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Optimization of Heating, Electricity and Cooling Services in a Microgrid to Increase the Efficiency and Reliability

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Abstract

We briefly review the general concept and expected market potential of microgrids, then discuss the optimization challenges associated with planning local cross-sectorial energy systems. A fair technology-neutral approach to this optimization task leads to a hard problem, which has to be tackled with advanced methods of mathematical optimization.

The power of this approach is illustrated in a case study, concerning the replacement of heating systems in an alpine valley. In this case study we see both the potential for cost reduction and for the reduction of CO_2 emissions by an integrated planning approach.

The contents of this report have been presented on the conference Electrify Europe, www.electrify-europe.com/ (formerly PowerGen Europe) in Vienna on June 20th 2018.

1. Microgrids

Microgrids, a research topic within the smart grids area, build on close spatial relationships between demand and supply. They are expected to create a 170 Bn. € market potential in 2020 (Utility Dive, 2016).[1] The close relationship between supply and demand will enable higher efficiencies (e.g. due to waste heat utilization), higher integration potentials for renewables (e.g. due to smart controls), reduce the CO_2 emissions, reduce the need for high voltage transmission line upgrades, and finally, incorporate local energy forms in a more efficient way (e.g. biomass or biogas).

The largest export markets for microgrid planning and control technologies are expected to be Asia (roughly 40%) and North America (33%), followed by Europe (14%) and the rest of the world (13%) (Microgrid Knowledge, 2016; Navigant Research, 2016). These individual markets are characterized by different technology needs. Microgrids or so called cellular energy systems are gaining attraction and are being installed already. More than 40% of all installed Microgrids in the US are at military sites, University Campuses, and Communities and 1/3 of the Microgrids have electric power of less than 1 MW. The markets are very different and show e.g. more than 40% CHP penetration in New York State, while California shows almost 30% solar and almost 15% electric storage penetration levels (Greentech Media, 2016).

Since the microgrids can be subject to very different needs, investment decisions and operation of such systems require sophisticated planning and control tools, which need to be based on mathematical optimization and typically make use of model predictive control (MPC) techniques.

2. Optimization Approach

The concept of microgrids can be expanded beyond the electric sector and can naturally encompass cross-sectorial energy systems. When treating different energy sectors on – at least in principal – equal footing, the complexity of the planning process tremendously increases. Using natural resources to satisfy human needs can be done in many different ways. The complexity of the resulting optimization problem is illustrated in in Figure 1. Clearly, standard methods are not sufficient to reliably find an optimal solution for this task, and advanced methods of mathematical optimization are to come into operation.

[1] Such quantitative estimates depend on the precise definition of the term *microgrid*, which range from coordinated distributed energy resources to an energy system which is fully capable of disconnecting from the higher-level grid. A comprehensive overview of definitions is available on https://building-microgrid.lbl.gov/microgrid-definitions.

