PLANNING OF SUSTAINABLE ENERGY SYSTEMS FOR RESIDENTIAL AREAS USING AN OPEN SOURCE OPTIMIZATION TOOL AND OPEN DATA RESSOURCES

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KEYWORDS

Multi Modal Energy System Simulation and Optimization, Open Science, Helmholtz Open Source Framework for INtegrated Energy System Assessment (FINE), Sector Coupling, Time Variance, Open Source, Open Data, Energy System Model, District Optimization.

ABSTRACT

Global warming and CO_2 emission reduction targets mandate a closer look to energy system planning on different levels. In this work we model a typical residential area that will be built and has to be equipped with a cost optimized, decentral energy system with a high degree of energy autarky and integration of renewable sources. We sketch out the optimization problem and show that the optimization can be done using open data and an open source tool, the Helmholtz Framework for Integrated Energy System Assessment tool, FINE, exclusively.

The energy system model chooses from a predetermined set of technologies, takes into account a temporal discretization approach for energy demands as well as for energy production capacities and considers decentralized sector coupling options. As a result, we get a cost-optimized energy system structure as a base for energy system design.

INTRODUCTION

“CO_2 emission reduction and increasing volatile renewable energy production mandate stronger energy sector coupling and the use of energy storage” (Ripp and Steinke 2019) and the investigation of decentral power supply.

In support, we model, optimize and assess the energy system of a residential area including a typical, time-discrete consumption structure as well as a multi modal, energy system. Main optimization targets are Goals Seven (Affordable and Clean Energy) and Eleven (Sustainable Cities and Communities) of the United Nations’ Sustainable Development Goals (UN SDG, https://sdgs.un.org/goals) - in addition to the minimization of costs for the applied technologies and the referring commodities.

Along with the trend to open science (Hilpert et al. 2018), we use open source data for demands, applied technologies and commodities in conjunction with the Helmholtz open source *Framework for INtegrated Energy System Assessment* (FINE, Welder et al. 2018b). On top of being available without additional cost, open source data and software ensure that our model is reproducible and can easily be developed further by interested communities. Furthermore, the open source modelling software FINE ensures high quality of code and functions as it will be constantly scrutinized by a top qualified scientific community – especially within the highly reputed Helmholtz Association (Balter 2015).

This kind of optimization tool, and further developments of it, can help with the choice of sectors, technologies and connections to incorporate for any kind of residential or industrial area. Thereby it can be a support to anybody who intends to design, plan or implement an energy network (Lund et al. 2017). Interested parties might include project developers, building contractors, planning offices, local authorities, institutional investors or credit institutions.

Existing studies on sector coupling modelling include for instance considerations of the integration of hydrogen into energy models (Welder et al. 2019), national energy systems (Welder et al. 2018; Welder et al. 2019; Ball et al. 2007) or appraisals of different modelling approaches (Hilpert et al. 2018).

In this work we enhance existing research with a use case, in which we show, that the open source optimization tool FINE is well suited to design and optimize a multi modal energy system for a real-world residential area. And it can be done using open source tools and open data, exclusively.

PROBLEM STATEMENT

The core of our decision problem is a residential area for which we want to configure an energy system that takes into account all of the framework conditions below. That means that from a given portfolio of technologies for energy production and supply, a technology mix should be chosen, that, considering the framework conditions, leads to minimized energy system costs and CO_2 emissions [capital expenditure (CAPEX) and operational expenditure (OPEX)]. Thus, the output of our energy system planning delivers recommendations for a future design of the system.

In rough terms our model follows a call for bids for the design of a residential area on a four-hectare commercial fallow land area in the city center of Brake in northwestern Germany. So, we will also be able to discuss our findings with the mayor of Brake to provide some input concerning the energy system of the final design of the area.

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FINE helps to capture the time-dependence of energy demands, fluctuation of renewable energy production and sector coupling options.

