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Economic and environmental benefits of decentralized multi-energy systems for energy communities

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Abstract. In the context of growing interest in decentralised multi energy systems, this work aims at quantifying the benefit of optimized energy concepts for energy communities at the neighbourhood scale compared to individually optimized solution. To tackle this question a multi-objective optimization framework was developed and applied to a case study of 6 buildings consisting of 85% of residential dwellings and 15% to retail shop and food stores. Grouped buildings have decreased costs and greenhouse gases emissions (GHGE) respectively by 18% and 12% in the cost optimum compared to individual buildings. In the environmental optimum, costs have decreased by 11%, while GHGE remains in the same range. This decrease is at both optimum driven by electricity prices favourable to large consumers since exchanges on the electrical microgrid for this neighbourhood is very small. Optimal decrease of GHGE is obtained with greater use of HPs and smaller natural gas consumption. This work illustrates the interest of multi-objective approaches to identify optimal energy solutions for groups of buildings.

1. Introduction

The energy demand profiles of buildings are influenced by many factors such as the building typologies, the user behavior, the heating, and domestic hot water (DHW) consumptions. In addition, the popularity of heat pumps for space heating (SH) increases the electricity demand in winter. Conversely, decentralized intermittent electricity production increases to meet national greenhouse gases emissions (GHGE) targets. Thus, there is a rising mismatch between the building electricity demand and the local electricity supply. Increased interest in decentralized multi-energy systems (DMES) concepts paves the way to find better solutions by looking at more than one building and by synergistic planning of local heating and electricity supply systems. [1,2] show that DMES offers a large potential for deployment by reducing energy consumption, costs, and environmental impact[1,2]. Nevertheless, so far, the interest of grouping buildings in energy communities has not been quantified compared to individually optimized solutions. This is the aim of the proposed work.

2. Methodology

While cost drives investments, reduction of GHGE is mandatory to reach the Paris agreement's goals, thus both indicators need to be considered at the same time. Therefore, multi-objective optimization (MOO) is essential to answer the set research question. Among other existing software (DER-CAM, urbs, python-ehub/hues presented in [3]) implement different optimization methods for the building energy sector such as Mixed-Integer Linear Programming (MILP), genetic algorithm, etc. Moreover, Open-source framework like FINE [4] and OEMOF [5] as well as commercial software like URBIO (https://www.urb.io/) and Sympheny (https://www.sympheny.com) were also found to be relevant for these questions. However, no open-source software directly provided a MOO tool.

Therefore to address the problematic, a MOO framework Optihood [6] was developed based on OEMOF as it met most of the requirements needed. It combines MILP optimization methods with dynamic energy and life cycle assessment (LCA) simulations. From a list of defined technologies comprising of heat pumps (air source: ASHP and ground source: GSHP connected to borehole heat exchanger: BHE), boilers, photovoltaic (PV) panels, solar thermal (ST) collectors and storage technologies (electrical and thermal), the framework optimizes the technology choice, the sizing, and the operation of the energy system based on two objective functions. Moreover, the tool enables to optimize the buildings energy system in two scenarios: 1) Buildings are considered individually with their own energy system; excess electricity production is sold to the local energy provider. 2) Buildings are grouped within an energy community through an electrical microgrid by allowing the local electricity production to be shared between them; electricity purchases are also mutualized and take advantage of a favourable pricing. In this work, no heat is shared between the buildings.

2.1. *Objective functions*

The optimization problem relies on the modelling of the two objective functions minimizing costs and GHGE. These depend on input data that were gathered for each considered technology. In the following section, the vector V stores all the variables calculated during the optimization.

To evaluate the economic performance of the system, the mean annual cost of the system is evaluated based on the simulation of a defined year and originates from the sum of the CAPEX, OPEX and feed-in revenues. Its expression is given in the following equation:

$$Mean\ annual\ cost = \sum_{t\ in\ technologies} V[use\ binary]_t \cdot (CAPEX_t + OPEX_t) - \sum_{f\ in\ flows} feed\ in\ tarrif_f \cdot V[quantity\ feed - in] \quad (1)$$

CAPEX includes material, planification and installation costs and is calculated according to equation (2) for each technology (t) chosen by the optimizer and discounted to account for lifetime and an interest rate fixed to 5%. OPEX: are the operational costs of the system and therefore includes the cost to buy the necessary energy inputs (i: natural gas or grid electricity) and the cost for the maintenance of the system.

