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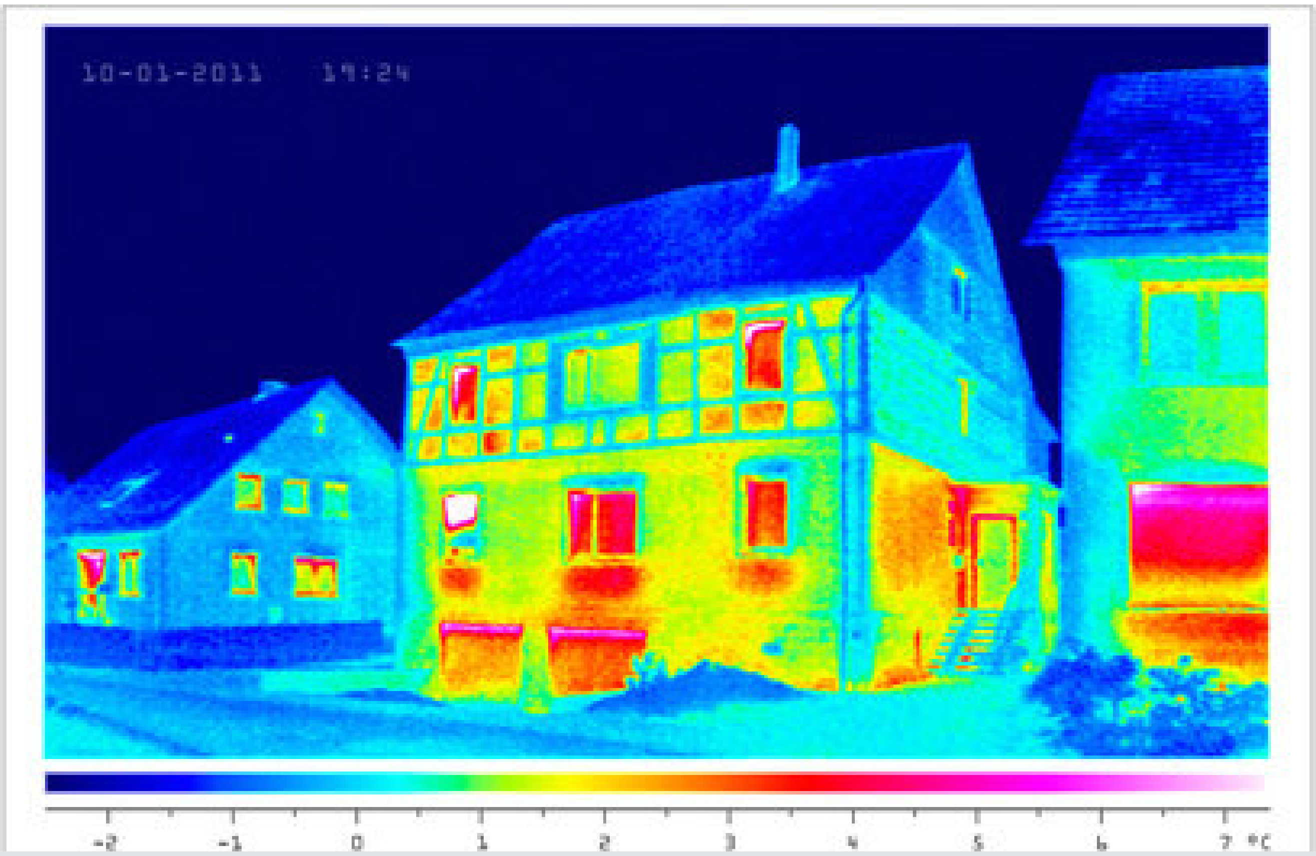

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In Germany over 700 energy cooperatives were established since 2006 and about 46% of installed renewable energy can be referred to as community energy. Decentralised community energy resources are often abundant in smaller, more rural communities. But these often lack the resources to develop extensive energy concepts and thus exploit these resources in a consistent way. Energy system analysis (ESA) offers useful insights in this context, but many energy system models focus on techno-economic aspects, without considering social aspects such as individual preferences. Much research in previous years has attempted to link social aspects and ESAs, often by employing a combination of ESA and multi-criteria decisions analysis (MCDA) tools. This paper presents an integrated participatory approach to developing feasible energy scenarios for small communities, with a focus on the transferability of the method and the consideration of uncertainties. For one exemplary municipality in south west Germany, stakeholder workshops are combined with ESA and MCDA. A total of eight alternatives for the 2030 energy system are elaborated, which vary in terms of the optimization objective between total costs, CO_2 emissions and net energy imports. The three alternatives optimized with respect to just one criteria can be rejected. Instead the community should focus on the remaining intermediate scenarios, which achieve the highest overall performance scores and are stable to variations in the criteria weights. Similarities between these five alternatives mean that concrete recommendations about building-level measures can be derived, supported by simply tools that are made available to the community.

Contents

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Abstract

In Germany over 700 energy cooperatives were established since 2006 and about 46% of installed renewable energy can be referred to as community energy. Decentralised community energy resources are often abundant in smaller, more rural communities. But these often lack the resources to develop extensive energy concepts and thus exploit these resources in a consistent way. Energy system analysis (ESA) offers useful insights in this context, but many energy system models focus on techno-economic aspects, without considering social aspects such as individual preferences. Much research in previous years has attempted to link social aspects and ESAs, often by employing a combination of ESA and multi-criteria decisions analysis (MCDA) tools. This paper presents an integrated participatory approach to developing feasible energy scenarios for small communities, with a focus on the transferability of the method and the consideration of uncertainties. For one exemplary municipality in south west Germany, stakeholder workshops are combined with ESA and MCDA. A total of eight alternatives for the 2030 energy system are elaborated, which vary in terms of the optimization objective between total costs, CO_2 emissions and net energy imports. The three alternatives optimized with respect to just one criteria can be rejected. Instead the community should focus on the remaining intermediate scenarios, which achieve the highest overall performance scores and are stable to variations in the criteria weights. Similarities between these five alternatives mean that concrete recommendations about building-level measures can be derived, supported by simply tools that are made available to the community.

1. Introduction

Local communities have a key role to play in the transition towards more sustainable energy systems. Whilst the energy-political framework, including overarching targets and policies, are set at national and regional levels, the implementation of measures towards this end occurs at the level of individuals and municipalities. A recent trend towards so-called community energy (Walker 2008; Walker et al. 2010) in Europe has been particularly strong in Germany, where in 2012 46% of renewable energy capacity could be classified as community energy (Klaus Novy Institut e.V. & trend:research 2011), which is mainly owned by private individuals and farmers. In this domain, many communities attempt to increase the fraction of energy supply from renewable sources and improve the energy efficiency of their existing buildings and infrastructure. Some of these communities are involved in the Covenant of Mayors (Kona et al. 2015) and/or the Energy Efficiency Award[1], two voluntary European initiatives that recognise local action in this field. At one end of the scale are relatively small-scale projects in which members of the community establish a co-operative or similar financing structure in order to invest in one or several wind turbines – 718 such energy cooperatives have been founded since 2006 (DGRV 2014). At the other end of the scale, larger projects involve communities declaring ambitious goals with respect to renewable generation and/or CO_2 emission reductions and/or energy autonomy[2], in some cases even buying the local electrical distribution network back from the local utility.

