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MULTI-STAKEHOLDER OPTIMAL ENERGY SUPPLY FOR MULTI-FAMILY HOUSES UNDER 2021 GERMAN MARKET CONDITIONS

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Abstract. Especially in the energy supply of multi-family houses, a wide variety of stakeholders are involved, from owners, to users, to energy service providers and society. They usually have different requirements and understandings of optimality, but ultimately have to make joint decisions and thus sensible compromises. In Germany in particular, there are a large number of multi-family houses and, at the same time, many government restrictions and subsidies in terms of energy supply. This makes it difficult to make clear recommendations for the choice of an energy supply concept that takes all stakeholder interests into account. We first identify the relevant stakeholders and define their objectives. In order to relate these with one another, we present a methodology based on energy system simulation and TOPSIS to make energy concepts objectively evaluable. A generic multi-family house with 40 residential units is examined, combining different energy technologies and insulation standards. There is no energy concept that satisfies all stakeholders equally and it is difficult to build coalitions between them. The best results are achieved by air-source heat pumps in combination with photovoltaic.

Keywords: energy system optimisation, energy system simulation, distributed generation, multiple-criteria decision analysis, TOPSIS, DIN V 18599.

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1. Introduction

The energy supply of buildings rarely concerns only individual stakeholders, but often encompasses a large number of different stakeholders who are affected in various ways by the chosen energy concept. In recent years, while the number of feasible generation and storage technologies has increased significantly, the objectives of stakeholders have diversified. Previously electricity simply came from the grid and heat was generated in gas or oil boilers, but today distributed energy generators such as combined heat and power plants (CHPs), heat pumps (HPs), photovoltaic (PV) or solar thermal (ST) are available. These energy sources can not only optimise costs, but also reduce emissions and stabilise the overall power grid. In the planning of distributed energy supply solutions, objective methods to combine the technical aspects of energy supply with the wishes of the stakeholders and to provide decision support are rarely used. Instead, decisions are often made by individual stakeholders and political intervention is needed, for example, to ensure environmental protection and social justice.

Multi-family rental buildings in particular bring together a wide range of interests from different stakeholders, which is why they are particularly interesting for more comprehensive and objective methods. Outside of energy systems, the interests of landlords for the highest possible rental income collide with those of tenants for the lowest possible rental costs. Then when it comes to energy supply, there are even more stakeholders and in order to satisfy all of them compromise is inevitable. What is particularly interesting here is the trade-off between better energy efficiency through better insulation or through better energy generation. An energy concept always consists of the interaction between these two factors.

In this respect, Germany is a particularly interesting market. The country wants to be a pioneer in climate protection and the energy transition, and therefore has great incentives to include renewable energies in the energy supply of buildings, both in new construction and in renovation. The majority of Germans do not own a house or land (52%) (Statistisches Bundesamt, 2019a) about 54.5% of households are situated in multi-family housing (Statistisches Bundesamt, 2019b). A successful decarbonisation of the building sector can, to a large extent, therefore not be achieved by individuals in single-family houses. Instead, it must take into account various stakeholders who are dependent on making compromises as described above.

The optimisation of energy systems is a widespread problem in the scientific literature, on which there are countless approaches and publications.

Specifically for the German market, there are various studies on which energy system is to be preferred and why. Mailach and Oschatz (2021) are investigating a single-family house and a 6-family house along with various energy systems in new buildings. For this purpose, the cost annuities are evaluated, which are highest for CHP systems and lowest for air-source heat pump (AHP) systems, for example. Other factors than this rather microeconomic view do not play a role in their study. Lindberg et al. (2016) focus specifically on what cost-optimal energy systems in zero energy buildings in Germany could look like. The unique facets of tenant electricity supply under current German subsidy conditions and the associated optimal energy systems are dealt with by Braeuer et al. (2022). The latter studies in particular, however, contradict each other depending on the time of preparation, the framework conditions and the modelling assumptions and usually only highlight special cases of building energy supply.

The methods chosen for the analysis of optimal energy supply are highly diverse and there is a wide range of methods for the design and evaluation of energy systems on the basis of certain KPIs. For example, Schmeling et al. (2022) present an approach for the multi-criteria optimisation of a residential neighbourhood using a metaheuristic. Here, too, a rather general valuation approach is chosen, but the energy technologies can be put together in almost any size and combination. Hancock et al. (2023) extends this approach even further and looks not only at energy technology, but also at improving the building envelope of single-family homes. Similar approaches can be found with Wegener et al. (2020) for a museum or Berendes et al. (2018) for a small island. What is often missing, however, is the view of the different stakeholders, who do not only look at system costs or system emissions but pursue other individual goals.

Roloff (2008) defines multi-stakeholder networks as those in which "business, civil society and governmental or supranational institutions come together in order to find a common approach to an issue that affects them all and that is too complex to be addressed effectively without collaboration". The involvement of local stakeholders in the design of energy systems is particularly important, as Kelly and Pollitt (2011) points out. They specifically target local governments to create small-scale solutions within the boundary conditions they are familiar with. Hettinga et al. (2018) highlight the need for the participation of different stakeholders in local solutions, which in their view are indispensable for achieving climate goals. They note that stakeholders have different perspectives on the optimisation and boundary conditions of an acceptable local energy system due to their different knowledge and skills. These can be understood as KPIs of the system and can vary greatly.

There are also methods for comparing and ranking different non-comparable goals, which are generally summarised under the term multiple-criteria-decision analysis (MCDA). For instance, Mela et al. (2012) use various MCDA methods to make optimal design decisions in the building context. They demonstrate established processes to optimise, for example, the wall construction of a single-family house in terms of cost, thermal insulation and customer satisfaction. Kirppu et al. (2018) apply such a methodology to choose a heat generation technology for the district heating network in Helsinki with the help of industry experts. Baumann et al. (2019) demonstrate different techniques using the example of selecting an energy storage technology. A more detailed insight into MCDA and the relevant methods will be given in a later chapter.

What has not been found so far is now the combination of these different approaches. Our goal is to be able to make statements about energy systems under the current German framework conditions by using MCDA and multi-stakeholder methods. We hope to provide decision-makers with a guideline for energy system design and to give politicians insights into the effects of current subsidy policies. It is our conviction that only through the full engagement and participation of all relevant stakeholders in the decision-making process towards the decarbonisation of the energy supply of residential buildings can be successfully and satisfactorily achieved.