$$CAPEX_t = Base_{cost_t} + V[capacity]_t \cdot Cost\_capacity_t \quad (2)$$

$$OPEX_t = \sum_{i\ in\ inputs}\left(Cost_i \sum_{f\ in\ flows} V[quantity\ of\ inputs]_{i,f}\right) + Cost\_maintenance \quad (3)$$

To evaluate the environmental impacts optimality, we use LCA data of each energy vector and technology. The main life cycle impact assessment method considered in this study is the Global Warming Potential (GWP) over 100 years as used in the Swiss KBOB 2009/1:2022 database [7]. The GHGEs of a technology (t) is calculated for a year accounting for the manufacturing, the use stage, and the recycling/disposal at the end-of-life. The use stage is calculated by summing the hourly energy vectors consumptions and productions (i) over a year. GHGE associated to the electricity grid consumption are accounted hourly according to the tool EcoDynElec [8].The impacts of manufacturing and end-of-life are added, yearly amortized by the infrastructure lifetime. Therefore, the following quantity of interest is used in the environmental objective function of the optimization:

$$GHGE = \sum_{i\ in\ inputs}\left(GHGE_i \sum_{f\ in\ flows} V[quantity\ of\ i]_f\right) + \sum_{t\ in\ technology} V[capacity\ of\ t] \cdot \frac{GHGE_t}{lifetime_t} \quad (4)$$

CAPEX, OPEX and GHGE for all considered technologies can be found in Table 1.

Table 1. Summary table of costs and GHGE for each considered technology

Technologies	Unit	Lifetime	CAPEX		OPEX	GHGE
			per u.	base		
	u.	[y]	[CHF/u.]	[CHF]	[% CAPEX/y]	[kgCO2eq/u.]
ASHP	kW	20	2156	16408	2	281
GSHP + BHE	kW	20	4058	19700	2	700
Gas Boilers	kW	40	122	6861	1.5	93
ST	m^2	30	820	5500	0.5	115
PV	kWp	30	1103	17950	2	1131
CHP-ICE	kWh	20	1153	24879	3	360
Batteries	kWh	15	981	5138	0	207
HWS*	L	20	1.4	1092	0	0.01
DHWS**	L	20	6.9	2132	0	0.04

*Hot water storage ; **Domestic hot water storage

2.2. *Description of the case study.*

The results presented in this article are an ex-post optimization of the energy concept applied to a new real estate development in the region of Lausanne (CH) comprising of six Minergie A buildings. The usage, area and actual installed energy concept are described in Table 2 All the buildings have PV panels and produce SH with GSHP. The building 4 which also supplies heat to building 5 and 6 also produces DHW with a GSHP whereas buildings 1, 2 & 3 use ST panels and a gas boiler for DHW production. Building 4, 5 and 6 are considered as one to reduce the complexity of the optimization problem.

Table 2. Buildings areas and actual installed energy system of the case study

Buildings	Nb of dwellings	Dwellings area (m²)	Shops area (m²)	Roof area (m²)	GSHP (kW)	Gas boiler (kW)	PV (kWc)	ST (m²)	DHW storage (L)	SH storage (L)
1	76	7 751	1 003	1100	188	320	~50	88	3 500	3 000
2	72	6 883	932	1100	170	300	~47	73	3 500	3 000
3	44	3 940	516	630	92	200	~30	37	2 500	1 000
4 (5&6)	92	8 237	810	1650	220	-	107	-	6 000	2 000
TOTAL	284	26 811	3 261	4 480	670	820	234	198	15 500	9 000

In addition, equipment for cooling and refrigeration needs for the supermarket are owned and operated by the retail company. No information is available on the actual equipment, only the electricity consumption is accounted for with the rest of the electricity consumption of the building 4. Also, the condenser heat of the cooling and refrigeration equipment for all the building is rejected in the borehole heat exchanger (BHE) and thus participates in balancing the heat source for the HPs.