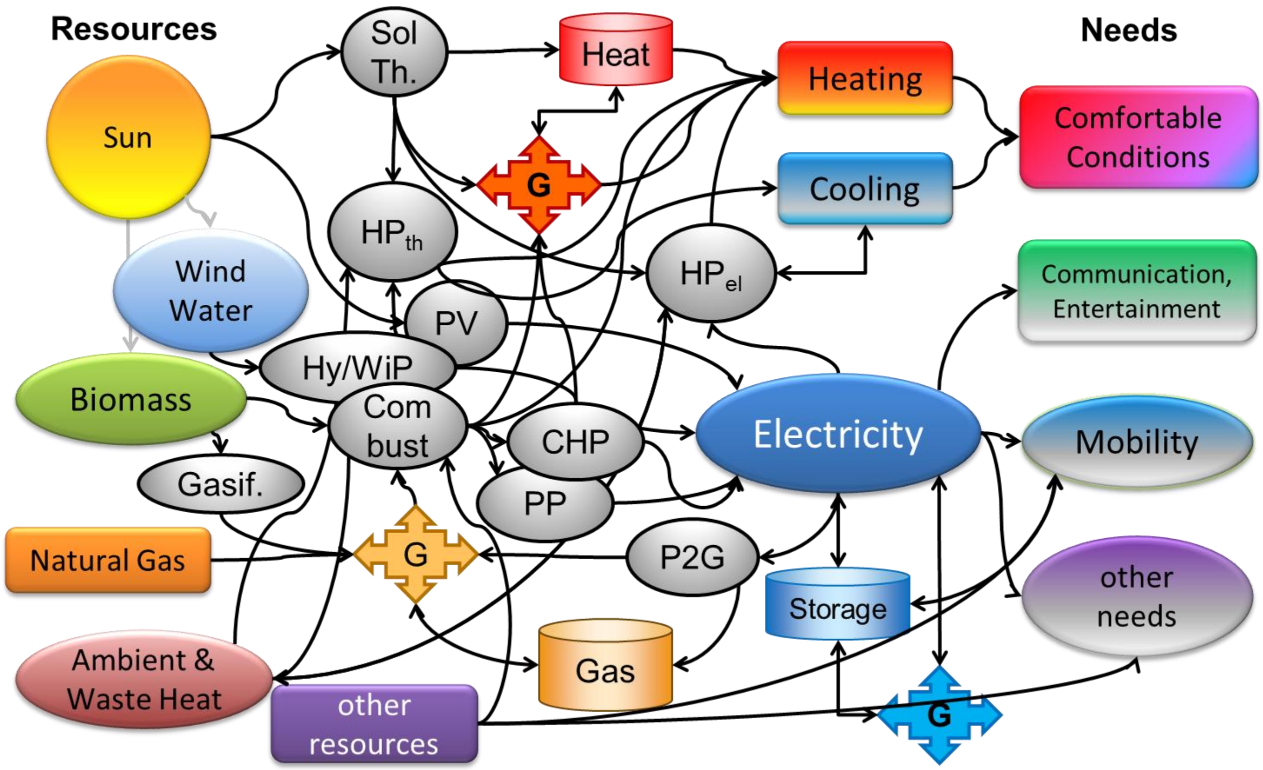

Figure 1: Illustrating the complexity of optimizing cross-sectorial energy systems. Each of the different sectors of the energy system (here electricity, heat and gas are explicitly shown) can contain storage devices and/or grids (denoted by "G").

For example, using solar energy for heating purposes can be done in the following ways:

- decentralized solar thermal devices, which have to be coupled with a storage tank (which is at least designed for shifting surplus gains during the day to the night),
- central solar thermal energy fed into a heating grid (which typically also incorporates other heat sources and may contain central or decentralized heat storage devices, even seasonal storage tanks),
- photovoltaics (PV) powering decentralized, electrically driven air or ground source heat pumps,
- PV and an electrically driven heat pump with a solar thermal system (including a heat storage device) as direct heat source,
- PV and electrically driven ground source heat pump with a solar thermal systems for regenerating ground heat during summer,
- thermal-powered heat pump with a solar thermal system as heat source, where the required high-temperature heat is provided by the combustion of synthetic natural gas, previously produced by PV (Power2Gas) and temporarily stored in the gas grid.

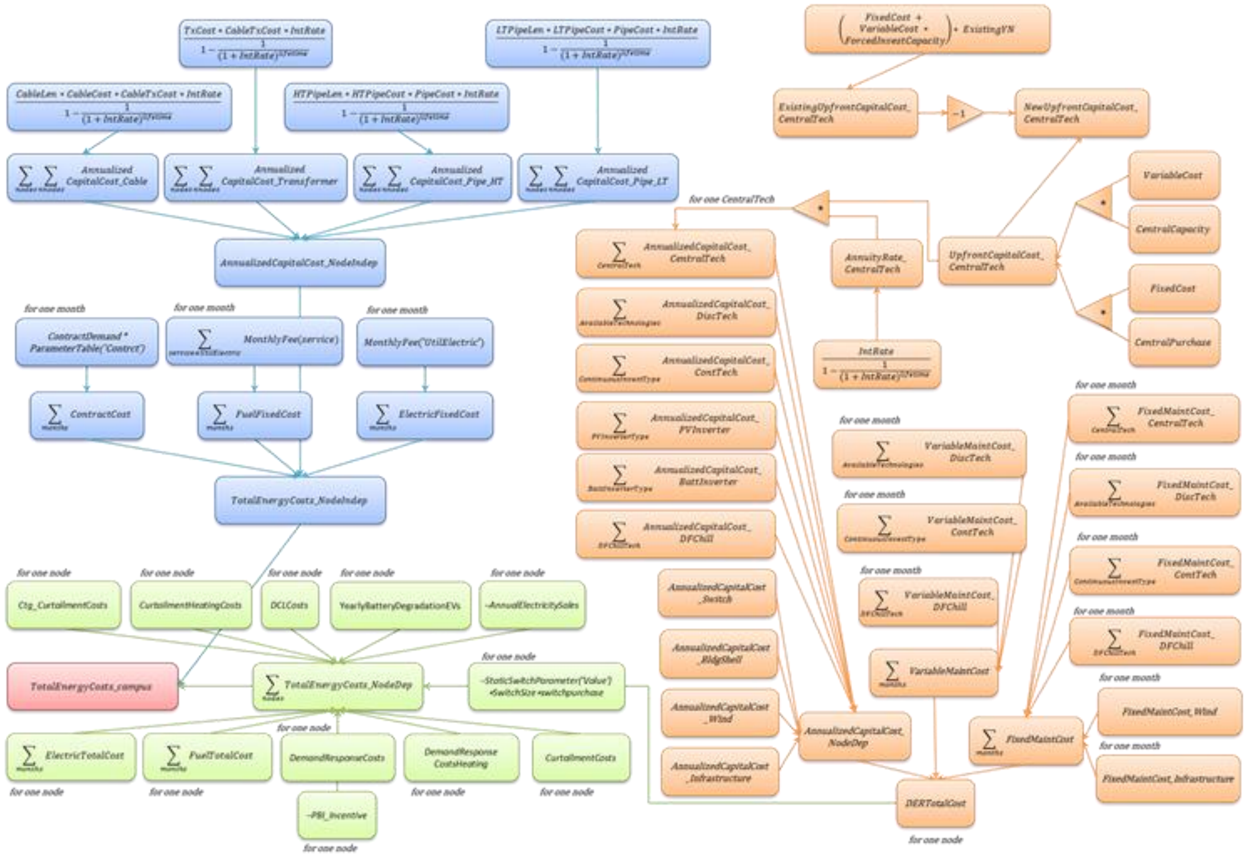

Figure 2: Graphical representation of the general structure of the optimization model

