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Impact of size optimisation on the multi-criteria assessment of local cross-sectoral energy supply concepts

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Abstract:

Key elements of the energy system transformation are decentralisation, decarbonisation and sector-coupling. Local energy systems are often customarily designed using heuristics for the technology layout. However, optimisation of the design and operation of energy systems is considered a powerful tool. Therefore, we investigate the influence of an optimised layout and the coupling of the electricity and heat sector on economic, ecological and technological criteria. Three variations from a reference energy concept are regarded for a case study of unrenovated, residential buildings in the city of Düsseldorf, Germany. The concepts supply the heat and electricity demands at different levels of sector-coupling. In a first step, the concepts are mathematically optimised by mixed-integer linear programming with the objective of minimising costs. Afterwards, the results of the criteria metrics are combined in an overall performance score obtained by the Analytic Hierarchy Process. We find that the concepts with an optimised layout do not only have lower costs, but also lead to a significant decarbonisation by several hundreds of kg of CO_2 annually. In the case of optimised layout, heat pump and storage units have smaller capacities. Especially, storages are oversized under the used heuristic. Nevertheless, the photovoltaic units are expanded by up to 300% in comparison to the heuristic layout. We thus find an advantage of the optimised layout on the multi-criteria assessment, even though the optimisation has only an economic objective. The coupling of the heat and electricity sector leads to CO_2 emission savings and a higher self-consumption of the PV energy produced within the system. The coupled system achieves the highest score under the three criteria, irrespective of the building type. The overall best performance under a sensitivity analysis of the criteria weights is found for the sector-coupled concept in the optimised layout.

Keywords:

ECOS Conference; Local energy systems; Mixed-integer linear programming; Multi-criteria assessment; Residential energy supply; Sector-coupling.

1. Introduction

The decentralisation and decarbonisation of national energy systems have been the focus of attention in energy system analysis during the recent years. National targets have been set up by many countries. These targets influence the design of energy systems down to the scale of buildings. Consequently, local energy supply concepts are required to be renewable and efficient. While the building owners and residents have a direct influence on the installation and design of the buildings' energy supply concepts, these building concepts can also be a potential business model for utility companies [1].

When it comes to designing the energy concept, rules of thumb are often taken into account. This form of layout, we call it the *heuristic layout*, can be compared to a layout which results from a mathematical optimisation, which we call the *optimised layout*. A comparison of different layout approaches has been performed by Ogunmodede et al. [2]. The authors found that the technology layout was smaller for the case of optimisation and therefore the system costs were lower. However, the system costs in the *heuristic layout* were already lower than those in the given reference system which corresponded to a fully grid-dependent supply.

Another structural change, that is associated with the transformation of the energy system, is the coupling of energy sectors. It has been shown that the sector-coupling has accelerated the decarbonisation of the European energy system [3]. Thus, we enlarge upon these findings by investigating the effect of sector-coupling on a building scale.

Moreover, the recent shifts in energy system analysis have been accompanied by the need for including multiple criteria in the analysis. Besides economic metrics, further factors have been considered: ecology [4–7], technology [4, 6–10], sociology [6, 7] or regulatory framework [6]. The use of methods for Multi-Criteria Decision

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Analysis (MCDA) to assess energy systems is widely spread [7, 11, 12]. Many studies have thereby applied the Analytic Hierarchy Process (AHP) [4–6, 8–10]. Hence, the energy concepts regarded in this paper are analysed with AHP under multiple criteria.

The aim of this paper is to investigate the multi-criteria behaviour of local energy supply concepts under the aspect of an *optimised layout* and the coupling of the electricity and heat sector. We examine the following questions:

- What impact does an optimised layout have on local energy supply concepts considering economic, ecological and technological criteria?
- How does the coupling of the electricity and the heat sector affect local energy supply concepts in terms of economic, ecological and technological criteria?

In a first step, we describe the methodology of optimisation and assessment used in this paper (Section 2.). Afterwards, we present the case of application and describe the investigated concepts in Section 3. The results of the multi-criteria analysis are shown in Section 4. and discussed in Section 5. Finally, we give a conclusion and outlook in Section 6.

2. Methodology

The methodology of this investigation is described by a two-stage approach. In the first stage, the local energy supply concepts are mathematically optimised under a cost objective. In the second stage, the different optimised concepts are regarded as alternatives and assessed under multiple criteria. Parts of this methodology have already been described in [13].