Within municipalities, buildings account for about 40% and 36% of the total European end energy consumption and greenhouse gas (GHG) emissions respectively (De Groote and Rapf, 2015). Around 75% of the total European building floor area is accounted for by residential buildings (Economidou et al., 2011), where the bulk (up to 80%) of energy use and emissions is related to heating applications (i.e. space heating and hot water). In addition, currently the around 87% of heat supply in European buildings is generated in or near to the object it supplies (Connolly et al., 2013). Decisions made at the individual, building (e.g. household or commercial premises) and municipality scale all have strong interactions with one another.

Hence the implementation of measures aiming at a more sustainable local energy supply and use presents several methodological challenges. Firstly, by working at the community level it is possible to identify the feasible, most suitable (according to diverse criteria), and efficient (combinations of) measures, but the implementation of these relies on the cooperation of the members of the community. Secondly, the number of and heterogeneity amongst stakeholders within a municipality are both typically quite high, so that any overall solutions(s) necessitate(s) a compromise of individual goals and aspirations. Thirdly, the problems encountered within community energy systems generally involve a combination of quantitative and qualitative characteristics. Fourthly, there is a significant amount of uncertainty associated with the way in which global parameters, such as energy prices, may develop in the medium term future. Fifthly and finally, in contrast to large cities, especially smaller communities do not have the available resources to develop climate or energy plans themselves (Marinakis et al. 2016).

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[1] A European award aiming at recognizing and benchmarking municipalities' efforts to improve their energy efficiency. At the time of writing there are around 1400 municipalities participating, of which 310 are in Germany: http://www.european-energy-award.de/eea-kommunen/.

[2] Defined here as the fraction of annual local energy demand that is met by local (renewable) generation.

Against this background the authors have developed an energy system model for community energy systems, which takes a central planner perspective, uses mostly open source data inputs and thus has a focus on transferability (Mainzer et al. 2015). They also have expertise in the field of multi-criteria decision analysis (MCDA) and more recently in the combination of energy system models with MCDA methods (Bertsch & Fichtner 2016). This contribution therefore combines these two areas by applying the community-level energy system model along with MCDA in the context of a case study to a community in the south west of Germany. The focus is on smaller municipalities, because these typically have fewer technical, administrative and economic resources (than larger ones) to devote to sustainability projects (Polatidis & Haralambopoulos 2004). The main novelties compared to existing contributions, as outlined in section 3, lie in the automated determination of costs and potentials for renewable energies and energy efficiency, the combination of optimisation model and MCDA framework to allow structured alternative formulation and the overarching participatory approach to the problem with key stakeholders, which explicitly considers uncertainties through a multi-dimensional sensitivity analysis and culminates in a natural language output generation module.

The paper is structured as follows. Section 2 gives an overview of some relevant literature on community energy, with a special focus on combining qualitative and quantitative methods. Section 3 then presents the general methodological framework, before section 4 introduces the case study municipality and the application of the method. Section 5 subsequently presents the results and section 6 discusses key aspects of the method. The paper closes with conclusions and recommendations in section 7.

2. Background work on community energy systems

There are a large number of tools and models for analysing the energy systems on the district scale (for reviews, see e.g. Allegrini et al. 2015, Keirstead et al. 2012). Most if not all of these approaches focus on more technical aspects and typically do not perform well in terms of considering social aspects. For example, Orehounig et al. (2014) apply their optimizing energy hub concept to the village of Zernez in Switzerland and determine future scenarios for a decentralised, local energy supply with minimal CO_2 emissions. But they neither seem to involve the community/citizens in their study nor analyse the trade-offs between partly competing objectives.

Much research in previous years has therefore attempted to overcome the respective limitations of these two types of approaches, partly but not only within the fields of hard and soft Operations Research (OR). Indeed, there is large and growing literature on mixing methods but successful examples in the context of environmental decision and policy making are scarce (Myllyviita et al. 2014). Examples include the combination of decision support methods such as Multi-Criteria Decision Analysis (MCDA) and Multi Attribute Value Theory (MAVT) surveys, workshops and focus groups.

Multi-criteria decision analysis (MCDA) represents a formalised framework, which draws on a variety of methods and models to provide transparent and systematic support in complex decision situations (Stewart, 1992). The methods explicitly acknowledge subjectivity in decision making, provide a framework for sensitivity analysis, and offer support for building consensus in group decision making. Multi-attribute value/utility theory (MAVT/MAUT) can be considered one group of methods within MCDA using linear additive value functions or multiplicative nonlinear utility functions to identify and rank a set of discrete decision alternatives (see Keeney & Raiffa 1976 for an overview).

The selection of the appropriate decision-support method depends on the nature of the community problem and alternatives to be analysed. Typically, MCDA is appropriate for finding the optimum solution amongst a theoretically infinite number of alternatives, e.g. with mathematical programming, whereas MAVT sorts a finite set of alternatives with discrete and finite alternatives (Duarte & Reis 2006). MAVT is strictly speaking only sufficient when the alternatives have complete certainty and the time horizon is disregarded. As neither of these requirements are generally fulfilled within community OR, measures such as uncertainty and/or sensitivity analysis are required to deal with this uncertainty.

Several studies have tried to link social aspects and energy system planning models, often by employing a combination of energy system analysis and MCDA tools (for reviews see e.g. Wang et al. 2009, Ribeiro et al. 2011). The combination of such quantitative scenarios and MAVT enables the complexity of socio-technical systems to be at least partly overcome (Kowalski et al. 2009). For example, Østergaard (2009) analyses the interdependencies between heat pumps and wind power in Denmark until 2020 with EnergyPLAN, but does not consider any social aspects. On the other hand, Ribeiro et al. (2013) couples a mixed integer linear program with an additive value function (AVF) considering social, technical, economic and environmental constraints in order to analyse the development of the Portuguese electricity sector. Further, Bertsch & Fichtner (2016) use MAVT to combine quantitative results from the optimisation model of the German electricity generation and transmission system, with qualitative assessments of the social acceptance, elicited in an online survey. They apply their approach to rank a set of discrete electricity generation portfolios, which are characterised by different shares of renewable energies and levels of transmission network expansion requirements on a national level in Germany. Finally, one particularly relevant application to community energy systems is from Trutnevyte et al. (2012), who combine expert workshops with MAVT and resource allocation scenarios for a semi-urban community of 2282 inhabitants in Switzerland. Some key limitations of this study, however, are that it does not consider cost constraints on the developed technical resource allocation scenarios and does not deal with future uncertainties in the scenarios considered.