As a tool to deal with this complexity, we present an optimization platform, which allows economic and environmental planning, considering technical constraints as power flow for microgrids and enable them for smart microgrid control systems. It is built on the highly advanced planning tool DER-CAM+, developed at Lawrence Berkeley National Laboratory (LNBL)[2], which is widely accepted and has already been used for a large number of case studies and peer-reviewed research articles.[3] The general structure of the model is depicted in Figure 2, an example for a sub-sector in Figure 3.

However, there are some limitations, which BIOENERGY2020+ is overcoming by adding new algorithms, especially on the heating and solar thermal side of DER-CAM+ and by extending the modelling of the gas sector.

In the final stage of development, the platform will fully consider renewable resources as PV, wind, solar thermal, biomass and biogas, the latter also considered in the context of combined heat and power (CHP).

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[2] https://building-microgrid.lbl.gov/projects/der-cam

[3] See https://building-microgrid.lbl.gov/publications for a list of publications

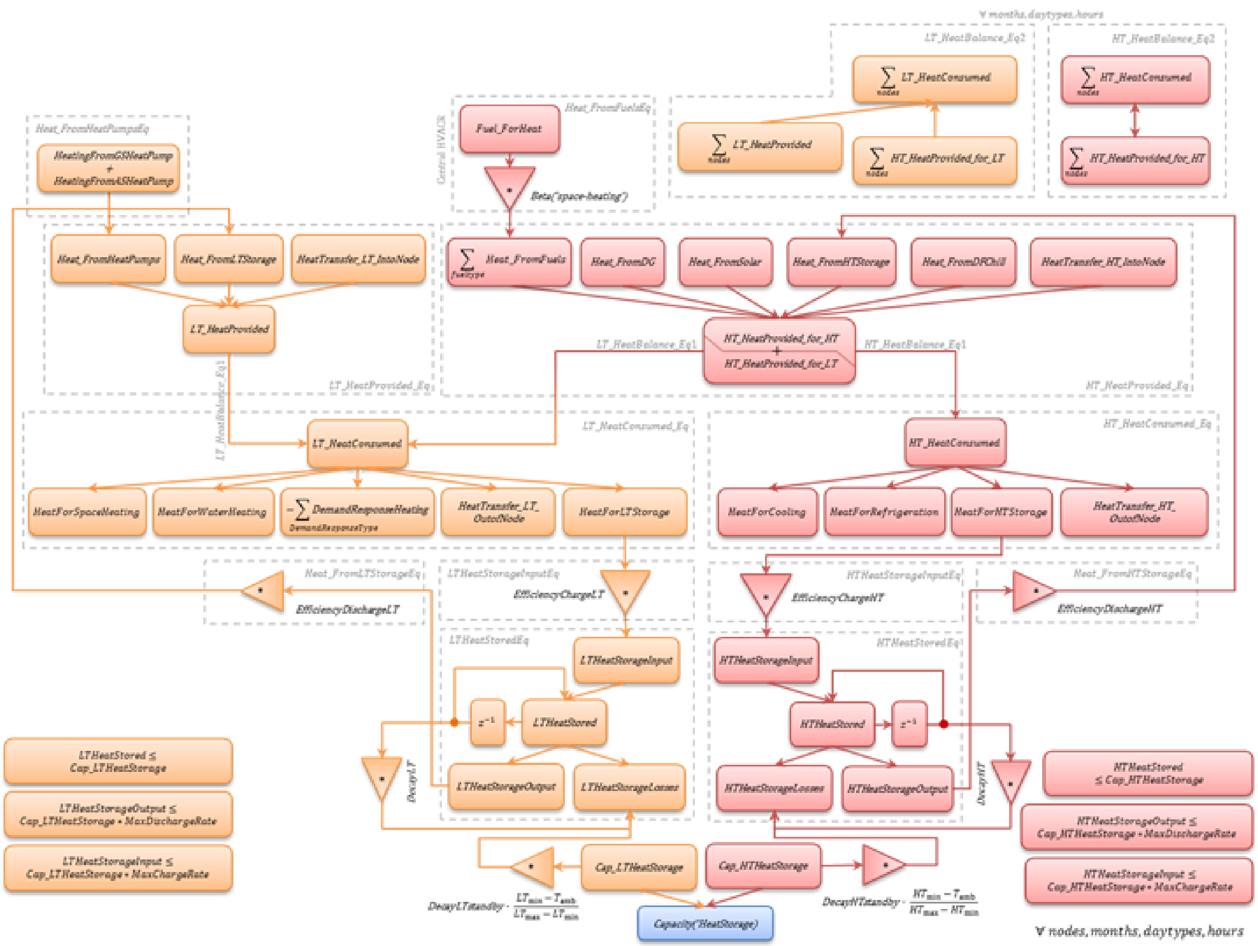

Figure 3: Preliminary graphical representation of the thermal sub-model

Of course, storage technologies (electric storage, hot water tanks and cold storage), which play a vital role in microgrid operation, are also included. Further technologies included in the approach are fuel cells, conventional internal combustion engines running on diesel, natural gas, or biofuel, as well as heat pumps and energy purchases from the utility. The operation of these technologies can consider bottlenecks in the heat distribution systems or electric distribution system as well.