In order to better understand this market and to be able to derive optimal energy concepts as a compromise of the interests of different stakeholders, a methodology is presented below and an analysis is carried out for a generic German multi-family house. Chapter 2 identifies the stakeholders relevant to the investigated subject and defines their objectives as Key Performance Indicators (KPIs). Chapter 3 then presents a method for multi-stakeholder decision making based on an energy system simulation and a decision-making methodology. Chapter 4 outlines the case study of a German multi-family house, the results of which are discussed and generalised in Chapter 5. The aim is to find general market trends and to be able to make generally valid recommendations by making assumptions about the German market that are as generic as possible.

2. Identifying relevant stakeholders and quantifying their objectives

Depending on the particular arrangement, a large number of different stakeholders may be involved in the energy supply of a building. In order to do justice to the claim of providing general statements about the current market situation and to demonstrate a methodology for investigating such questions, only the stakeholders directly involved in the energy supply are defined directly. This includes the building owner, the building user (e.g., tenant), and the energy service provider. All interests going beyond this are subsumed in a stakeholder referred to as "society". Indirectly, but still important is the legislator. The legislator sets the framework for action that they want fulfilled. An overview of the relevant stakeholders and their relationships can be seen in Figure 1, their exact role and objectives are explained below. However, the stakeholders identified for the purpose of this study and their objectives here are only to be understood as exemplary for the application in the case study used later. Depending on the nation and the associated framework conditions, there may be other stakeholders or other objectives. The methodology used is nevertheless transferable without restriction.

The **owner** owns the property and is therefore responsible for all decisions and investments concerning the building components. Income is generated by the sale or rental of the premises. It is therefore in their interest that the investment costs remain as low as possible, that they receive a high state subsidy (which, in addition to monetary incentives, also brings benefits in terms of reputation and marketing), and that they can rent out/sell as much space as possible, i.e., that the wall structures do not become too thick and thus reduce the room sizes. The investment costs for the insulation are estimated according to Schöndube et al. (2018). The state subsidy amounts are derived from the KfW's BEG subsidy program (Credit Institute for Reconstruction – Federal funding for efficient buildings) as of mid 2021 and are treated as a separate KPI. Under this programme, buildings are subsidised with a 15% (KfW55) or 20% (KfW40) repayment subsidy if they comply with certain minimum energy standards. A further 2.5% is added if the system covers its heat from at least 55% renewable energies (KfW55EE/KfW40EE) (Bundesministerium für Wirtschaft und Energie, 2021).

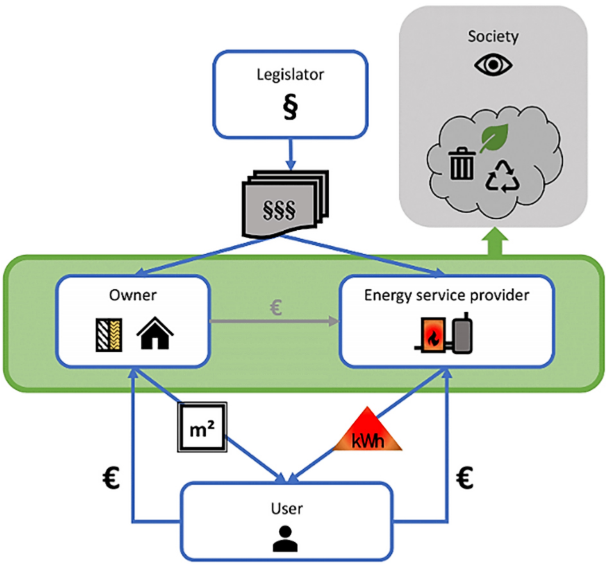

Figure 1. Graphical representation of the main relevant stakeholders identified for multi-family home energy supply and their interactions as modelled and discussed in this study

The **energy service provider** invests in and operates the energy generating facilities. The costs incurred for this are charged to the user. In order to offer the user a marketable energy price, they may be dependent on a subsidy for construction costs from the owner, who must take these costs into account in their investments. They are trying to maximise their profits. In order to ensure this with as little risk as possible, it is advantageous for them to have a high percentage of Capital Expenditures (CapEx) and a low percentage of Operational Expenditures (OpEx), since the energy procurement costs and the energy purchase quantities can fluctuate strongly. The profits are calculated by KEHAG Energiehandel, an energy service provider operating in Germany, using internal tools and assumptions.

The **user**, in turn, wants to have the lowest possible heating costs. For them, a high proportion of OpEx is advantageous, since they can then achieve a high effect on their heating costs by changing their behaviour. The calculation of the residents' energy costs is also based on internal calculations with the support of KEHAG Energiehandel.

While the other stakeholders mainly look at economic parameters, **society** focuses on the environmental impact of energy supply. The aim is to release as few emissions as possible. Here, too, a higher proportion of emissions during the use phase is advantageous, since these can be optimised by changing user behaviour. For this purpose, the global warming potential (GWP) is calculated, i.e. the CO_2 equivalents from construction over an operation period of 20 years to disposal. If the life expectancy of the components is higher or lower, these are taken into account proportionally. Emission data from various sources are included in the calculation (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2022; Stamford & Azapagic, 2018; Umweltbundesamt, 2022).

Table 1 provides an overview of the identified objectives. Due to the claim of an investigation that is as generic as possible, the objectives and their exact calculation were not developed by the stakeholders themselves, as the later case study corresponds to a generic multi-family house and not a real project, but through expert interviews and KEHAG Energiehandel's many years of experience as a provider of energy supply solutions for residential buildings. If the method should be applied to a real estate project, there is no reason why the KPIs of the stakeholders should not be quantified individually through appropriate interviews and surveys and used for the analysis.