Table 1: Overview of selected studies in the field of community energy systems

Source	Objective(s)	Application	Method(s)	Source of MCDA inputs	Source of MCDA weights	Sensitivity analysis?[3]
Kowalski et al. (2009)	Assess sustainable energy futures for Austria (ARTEMIS project)	Lödersdorf & Raabau	Scenario building and PROMETHEE	Qualitative stakeholder input and quantitative modelling	Stakeholders	No
Bertsch & Fichtner (2016)	National power generation and transmission system planning	Germany	MAVT	Linear optimisation model	Online survey of the population	Yes, multi-dimensional
Ferretti (2016)	Determine location of parking areas in a UNESCO site in Italy: decision between distinct, pre-defined alternatives	Alberobello	MAVT	Parking area locations proposed by local authority	Stakeholder analysis and cognitive mapping	Yes
Marinakis et al. (2016)	Develop a Sustainable Energy Action Plan for a Greek municipality within a participatory supportive framework	Eurota	UTA II	Desktop analysis	Stakeholders	No
Orehounig et al. (2014)	Determine future scenarios for a decentralised, local energy supply with minimal CO2 emissions for a small Swiss community	Zernez	n.a.[4]	Linear optimisation model (energy hub)	Public data and assumptions	No
Trutnevyte et al. (2012)	Link visions and quantitative resource allocation scenarios for small Swiss community	Urnäsch	MAVT	Double description method	Stakeholders	No
Ribeiro et al. (2013)	Assess electricity production scenarios in Portugal	Portugal	AVF	Linear optimisation	Experts	No
Tsoutsos et al. (2009)	Technology-focussed sustainable energy planning on Crete	Crete	PROMETHEE	Authors' own definition	Stakeholders	Yes
Schmidt et al. (2012)	Autonomous, mainly biomass-based energy supply for rural districts	Sauwald, Austria	Optimisation and land use models	n.a.[4]	Questionnaire and assumptions	No
Jenssen et al. (2010)		Average German rural village	LCA, exergy allocation, CO2, cost/energy balances	n.a.[4]	Unclear	No
Burgess et al. (2012)		Marston Vale, UK	Land-use mapping for per-capita potentials and demands	n.a.[4]	Literature and public data	No

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[3] 1D unless stated

[4] Not applicable

The overview of selected literature in Table 1 highlights the lack of studies combining fully participatory approaches with stakeholders, a detailed quantitative energy system model as the source of inputs for the MCDA, and a multi-dimensional sensitivity analysis with natural language output generation. In order to fill this gap, we developed the approach presented in this paper with the following crucial extensions:

1. With the analysis of the existing energy system and RES cost-potentials being based on open data (e.g. OpenStreetMap), our approach can be used as a blueprint for the participatory development of local energy concepts with interested communities globally.
2. The combination of value-focused thinking and a flexibly adaptable energy system optimisation model ensures a structured generation of high-quality alternatives for the MCDA. I.e. the optimisation model's target function is flexibly adjusted (and adjustable) to the objectives determined when using value focused thinking in the problem structuring process within the MCDA. This procedure ensures that the alternatives perform well in terms of achieving the objective(s). Furthermore, it enables an explicit calculation of tradeoffs between the objectives beyond the identification of the most preferred alternative.
3. Perhaps most importantly, our approach is a participatory one and is aimed at making energy system optimisation models more accessible to smaller communities (being based on facilitated workshops, use of open data etc.). While it explicitly considers the uncertainties of the stakeholder preferences through advanced sensitivity analyses as elicited in the face-to-face workshops, it makes use of a recently-developed natural language generation module to increase understanding and traceability of multi-dimensional sensitivity analyses.

3. An integrated participatory approach towards feasible community energy concept development

Generally, we use multi-criteria decision analysis (MCDA) in facilitated workshops to link an analysis of the existing energy system and energy system modelling with social aspects and local preferences. In this section, we therefore first describe our approach to analysing the existing energy system (details of the determination of cost potentials for renewable energy sources are given in section 5.a), before we give a brief overview of the energy system model used in section b. We then describe the key phases of MCDA and how they can be applied in facilitated workshops (section c). In section d, we describe how we combine these individual elements in the integrated participatory approach developed in the context of our research, also shown in Figure 2.

a. Analysis of the existing energy system

The energy infrastructure is important since it provides the optimisation model with constraints on the geographical availability and maximum flow capacity of different energy carriers. Some of the required data can be retrieved from open sources (e.g. power grid topology from OpenStreetMap (2016)), but in many cases, the data available is limited. When there is no information on possible grid bottlenecks, no restrictions are applied to the power and gas grids.

The heat demand for each building type is calculated by analyzing the local climate conditions (MINES ParisTech / Transvalor S.A. 2015), combining statistical building stock data (Statistische Ämter des Bundes und der Länder 2014) with high-resolution building footprints (OpenStreetMap-Contributors 2016), and applying a one-zone heat demand calculation method (IWU 2015 / DIN EN ISO 2008), which takes into account the heat transfer by transmission and ventilation, as well as the contribution of internal and solar heat gains.

The electricity demand is calculated using a bottom-up electricity demand simulation model for German households (Hayn 2016), which employs statistical assumptions on appliance ownership and user presence and combines these with technical characteristics (e.g. power consumption profiles) of appliances.

In order to determine the possible contributions of local renewable energies, the potentials for photovoltaics (PV), wind and bioenergy are assessed. A description of these methods as well as the results can be found in section 5.a, while for a more detailed description, the reader is referred to Mainzer et al. (2016a) and (2016b).

b. Optimisation of the energy system

The employed model is in the class of energy and material flow tools, with detailed techno-economical properties for technologies on the supply- as well as on the demand-side (see Figure 1). Apart from the technological characteristics (e.g. energy conversion efficiencies, technical lifetimes), the model also takes into account economic factors, such as investment, technology utilisation costs, and costs for energy import and distribution.

The key driver of the model is residential energy service demand, and thus the most important constraints of the model are those that ensure the energy balance, which means that the demand has to be satisfied for each geographical node (typically a district, cf. Figure 1) and each time step. Other constraints include energy flow, potential and emissions restrictions (for further details see Appendix 1).

Geographically, the analysed city/municipality is divided into districts, and within each district buildings are grouped into building types. These types are oriented towards the TABULA/IWU building typology (IWU 2015), but tailored to the analysed municipality. The model is able to perform a long-term energy system optimisation (e.g. from 2015 to 2030), whereby usually each 5th year is modelled explicitly and divided into 72 time slices (4 seasons, 2 day types, 9 time slices within each day).