The optimization problem is formulated as a mixed-integer linear program (MILP) that finds the optimal technology-mix (investments) while minimizing total energy costs or carbon dioxide (CO_2) emissions, or achieving a weighted objective that simultaneously considers both criteria. Unlike simulation-based models or optimization models based on heuristic and non-linear formulations, this allows quickly finding optimal solutions to this highly complex problem.

The key challenge lies in developing and implementing linear formulations that adequately represent different non-linear phenomena.

Optimization Inputs

In order to find the optimal investment portfolio, the following input parameters are required by the model:

1. **Load Data** - Customer's end-use hourly load profiles – disaggregated by major end-uses: e.g. space heat, hot water, natural gas, cooling, refrigeration, and electricity on at least 1 hour time steps, to model load shifting and demand response.
2. **Electricity Tariff and Fuel Costs** – The rates of the customer's electricity tariff, natural gas prices, and other relevant utility price data.
3. **Technology Costs & Parameters** – Capital costs, operation and maintenance costs, along with fuel costs associated with the operation of various available technologies and basic technical performance indicators of generation and storage technologies (e.g. electrical and heating efficiencies).
4. **Investment Parameters** – The discount rate on customer investment and maximum allowed payback.
5. **Network Topology** – In case of multi-node microgrids, energy networks models (electricity cables and gas/heat pipes characteristics) as well as their operational limits are considered.

Optimization Outputs

The main outputs determined by the optimization are:

1. **Optimal capacity** – The capacity of each technology considered per node (e.g. capacity in kWh of stationary battery).
2. **Optimal dispatch** – The suggested use of each installed technology, using energy management techniques (e.g. charge stationary battery from 15:00-17:00).
3. **Economic and ecologic results** – Detailed cost breakdown of supplying end-use loads and carbon emissions associated with supplying end-use loads (e.g. annualized investment cost of stationary battery).

3. Case Studie

In a characteristic case study, we demonstrate some of the key benefits of microgrids: higher efficiencies, higher penetration of renewables, and cost and CO_2 savings.

The aim of this use case was to determine the extent to which a comprehensive substitution of oil boilers in single-family households by alternative energy systems has an impact on energy costs and CO_2 emissions in a typical alpine valley.

For this purpose, data from various publications, specialist literature, statistical databases have been systematically analyzed and fed into the developed optimization model. This use case takes into account oil boilers, air and soil heat pumps, photovoltaics as well as solar thermal systems, heat storage and electricity storage.

All relevant techno-economic information regarding available generation and storage technologies are taken into account. All considered technologies have their own specific technical parameters such as efficiencies, response times, physical boundaries, conversion rates etc. In the case of electricity and heat storage systems storage specific parameters such as storage decay (portion of energy losses due to self-discharge over time) minimum and maximum state of charge and charge and discharge rate are taken into account. In addition to the technical characteristics of individual technologies, costs for acquisition, operation and maintenance, as well as lifetimes of the technologies, are included in the calculation.

Data regarding building stock, number of inhabitants (STATISTIK AUSTRIA, 2017; STATISTIK AUSTRIA, 2011), as well as the load data based on that (energy demand for hot water, space-heating as well as electricity demand for all other applications) (Edwards, Beausoleil-Morrison, & Laperrière, 2015; Fischer, Wolf, Scherer, & Wille-Haussmann, 2016) form the basis for the generation of load profiles. The load profiles are in the form of averaged hourly values for every hour of the month over the period of a full year.

Site-specific weather data such as temperature, solar radiation and wind speed are also entered in this format.

In addition, energy prices and CO_2 emission values of the energy sources used (oil and electricity purchased from the grid) are taken into account. The price for electricity used in this use case is 0.123 €/kWh + 12.81€ grid costs/month based on the tariff calculator from the E-Control (E-Control, 2018). For the fuel expenses 0.0647 €/kWh is used according to the Austrian Biomasse-Verband (Österreichischer Biomasse-Verband, 2017). The used CO_2 emission values for fuel of 0.28 kg/kWh refer to the info sheet CO_2 of the e5 Country's Energy Efficient Municipal Program (e5 landesprogramm für energieeffiziente gemeinden, 2017). For electricity purchased from the grid CO_2 emission rates are calculated depending on import statistics (E-Control, 2017) and emission rates of the considered neighbor countries (see Table 1).