2.1. Mathematical energy system optimisation

In order to calculate key performance indicators of the concepts, we perform a mathematical optimisation under a cost minimisation objective. The concepts are thereby modelled as Mixed-Integer Linear Programs (MILP) with ESyOpT®, a modelling tool based on the python package oemof-solph [14]. The considered optimisation problems are solved by the Gurobi solver [15] with a branch-and-cut algorithm. The optimisation horizon comprises one year with an hourly resolution.

The python package oemof-solph provides a modular modelling framework of energy systems in which each component, or technology respectively, comes with its own specific constraints for the operation and installation. The energy flows in the system are uniquely set by connections among the components. For the regarded energy concepts of this work, we model the following components: the electricity grid, the gas grid, gas boilers, thermal storages, photovoltaic (PV) modules, batteries and air-water heat pumps. The gas and electricity grids as well as the PV modules are modelled as sources. The PV plant can be used in the building's energy system to meet the electricity demand, but the generated electricity can also be fed into the grid again. The grid feeding is modelled as a sink of the system. The household demands for electricity, space heating and hot water are represented as sinks, too. To implement the other components, we use the class *Transformer* provided by oemof-solph to write our own models.

The gas boiler and the heat pump have an operational constraint on the outflow due to the minimum part load (MPL). This means they can only be operated within the range of the MPL and the nominal power P_{nom}. The gas boiler moreover has a constant efficiency while the heat pump has a time-resolved coefficient of performance (COP) that is dependent on the ambient and the supply temperature, but not on ambient humidity. The COP ranges from 1.53 to 6.40 according to a high-temperature air-water heat pump with a R407c refrigerant [16]. The heat storage is modelled with a capacity-dependent loss [17] and a level-dependent loss [17]. The battery is modelled with a fixed self-discharge loss of 0.025% per day [18] and degradation is not considered. The normalised power output per kW_{peak} of the PV plant is calculated using a pvlib-python model [19]. Data for investment and maintenance cost were taken from studies and market data [20–23].

We distinguish between two optimisation objectives and modelling approaches respectively - a *heuristic layout* and an *optimised layout*. For the case of *heuristic layout*, we perform a dispatch optimisation with a rule of thumb layout of each technology (Section 3.3.). We compare this to the case of an *optimised layout* in which both dispatch and size of the technologies are optimised. The methods differ in their objective function f and the components' set of decision variables.

In the case of a *heuristic layout*, the objective function consists of the annual maintenance and operational costs (*OPEX*) of the concept:

$$min\,(f_{heuristic}) = min\,(OPEX_{annual}) \tag{1}$$

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For the case of the *optimised layout*, the objective function consists additionally of the annual investment and installation costs (*CAPEX*) of the concept and therefore equals the total costs (*TOTEX*):

$$min\left(f_{optimised}\right) = min\left(TOTEX_{annual}\right) = min\left(CAPEX_{annual} + OPEX_{annual}\right) \tag{2}$$

The mostly non-linear relations between the components' sizes and their total *CAPEX* are linearised into a fixed term $CAPEX_{fix}$ and a variable term $CAPEX_{variable}$ to be incorporated in the MILP representation. In this manner, scale effects can be considered. The total *CAPEX* are further discounted over the lifetime of the technology to the year of investment, using the weighted average cost of capital (WACC).

$$CAPEX_{annual} = \left(CAPEX_{fix} + CAPEX_{variable} \cdot SIZE\right) \cdot \frac{WACC \cdot (1 + WACC)^{LIFETIME}}{(1 + WACC)^{LIFETIME-1}} \tag{3}$$

The set of decision variables of the *heuristic layout* comprises operational variables $Y_{op}(t)$, which are binary variables indicating whether the component is operating in timestep t, and the power in- and outflow $P_{in/out}(t)$ of the component. The nominal power P_{nom} of the energy supply technologies and the capacity E_{cap} of the storage technologies have to be given for the case of the *heuristic layout* (Section 3.). In the case of the *optimised layout*, however, these variables are optimised as well.

2.2. Multi-criteria decision analysis

The optimised concepts are assessed and ranked under economic, ecological and technological metrics. In order to compare and rank the alternatives by only a single metric, a MCDA method is used. Since we aim at obtaining one performance score for each alternative, we choose a method that follows a Full Aggregation Approach [24]. The method used in this paper is the AHP [10, 25].

In a first step, the metrics for the respective criteria are chosen. Afterwards their preference weights are determined. And finally, the decision metric is determined.

2.2.1. Choice of criteria metrics

The chosen economic metric is the total annual costs ($TOTEX_{annual} = CAPEX_{annual} + OPEX_{annual}$). For the *heuristic layout* the annual *CAPEX* are calculated in the postprocessing of the optimisation using the heuristic sizes of the technologies. In the case of the *optimised layout*, the economic metric corresponds exactly to the objective function.