For our use case, we model a typical residential area (composition see Figure 1) including the following framework conditions:

- 65 residential units (houses & apartment blocks)
- Integration of public and commercial infrastructure (Figure 1 and Table 1)
- Decentralized energy supply and a high degree of self-sufficiency (in terms of energy)
- Integration of renewable energy sources and components (technology portfolio see Figure 2)
- Individual traffic with a high share of electro mobility
- Creation of a heat compound system as an isolated solution

All energy demands in this work are stated in yearly numbers.

Objective Function

Target of the optimization process is to minimize the total costs (CAPEX and OPEX) of the energy system (Welder et al. 2018a), to maximize revenues from feeding surplus electricity into the public electricity grid, and to minimize induced CO_2 emissions (covered in the OPEX).

Min → Costs over Lifetime

$$= CAPEX + \sum_{t=1}^{n} OPEX_t - \sum_{t=1}^{n} Revenues_t$$

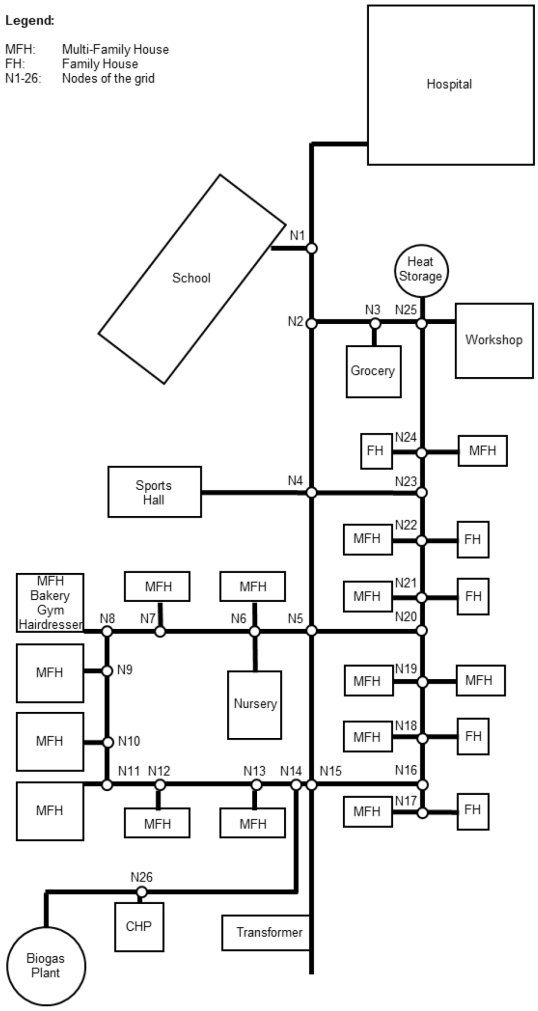

Figure 1: Schema of Buildings, Components and Grid

Table 1: Demands and Capacities of Residential Area Infrastructure per Building Type

Infrastructure classification	Building Type	No. of Buildings	No. of House holds	No. of Residents /Unit	Electricity Demand [kWh]	Heat Demand [kWh]	Roof Surface for Solar Thermal/ Photovoltaic System [m²]	PV Potential Capacity [kWp]	Solar thermal Capacity [kW]	P2H Capacity [kW]	Max. Battery Storage Capacity [kWh]	Max. Heat Storage Capacity [kWh]
Residential	Multi-Family House	3	8	3	114,880	108,000	300	48.0	103.8	255.0	150.0	295.3
	Multi-Family House	1	6	3	29,091	27,000	100	16.0	34.6	85.0	50.0	78.4
	Multi-Family House	4	4	3	76,587	72,000	400	64.0	138.4	340.0	120.0	196.8
	Multi-Family House	7	2	3	69,608	100,800	560	89.6	193.7	595.0	140.0	176.4
	Family House	5	1	4	24,755	45,000	250	40.0	86.5	425.0	50.0	84.5
Public	School	-	-	-	25,000	262,500	500	80.0	173.0	85.0	30.0	-
	Nursery	-	-	-	7,500	78,750	100	16.0	34.6	85.0	-	-
	Sports Hall	-	-	-	26,250	70,000	320	51.2	110.7	85.0	-	-
	Workshop	-	-	-	9,000	33,700	450	72.0	155.7	85.0	-	-
	Hospital	-	-	-	-	-	600	96.0	207.6	-	-	-
Commercial	Grocery Store	-	-	-	6,075	10,125	200	32.0	69.2	85.0	-	-
	Bakery (Int. in MFH 6 HH)	-	-	-	150,000	54,000	-	-	-	-	-	-
	Gym (Int. in MFH 6 HH)	-	-	-	19,440	16,200	-	-	-	-	-	-
	Hairdresser (Int. in MFH 6 HH)	-	-	-	5,265	12,555	-	-	-	-	-	-
Total		**20**	**21**	-	**563,451**	**890,630**	**3,780**	**604.8**	**1307.7**	**2125.0**	**540.0**	**831.4**