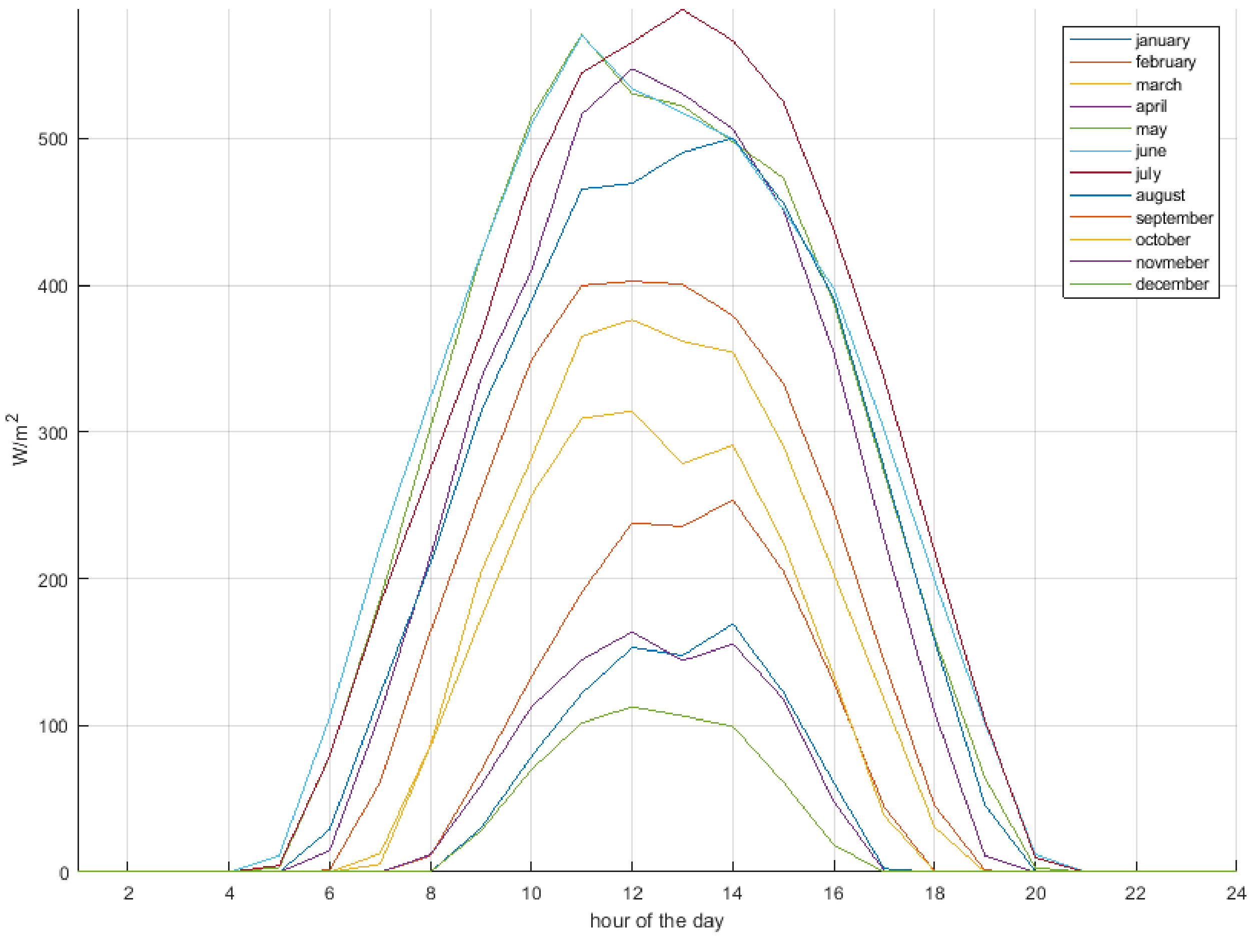

Figure 4: Global hourly solar radiation

In this use case, several locations (nodes), which extend over a valley with a length of approximately 42 km, are connected via electrical cables and a connection to the power grid (Point of Common Coupling = PCC) is provided at one side of the valley (see Figure 5).

The optimization runs provide results on CO_2 and cost saving potential, as well as expected electrical loads when switching from oil boilers to renewable forms of energy.

In the reference scenario (base case), the required electrical energy is obtained exclusively from the grid. The heat energy is provided by central heating boilers (oil heating). In the optimization calculations, optimization was once optimized for costs (Optimization I) minimization and once for CO_2 (Optimization II) minimization. In the latter case, the total annualized energy costs of the base case have been held (almost) fixed.