The chosen ecological metric is the concepts' total annual direct CO_2 emissions which are caused by the grid connections in the modelled energy concepts and do not consider indirect emissions that are caused by production.

The technological metric, the energy performance *EP*, is computed from the self-sufficiency and the self-consumption of the concept. The self-sufficiency *SES* is a measure for the grid-independence. This is calculated as the relative amount of energy produced within the system boundaries (independent from a grid connection) and used for the demands from all the energy in the system which fulfils the demands. A value of 0 indicates a complete dependence on gas and/or electricity grids while a value of 1 indicates a full independence from these grids.

$$SES = \frac{\text{used energy which is produced within the systems boundaries}}{\text{total used energy}} \tag{4}$$

The self-consumption *SEC* gives the ratio of energy produced within the system boundaries and used in it from all the energy produced within the system boundaries. A value of 0 indicates no use of the energy produced within the system boundaries for the system, while a value of 1 indicates full use of the energy produced within the system boundaries for the system.

$$SEC = \frac{\text{used energy which is produced within the systems boundaries}}{\text{total energy which is produced within the systems boundaries}} \tag{5}$$

The *EP* is finally calculated as the average of the two performance indicators:

$$EP = \frac{SES + SEC}{2}. \tag{6}$$

2.2.2. Determination of criteria weights with AHP

The AHP was first introduced by Saaty [25] as a method of measurement with ratio scales. The method can be used for criteria weight determination and alternative assessment. Both are used in this paper. The method's

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Table 1: The AHP scale adapted from Saaty [25].

Absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement moderately favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured, and its dominance demonstrated in public
9	Extreme importance	The evidence favouring one activity over another is one of the highest possible orders of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

basis is a fundamental scale (Table 1) by which the preferences of the criteria and the alternatives concerning the criteria are identified via pair comparisons. For the determination of the criteria weights, a pair of criteria (i, j) is compared according to the AHP scale. If i is preferred over j, the value in the pair comparison matrix takes the value v_{AHP} from the scale: $a_{ij} = v_{AHP}$, while $a_{ji} = \frac{1}{v_{AHP}}$, and vice versa. Note that all $a_{ii} = 1$. The eigenvector of the first eigenvalue of the pair comparison matrix equates to the criteria weights.

The pairwise comparison of the criteria was performed through a survey in which employees of a local utility company participated. The survey contained a pairwise comparison of economic, environmental and technological criteria. In total, eleven employees of the local utility company filled out the survey and each resulting set of criteria weights was determined using the AHP method and the weights were then averaged. The final set of criteria weights resulted in:

- economic: 0.33,
- ecological: 0.26,
- technological: 0.41,

which were used as default weights for the application of the ranking assessment with the AHP method.

2.2.3. Ranking of alternatives with AHP

The second step of Saaty's method is the ranking of alternatives [25]. In order to perform a ranking of the different alternatives, they are assessed according to the criteria and their weights. If the criterion is qualitative, the algorithm goes equivalent to the process of weight determination (Section 2.2.2.). The alternatives are pairwise compared concerning the criteria according to the AHP scale and the pairwise comparison matrix is built. The first eigenvector of this matrix is calculated for all these qualitative criteria and saved for the next step of the algorithm. The procedure for quantitative criteria deviates from the above-described step in the sense that the normalised vector is built from the alternatives' values for the given criterion. In case the quantitative criterion has a negative ordered scale (meaning, a lower value is preferable), the alternatives' values need to be inverted in a first step, so that the highest value of the normalised vector corresponds to the best parameter value for the given criterion. The matrix of the vectors for all the (qualitative and/or quantitative) criteria is eventually multiplied with the vector of criteria weights. The performance score indicates the multi-criteria metric for each alternative and the ranking of the alternatives follows these performance scores with the best alternative being the one with the highest score.

3. Case study

To illustrate the described methodology, an exemplary case study for unrenovated, residential buildings in the city of Düsseldorf, Germany, is carried out. We take three different typical buildings into account that comprise one flat (single-family house, SFH), eight flats (multi-family house, MFH8) or twenty flats (multi-family house, MFH20), respectively.