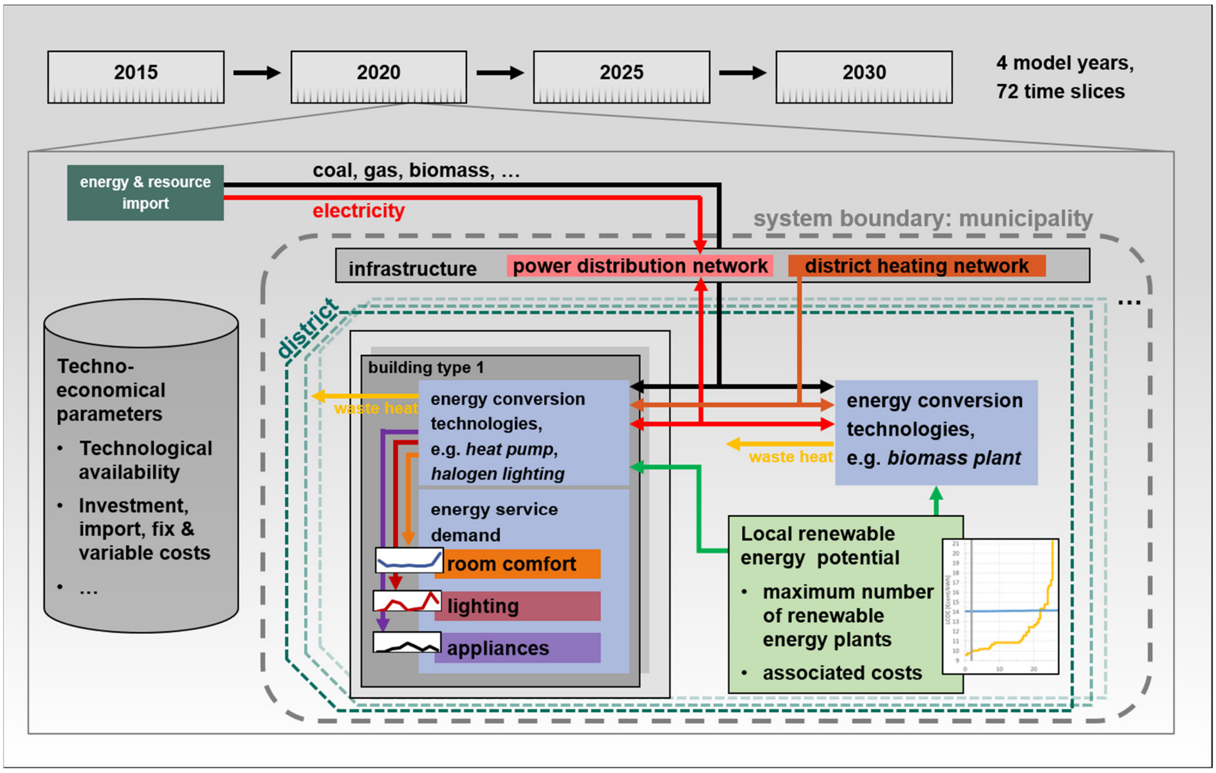

Figure 1: Schematic overview of the energy system optimisation model

The standard objective function embodies the minimisation of total discounted system costs, but it is also possible to minimise the (discounted) CO_2-Emissions, as well as the (discounted) net energy imports from outside of the region. This allows the model to determine the upper bounds of what is achievable in terms of cost savings, emission reductions or energy autonomy for the analysed community. These bounds can later be used as constraints in further alternatives in order to analyse the trade-offs between different objectives. Equations 1 to 3 define the three objective functions employed in this paper. A more detailed model description can be found in Appendix 1.

$$\min \sum_{y \in MY} \left(DF_y * NY_y * \left(c_y^{ei} + c_y^{et} + c_y^{ed} + c_y^{ia} + c_y^{fx} + c_y^{vr} + c_y^{em} \right) \right) \tag{1}$$

$$\min \sum_{y \in MY, d \in DS^{en}} \left(DF_y * NY_y * \left(\sum_{t \in TS} \left(NT_t * em_{y,t,d} \right) \right) \right) \tag{2}$$

$$min \sum_{y \in MY} \left(DF_y * NY_y * \sum_{t \in TS, e \in EC} \left(NT_t * \sum_{d1 \in DS^{ex}, d2 \in DS^{en}} \left(fl_{y,t,d1,d2,e}^{d} - fl_{y,t,d2,d1,e}^{d} \right) \right) \right) \tag{3}$$

In equations 1-3 the following definitions apply: the sets MY stand for model years, DS^{en} for endogenous and DS^{ex} for exogenous districts (used for energy import), TS for timeslices and EC for energy carriers. The parameter DF denotes each year's discount factor, NY is a scale factor for model years and NT for timeslices. The variable em contains emissions and fl^d represents the energy flow between districts.

The total discounted system costs are comprised of cost factors for energy import (c_y^{ei}), energy transmission (c_y^{et}), local energy distribution (c_y^{ed}), investment annuities (c_y^{ia}), fixed (c_y^{fx}) and variable (c_y^{vr}) operating costs as well as emissions (c_y^{em}). Taxes and subsidies are not considered, i.e. the model incorporates a macro-economic "central planner" perspective where these are considered merely as a redistribution of costs with no impact on total welfare.

As a result, the combination, capacity and optimal dispatch for all employed energy conversion technologies are computed. The available technologies comprise supply- and demand-side technologies on a decentral scale. Large scale technologies (e.g. power plants) are considered to be part of the upper (i.e. high voltage transmission) grid layers and not explicitly considered for local energy production.

The model is formulated as a mixed-integer linear program (MILP). Discrete decision variables greatly increase the complexity of the model, however they are necessary to correctly determine, for example, the number of new heating technologies installed.

A more detailed description of the model can be found in Appendix 1 and Mainzer et al. (2015).

c. MCDA and sensitivity analysis

We chose MAVT as the MCDA method in the present contribution because of its transparent nature and its straightforward suitability for bringing together quantitative (e.g. economic, ecological) and qualitative (e.g. acceptance) information. However, our general approach (see section d) is flexible with respect to the choice of MCDA method. MAVT typically comprises the following key phases:

1. Problem structuring:
   There are manifold approaches to structuring a so-called 'decision problem', all of which are aimed at identifying values, objectives and attributes, and subsequently structure them hierarchically into an attribute tree. Moreover, the identification/generation of decision alternatives is an important part of the problem structuring process. We employ an approach similar to value focused thinking (Keeney 1992, 1996), starting the workshop discussion by focussing on the decision makers' values and objectives. We then use energy system modelling (see section b) to generate decision alternatives aimed at achieving these objectives.
2. Elicitation of preferential and other qualitative information:
   MAVT distinguishes between *intra-criteria preferences*, defining the strength of preference within each criterion and *inter-criteria preferences*, reflecting the relative importance of the considered criteria. Intra-criteria preferences are modelled by value functions and inter-criteria preferences by weighting factors in MAVT. The value functions are used to evaluate alternatives relative to the different attributes by mapping their performance with respect to each individual attribute to the interval [0, 1]. The weights of the attributes are typically normalised, i.e. their sum equals one.