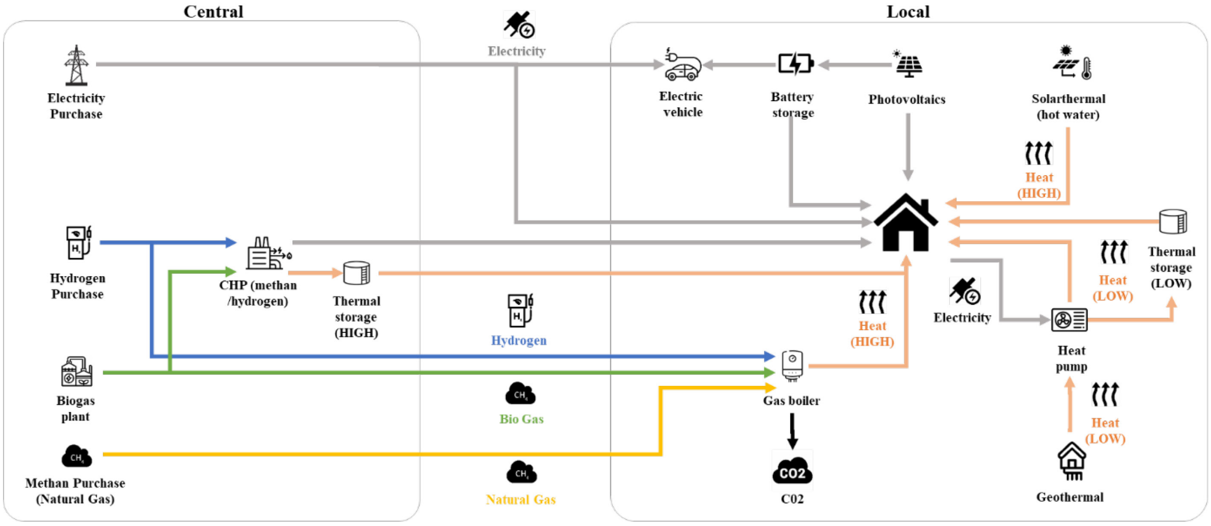

Figure 2: Schematic Diagram of Technology Composition and Interdependencies

In order to evaluate the competitiveness of the resulting energy system we also simulate the referring Levelized Cost of Energy (LCoE) for power and heating of the resulting system.

$$\mathrm{LCOE} = \frac{\text{SUM OF COSTS OVER LIFETIME}}{\text{SUM OF ENERGY PRODUCED OVER LIFETIME}}$$

$$= \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+i)^t}}{\sum_{t=1}^{n} W_t}$$

I_t: Investment expenditures in the year t
M_t: Operations and maintenance expenditures in the year t
F_t: Fuel expenditures in the year t
W_t: Energy generated in the year t
i: Interest rate
n: Expected lifetime of the energy system (Panos 2017).

Whereas F comprises methane and hydrogen.