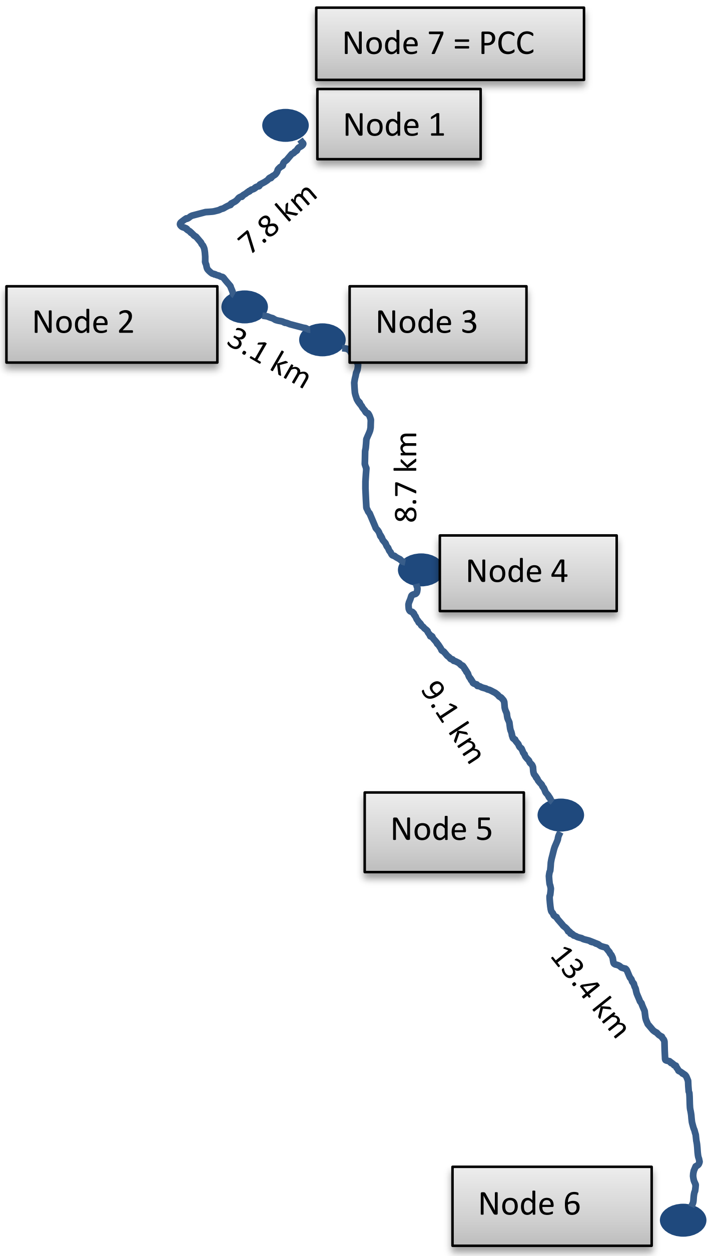

Figure 5: Topology of considered valley

When comparing the results of the two optimization runs (I and II), it becomes clear that in this setup the minimization of energy costs is also accompanied by a significant reduction of CO_2 emissions (37%), not much smaller than the one achieved by optimization with respect to CO_2. This result is of course heavily influenced by the CO_2 emissions attributed to the electricity purchase from the utility (see

Table 2).

Table 1: Emission rates for electricity production

CO_2 electricity mix		
	CO_2 in kg/kWh	**Source**
Austria	0.061	(Energie-Control Austria, 2017)
Czech Republic	0.67	(Jursová, Burchart-Korol, Pustejovská, Korol, & Blaut, 2018)
Germany	0.471	(BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2017)
Hungary	0.206	(European Enviroment Agency, 2017)
Italy	0.229	(European Enviroment Agency, 2017)
Slovenia	0.178	(European Enviroment Agency, 2017)
Switzerland	0.1494	(Alig, 2017)

Table 2: CO_2 emissions for electricity purchase

calculated CO_2 emissions in kg/kWh	
Month	**CO_2 emissions**
January	0.376
February	0.365
March	0.383
April	0.216
Mai	0.114
Jun	0.061
July	0.061
August	0.061
September	0.121
October	0.222
November	0.293
December	0.271

Table 3: Results of optimization runs with different objective functions

	Base case	Optimization I (cost minimization)	Optimization II (CO_2 minimization)
Description	electricity only from energy supplier; heat from central oil heating	electricity from energy supplier and new installed generation technologies; heat from renewable technologies	electricity from energy supplier and new installed generation technologies; heat from renewable technologies
Total Annual Energy Costs (incl. annualized capital costs and electricity sales) (€)	8,640,705	5,818,223	8,621,988
Reduction of Energy Costs (% of base case)		33%	0%
Total annual CO_2 emissions (kg)	8,161,630	5,162,512	4,989,135
Reduction of CO_2 emissions (% of base case)		37%	39%
Total annual electricity purchase (kWh)	11,611,355	18,326,494	17,653,090
Additional electricity purchase (% of base case)		58%	52%
Total annual fuel consumption (kWh)	63,735,586	0	0
Central heating oil ($kW_{thermic}$)	25,453	0	0
Air source heat pump ($kW_{electric}$)	0	0	871
Ground source heat pump ($kW_{electric}$)	0	3,107	5,752
Photovoltaic (kW), peak power under test conditions	0	3,054	3,054
Battery storage (kWh)	0	0	5,646

Heat Storage (kWh)	0	59,953	6,665

When the results of Optimization II and of Optimization I are compared, following differences can be observed:

- The installed power of heat pumps is more than doubled (6,623 kW vs. 3,107 kW).
- In addition to ground source heat pumps, also air source heat pumps are used, though exclusively in summer, since the temperature dependence of the coefficient of performance (COP) has a much larger effect for this technology (see also the detailed discussion on the next pages).
- The amount of thermal storage is reduced almost by a factor of ten (6,665 kWh as compared to 59,953 kWh).
- In addition, electric battery storage (5,646 kWh) is installed.