3.1. Input data

The assumptions that are made for the annual energy demands and PV potential of each building type are summarised in Table 2. Synthetic load profiles are simulated following VDI 4655 [26]. The norm provides

Table 2: Assumed annual energy demands and PV potential for each building type.

building type	total space heating demand [*kWh*]	total hot water demand [*kWh*]	total electricity demand [*kWh*]	roof area [m^2]
SFH	21000	2800	4000	65
MFH8	56000	9520	14320	175
MFH20	112000	21000	33000	175

reference load profiles of existing residential buildings for ten categories of typical days. These categories are dependent on the seven-day-rolling-average of the ambient temperature, the cloudiness, and the day of the week. Moreover, geographical information is used to multiply the reference profiles by a correction factor. Through the algorithm provided in the norm, the annual demand is distributed over the year accordingly.

The optimisation results are obtained using the test reference year weather data set provided by Deutscher Wetterdienst [27] and historical energy market data. The reference year for the energy market data is the year 2021. We assume a household electricity tariff of 33.7 ct/kWh, a gas tariff of 8.3 ct/kWh and a PV feed-in tariff of 7.3 ct/kWh. For the emission factors of the grid-related direct CO_2 emissions we assume 420 $g\ CO_2/kWh$ [28] for the electricity grid and 201 $g\ CO_2/kWh$ for the gas grid.

3.2. Cross-sectoral local energy supply concepts

The reference energy supply concept (*REF*) consists of an electricity grid connection and a gas boiler with a gas grid connection and a thermal storage to supply electricity, space heating and hot water to residential buildings. A schematic graph of the energy flows in the reference concept is shown in Fig. 1. In our analysis, we first adapt the electricity sector of the reference concept, then the heat sector and finally a combination of both adaptations in order to investigate the effect of sector-coupling. The adaptation in the electricity sector (*EA*) is performed through adding the electricity supply option of PV modules on the buildings' roofs with a battery storage. The adaptation in the heat sector (*HA*) is performed through exchanging the gas boiler with an air-water heat pump. These adapted concepts are shown in Fig. 2. Finally, both sectors are adapted simultaneously in a coupled manner (*SC*) so that the PV power can be used for operating the heat pump. The corresponding energy flows of the coupled concept are shown in Fig. 3.

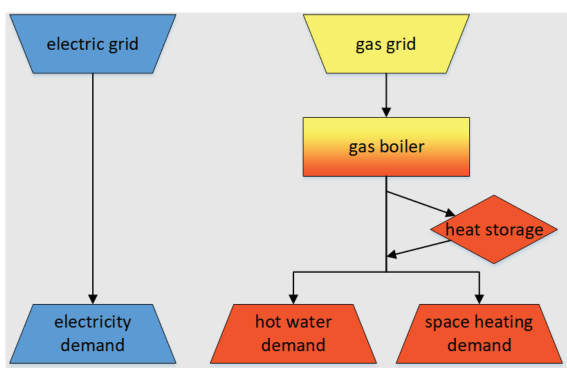

Figure 1: Reference concept (*REF*). The electricity, gas and heat sectors are indicated in blue, yellow and red, respectively.

3.3. Heuristic layout of energy concept technologies

As mentioned in Section 2.1., one of the optimisation approaches is a *heuristic layout* in which the nominal power and capacities of the technologies are kept constant. The heuristics apply to all concepts except for the reference concept. A *heuristic layout* is given for the heat pump, the thermal storage, the PV plant and the battery. A summary of all layouts is given in Table 3.

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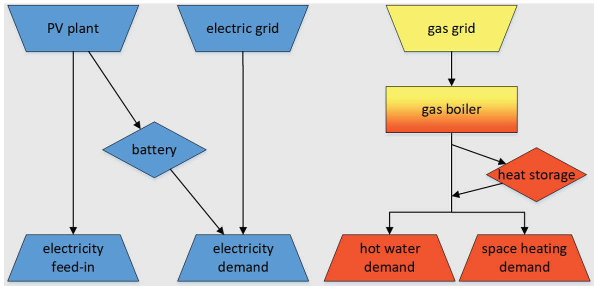
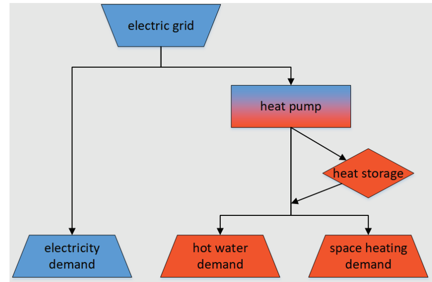


(a) Electricity adapted concept (*EA*).



(b) Heat adapted concept (*HA*).

Figure 2: Concepts that have been adapted in one sector. The electricity, gas and heat sectors are indicated in blue, yellow and red, respectively.