3. Aggregation:

   In this step, the alternatives are rank ordered. Let m denote the total number of considered attributes ($m \in N$), j be the attribute index ($1 \leq j \leq m$), and $w = (w_1, ..., w_m)$ be the weighting vector (where $\sum_{j=1}^{m} w_j = 1$, $w_j \geq 0 \ \forall \ j$). Let further $s_j(a)$ denote the score of alternative a with respect to attribute j and $v(a) = (v_1(s_1(a)), ..., v_m(s_m(a)))$ be the vector of value functions. Assuming that the attributes are mutually preferentially independent (preferences for certain outcomes with respect to each attribute do not depend on the level of outcomes with respect to other attributes), the overall performance score ops of an alternative a can be evaluated additively (Keeney & Raiffa, 1976):

$$ops(a) = w \bullet v(a) = \sum_{j=1}^{m} w_j \cdot v_j(s_j(a)) \tag{4}$$

4. Sensitivity analysis:

   Given the inherently subjective nature of preference parameters, sensitivity analysis constitutes a crucial step in MCDA to explore the sensitivity of a ranking with respect to variations of these parameters. In its simplest form, sensitivity analysis allows the effects of varying a weighting parameter of an MCDA model to be examined. While such a sensitivity analysis can provide valuable insights, it is limited to varying one (weighting) parameter at a time. Consequently, many researchers and practitioners in the field of decision analysis proposed approaches for investigating the impact of varying several preference parameters at a time (Ríos Insua & French, 1991; Butler et al., 1997; Matsatsinis & Samaras, 2001; Jiménez et al., 2005; Mustajoki et al., 2005; Mateos et al., 2006; Mavrotas & Trifillis, 2006; Bertsch et al., 2007; Jessop, 2011; Jessop, 2014; Scholten et al., 2015).

In the present contribution, we use the MCDA tool SIMADA, a MATLAB implementation of MAVT providing various visualisations for sensitivity analyses of different preference parameters (Bertsch & Fichtner, 2016). A key challenge in relation to applying MCDA in facilitated workshops with small communities is that, on the one hand, the use of sound and advanced sensitivity analysis techniques is indispensible for making informed decisions. On the other hand, however, the methodological complexity of multi-dimensional sensitivity analyses impedes its accessibility for such communities. We therefore make use of a natural language generation module, which has recently been added to SIMADA to enhance understanding and traceability of multi-dimensional preferential sensitivity analysis in multi-criteria decision making and thus contributes to making such advanced modelling techniques more accessible to non-experts (Wulf & Bertsch, 2016).

d. The developed approach

Our approach combines a number of methods which have been described individually in sections 0-c: an analysis of the existing energy system including a determination of the cost potentials for RES and energy efficiency, energy system modelling and multi-criteria decision analysis (MCDA) in facilitated workshops to ensure the consideration of social aspects and local preferences. The approach is aimed at actively engaging with smaller communities and at overcoming burdens related to model complexity which might otherwise lead to complex modelling methodologies not being used at all. The overall target of our approach is the participatory development and multi-criteria evaluation of feasible energy concepts in line with the preferences of a community. An overview of the developed approach showing how it combines the individual methods is given in Figure 2 below.

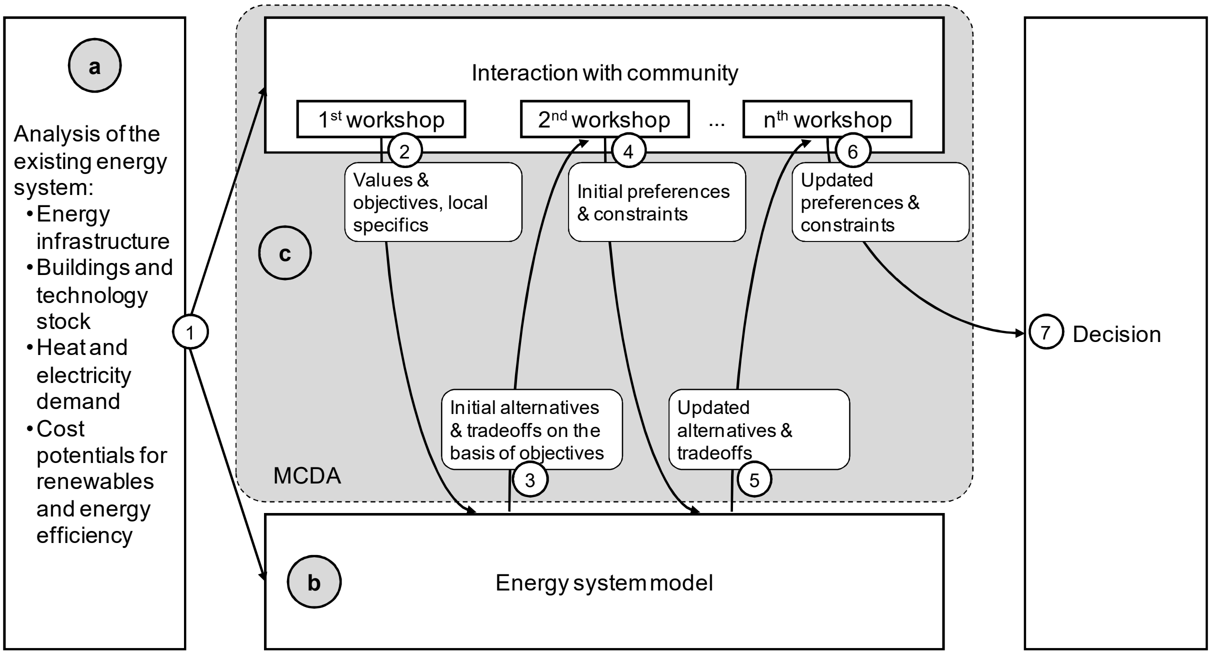

Figure 2: Overview of the developed approach including an analysis of the existing energy system, energy system modelling as well as MCDA and facilitated workshops

The method consists of the following stages (cf. Figure 2):

1. Determination of total cost-potentials for renewable energies in the selected community. Based on a combination of publicly available data from sources such as OpenStreetMap (OSM) and local statistics, augmented by data from the municipality, detailed technical potentials and costs are determined for renewable energies.
2. A first workshop with the community stakeholders enables a discussion of these potentials. More importantly, this workshop enables the identification of values and objectives of the community (e.g. cost minimisation, autonomy maximisation, emission reduction). Furthermore, local specifics need to be understood (e.g. areas and/or technologies can be excluded from the analysis). From an MCDA perspective, all information elicited in this workshop provides input

to construct an attribute tree, i.e. the first workshop can also be referred to as problem structuring workshop (step 1 in section c above).