Table 1. Tabular overview of the stakeholders and their exemplary objectives. The arrows in front of the

Stakeholder	KPI
Owner	↓Investment for energy system ↓Increase in wall thickness ↑State funding
Energy Service Provider	↑Profit ↓Sensitivity (OpEx vs. CapEx)
User	↓Heating cost ↑Sensitivity (Energy vs. Basic Rate)
Society	↓GWP_{t20} ↑Sensitivity (Variable vs. Fixed Emissions)

Of course, it can happen that certain stakeholder groups overlap, e.g., the owner is also the user of the property. Especially in these cases, it is advisable to discuss the objectives used for the project with the local stakeholders and adapt them individually. In the above-mentioned case of an identical owner and user, the focus would presumably be placed on the overall system costs, i.e., CapEx plus OpEx, as these are borne by the same person. However, as it is quite common in Germany to live in multifamily houses for rent (cf. Introduction), these groups of people are considered separately and their interests are only brought together with the MCDA later on.

3. Design of a methodology for multi-stakeholder energy system valuation

Now that we have a better understanding of the exemplary stakeholder goals, an objective methodology is needed to make different energy systems comparable. First of all, a methodology is needed to be able to calculate the KPIs altogether, which simulates and evaluates the different energy system depending on the design. This is presented in the next subsection. Based on this, a method is needed to make the different alternatives comparable on the basis of stakeholder interests and to create an objective, global ranking of the alternatives. More details on this can be found in the chapter after the next. The process is depicted graphically in Figure 2.

3.1. Energy system modelling and simulation

In order to use the previously defined methodology, the identified stakeholder KPIs must be quantified. This requires more detailed specifications and analyses, e.g., of the energy system sizing as well as their mode of operation during the year. For this purpose, both the building envelope and the energy systems used must be modelled and simulated in an appropriate way. In addition to purely technical modelling, this includes country-specific features such as legal framework conditions or subsidy programs.

In many countries it is even required by law that such a simulation be carried out according to a technical standard for new buildings or extensive renovations. In the EU, this is regulated in the "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of building" (European Union, 2002), implementation is up to the member states. Legal limits are then set and subsidies are offered if the planned building complies with certain framework conditions. The aim is to ensure that buildings become more energy-efficient and thus more climate-friendly in the future in order to make an active contribution to climate protection. In Germany, the Building Energy Act (Gebäudeenergiegesetz, GEG) stipulates that every new building or comprehensive building renovation must be assessed in accordance with DIN V 18599-1:2018-09 (2018). The basics of the calculation are roughly outlined here, for more information please refer to the standard.

For simulation, the building is first defined based on its dimensions and location. Afterwards, catalogues are created in which each component (exterior wall, windows, roof area, floor slab, ...) is defined with its building physics properties and orientation. The technical building equipment including the required distribution and transmission are also specified. The standard then determines the useful heat demand in a monthly process from the internal and solar gains, which are offset by losses due to transmission, thermal bridges and ventilation. The difference between gains and losses must then be provided by the heating system, which also suffers losses in the conversion from primary energy to useful energy. The most important results in terms of legislation are, firstly, the primary energy demand of the building Q_p and, secondly, the transmission heat loss H_T.

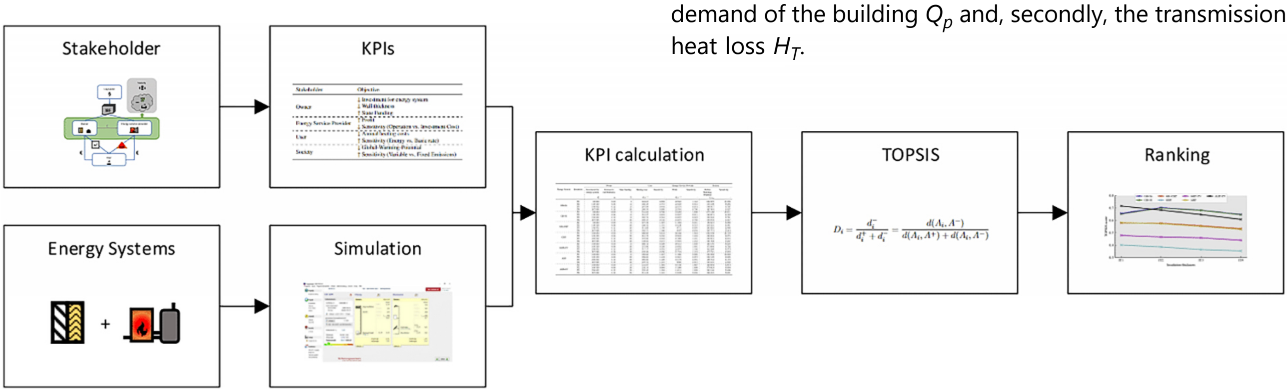

Figure 2. Illustration of the chosen methodology for the valuation of different energy supply concepts from the point of view of different stakeholders

The primary energy demand Q_p is defined as the sum of the final energy used $Q_{f,in,j}$ multiplied by a fuel-specific primary energy factor f_{p_j} per energy form used j, which is 1.8 for electricity and 1.1 for natural gas. This factor takes into account the upstream chain of energy production and the fossil primary energy used in this process. Energy generated in or on the building (e.g., from PV) that cannot be used directly but is fed into the grid $Q_{f,out,j}$ must be deducted from this. The primary energy factors may differ depending on the direction of the flow. This results mathematically in:

$$Q_p = Q_{p,in} - Q_{p,out} = \sum_j Q_{f,in,j} \cdot f_{pj} - \sum_j Q_{f,out,j} \cdot f_{p_j}. \quad (1)$$

The transmission heat loss H_T, on the other hand, is calculated only from the building physics and neglects the technical building equipment. For this purpose, the aforementioned component catalogue is used and the area A_i of each component i is multiplied by its U-value U_i. A correction factor F_{Xi} is applied, which takes into account that heat losses to the outside air are higher than to the ground. A general thermal bridge surcharge ΔU_{WB} is then added, which is also calculated from the component areas. Thus, the entire expression reads:

$$H_T = \sum_i \left(U_i \cdot A_i \cdot F_{Xi} \right) + \Delta U_{WB} \sum_i A_i. \quad (2)$$

Details of how the characteristic values are determined and, in particular, how the performance during the year is calculated in relation to buildings and energy technology are set out in DIN V 18599 on approx. 1900 pages. Some of the guidelines are extremely complex and concern a large number of special cases and innovative technologies. Accordingly, there are many software solutions on the market that meet precisely these requirements and are developed and distributed commercially. An overview for the relevant German market can be found at Behaneck (2018) or Venzmer (2011). We are using the software "Hottgenroth Energieberater 18599 3D PLUS" (https://www.hottgenroth.de/M/SOFTWARE/EnergieNachweise/Energieberater-18599-3D/Seite.html,73274,80422) for the following analysis. However, there are also open source solutions such as energyPLUS (Crawley et al., 2001) which have been developed in academia and can therefore be used rather universally but which lack many usability features.