Constraints:

- All energy production, except from natural gas, must be from renewable sources
- For purchased electricity from local utility we assume eco-electricity contracts
- Overproduction can be sold
- CO_2 emissions are controlled via penalty costs

Assumptions:

- Commodity prices keep constant
- Power- and heat demands are time-varying
- All data input is deterministic
- CAPEX and OPEX for cables (electricity) and pipelines (heat, H_2, natural gas) are not considered. Our model is confined to identify the necessary performance levels

The planning horizon for our model conforms to the predicted technological life-spans for most of technologies for choice, which is 20 years.

Thus, we can characterize the optimization that we solve, as dynamic decision making (DDM, Hotaling et al. 2017) for a defined period of time with predetermined options (Figure 2) and deterministic planning. The stochastics of exogenous parameters to the system are not considered in our study (see section Solution Approach).

SOLUTION APPROACH

Modelling- and Optimization Tool

For solving our problem, we use the Framework of INtegrated Energy System Assessment (FINE), that was developed by the Helmholtz Energy Computing Initiative (HCEI, Welder et al. 2018a and 2018b). For download, documentation, tutorials and examples please refer to https://github.com/FZJ-IEK3-VSA/FINE.)

FINE is an open source, Python based framework that offers algorithms, component and commodity libraries, variables, and data import features to model, optimize and assess energy systems. It can tackle the challenge of representing the spatial, the temporal as well as the sector-coupling dimensions of multimodal energy systems. Load- and feed-in profiles can be considered in full temporal resolution. The component libraries comprise state of the art options for all parts of the system: Source, conversion-, sink-, storage- as well as transmission component and commodity choices.

We adapt the Urban District Optimization (UDO) workflow, that is recommended by HCEI, to our needs. (https://github.com/FZJ-IEK3-VSA/FINE /blob/master/examples/District_Optimization /Urban_District_Optimization_Workflow.ipyn):

First, based on the structure of the residential area, the energy demands (electricity and heat) have to be determined. In the second step, the possible technology portfolio with the relevant techno-economic parameters has to be identified. In the third step, all data requirements for determining the load profiles are to be established and the data must be processed. The technology portfolio and the load profiles are input information to the fourth step, the modelling of the energy system model in FINE (Example see Figure 3).

```
esM.add(fn.Source(esM=esM,
                  name='H2Purchase',
                  commodity='hydrogen',
                  hasCapacityVariable=False,
                  operationRateMax=data['H2 Purchase, operationRateMax'],
                  commodityCost=0.285))
```

```
esM.add(fn.Source(esM=esM,
                  name='PV',
                  commodity='electricityPV',
                  hasCapacityVariable=True,
                  hasIsBuiltBinaryVariable=True,
                  operationRateMax=data['PV, operationRateMax'],
                  capacityMax=data['PV, capacityMax'],
                  sharedPotentialID ='roofArea',
                  interestRate = 0.04,
                  investIfBuilt=1000,
                  investPerCapacity=1400,
                  opexPerCapacity = 14,
                  bigM = 700))
```

Figure 3: Example of Commodity Sources Definition

In this step the energy system is modeled using the subclasses sources, sinks, conversions, storages and transmissions. After modelling the energy system, it has to be optimized to get a recommendation for the energy system structure of the residential area. For this optimization we use the FINE standard solver Gurobi in the current version 9.1.1.

We were able to define all choices of components and commodities for our residential area model as well as the associated cost- (CAPEX and OPEX), capacity and demand variables in FINE. It is also possible to define a presetting that includes all of the framework conditions mentioned above, including time series for the time-dependence of energy demands and production.

Our model includes the following energy system components (Figure 2):

- Sources: Photovoltaics, solar thermal collectors, biogas plant, electricity purchase, hydrogen purchase, natural gas purchase
- Conversion: Geothermal, gas boilers, combined heat and power plant (CHP), P2H
- Storages: Battery storages, thermal storages (high, low)
- Transmission (commodities): Electricity, hydrogen, natural gas, biogas, heat (high)
- Sinks: Electricity demand, heat demand, electricity sales PV, electricity sales CHP

Collection, Preparation and Processing of Data

The accuracy and results in energy system modelling depend on the availability, selection and preprocessing of input data. For our model we need electricity and heat demands, load profiles, generation capacities as well as techno-economic parameters. Temporal and spatial scales determine level of detail and resolution requirements.