3. Based on the cost-potentials and information elicited in the first workshop, an initial set of alternatives can be developed, whereby the alternatives differ in terms of the overarching objective and restrictions, e.g. relating to costs, energy autonomy and emissions. We then use an energy system model to optimise the whole energy system for each alternative / for each objective identified in 2., i.e. the objective function relates to the corresponding alternative (e.g. minimise cost, CO_2 emissions, energy import etc.) with acceptance aspects quantified as constraints (cf. Mainzer et al. 2015 and Appendix 1). As a result of each optimisation, a decision alternative towards reaching the given objective is obtained, which is defined by an optimal pathway of required investments in energy supply and demand technologies.
4. MAVT is applied in a second expert workshop with the community stakeholders aimed at integrating the optimisation results for all alternatives and the subjective assessments of the community stakeholders. The analysis in the workshop includes an interactive and iterative elicitation of the weights of the decision criteria, an aggregation into overall performance scores and a number of sensitivity analyses to support a structured discussion. From an MCDA perspective, the second workshop combines preference elicitation, aggregation and sensitivity analyses (steps 2-4 in section c above).
5. Based on the discussion in the second workshop, the set of alternatives may be refined or extended. It should be expected that workshop participants gain insight and understanding through the MCDA based on the initial alternatives which allows them to express their preferences more accurately and to develop ideas for optimising decision alternatives. Based on such input from the stakeholders, which may take the form of constraints for instance, the energy system model may be used again to generate additional or replace existing alternatives.
6. Based on the new set of alternatives from step 5, step 4 (using MAVT in a workshop with community stakeholders) needs to be repeated. In theory, step 5 and 6 should be repeated until convergence and consensus are achieved. In practice, however, there are often time or other limitations. Moreover, experience shows that 3 workshops are often sufficient.
7. Based on the results of steps 1-6, a recommendation can be given to make an informed decision.

Further details concerning each of these steps and the methods application to a community in south-west Germany are provided in sections 4 and 5.

4. Application to the case study community

a. Introduction to the case study community of Ebhausen

The municipality of Ebhausen lies in the rural district of Calw, about 60 km south west of Stuttgart (the capital city of Baden-Württemberg). It had a population of about 4,700 in 2013, consists of four spatially distinct and separated districts taking up a total area of 25 km^2, with a consequent population density of 188/km^2 (compared to the German average of 227/km^2). Ebhausen is dominated by domestic buildings and a few small commercial premises, but no industry, with the majority of the population being commuters to nearby centres such as Pforzheim and Stuttgart. These facts lead to the municipality being quite structurally weak, with only moderate income from local business tax.

Ebhausen has already been quite active in terms of sustainability projects in the context of the EEA and beyond, including for example a PV campaign and an electric vehicle. It has also had several previous studies aimed at examining, amongst other things, the potential for renewable energies (Kraus et al. 2011) and developing energy concepts for two of its four districts (in 2013 and 2014). But most identified measures have not (yet) been implemented due to the existence of barriers.

The current energy system in Ebhausen is dominated by domestic buildings and transport, with little services and no industry. Only one of the four districts (Ebhausen) has a gas network connection, whereby around 50% of households are connected to the grid. The remaining three districts do not have a gas network connection so use oil tanks or other fuels. Hence heating is provided by gas, oil and wood fuels as well as a small fraction of electricity. The majority of the electricity demand is covered by imports from the grid, apart from the indigenous generation from the installed PV plants (see section 5.a.).

The system boundary for this study is taken as the administrative boundary around the municipality. The approach attempts to capture all of the direct energy flows within this system boundary, in terms of heat and electricity, with the exception of transport. In addition, imports and exports of embodied energy across the system boundary are not considered. Imports and exports of electricity and fuels are possible, with prices and emissions factors as specified in Appendix 1.

b. First workshop: problem structuring

The first of three workshops was held in Ebhausen in June 2016. The aims were to identify the municipality's objectives and to record any existing quantitative targets, to determine what the general priorities are and to understand whether any areas/technologies should be excluded from the analysis. In total there were 19 participants, including members of the municipal council and the mayor, members of the "Energy Team" (which is involved with energy-related projects such as the European Energy Award), farmers, representatives of the municipal administration, and private individuals. It started with a short introduction of the participants, followed by a presentation of the project, including the goals, methodology and the type of results that can be expected. After this presentation there was a semi-structured discussion moderated by the authors, which revolved around different aspects of the study. It was agreed to clearly distinguish between stakeholder preferences and social acceptance of technologies and/or measures. In this context "stakeholder preferences" refer to e.g. the relative importance of different objectives to be considered, as discussed and quantified during the second workshop (see below). Social acceptance on the other hand was agreed to be considered as "hard acceptance" and therefore refers to the categorical acceptance or exclusion of a particular technology or measures in particular areas.

As in value focused thinking, the workshop discussion initially focussed on the municipality's wider values and objectives. The discussion clearly demonstrated that total costs/affordability have a high priority for the municipality, which means considering the limited amount of capital that it has available and the relatively short payback periods required. Moreover, whilst the community does not yet have any quantitative targets in terms of renewable energy fractions or CO_2 emission reductions, the workshop participants expressed clear aspirations towards reducing CO_2 emissions and community net imports. In summary, a total of four high level objectives emerged from this discussion: minimisation of total costs for energy supply, minimisation of carbon emissions, minimisation of community net imports (maximise autonomy) and minimisation of primary energy imports.

Moreover, the discussion showed that, whilst there are no areas or technologies that would not be accepted per se, the additional potential for bioenergy exploitation are thought to be very limited. For one, the woodland within the municipality is mainly owned by farmers and private individuals, and the existing forest residues are thought to be used already in open fires for heating. In addition, substantial quantities of biogas substrates are exported and utilised outside the municipality and it is not desired to increase the production of these in the future, especially not if this involves reducing food production on the same agricultural area. Hence further biomass and biogas production and exploitation in heating and/or CHP plants is excluded from the further analysis. Overall, it was agreed that a main objective of the study should be to determine realistically-achievable targets in the medium term (2030) under consideration of the above-described framework conditions.

c. Second workshop: elaboration and consequence assessment of alternatives and preference elicitation

As mentioned above, four high level objectives emerged from the discussion in the first workshop. On this basis, four alternatives were initially generated, where each high level objective determined the objective function for one alternative in the employed energy system model (see section 3.b). In other words, the decision alternatives are explicitly generated as a means to achieving the identified objectives. While this is generally in line with Siebert & Keeney (2015) and Keeney (1996), we additionally use energy system modelling to provide structured support in generating decision alternatives and assessing their consequences.