3.2. Joint decision-making using TOPSIS

As shown in Chapter 2, the goals of the relevant stakeholders are very different, but as shown in Chapter 3.1, they can be quantified relatively easily with suitable software solutions. In many cases the goals even contradict each other, e.g., the user demands a high OpEx share that he can influence, while the energy service provider favours a high CapEx share for risk minimisation. The same can be argued for the climate protection demanded by society in contrast to the affordability and profit of the other stakeholders. Nevertheless, in the end, joint decisions have to be made, taking into account all stakeholder objectives, and an energy system has to be selected and implemented. It will be impossible to satisfy all stakeholders comprehensively, but the aim should be to find suitable compromises. In abstract terms, this means that different options for action have to be evaluated on the basis of certain indicators that cannot be compared with one another. The decision-making problem between different stakeholders considered here is thus a group decision-making problem.

In science, various tools and methods are known for this purpose, which allow to support such decision processes and to make reasonable compromises. The methods are grouped under the umbrella term Multiple-Criteria Decision Analysis (MCDA). A general overview of the methods can be found, e.g., at Løken (2005) or Abdullah et al. (2021). Matsatsinis and Samaras (2001) find that for the problem of group decision support described here, MCDA is well suited to achieving consensus or at least reducing conflict between stakeholder. Here we will briefly outline the most important MCDA methods and justify our selection.

In **Analytic Hierarchy Process (AHP)**, the alternatives are evaluated in pairs by experts, thereby creating an alternative matrix that can then be mathematically transformed into a ranking (Saaty, 2004). AHP is one of the simplest MCDA methods, but requires a lot of expert knowledge. In addition, the technique is susceptible to rank reversal.

Elimination and choice translating reality (ELECTRE) incorporates various methods and can evaluate a large number of very different problems, including those under uncertainty (Figueira et al., 2016). However, the methodology and results are difficult to apply as well as to explain.

Preference ranking organization method for enrichment evaluation (PROMETHEE) is similar in approach and scope to ELECTRE, both belonging to the European school of MCDA (Brans & Mareschal, 2005).

In **Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)** the alternative is sought that is not only close to the optimum but also far from the pessimum (Pavić & Novoselac, 2013). It is much easier to set up and follow than the previous ones and still provides reliable results.

A very similar approach to TOPSIS is **Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR)**, which not only results in a single ranking, but the method outputs three different rankings based on the calculated distances to the optimum (Opricovic & Tzeng, 2004). The results between TOPSIS and VIKOR tend to be rather different, though for few evaluation criteria and alternatives they tend to be fairly similar (Shekhovstov & Sałabun, 2020).

An approach often used in combination with other methods, especially for complex problems, is **Decision Making Trial and Evaluation Laboratory (DEMATEL).** What is particularly interesting about this method is that even complex alternatives can be represented in a graphical method (Si et al., 2018).

According to Mela et al. (2012), which compares the MCDA methods presented here and others in the context of the construction industry, the methodology of choice is the one that provides a good compromise between user-friendliness and informative value. We have therefore chosen the TOPSIS method, which allows us to identify trends relatively easily with small data sets and little effort. The seven steps of the TOPSIS method are therefore described here with reference to Pavić and Novoselac (2013):

Problem formation: Out of m different options A_i which differ in n different criteria x_{ij} the best option is to be chosen. The criteria are divided into benefit (x_1, ..., x_k, monotonically increasing preference) and non-benefit (x_{k+1}, ..., x_n, monotonically decreasing preference).

Step 1 – evaluation matrix: First, an evaluation matrix X is formed in which each column represents a criterion and each row represents an option:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \quad (3)$$

Step 2 – Normalisation: Since the criteria are not comparable with each other and represent completely different orders of magnitude, they must be normalised by replacing each value x_{ij} with a normalised value r_{ij} as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} {x_{ij}}^2}}. \quad (4)$$

Step 3 – Weighted normalised matrix: Now, weights for the various criteria are defined and included on the basis of the individual criteria relevance. For this purpose, each previously normalised value is multiplied by a weighting factor w_j, where $\sum_{j=1}^{n} w_j = 1$, which results in the matrix A:

$$A = \begin{bmatrix} r_{11}\cdot w_1 & r_{12}\cdot w_2 & \cdots & r_{1n}\cdot w_n \\ r_{21}\cdot w_1 & r_{22}\cdot w_2 & \cdots & r_{2n}\cdot w_n \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1}\cdot w_1 & r_{m2}\cdot w_2 & \cdots & r_{mn}\cdot w_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}. \quad (5)$$

Step 4 – Determination of the best and worst solution: Based on the normalised and weighted alternatives, the globally positive and negative optimal solution (A^+; A^-) vectors are now to be determined. These consist of the best and worst value per criterion, i.e., ($A^+ = \left(a_1^+ a_2^+ \ldots a_n^+\right)$; $A^- = \left(a_1^- a_2^- \ldots a_n^-\right)$). The individual entries are to be defined from:

$$a_j^+ = \begin{cases} \max_i a_{ij} & \text{for } j = 1,\ldots,k \\ \min_i a_{ij} & \text{for } j = k+1,\ldots,n \end{cases},$$

$$a_j^- = \begin{cases} \min_i a_{ij} & \text{for } j = 1,\ldots,k \\ \max_i a_{ij} & \text{for } j = k+1,\ldots,n \end{cases}. \quad (6)$$