Our residential area consists of 26 buildings, a biogas plant, a CHP as well as a central heat storage in a spatially distributed network with 26 nodes and a transformer (Figure 2).

The investigated annual electricity and heat demands of the residential, public and commercial units as mentioned in Table 1, depend on the number of residents and households per building, the number and usage of electrical vehicles (e-vehicles) and individual user behaviour for hot water demand (Worm and Rathert 2015; Mailach and Oschatz 2016; Stadtwerke Gießen AG, n.d.)

In our model, the temporal resolution is one hour which results in 175,200 time steps for twenty years. The basis for the simulation of the loads and generation profiles is the historical weather data by the German Weather Service (DWD) with mean temperatures for the period of 2010 to 2020 on hourly level for the Bremen region.

The annual demands are distributed temporally as well as according to the load profiles for electricity and heat demand. The load profiles we use are provided by the project DemandRegio (Gotzens et al. 2020; https://github.com/DemandRegioTeam/), as well as by the Open Source Load Profile Generator (Pflugradt 2016; https://www.loadprofilegenerator.de/) for e-vehicles and hot water profiles.

For the electricity demands the following profiles are applied:

Table 2: Applied Load Profiles Buildings

Building Type	**Load Profile**	
Private Households	H0	Household dynamized
School, Nursery, Workshop	G1	Commerce in General
Sportshall, Gym	G2	Businesses with heavy to predominant consupmtion in the evening hours
Grocery Store	G3	Commerce Continous
Bakery, Hairdresser	G4	Sales Outlet/Barber Store

The profiles for electricity demand consider the seasonality in general and a daily factor in case of profile private households (H0).

The e-vehicle profiles are also generated using the Load Profile Generator and distributed among the residential buildings:

Table 3: Applied Load Profiles E-Vehicles

No.	**Load Profiles E-Vehicles**		**Charging Power [kW]**
3	CHS01	Family, 2 children, single family home, 2 Cars	3.5
9	CHR02	Couple, 30-64 years, with work, multi-family house, 30 km commuting distance	11
5	CHR51	Retired, >65 years, multi-family house, 5 km commuting distance	11
4	CHR07	Single, with work, muliti-family house, 30km commuting distance	22

Furthermore, we use the Technical University of Munich (TUM) Sigmoid Function (BDEW/VKU/GEODE-Leitfaden 2018). This function uses the annual heat demand, above mentioned historical mean temperature and the parameters in its specification 33 (medium heating demand) to calculate the hourly heat demand per building type.

Depending on the building type, the following heat profiles are used: SpaceHeating-EFH for Family Houses; SpaceHeating-MFH for Multi-Family Houses; GKO: Local authorities for School, Nursery and Sports Hall; MK: Metal and automotive for Workshop; BA: Bakery for Bakery; HA: Retail and wholesale for Grocery Store; BD: Other operational service for Gym and Hairdresser.

Hot water profiles are generated using the Load Profile Generator for a 3-person household and a 4-person household.

For the photovoltaics (PV) and solar thermal energy generation profiles the above-mentioned historical weather data with direct and diffuse solar radiation data is used to calculate the global solar radiation on an hourly basis. The maximum installable capacity for PV and solar thermal collectors is determined by the available roof area and has to be split between both. The module efficiency factor for PV is set to 0.16 and the solar constant to 1,000 W/m². For solar thermal the overall equipment effectiveness is set to 0.3 and tilt factor of 1.1. FINE then calculates the hourly electrical (PV) and thermal (solar thermal) yield with the help of global solar radiation, installable capacity and set P-Ratio of 0.85 (PV, Quaschning 2013).

The area that could be used for geothermal collectors, theoretically would be limited by the existing area. For simplification purposes, we assume it as unrestricted so that all necessary heating capacities can be installed.

For the central high heat storage, we allow for a capacity of 35,000 kWh and a lower limit of 2,500 kWh. For the local heat storages, aggregated from low and high heat, maximum capacities are specified in Table 1.