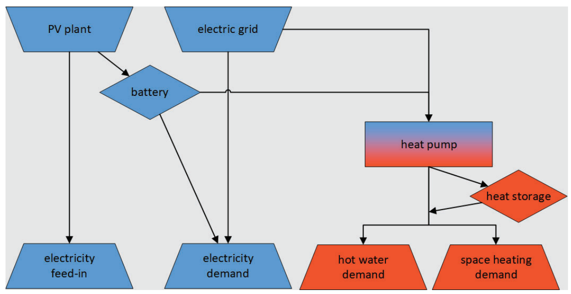


Figure 3: Sector-coupled adapted concept (*SC*). The electricity and heat sectors are indicated in blue and red, respectively.

The heuristic nominal power of the heat pump is computed according to the norm DIN-EN 12831, Supplement 2. According to the norm, the power is dependent on the hours of operation, the heating threshold temperature T_{lim} as well as the ambient temperature T_{amb} and the annual space heating and hot water demands. In this paper, we refer the hours of operation only to the heating period when $T_{amb} < T_{lim}$.

The heuristic to determine the peak power of the PV plant follows the simple rule that 1 kW_{peak} is assumed to be able to produce up to 1000 kWh of electricity per year. Therefore, we divide the annual electricity demand by the factor 1000 to determine the PV peak power.

The heuristic for the storage capacities of the thermal storage and the battery corresponds to the layout of a 24h-storage, meaning that the storage capacity is chosen so that an average daily amount of energy in the heating period can be stored. The in- and outflow power of the storages are configured so that the average energy that is necessary in one hour can flow from or to the storage.

4. Results

4.1. Results of the different concepts and building types under the three indicators

The mathematical optimisation of all three concepts has been performed under the two different optimisation objectives and for the three different building types. Additionally, the reference concept was optimised for each building type. This equals to a total of 21 sets of obtained results.

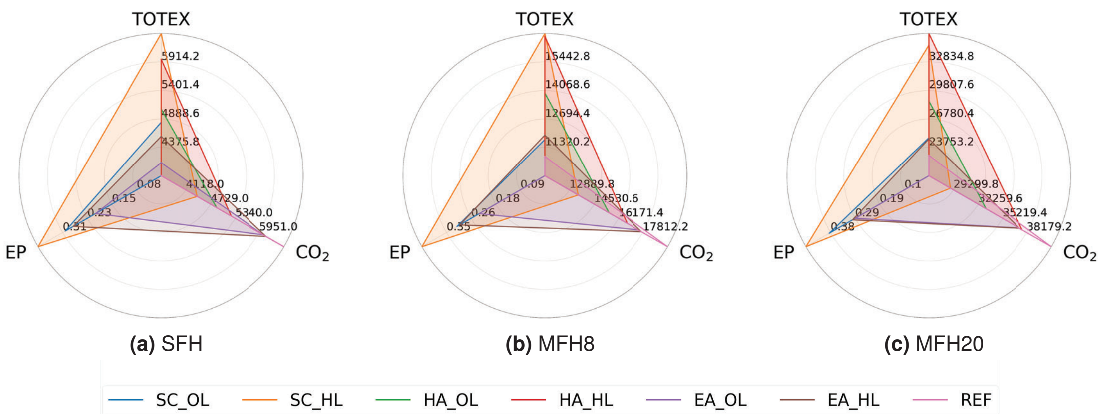
When comparing the implemented sizes of the energy technologies in the case of heuristic layout (HL) with the optimised layout (OL), we find that the storages have smaller capacities in the optimisation than according to the heuristic. We also find that the heat pump does not need as much installed power if the concept is optimised. However, the PV plant is built up to the limiting size of the roofs in the case of optimisation. For the single family house, this corresponds to an amplification of about 300 % in comparison to the HL.

For all 21 sets of concept results, we analyse the three criteria metrics presented in Section 2.2.1. An overview of the distribution of the criteria values is given in the radar charts in Fig. 4. Each axis of the graph represents one criterion and spans the value range of the criterion's metric in the set of results.