The reduction of thermal storage can be compensated by the additional battery storage, since a larger amount of heat pump power is available to produce heat on demand. Still, taking into account realistic COP values of 4, the total storage capacity of Optimization II is smaller than the one of Optimization I.

The investment costs of Optimization II are significantly larger than the ones of Optimization I, and this can only by partially compensated by the lower costs for electricity purchase, at least for the current level of prices for electric energy. In the case of Optimization II, a certain redundancy of technologies is present: In winter, only ground-source heat pumps are used, while in summer air-source heat pumps are favored due to the better COP. (Note that each node represents a well-connected agglomeration of producers, consumers and prosumers, not – at least in general – a single building. The result concerning heat pump technology is expected to be different if no aggregated description of buildings is used.)

Now, we take a closer look at some detailed results of the optimization.

Looking at the results of the Optimization II in the summer month (July) and the winter month (November), the interaction of the individual technologies can be represented very well. In July, with sufficient power generation, the battery is charged. The battery provides the stored electricity for afternoon hours, during which the power production of the PV system decreases (see Figure 6).

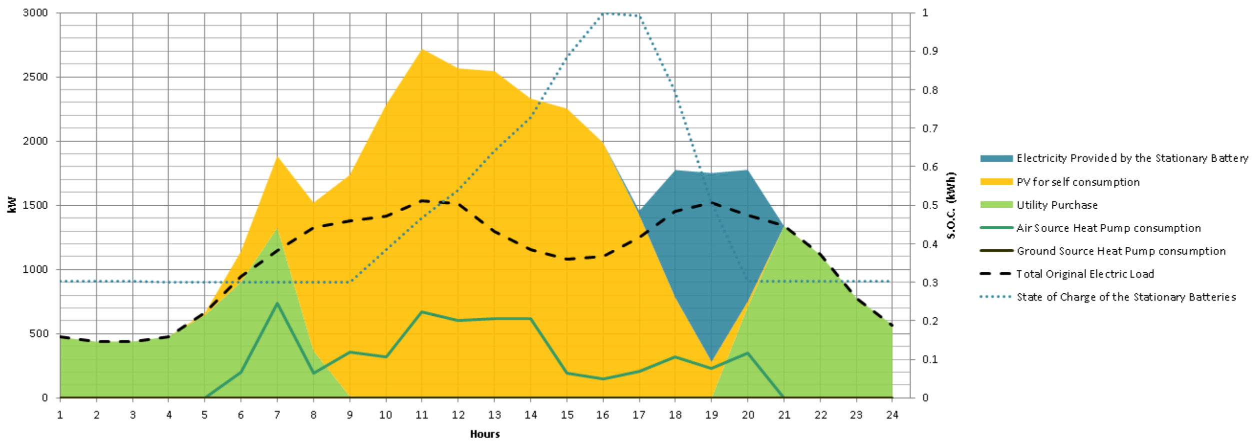

Figure 6: Optimal Dispatch for Electricity Technologies (July weekday)

The heat profile (Figure 7) shows that the heat storage is charged between 10:00 and 14:00. The stored heat is used in the evening hours to reduce the use of the air source heat pump.

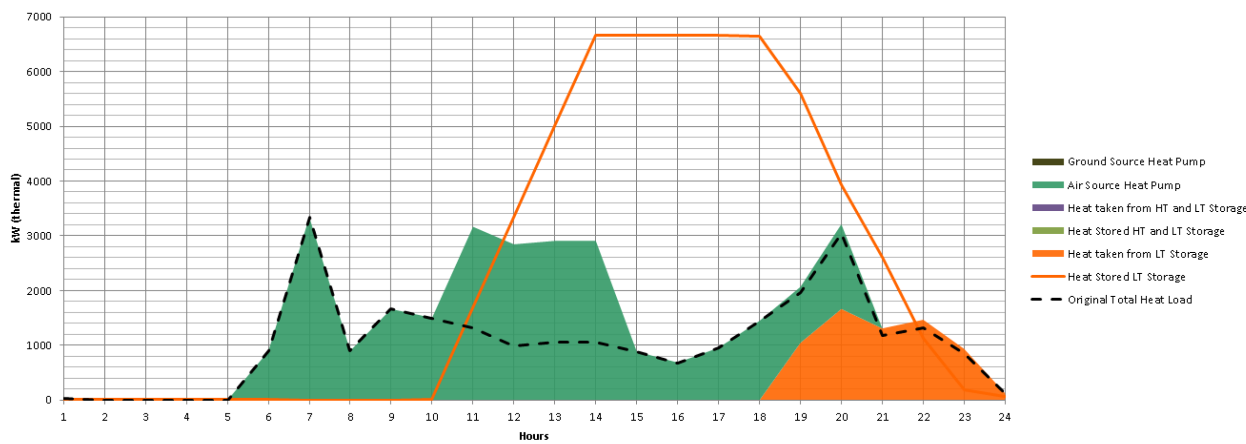

Figure 7: Optimal Dispatch for Heating Technologies (July weekday)

In November, a large part of the electrical energy is used for heat generation by a ground source heat pump. Due to the lower solar radiation in the winter months, the output of the PV system is not sufficient to make adequate use of the battery storage (see Figure 8).