The battery storages capacity for each building can be extracted from Table 1.

Maximum capacities of local Power-to-Heat (P2H) comprise 85 kWh at every residential infrastructure, the School, Sport Hall, Nursery, Workshop and Grocery Store each. A central P2H plant encompasses a maximum of 2,000 kWh and a lower limit of 500 kWh at the central heat storage location. CHP capacities comprise one 500 kWh unit with a lower limit of 100 kWh and one 1,500 kWh unit with a lower limit of 500 kWh at the CHP location as well as two 500 kWh units with a lower limit of 100 kWh, each, at the Hospital location.

We assume the cost structure of the technology portfolio (Tables 4 and 5) based on the following studies: Fattler et al. 2019; Lauinger et al. 2016; Lindberg et al. 2016a; Lindberg et al. 2016b; Mayer et al. 2015; Samweber and Schifflechler. 2017; Stenzel et al. 2019; Sterchle et al. 2016; Streblow and Ansorge 2017; Bundesnetzagentur 2021; Kraft-Wärme-Kopplungsgesetz - KWKG 2020.

Other techno-economic parameters include the following:

Table 4: Other Techno-Economic Parameters

Interest Rate	4%
Household Electricity Price	0.2986 €/kWh
Household Natural Gas Price	0.0615 €/kWh
PV Feed-In Tarif	0.08 €/kWh
CHP Feed-In Tarif	0.073 €/kWh
Purchase Price Biogas	0.12 €/kWh
Purchase Price Hydrogen	0.285 €/kWh

For power and gas from local utility, we assume 0.33 and 0.2 kg/kWh CO_2 emission into the atmosphere. In our model we impede these emissions by applying penalty costs of 1,000€/kg CO_2.

We assume that the distribution grids for electricity, natural gas, biogas and hydrogen are already in place. Therefore, the costs for the distribution grids are not part of the optimization.

Kannengiesser et al. 2019 suggest that a clustering of 20 typical time periods would be the most appropriate trade-off between accuracy and computional load, in their setting. Still, due to restrictions of time and computing capacities, we applied a clustering of 5 typical periods. For that same reason a mixed integer programming gap (MIPGap) tolerance of 0.0005 is set.

Table 5: Technology Portfolio - Cost Structure

Installation	**Technologies**	**$CAPEX_{Cap}$**	**$CAPEX_{Fix}$**	**$OPEX_{Cap}$**	**Efficiency**
Local	**PV**	1,400 €/kWp	1,000 €	1.0% of $CAPEX_{Cap}$	-
	Solar Thermal	1,400 €/kWp	1,000 €	1.0% of $CAPEX_{Cap}$	-
	Geothermal Heat Pump	1,700 €/kWth	-	1.3% of $CAPEX_{Cap}$	-
	Condensing Boiler	200 €/kWth	5,600 €	5.0% of $CAPEX_{Cap}$	95.0%
	PH2	350 €/kWth	-	2.0% of $CAPEX_{Cap}$	
	Battery Storage	1,300 €/kWel	2,000 €	-	0.01%/h
	Heat Thermal Storage	55 €/kWth	-	-	0.1%/h
Central	**CHP**	720 €/kWel	-	4.0% of $CAPEX_{Cap}$	45%el/40%th
	Battery Storage	1,000 €/kWel	-	-	0.01%/h
	Heat Thermal Storage	18 €/kWth	-	-	0.1%/h

RESULTS

With regard to the overall effort for the simulation, we can state that the biggest share goes into research and preparation of the required data. The work needed for the modelling depends on the size of the problem, e.g. the number and variation of buildings, the temporal resolution (number of time steps) and the time span that is calculated. As FINE is a Python based software, we consider the coding process for the simulation as manageable. The pure calculation time of one simulation run depends on the size of the problem as well as on the configuration of the available hardware. For a detailed introduction please refer to Welder et al. 2020. All in all, FINE proved well suitable for the task.