Table 3: Heuristic power and capacity of the implemented technologies. (hp=heat pump, tes=thermal storage, ba=battery)

building type	$P_{nom,\ hp}$ $[kW]$	$P_{peak,\ PV}$ $[kW]$	$E_{cap,\ tes}$ $[m^3]$	$P_{in/out,\ tes}$ $[kW]$	$E_{cap,\ ba}$ $[kWh]$	$P_{in/out,\ ba}$ $[kW]$
SFH	14.86	4	2.81	2.72	12.82	0.46
MFH8	40.03	14.32	7.74	7.48	45.91	1.63
MFH20	82.48	33	15.7	15.18	105.79	3.77

The reference concept is found to be the concept yielding the highest CO_2 emissions, irrespective of the building type. This concept, plus the two concepts with the electricity adaptation, lead to $EP = 0$ because they are fully grid-dependent. As expected, we observe for all concepts that the *TOTEX* decrease in the OL by on average 27%. What is more surprising, the CO_2 emissions also decrease by on average 11%. On the contrary, the HL shows a better performance of *EP*. The latter is explained by the high *SEC* in the HL concepts.



(a) SFH **(b)** MFH8 **(c)** MFH20

Figure 4: Radar charts of the performance of the seven concepts in the three criteria for each building type. The axes are defined by the resulting values from the concepts.

4.2. Results of the AHP ranking for the three building types

In order to condense the information about the concepts, we used the AHP method to determine overall performance scores for each concept. Under the usage of the criteria weights presented in Section 2.2.2., we determine the final rankings as shown in Fig. 5. The ranking orders of the concepts are mostly identical for the different building types. For the MFH20, the ranking order of the two *EA* concepts is swapped. In all cases, the sector-coupled concept with the HL obtains the highest performance score. This is to some extent surprising as it performs worse in the economic and the ecological criterion than the OL of the sector-coupled concept. However, the technological performance is higher than in the OL and it has the highest weight (Section 2.2.2.) and is therefore dominating when the overall performance score is built with AHP.

In the rankings, we also find that the sector-coupled (*SC*) and the electricity adapted (*EA*) concept, in both layout specifications, make the top four positions. On the other hand, the reference (*REF*) concept and the heat adapted (*HA*) concept obtain a significantly lower score. This, again, can be explained by the high weight on the technological criterion and the fact that these three concepts are fully grid-dependent.

4.3. Sensitivity analysis of the criteria weights in the AHP method

The ranking results are highly dependent on the choice of the criteria weights. Therefore, we perform a comprehensive local sensitivity analysis of the criteria weights on the AHP performance score. The criteria weights from the survey are regarded as default weights. Additionally, we vary each weight in the interval [0.0, 1.0] with a step size of 0.1. While varying one weight, the other two weights are adapted while keeping the exact relation that they had in the default weights. The ratio of the economic to ecological weight is 56 : 44, the economic to technological weight is 45 : 55 and the ecological to technological is 39 : 61, respectively.

The resulting graphs are shown in Fig. 6. It is clearly seen how the concepts' performance differs under

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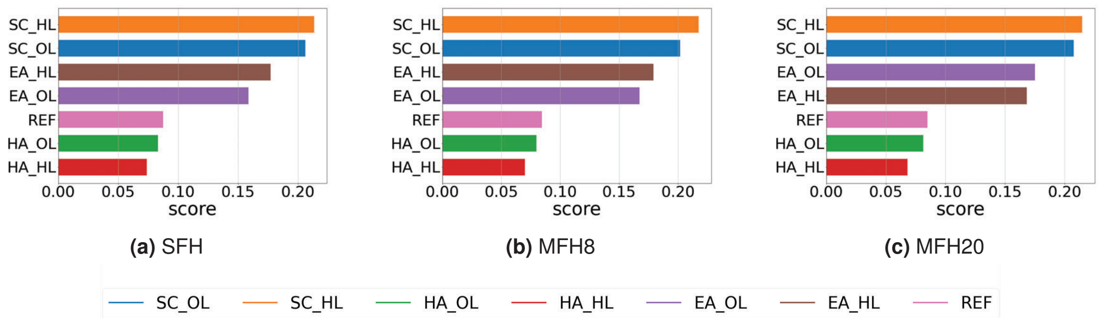

(a) SFH **(b)** MFH8 **(c)** MFH20

Figure 5: AHP Ranking results for each building type.

varying weights. From the graphs, it is noticeable that the scores of the *REF* and *HA* concepts, for the increase in each weight, show opposite trends to the *SC* and *EA* concepts. Moreover, the trends are equal for the economic and ecological weight, while the trends are swapped for the technological weight. However, there is one exception to this observation. The score of the electricity adapted concept in the OL rises with increasing economic weight. From Fig. 4 we see that this concept has either the lowest or second to lowest *TOTEX* (depending on the building type) and therefore the overall score benefits from a higher emphasis on the economic criteria. Another observation is that the value range of the resulting scores is the highest in the case of a high technological weight. This is induced by the value of *EP* = 0 for the three grid-dependent concepts which makes them uncompetitive. On the contrary, for high economic weight or high ecological weight, the scores of all concepts are close to each other.