Step 5 – Determining the Euclidean distances: For each criterion of each alternative, the distance to the optimum A^+ and pessium A^- can now be jointly determined, from which the distance vectors d^+ and d^- result where $d^+ = \left(d_1^+ d_2^+ \ldots d_m^+\right)^T$ and $d^- = \left(d_1^- d_2^- \ldots d_m^-\right)^T$. The Euclidean distance is calculated as follows:

$$d_i^+ = d\left(A_i, A^+\right) = \sqrt{\sum_{j=1}^{n} \left(a_{ij} - a_j^+\right)^2},$$

$$d_i^- = d\left(A_i, A^-\right) = \sqrt{\sum_{j=1}^{n} \left(a_{ij} - a_j^-\right)^2}. \quad (7)$$

Step 6 – Determination of the relative distances: Finally, the distance of each alternative to the optimum and to the pessimum must be put into relation, resulting in the quality value D_i of alternative A_i:

$$D_i = \frac{d_i^-}{d_i^+ + d_i^-} = \frac{d\left(A_i, A^-\right)}{d\left(A_i, A^+\right) + d\left(A_i, A^-\right)}. \quad (8)$$

Step 7 – Ranking: Finally, the various alternatives can now be compared. The previously calculated value D_i represents an ordinal number according to which the different alternatives can be sorted. The highest value of the alternatives thus corresponds to the best solution, the lowest to the worst.

4. Application to a case study

To demonstrate the methodology and to draw conclusions about optimal energy systems under the current German framework conditions, the energy concept of a typical German multi-family house will be applied. For this purpose, the building structure of the "Mehrfamilienhaus groß'" (large multi-family house) is used, which was defined in 2010 by the Center for Environmentally Conscious Building (Zentrum für umweltbewusstes Bauen e.V.) as a reference building for such studies (Klauß & Maas, 2010). The building has 40 residential units of 71.25 m^2 each and has a flat roof with a recessed upper story. It thus corresponds to the typical new construction of German residential buildings in larger cities.

As previously indicated, we understand energy concepts not only as pure energy generation technology but always as their interaction with the insulation of the building envelope. The quality of the energy supply can only be adequately understood in the interaction of these two systems.

For the study, we consider different technology concepts which correspond to the technologies predominantly in use in Germany today. The primary energy source for newly erected buildings in Germany in 2020 was natural gas (32.3%) geothermal energy (8.2%), environmental thermal energy (44.6%) and wood pellets (3.4%) (Statistisches Bundesamt, 2021). Concepts that are no longer legally permissible in new buildings (pure natural gas or oil boilers) and technologies that are not yet established on

Table 2. List of the energy technology investigated for the case study and its dimensioning, as automatically designed by the simulation software. In the following, the abbreviations mentioned in the first column are used

Abbreviation	Primary heat source	Secondary heat source	Heat Storage	Additional electricity source
GB+S	Solar Thermal 114 m^2	Gas Boiler 103 kW_{th}	6.0 m^3	---
GB+CHP	Combined Heat and Power Plant 5–9 kW_{el}	Gas Boiler 103 kW_{th}	1.4 m^3	---
GHP	Ground-source heat pump 62–82 kW_{th}	---	1.4 m^3	---
GHP+PV	Ground-source heat pump 62–82 kW_{th}	---	1.4 m^3	Photovoltaic 13–17 kW_p
AHP	Air-source heat pump 62–82 kW_{th}	---	1.4 m^3	---
AHP+PV	Air-source heat pump 62–82 kW_{th}	---	1.4 m^3	Photovoltaic 15–20 kW_p
PB	Wood Pellet Boiler 132 kW_{th}	---	7.6 m^3	---

the market (such as hydrogen) are not taken into account. The same applies to district heating, as the energy sources and technologies used are highly diverse and cannot be generalised.

Table 2 presents the energy-related equipment used in the following, which is based on the statistically most frequent ones. The sizing was carried out by the simulation software used based on empirical formulas defined in DIN V 18599 without further optimization. The size ranges given in some cases are situations in which the sizing depends on the building's overall design. The lower the thermal demand, the smaller the heat pump can be dimensioned and also the PV system can be smaller. For boilers, the standard does not provide for such interdependence.

In each technology concept, the house is connected via a 2-pipe system. Domestic hot water (DHW) is produced locally in each flat via a fresh water station. The HP systems work with system temperatures of 40 °C for added efficiency, so to ensure legionella-free water, the fresh water stations are extended with a flow heater that brings the water up to 60 °C. All concepts are equipped with the same central ventilation system including heat recovery.

These are combined with 4 different insulation thicknesses from IT1 (low insulation) to IT4 (high insulation) which are specified in more detail in Table 3. IT1 corresponds to the minimum legally permissible insulation, IT4 to the maximum insulation thickness of products available on the market. IT2 and IT3 are respective intermediate steps. The wall construction, the roof construction and the basement ceiling are varied; elements such as doors and windows are assumed to be constant.

All in all, this results in 7 technologies · 4 insulations = 28 different alternatives to be ranked.

The subject of energy prices is particularly important and is currently the focus of a great deal of political attention. Here, we take data from the German Federal Statistical Office from the first half of 2021. At that time, the electricity price was 20.12 ct/kWh, the gas price 3.70 ct/kWh and the price for wood pellets 226 €/t.

Table 4 shows the stakeholder KPIs calculated using the simulation software for these energy systems. As previously argued, it is impossible to make even approximate statements about the quality of the systems based on this data alone, which is why they have to be analysed in TOPSIS.

Table 3. Overview of the insulation thicknesses used for the relevant components. The values are taken from the product database of the software used and reflect products commonly used in Germany today

		IT1	IT2	IT3	IT4	
Wall construction	Insulation thickness	12	18	24	30	cm
	U value	0.26	0.18	0.14	0.11	$Wm^{-2}K^{-1}$
Roof construction	Insulation thickness	16	21	26	30	cm
	U value	0.20	0.16	0.13	0.11	$Wm^{-2}K^{-1}$
Basement ceiling	Insulation thickness	4	10	16	22	cm
	U value	0.34	0.22	0.16	0.12	$Wm^{-2}K^{-1}$

The weightings shown in Table 5 are used for the further analysis. Each stakeholder first determines the weightings of their own objectives, which must add up to 1. In order to bring the different stakeholders and their interests together, an additional weighting of the stakeholders must be defined. These would have to be negotiated between the stakeholders for an actual project, which would incur a significant level of effort.