As a result of the optimization, FINE recommends the following mix of technologies for installation. The power demand is covered by photovoltaic and CHP. In addition, a central electricity battery storage with a capacity of approx. 26 kWh is suggested. The power system results in total costs of approximately 2 Mio. EUR for 20 years. The heat demand of the locations is covered by CHP capacities. Furthermore, the residential houses will be supplied by local geothermal capacities. In the location 'School' a condensing boiler plus a Power-2-Heat (P2H) capacity is suggested. In addition, thermal storages are planned as a local solution. Biogas and (green) hydrogen are used as fuels for the CHP. Biogas is also used in the condensing boiler. The total costs of the heating system amount to approximately 2.54 Mio. EUR. The aggregated results of the energy system optimization are shown in Table 6. Elements of the technology portfolio that have not been considered by the optimization are not mentioned in the table.

The levelized costs of electricity for our system amount to 0.15 EUR/kWh. The levelized costs of heat amount to 0.12 EUR/kWh. (The LCoE are calculated with an interest rate of zero; costs of distribution are not considered in the model).

Based on data of the Federal Office of Statistics (Statistisches Bundesamt 2021), the average costs of electricity sum up to approximately 0.3 EUR/kWh in 2020; for district heating approximately 0.1 EUR/kWh. That means, in the FINE optimized system about 0.15 EUR/kWh could be spend on electricity cables as distribution capacities.

Considering the results of our study, it seems possible to build and operate a competitive and sustainable energy system with zero CO2-emissions.

Table 6: Optimization Results - Recommended Energy System Structure and Cost Information

PV Generation - Hospital		**Unit**	
PV capacity	86	kW	
PV generation	88,516	kWh/a	
Heat Geothermal	(All residential buildings receive geothermal energy)		
Geothermal capacity	78	kW	
Geothermal generation	390,438	kWh	
Fuels			
Biogas	1,400,012	kWh/a	
Hydrogen	59,349	kWh/a	
CHP	**Electric Capacity [kW]**	**Electricity Generation [kWh]**	**Heat Generation [kWh]**
Central CHP	100	228,591	203,192
Local CHP - Hospital	125	352,326	313,178
Boiler	**Capacity [kW]**	**Heat Generation [kWh]**	
Boiler - School	51	160,013	
P2H	**Capacity [kW]**	**Heat Generation [kWh]**	
Local PH2 - School	2	2,970	
Storage	**Capacity [kWh]**		
Central Battery (Medium)	26		
Local Thermal High Heat	423		
Local Thermal Low Heat	112		
CAPEX/OPEX	**CAPEX [EUR]**	**OPEX [EUR/a]**	
PV	122,033	1,210	
Geothermal	132,291	1,712	
Central CHP	72,219	2,909	
Local CHP - Hospital	89,781	3,616	
Boiler	15,884	514	
P2H	793	16	
Central Battery (Medium)	26,245	-	
Local Thermal High Heat	23,261	-	
Local Thermal Low Heat	6,137	-	
Fuel Costs	**[EUR/a]**		
Biogas	168,001		
Hydrogen	16,914		
Levelized Costs of Heat	**Total Costs [EUR]**	**EUR/kWh**	
CHP	1,614,928		
Geothermal	459,677		
Boiler	430,411		
P2H	10,029		
Storages	29,398		
Total costs	**2,544,442**	**0.1189**	
Levelized Costs of Electricity	**Total Costs [EUR]**	**EUR/kWh**	
CHP	1,825,903		
PV	146,240		
Storages	26,245		
Total costs	**1,998,387**	**0.1502**	
Electricity Demand	**665,408**		

CONCLUSIONS

Our main finding is that FINE is an appropriate tool to model and optimize energy systems based on open access energy data. The consideration of time-dependent demand and supply fluctuation as well as sector coupling options are features that will be needed to handle future energy system management. Based on the problem statement of creating a sustainable energy system for a residential area, we were able to show that specifically in terms of LCoE our result appears to be competitive with current (conventional) energy systems.

In future research and applications, the results of the study can be transferred to similar energy system planning problems like other residential areas, industrial compounds or village structures.

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