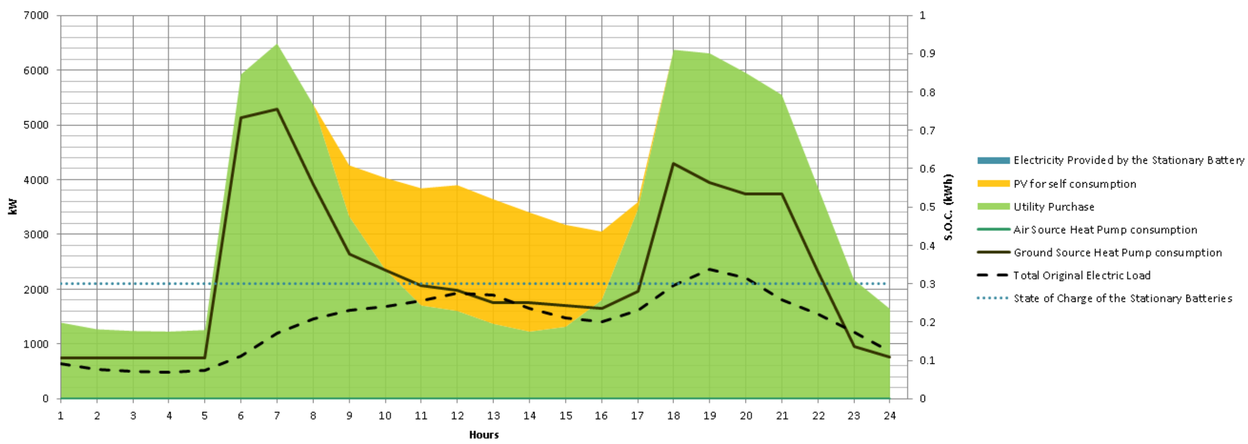

Figure 8: Optimal Dispatch for Electricity Technologies (November weekday).

From Figure 9 it can be seen that the entire heat production in the winter month of November is provided by the ground source heat pump. The air source heat pump is not used because of the low COP value caused by low outside temperatures.

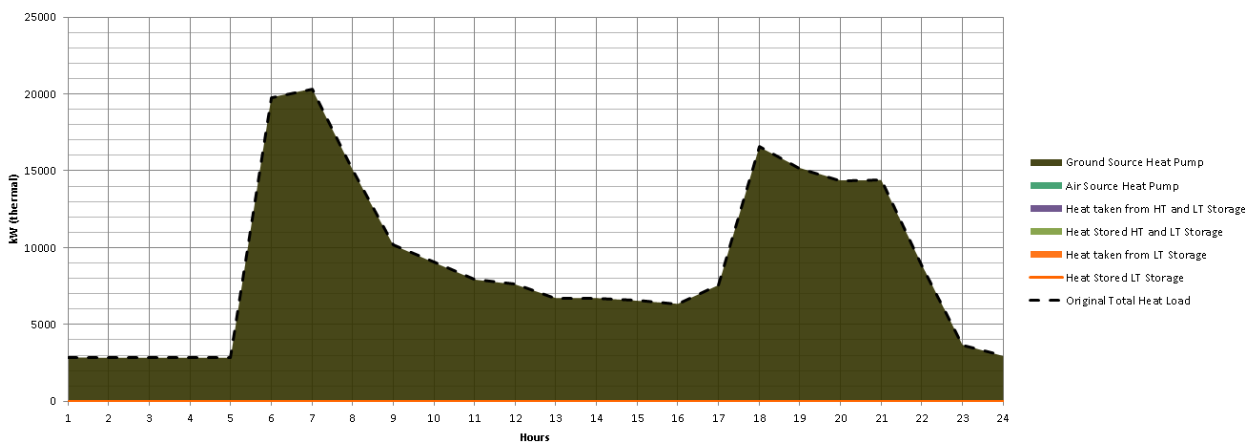

Figure 9: Optimal Dispatch for Heating Technologies (November weekday).

4. Conclusions and Outlook

In the case study presented in this article, while the costs and/or the CO_2 emissions could be significantly reduced by choosing an optimization-based solution, the considered valley is far from being autonomous. The electricity purchase from utility has even increased due to the use of heat pumps. Still, when choosing different boundary conditions, the present tool can also be used (and is indeed particularly well-suited) for the planning of microgrids, which can act autonomously and which in particular can disconnect from the utility in the event of a grid disturbance. For this case, both a high-level energy management system (typically based on model predictive control) and low-level controllers that can react within milliseconds on severe disturbances are required. For the communication between the different control layers, a proper interface, as defined in the Microgrid Controller Standard IEEE 2030.7, has to be available.

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