The resulting four alternatives were presented and discussed in the second workshop, in August 2016, with the same participating groups. While the community stakeholders confirmed that primary energy imports should be considered as an evaluation criterion for the alternatives, they did not want to consider a separate alternative based on minimising this criterion and this alternative was therefore removed from the set of alternatives.

Table 2: Elicited weight intervals

Criterion	Weight Interval	Normalised Mean
Total costs	0.40-0.60	0.51
CO_2 emissions	0.15-0.30	0.23
Community net imports	0.10-0.35	0.23
Primary energy imports	0.00-0.05	0.03

Following the presentation and discussion of the initial alternatives, inter-criteria preference (i.e. the weights) were elicited in the second workshop. For this purpose, we used the SWING weighting method (Von Winterfeldt and Edwards, 1986), where all workshop participants agreed that expenses for energy supply is the most important criterion, so 100 points were assigned. Concerning the relative importance of the other criteria in relation to expenses, a consensus was not immediately achieved. Therefore, the participants provided their relative preference statements individually and a set of weights was calculated for each participant. Since no consensus could be achieved in the first instance, this procedure obviously leads to weight intervals as opposed to discrete weights. The resulting weight intervals are summarised in Table 2 below. In addition to the elicited weight intervals, Table 2 shows discrete weights which are calculated as 'normalised means' of the weight intervals respectively, i.e. they sum up to 1. These weights are used for comparison purposes and as a starting point in section 5 before presenting the results of the multi-dimensional sensitivity analysis on the basis of the weight intervals.

Table 3: Overview of considered alternatives

Alternative name	Total costs	CO_2 emissions	Community net imports
MinCOST	Minimise	Free	Free
MinCO2	Free	Minimise	Free
MinNI	Free	Free	Minimise
MinCO2@110	110% of min.	Minimise	Free
MinCO2@120	120% of min.	Minimise	Free
MinNI@110	110% of min.	Free	Minimise
MinNI@120	120% of min.	Free	Minimise
MinCO2NoNI@150	150% of min.	Minimise	Zero

Following the preference elicitation and the discussion and evaluation of the three remaining initial alternatives, five additional 'intermediate' alternatives were defined in the workshop aimed at analysing the trade-offs between the different criteria. Hence the set of eight alternatives were defined as shown in Table 3 below. The timeframe was set to 2030, in agreement with the wishes of the community (first workshop).

For each alternative, the results include the optimal capacities, combination and dispatch of technologies including renewable electricity generators, heating systems, building insulation and different electrical appliances. For each modelled year the model determines the total costs, emissions, energy imports and primary energy consumption for each alternative.

5. Results of the case study

a. Cost-potentials for renewables and energy efficiency

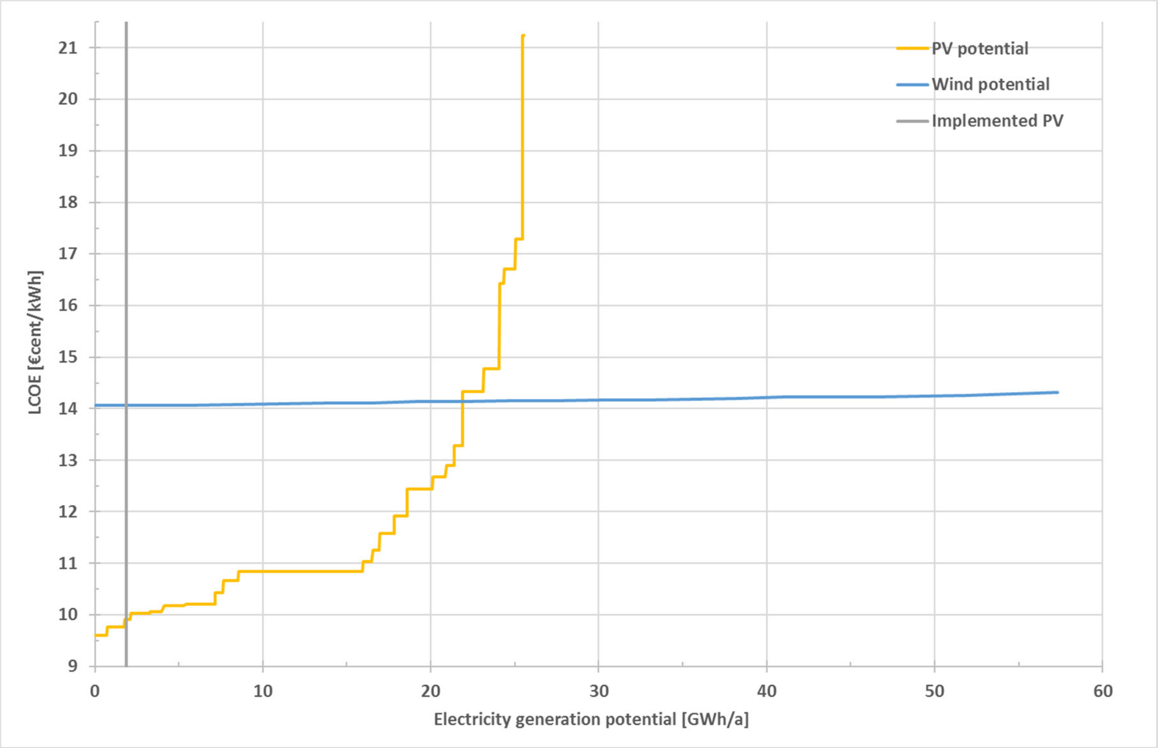

Figure 3: Cost-Potential Curve for Wind and PV in Ebhausen

For an estimation of the PV potential in Ebhausen, the exact shape and orientation of all available roof areas has been determined by employing a method that combines building footprint data with satellite images (Mainzer et al. 2016b). Roofs that are already equipped with PV modules are detected automatically and subtracted from the available areas. Next, a quarter-hourly simulation over one year determines the radiation received and the electricity produced for each roof area that could be equipped with PV modules. For Ebhausen, it was shown that ~25 GWh of electricity could be produced per year, if the complete technical potential was to be used (see Figure 3) - significantly more than the ~2 GWh/a that has already been exploited as of 2015[5]. It has to be noted, however, that this estimate also includes suboptimal areas with rather high costs, which would in most cases not be exploited.