2.3. *Boundaries of the energy tariffication*

Energy tariffs depends on the type of consumers, large consumers are granted with lower energy prices because of effects of scale. Therefore, a difference between energy community and individual solutions occurs. To account for this difference 3 optimisations are carried out with different price scheme: one for the energy community ("group") and two individual optimizations. The energy community is considered as a large consumer for the tariffication of electricity. It owns the electrical microgrid connecting the buildings together and to the medium voltage/low voltage transfer station allowing electricity purchases and feed-in to the local utility. In the case of the individual optimization, each building is considered individually, the on-site electricity production cannot be shared between buildings. Two electricity prices are considered: one on/off peak scheme and one constant scheme. Based on data from the project partner, it is assumed that the CAPEX (cables, transfer station, installations, …) and OPEX (maintenance and metering cost) of the microgrid is equal to the subscription cost of all individual electricity meters paid to the local energy provider. Therefore, these are not considered in the mean annual cost of the 3 optimisations. Gas prices are considered equal for all three scenarios. The corresponding values are summarized in Table 3.

Table 3. Energy prices considered for each investigated scenario in the case study

Cost Hypothesis	Group Optimization	Individual Optimization Peak/Off-peak prices	Individual Optimization constant prices
Gas	8.7 c./kWh	8.7 c./kWh	8.7 c./kWh
Electricity	19 – 12 c./kWh	22 - 12 c./kWh	22 c./kWh
Electricity feed-in	7.2 c./kWh	9.5 c./kWh	9.5 c./kWh

3. Results

General conclusions can be drawn from results displayed on the Figure 10, presenting the Pareto front of all the investigated price scenarios. Indeed, the Pareto front clearly reveals the benefit of the grouped optimization, compared to individual optimization in terms of costs and GHGE.

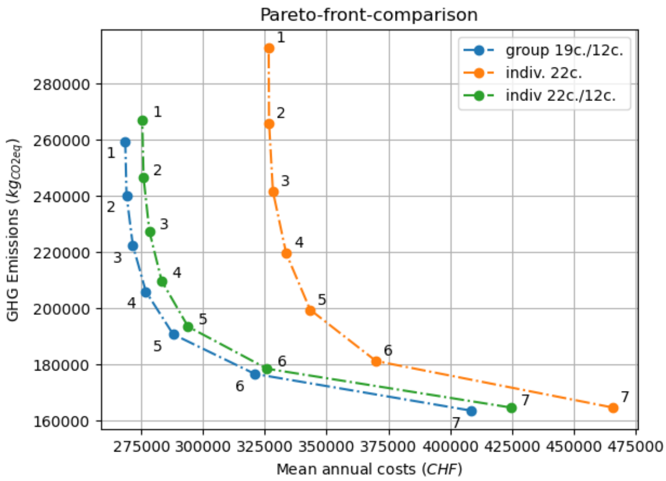

Figure 1. Pareto front of the 3 scenarios: orange line: individual optimization of the buildings with constant electricity prices of 22c./kWh, green-line: individual optimization of the buildings with peak/off-peak prices, blue-line: grouped optimization with peak/off-peak prices.

The evolution along the Pareto front for individual building with constant electricity at 22c./kWh (Figure 1 – orange line) of the installed capacities per technology for all the 4 buildings. The cost optimum (optimization 1) relies on a combination of gas boiler and ASHP for the SH and DHW needs with capacities of 350 kW and 153 kW for a total capacity of about 503 kW. By looking at each building, the same energy concept is found. On the other side of the Pareto front, the GHGE optimum relies only ASHP for heat. The total heating capacity reaches 529 kW. A value very close to the energy system chosen for the cost optimum. In terms of local electricity production capacities, PV is maximized from the cost optimum and on with 433 kWp installed. At the cost optimum, the heat demand is covered at 69% by the ASHP against 31% by the natural gas boiler, while for electricity, the PV covers 22% against 78% of grid purchase. Concerning storage capacities, electric batteries are installed only on reaching the 6th optimization and are maximized at the GHGE optimum. In parallel, it is noted that thermal energy storage from SH and DHW are maximized at the GHGE optimum. However, capacities are constant between points 1 and 4, this means that there is no clear benefit in terms of GHGE reductions.

For individual buildings with peak/off-peak electricity prices, the energy concepts for the optimums and their evolution along the Pareto (Figure 1 – green line) is similar than with constant electricity price of 22c./kWh (see 3.1). Natural gas boilers are smaller in average by 14% and cover 29% less of the heat demand.

As well, the energy concepts along the pareto for grouped building with on/off-Peak electricity prices (Figure 1 – green line) are similar. The natural gas boiler capacities and usage are further decreased in favour of ASHP by 18% and 37%. However, the PV installations are smaller at about 404 kWp and 412 kWp between point 1 to 5 then they are maximized from optimization 6. This is caused by the lower feed in tariff and lower electricity cost.