The weights of the overall analysis then result from the multiplication of both values and add up to 1 as well. Since we are working with an abstract case study without real stakeholders, we have determined the weightings ourselves for demonstrational purposes to the best of our knowledge and experience.

Under the given weights, we can now calculate the TOPSIS scores, both from the point of view of the individual stakeholders, if they could decide on their own, and from the point of view of the stakeholder community. The results can be found in Table 6.

5. Discussion

Table 4 shows clearly how different the results are depending on the energy concept and insulation. For example, the investment costs between the GB+S with IT1 and the GHP+PV with IT4 differed by a factor of 5, while the heating costs between the GHP with IT1 and the AHP+PV with IT 4 differed by a factor of 3. There are similarly dramatic differences between the alternatives in terms of emissions and profits. This makes it impressively clear how important it is not only to decide on an energy system based on individual performance indicators of individual stakeholders, but also to carry out holistic investigations and look at the decision problem from different perspectives.

Based on Table 6, we are able examine what would happen if the stakeholders were allowed to decide without regard to the others.

Table 4. Results of the stakeholder KPIs identified in Table 1 for the different energy concepts used in the case study

Energy System	Insulation	Owner			User		Energy Service Provider		Society	
		Investment for energy system	Increase in wall thickness	State funding	Heating cost	Sensitivity	Profit	Sensitivity	GWP	Sensitivity
		€	m	%	€/a	–	€/a	–	t_{CO2}	–
GB+S	IT1	60 000	0.00	0	341.84	0.780	24263	1.090	675 169	15.011
	IT2	129 539	0.06	15	318.27	0.652	24287	0.915	569 674	8.562
	IT3	198 852	0.12	15	305.74	0.584	24287	0.823	522 048	5.781
	IT4	267 008	0.18	20	298.47	0.545	24275	0.769	500 859	4.347
GB+CHP	IT1	60 000	0.00	15	377.76	1.387	11382	0.351	180 219	3.386
	IT2	129 539	0.06	20	336.52	1.191	10446	0.518	248 321	3.381
	IT3	198 852	0.12	20	314.86	1.100	9751	0.605	283 082	2.868
	IT4	267 008	0.18	20	302.71	1.046	9397	0.658	307 774	2.443
GHP	IT1	100 000	0.00	15	690.00	0.424	26048	1.364	602 539	14.133
	IT2	169 539	0.06	20	619.73	0.450	22803	1.403	569 848	9.075
	IT3	238 852	0.12	20	578.90	0.462	21006	1.431	560 616	6.616
	IT4	307 008	0.18	20	549.63	0.457	19919	1.452	561 830	5.237
GHP+PV	IT1	100 000	0.00	15	609.12	0.329	28515	1.038	483 176	6.025
	IT2	169 539	0.06	20	557.90	0.330	24952	1.091	473 646	4.792
	IT3	238 852	0.12	20	517.17	0.352	22974	1.102	442 286	3.573
	IT4	307 008	0.18	20	493.46	0.350	21784	1.124	472 781	3.222
AHP	IT1	100 000	0.00	15	320.66	1.467	11380	3.926	524 262	14.089
	IT2	169 539	0.06	20	299.00	1.433	10621	3.872	502 122	8.628
	IT3	238 852	0.12	20	286.66	1.420	10179	3.855	498 742	6.170
	IT4	307 008	0.18	20	279.75	1.416	9906	3.910	503 455	4.838
AHP+PV	IT1	100 000	0.00	15	241.87	1.094	16726	1.967	400 894	4.973
	IT2	169 539	0.06	20	232.13	0.994	15269	1.990	376 923	3.694
	IT3	238 852	0.12	20	222.43	1.034	14451	1.999	363 146	2.806
	IT4	307 008	0.18	20	214.43	1.041	13942	2.038	398 545	2.601
PB	IT1	60 000	0.00	15	504.43	0.611	15365	1.693	106 178	1.795
	IT2	129 539	0.06	20	473.13	0.513	15115	1.534	113 915	1.056
	IT3	198 852	0.12	20	456.87	0.460	15180	1.445	125 921	0.730
	IT4	267 008	0.18	20	447.27	0.429	15148	1.430	141 684	0.583

Table 5. Summary of the selected stakeholders and objective weights

Stakeholder	Stakeholder weight	Objective	Objective weight	Overall weight
Owner	0.25	Investment for energy system	0.40	0.100
		Increase in wall thickness	0.30	0.075
		State funding	0.30	0.075
User	0.35	Heating cost	0.90	0.315
		Sensitivity	0.10	0.035
Energy Service Provider	0.25	Profit	0.95	0.238
		Sensitivity	0.05	0.013
Society	0.15	GWP	0.90	0.135
		Sensitivity	0.10	0.015
SUM	1.00			1.000

Table 6. Results of the TOPSIS calculation for the abstract case study from the perspective of the individual and all stakeholders. The colour code is formed for each column and ranges from green (best result) to yellow and red (worst result) and should help to classify the results visually more quickly

Energy System	Insulation	Owner	User	Energy Service Provider	Society	Overall
GB+S	IT1	0.666	0.725	0.776	0.155	0.627
	IT2	0.687	0.768	0.779	0.205	0.670
	IT3	0.446	0.790	0.779	0.272	0.656
	IT4	0.333	0.802	0.778	0.305	0.627
GB+CHP	IT1	0.863	0.660	0.134	0.812	0.573
	IT2	0.725	0.743	0.096	0.719	0.567
	IT3	0.489	0.787	0.078	0.663	0.545
	IT4	0.333	0.810	0.073	0.623	0.521
GHP	IT1	0.862	0.010	0.870	0.197	0.406
	IT2	0.668	0.147	0.702	0.207	0.388
	IT3	0.457	0.232	0.608	0.211	0.365
	IT4	0.334	0.293	0.552	0.204	0.352
GHP+PV	IT1	0.862	0.168	0.987	0.338	0.483
	IT2	0.668	0.275	0.814	0.352	0.469
	IT3	0.457	0.359	0.711	0.403	0.459
	IT4	0.334	0.408	0.649	0.350	0.436
AHP	IT1	0.862	0.779	0.103	0.301	0.565
	IT2	0.668	0.825	0.064	0.314	0.556
	IT3	0.457	0.849	0.041	0.312	0.535
	IT4	0.334	0.864	0.027	0.301	0.513
AHP+PV	IT1	0.862	0.930	0.385	0.476	0.697
	IT2	0.668	0.938	0.310	0.513	0.665
	IT3	0.457	0.951	0.268	0.534	0.632
	IT4	0.334	0.955	0.242	0.474	0.594
PB	IT1	0.906	0.388	0.313	0.852	0.513
	IT2	0.735	0.452	0.301	0.843	0.515
	IT3	0.508	0.485	0.304	0.835	0.499
	IT4	0.358	0.504	0.303	0.824	0.476