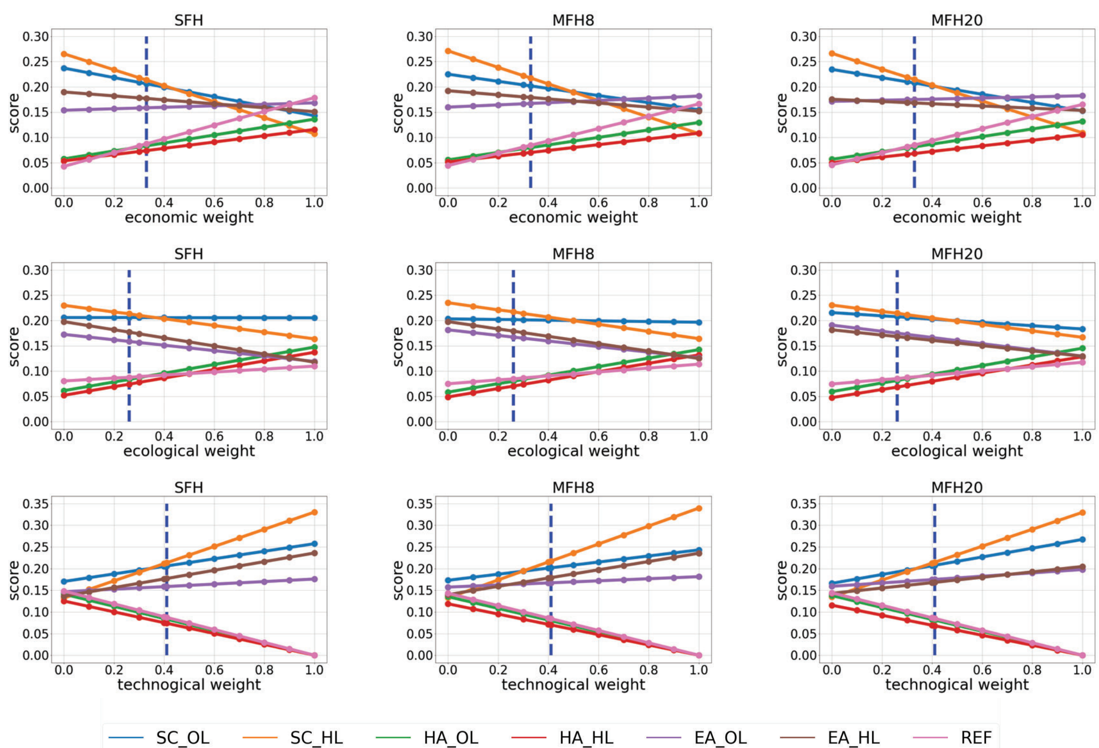

Figure 6: Sensitivity analysis on each criterion for each building type. The blue dashed line in each graph indicates the position of the default weight ranking. The top, middle and bottom row shows the analysis of the economic weight, the ecological weight and the technological weight, respectively.

The results of the sensitivity analysis are further used as a sample for the overall performance analysis of the concepts. The data points of Fig. 6 build a representative set of the concepts' performance results under multiple criteria. Each concept with a corresponding layout choice has been assigned a performance score and a ranking position under different criteria weight choices. Based on all these ranking positions, including the one corresponding to the default weights, we determine the average ranking positions for each concept. The results of this analysis are summarised in Table 4.

Table 4: Average ranking order of the concepts for each building type.

rank	SFH	MFH8	MFH20
1	SC OL	SC OL	SC OL
2	SC HL	SC HL	SC HL
3	EA HL	EA HL	EA OL
4	EA OL	EA OL	EA HL
5	REF	REF	REF
6	HA OL	HA OL	HA OL
7	HA HL	HA HL	HA HL

The table shows that the *SC* concept in the OL reaches the highest average position in all rankings produced by the sensitivity analysis. Except for the *EA* concept for the SFH and MFH8 building types, all concept alternatives in the OL reach higher average ranking positions than their HL partner concept. The *HA* concept performs worse than the *REF* concept because even though it has lower CO_2 emissions, the extra cost are significant enough to lead to a lower overall performance score for the totality of all regarded weight variations.