The evolution of the Pareto front between optimization 1 and 5 reveals the cost of reducing GHGEs are as low as 180 CHF/tCO_2eq (indiv 22c,/kWh), 252 CHF/tCO_2eq (indiv. On/off peak), 283 CHF/tCO_2eq (group). These values are nevertheless higher than the actual set carbon tax of 120 CHF/tCO_2eq in Switzerland.

4. Discussion

At the cost optimum, grouped buildings have decreased costs and GHGEs respectively by 18% and 11% compared with the scenario individual buildings with electricity price of 22 c./kWh and 2.5% and 3% with on/off prices of 22c.-12c/kWh. This decrease in GHGEs is due to a greater use of HPs and a lesser use of gas boilers because the grid electricity is cheaper in the grouped optimization. At the environmental optimum, costs have decreased by 12% respectively 4%, while GHGEs remains in the same range for all three scenarios. This proves the benefit of grouping building together; however, the benefits seem to be driven by the cost of the electricity as it suggested by the results of the on/off peak prices scenario. This could also be explained because locally produced electricity i.e., with PV is mostly consumed within the building where the installation is mounted. The results show that exchanges on the microgrid are very small for this specific case.

Optihood sizes the heat production at around 500 kW which is close to the actual neighbourhood installed capacity of the GSHP of 670 kW. However, the actual neighbourhood has also 820 kW of gas boilers for redundancy. The gap between the Optihood and the actual system can be explained because Optihood sizes without any redundancy and according to the actual consumption of the year 2021. A normative sizing procedure uses weather data and sizing factors that guarantee heat supply over several days in the coldest possible weather. To be used in the field, Optihood should be extended to take these latter into account. The data reveals also that the DHW storage tank is also smaller and the SH storage bigger, hence more investigations are needed to analyse which one is over or under-sized. Also, the optimizer choses larger PV plants compared the 234 kWp installed. This shows the competitiveness of PV. Roof area used for ST in the actual neighbourhood would be replaced because of its profitability.

Another point is that Optihood rules out CHP, GSHP and ST with the given hypothesis. These technologies are not competitive compared to ASHP and PV. GSHP suffers from the cost and environmental impact of the BHE, ST is also not interesting because of the cost competitiveness of PV and the low GHGE of the Swiss electricity mix in summer, the ratio of gas to electricity price is unfavourable to CHP. Thus, no direct valorisation of the electric power produced by the CHP is yet presently contemplated in the optimization framework and might represent an interesting future research perspective.

5. Conclusions

The results obtained by applying Optihood to a group of 6 buildings consisting of almost 85% of the heated area is dedicated to residential and 15% to retail shop and food stores show decreased costs and GHGE respectively by 18% and 11% in the cost optimum for energy community compared to individual buildings. This decrease in GHGE is due to a greater use of HPs and a lesser use of gas boilers because the grid electricity is cheaper in the grouped optimization. In the GHGE optimum, costs have decreased by 12%, while GHGE remain in the same range. This result illustrates the benefit of grouping building together. However, in this case, the only driver of cost reduction was the price of the grid electricity. Indeed, the electricity between the building on the microgrid was found to be very small as the electricity demand of each building is sufficient to consume the locally produced electricity. Further investigations are needed with different neighbourhood typologies to assess beneficial building form factor. Moreover, a change in energy prices for example with winter/summer prices or increased of electricity prices compared to natural gas could lead to other conclusions.

6. Appendix

Table A1. Summary table of the nominal performance indicators of each considered technology.

Technologies	Performance indicator and nominal conditions	Value
ASHP	COP @A-7/W35	3.5
GSHP + BHE	COP @B0/35 and specific extraction heat rate of the BHE	4.65, 20 W/m
Gas Boilers	Conversion efficiency over lower heat value	0.9
ST	Conversion efficiency for a global irradiation of 800 W/m2; an ambient/fluid temperature difference of 40K	0.61[1]
Photovoltaic	Conversion efficiency	0.2
CHP-ICE	Conversion efficiencies for electricity, SH and DHW	0.25, 0.6, 0.6
Batteries	Input and output flow efficiencies	0.9, 0.86
HWS and DHWS	Insulation thickness, conductivity	100 mm, 0.03 W/(m.K)

[1]With $\eta_0 = 0.73,\ a_1 = 1.7, a_2 = 0.016$

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