phases of the analysis:

- The least cost solution for meeting the heating demands of the site is with district heating

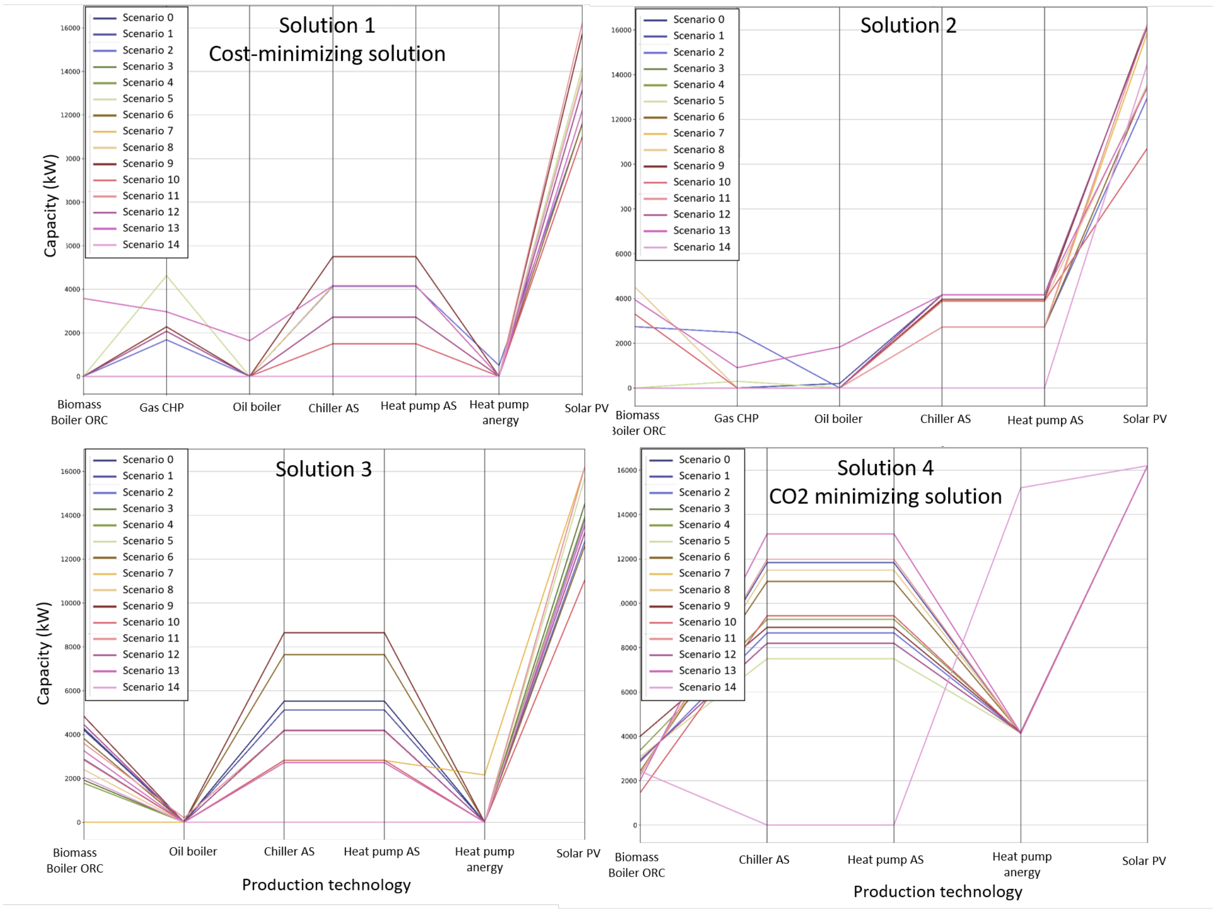


Figure 1.8: Optimal dimensioning of production technologies for each solution in the sensitivity analysis.

Scenario #	Parameter modification	Default value	Cost change (%)	CO2 change (%)
0	Base scenario	N/A	N/A	N/A
1	Gas price +20%	0.063 CHF/kWh	2	-16
2	Gas price -20%	0.063 CHF/kWh	-1	1
3	Biogas price +20%	0.15 CHF/kWh	0	11
4	Biogas price -20%	0.15 CHF/kWh	1	11
5	Electricity price +20%	0.16 / 0.14 CHF/kWh	6	3
6	Electricity price -20%	0.16 / 0.14 CHF/kWh	-6	-13
7	Biomass price +20%	0.044 CHF/kWh	1	11
8	Biomass price -20%	0.044 CHF/kWh	-1	-24
9	Energy demands +20%	Hourly profile	19	23
10	Energy demands -20%	Hourly profile	-17	-43
11	PV price -50%	2500 CHF/kWp	-16	4
12	Battery price -50%	2000 CHF/kWh	0	0
13	District heating (SiBaNo) excluded	Included	3	-24
14	Unlimited use of groundwater	Limited use	-3	-14

Figure 1.9: Percentage change in life-cycle costs and CO2 emissions across the different scenarios of the sensitivity analysis, in comparison with the base scenario.