5. Discussion

The OL does not only lead to a decrease in total annual costs, but also to a decrease in the total annual direct emissions. This can be explained by the better operational use of the installed energy technologies. In the case of the OL, the installed power/capacity of each technology is perfectly matched to meeting the demands. Since the operational costs and the direct emissions have the same origin - the grids - the reduction of either is directly coupled to the other. The contrary effect is the installation of new technologies for the *EA*, *HA* and *SC* concept, which comes with installation costs. For the *HA*, the heat pump is built with a lower nominal power in the case of optimisation, so that the *TOTEX* are lower for the OL than for the HL. For *EA* and *SC* we observe that the PV is dimensioned much bigger if the layout is optimised. This comes with higher installation costs. However, the storages (battery and heat storage respectively) are installed at lower capacities in the case of an OL. For the *EA* and *SC* concept this balances the higher PV costs out and still, the *TOTEX* decrease for the OL. The strong decrease in installed capacity of the storages if the layout is optimised, shows how much the capacities were overestimated with the used heuristic. The capacities of the storages, moreover, influence the *SEC* and thereby the *EP*. The high capacities in the HL lead to a high *EP*.

The sensitivity analysis of the criteria weights has shown a uniform behaviour of the economic and the ecological criterion. With varying weight, the same concepts show the same behaviour for both criteria. This behaviour is inverted in the technological criterion. The fact that for a high weight on either economic or ecological criterion or a low weight on the technological criterion, the score of all concepts lie closer to each other, shows that the gap between the concepts' performance results mostly from the values of the technological metric and their competitiveness is balanced out if the other metrics have a higher importance.

To answer the second research question, we observe that the two concepts associated with the sector-coupled concept are the two highest ranked for most of the weight variations. Only for a high economic weight, these two concepts obtain lower positions in the ranking. Thus, the coupling of the heat and electricity sector specifically reduces CO_2 emissions and increases the energy performance which leads to a high ranking of the respective concept in the MCDA under the three given metrics.

Finally, the reference concept is found to perform well in the economic criteria as it has low *TOTEX* for all building types, but it shows the worst performance for CO_2 emissions and *EP*. This effect occurs for the given case study because we do not regard installation costs in *REF*. We assume that the gas boiler is already installed and the investment has been made in the past and is not part of the optimisation horizon.

The method used to calculate an average ranking is based on the ranking position that resulted from each weight variation in the sensitivity analysis. A different approach would be to compute the average performance score instead and base the overall ranking on this score. The approach of comparing ranking positions takes equidistant positions between the concepts, while a comparison on performance score could show dominance

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between the concepts. However, the ranking position is taken as the supporting indicator for performance of the concepts.

6. Conclusion and outlook

To conclude, we investigated local heat and electricity supply concepts with a different level of coupling the sectors and different layout approaches. We find that the OL decreases the total annual costs by on average 27% and decreases the total annual direct CO_2 emissions by on average 11%. The installation of PV is enforced if the layout is optimised instead of following a rule of thumb. A coupling of the heat and electricity sector leads to CO_2 emission savings and a better energy performance. Between the three different building types we find almost no difference. Yet, the study can be extended towards other building archetypes including non-residential buildings. Furthermore, the energy price markets have recently faced a lot of instabilities. Hence, the robustness of the rankings against different price inputs can be investigated. Lastly, the investigation at hand only refers to the use of one specific MCDA method. However, different methods can lead to different ranking decisions. It can therefore be advised to repeat the analysis with other methods and check if the concepts obtain similar ranking positions.

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Nomenclature

Letter symbols

a	decision matrix
E	energy, kWh
f	objective function
P	power, kW
T	temperature, °C
t	timestep
v	value
Y	binary decision variable

Subscripts and superscripts

amb	ambient
cap	capacity
i	row of the decision matrix
in/out	in- and outflow
j	column of the decision matrix
lim	heating threshold
nom	nominal
op	operational

Abbreviations

AHP	Analytic Hierarchy Process
ba	battery
CAPEX	capital expenditures/investment costs
COP	coefficient of performance
EA	electricity adapted concept
EP	energy performance
HA	heat adapted concept
HL	heuristic layout
hp	heat pump
MCDA	Multi-Criteria Decision Analysis
*MFH*8	multi-family house with eight flats
*MFH*20	multi-family house with twenty flats
MILP	Mixed-Integer Linear Programming
MPL	minimal part load
OL	optimised layout
OPEX	operational expenditures/costs
PV	photovoltaic
REF	reference energy concept
SC	sector-coupled adapted concept
SEC	self-consumption
SES	self-sufficiency
SFH	single-family house with one flat
TOTEX	total expenditures/costs
tes	thermal storage
WACC	weighted average cost of capital

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