Owner

The owner shows a strong dependence on the insulation thickness. This seems logical, as stronger insulation means higher investment costs and less leasable space for the owner. The resulting possibly higher state subsidies do not seem to cancel out this effect, but they do play a role in the choice of energy technology. ST systems, for example, only receive low state subsidies, whereas CHP- and HP-based systems offer higher subsidies with the same level of insulation. The slightly higher state subsidy for heat pumps due to the use of renewable energies (KfW55EE/KfW40EE) is exactly offset in this case by the cheaper DHW system of the CHP solution. The optimal system from the owner's point of view is therefore wood pellets with low insulation, which offers both high state subsidies and the simpler DHW system and minimum investment cost.

User

However, from the point of view of the user, who mainly focuses on heating costs, a higher level of insulation would be advantageous, as this would reduce the consumption-dependent costs. Technologically, they would prefer systems with low total heating costs, which seem to apply especially with AHP systems. The addition of PV is also a great advantage for the user. GHPs are particularly disadvantageous for them, which should be mainly caused by the high investment costs. Their optimal system would therefore be an AHP and PV combination with maximum insulation.

Energy Service Provider

Again, the energy service provider has advantages from low insulation, as it can sell more energy as a result. However, the effects are in most cases not as prominent as with the other stakeholders. It is interesting to note that there is hardly any effect to be seen with ST systems. On the other hand, strong technological trends can be seen here as well. The low investment costs of the AHP and CHP solutions lead to low margins, whereas the GHP solutions with high investments make them appear attractive. In the energy service providers view, the optimal system would therefore be the most capital- and energy-intense, a GHP-PV combination with low insulation.

Society

For society, on the other hand, CHP and pellet systems are quite advantageous. The CHP ranking should be mainly due to the fact that large amounts of electricity are produced, which are still based on fossil fuels, but displace inefficient power plants on a national level. The avoided emissions elsewhere are therefore credited to this system. The same applies to HP systems with the addition of PV. The pellet system is the only one that today already relies entirely on renewable energies and has only low emissions in construction and in the upstream chain of pellet production. ST systems perform poorly due to the quantities of natural gas required, whereas HP systems come out in the middle. What is interesting here is the trade-off between higher emissions due to insulation or due to more intensive system operation. There do not seem to be any unifying trends here; instead, they are largely dependent on the technologies used. Some systems have a negative or positive effect through an increase in insulation; for some, even a medium level of insulation is the best compromise. Nevertheless, the optimal energy system from a social point of view is a pellet boiler with low insulation.

An interesting aspect to analyse is how the interests of the stakeholders relate to each other. To do so, the correlation coefficient $\left(r_{x,y} = \frac{\Sigma\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\Sigma\left(x_i - \bar{x}\right)^2 \Sigma\left(y_i - \bar{y}\right)^2}} \right)$ of the TOPSIS scores of the different alternatives is calculated. For stakeholders with similar interests, one would expect a value close to 1, and for stakeholders in strong competition, close to –1. Stakeholders with little influence on their preferences have values close to 0. These values could indicate possible coalitions and oppositions. For the multi-family house, the results are presented graphically in Figure 3.

It turns out that only weak trends and dependencies are evident. The strongest opposition is between society and the energy service provider. This seems logical, as society prefers efficient energy consumption, while the energy service provider profits significantly from high sales volumes. A similar reason exists for the high opposition between energy service provider and user. Moreover, in both cases the sensitivity parameters are opposite. One would therefore expect the user and the society to form a good coalition, but this is not the case. Only the user and owner still show slight negative correlations, all other stakeholder combinations hardly influence each other. It might now be thought that, on the other hand, there could be an opportunity for certain stakeholders to form coalitions, since similar energy concepts are advantageous to them, albeit for different reasons. However, no such positive correlations are found, which again underlines how important it is for all these stakeholders to participate in such decision-making processes.

The key point, however, is how the stakeholder community would decide, taking all interests into account. In addition to Table 6, Figure 4 shows a graphical evaluation of the TOPSIS scores for easier analysis.

The AHP+PV solution with TS1 insulation turns out to be the absolute best solution. Although this solution is not optimal for the energy service provider due to the low investment costs, it is very optimal for the owner as well as the user due to the low costs and high subsidies. Socially, it is in the middle. It is very interesting that for larger insulation especially this solution is directly followed by the ST solutions, which were always in the middle ground of the previous discussion. However, this solution is only problematic for society, which is given rather little consideration in the current weightings. The worst solution is clearly the pure GHP solution. Here, extremely high costs for the users come together with poor ecological values that cannot be compensated by the good values of the energy service provider. The addition of PV to the two HP systems is fundamentally positive and, in all cases, improved the score for all stakeholders. Without PV, the AHP, for example, only reaches the middle ground along with to the CHP-based system. The increase of insulation means in (almost) all cases a deterioration of the score, as here especially the owner has very strong dependencies. The only exception is ST systems, where higher state subsidies can be achieved in this way.

It can thus be abstracted from the above that under the current German framework conditions and market prices, both electricity-based heat generation (AHP) and gas-based heat generation (GB+S) can be advantageous in multi-family houses. A high standard of insulation is not necessarily beneficial, as is often assumed, but may well have a negative impact on stakeholders, who would be better off with a more efficient energy generating system. The poor performance of GHP solutions, which in our perception enjoy a very good reputation on the German market, is particularly interesting. While this solution may make a lot of sense from a physical-technical point of view, both costs and emissions are rather mediocre here. The opposite is true of the purely gas-based CHP solutions, which are viewed rather sceptically by the public. These make it into the middle rankings even without using renewable energies. However, this may change in the near future if the conditions for purchasing electricity and natural gas change significantly as a result of consistent pricing of CO_2 emissions and the increase in renewable energies in the electricity grid. Conversely, what is already worthwhile for all stakeholders today and will probably become even more important in the future is the use of radiant energy either through ST or PV systems. This basically adds value to the overall system and should therefore be considered in all cases.