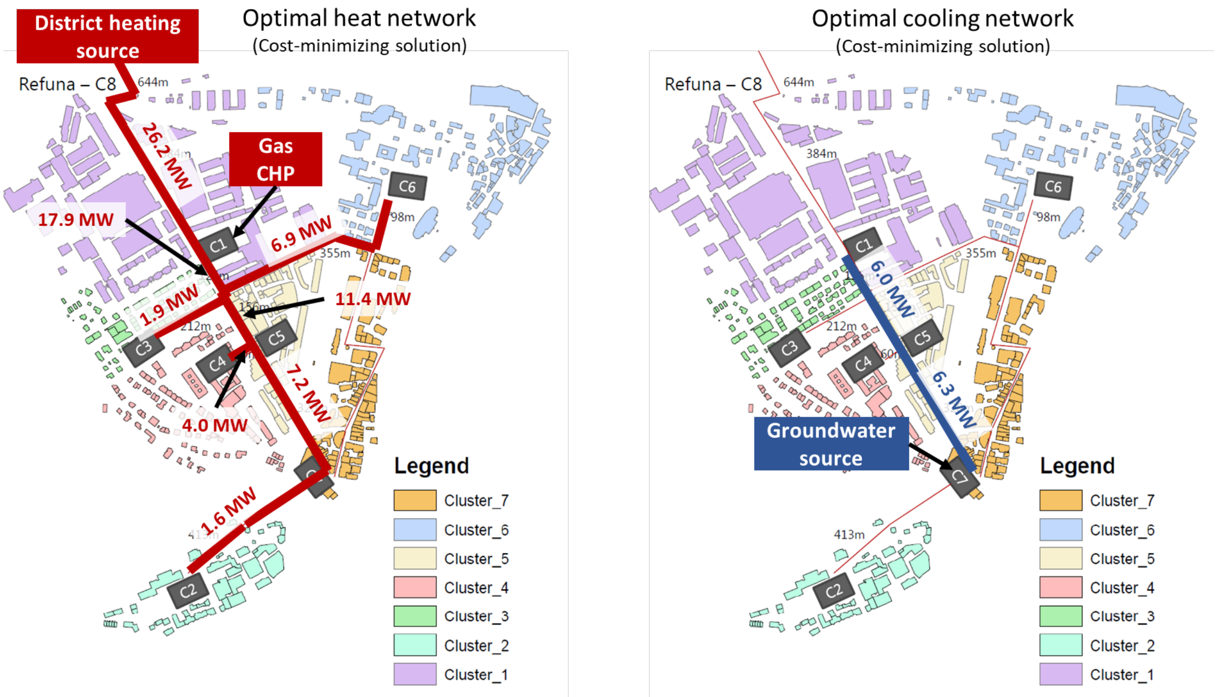


Figure 1.10: Results of the detailed analysis for the cost-minimizing solution.

SiBaNo (Region Siggenthal - Baden Nord), complemented by air-source heat pumps and rooftop PV installations.

- If district heating is not a feasible solution (e.g. due to lack of available heating energy in the winter months), the least cost solution for meeting heating demands is with a combination of technologies, including a biomass boiler ORC, gas CHP and oil boilers.
- A 75% reduction in operational CO2 emissions with respect to the least cost solution can be achieved through a shift to heating supply primarily based on a biomass boiler ORC. As in the least-cost solution, this is complemented by air-source heat pumps and rooftop PV installations. The resulting life-cycle costs are found to be ca. 7% higher in comparison with the least cost solution.
- Air-source chillers combined with groundwater-based freecooling is the most cost-effective and sustainable solution for meeting on-site cooling demands. If groundwater availability and temperature is sufficient, a purely groundwater-based (free)cooling solution is found to be most efficient.

In addition to those listed above, the present study rests on certain assumptions which may limit the applicability of the results. This includes, for instance, the assumption of flat (output-independent) technology efficiency curves, meaning that the operational performance of certain technologies may be overestimated, especially under part-load conditions. Another important assumption is that technology capital costs, including network costs, increase linearly with technology dimensioning. This neglects economy-of-scale effects that can be observed in practice. With respect to the analysis in Phase 3, certain practical considerations which may influence the optimal routing of thermal networks were not considered. These assumptions may be addressed via further iterations of the applied methodology, including a smaller set of technologies but with a more detailed representation and considering additional practical constraints in system implementation. More broadly, the specific results are specific to the location of Baden Nord and cannot easily be transferred to other locations. However, the overarching approach and methodology may be similarly applied to other locations from the scale of a neighborhood to an urban district, offering a way to identify optimal energy transformation pathways at local scale towards the Energy Strategy 2050.

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