Overall, however, the topic presented is highly dynamic. For example, the war in Ukraine and the associated debate about stopping the import of Russian natural gas into the EU, as well as the significant change in the funding for energy-efficient buildings by the new German government at the beginning of 2022, have shown how volatile such studies and recommendations can be. These developments were in no way foreseeable at the time this study was conducted.

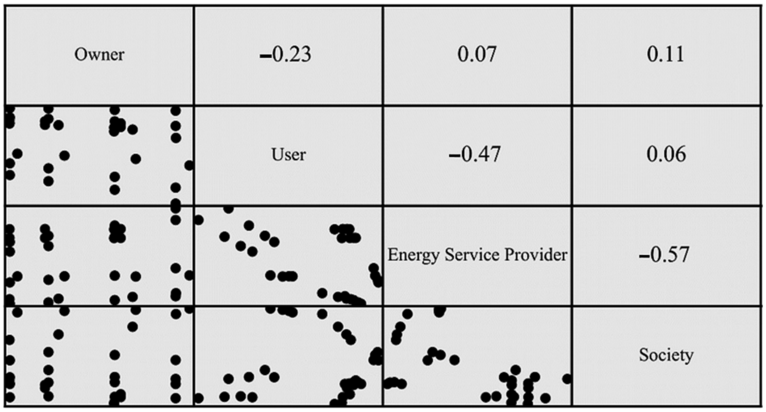

Figure 3. The optimality of the different energy concepts (TOPSIS scores) of the stakeholders are shown as a scatter plot to the other stakeholders (bottom left). The correlation coefficient is calculated from this (top right). The better the interests of these stakeholder pairs correlate the closer the value is to 1, the stronger the stakeholders have different understandings of optimality the closer to –1. A 0 means that the interests of the stakeholders are independent of each other

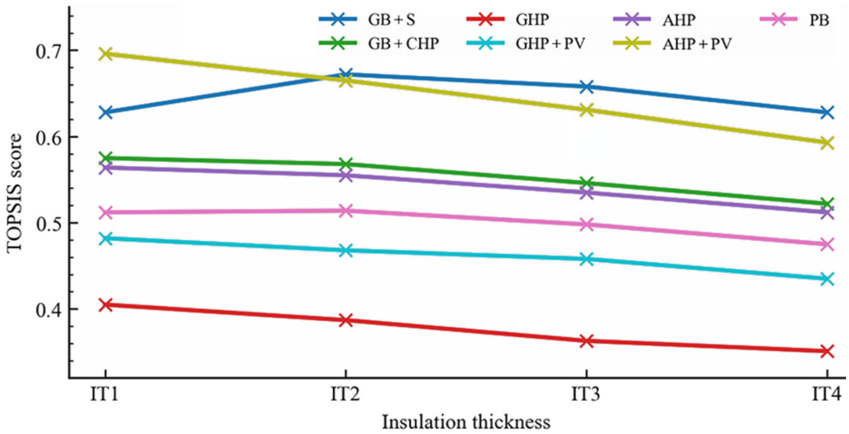

Figure 4. Visualization of the TOPSIS scores from the perspective of all stakeholders for the case study used. The different energy solutions are shown as lines over the insulation thickness (x-axis). The closer the value to 1, the better the energy concept, taking into account all stakeholder interests

It must be pointed out again that the building presented here and the assumed stakeholders are characteristic of the German building stock, but of course do not represent the entire real estate market. This study provides only insights and trends as to which strategies should be used to approach energy concepts in multi-family houses, but there will always be exceptions and special cases. In these cases, however, it can be of great value to apply the method used here on a project-specific basis and to use it individually for the building and the existing stakeholders in order to reach the best possible compromises.

6. Conclusions

In summary, methods such as the one used here can provide insight into the interrelationships of energy system design and can be helpful in the decision-making process. We were able to show that finding a compromise is not always obvious and that energy concepts include not only energy production but also energy savings in the building envelope. The methodology used can be easily transferred to other countries and sectors and can be used both for generic studies such as this one and for project-specific analyses.

With regard to the German market and multi-family houses analyzed, it can be stated that both gas- and electricity-based systems continue to be attractive solutions. A focus should be on ST systems and AHPs, but CHP systems are also competitive. The use of PV has a generally positive effect on HPs. The technical components seem to be the deciding factor. Excessive insulation has a negative effect on any energy system. However, this is of course only a snapshot, which is very dynamic due to both further technical development and political will.

Basically, one can ask at this point whether the results of this study reflect the will of German politics, i.e. whether the current incentives are set correctly. They would like to change the heat market as quickly as possible from gas-fired systems to heat pumps and the use of solar radiant energy. Currently, it is more attractive to use large quantities of natural gas in CHPs than to install an efficient GHP.

Notations

Abbreviations

AHP – Air-Source Heat Pump;
CapEx – Capital Expenditures;
CHP – Combined Heat and Power Plant;
DHW – Domestic Hot Water;
GHP – Ground-Source HP;
GWP_{t20} – Global Warming Potential;
HP – Heat Pump;
KPI – Key Performance Indicator;
MCDA – Multiple-Criteria-Decision Analysis;
OpEx – Operational Expenditures;
PV – Photovoltaic;
ST – Solar Thermal;
TOPSIS – Technique for Order Preference by Similarity to Ideal Solution.

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Author contributions

Conceptualisation and Methodology: LS; Software: FW and LS; Data Curation: FW, LS and TE; Formal Analysis: LS and FW; Validation: LS and TE; Visualisation: LS; Writing – Original Draft Preparation: LS; Writing – Review and Editing: FW, PK, BH and BS; Project Administration: LS, TE and PK; Supervision: TE, PK, BH, KvM, CA and BS.

Disclosure statement

The authors declare no conflict of interest.

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