In a similar fashion, the potential for electricity production from wind power has been determined. First, the available areas are calculated by combining land use (OpenStreetMap-Contributors 2016), minimum distance specifications (Klein 2015) and topography (Jet Propulsion Laboratory 2015), allowing for a maximum slope of 20°. In the next step, the best-suited wind turbines are chosen, based on the local wind frequency distribution (MINES ParisTech / Transvalor S.A. 2015) and the technical characteristics of the available wind turbines. Using minimum distances between turbines (8 times the rotor diameter in main wind direction, 5 times in other directions) and a heuristic packing algorithm, the total number and individual locations of all potential wind turbines are determined. As a result, 21 wind turbines of type Gamesa G114 (2 MWp, 120 m hub height, 114 m rotor diameter) could possibly be installed, producing up to 57 GWh electricity per year at average costs of about 14 €cent/kWh. The placement of wind turbines and PV modules in the district of Rotfelden are depicted in Figure 4. Due to the location of the nearest electrical substation to the south, the turbines to the south of the municipality are slightly more economical due to lower network connection costs.

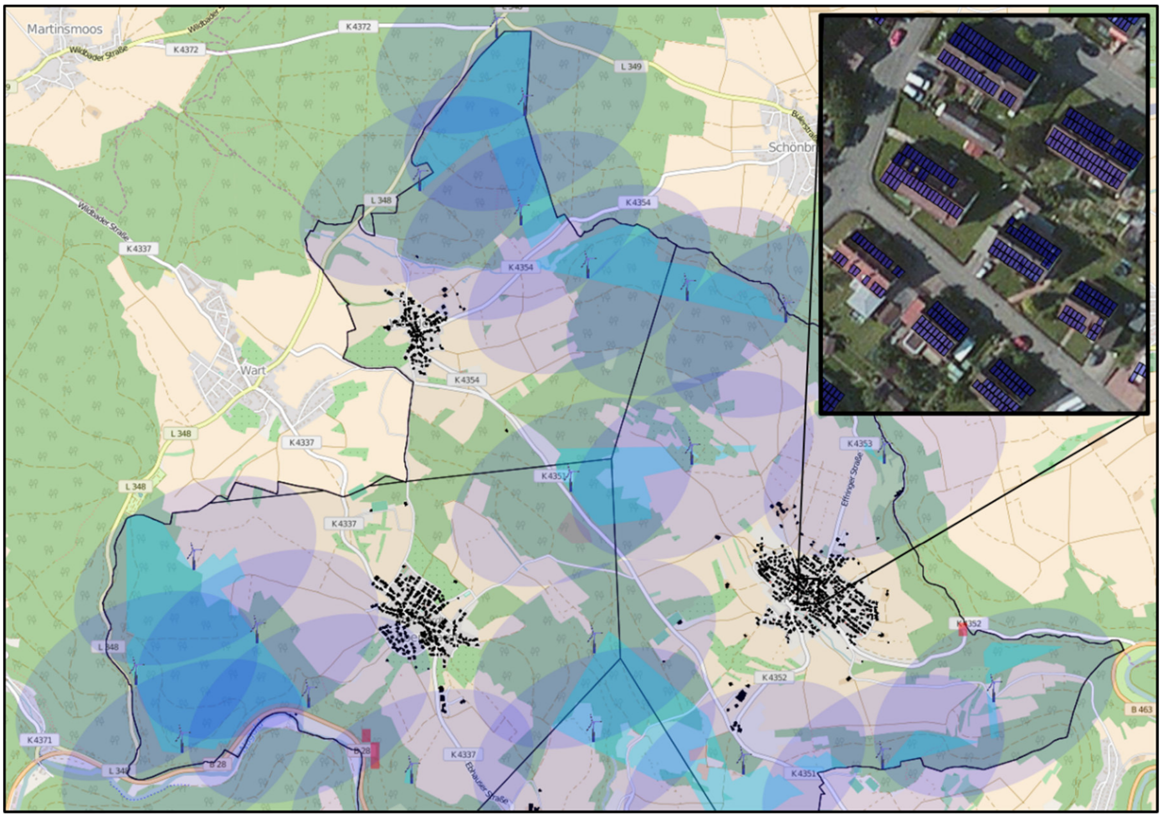

Figure 4: Wind and PV module placement in the district of Rotfelden (source: own depiction with image data from Bing Maps)

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[5] In 2016 around 2 MW capacity with 2.1 GWh generation: http://www.energymap.info/energieregionen/DE/105/110/160/574/15929.html.

b. Results of optimisation model for alternatives

In the present application, the optimization model totals to about 6 million equations and 1.5 million variables (13,729 of which are binaries). On a 3.2 GHz, 12 core machine with 160 GB RAM, depending on the chosen objective, it can take between 7 and up to 26 hours to solve within an optimality gap of 2.5%. The processing time can be reduced significantly (by up to 95%) however, by providing valid starting solutions from previous runs for subsequent alternatives.

The key results of the 8 alternatives for Ebhausen in 2030 are shown in Table 4. It is clear that these results differ substantially from one another, for example in terms of the wind and PV capacities installed, as well as the insulation and efficiency of electrical appliances. Lighting is the only energy service demand that is met by the same technology, in this case LEDs, for all of the alternatives. In addition, the installed heating technologies in 2030 are shown in Figure 5, which again shows substantial diversity between the alternatives.

Table 4: Overview of the eight developed and analysed alternatives

#	Alternative name	PV Capacity (MW)	Wind Capacity (MW)	Insulation[6]	Appliances[7]
1	MinCOST	2.0	6.0	2	50
2	MinCO2	1.7	2.0	3	100
3	MinNI	23.9	0	3	100
4	MinCO2@110	1.5	8.0	2/3	90
5	MinCO2@120	0.6	8.0	2/3	90
6	MinNI@110	18.3	6.0	2	30
7	MinNI@120	24.8	0	2	40
8	MinCO2NoNI@150	24.9	0	3	90

The *MinCOST* alternative implies moderate PV and wind (3 turbines) capacity additions, insulation and electrical appliance improvements, with a mixture of heating systems including gas boilers and heat pumps, as well as some electric storage heaters. In contrast, the *MinCO2* and *MinNI* alternatives have rather extreme results. The former translates into a moderate PV and wind (1 turbine) capacity, maximum efficiency levels of insulation and appliances, and heating dominated by pellets boilers. The latter (*MinNI*) alternative involves a very high level (24 MW) of PV capacity, no wind capacity, maximum efficiency levels of insulation and electrical appliances, as well as heating systems dominated by heat pumps.

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[6] Dominant level of building insulation employed, i.e. from 1 (low) to 3 (high), whereby 2/3 implies a roughly 50/50 split

[7] Fraction (%) of highest standard, i.e. A+++

Whilst these three “extreme” alternatives represent a somewhat unrealistic vision of a future community energy system, they do illustrate what the system would look like when optimised according to these single criteria. The other five alternatives represent a compromise between these extremes, some of which have additional constraints.

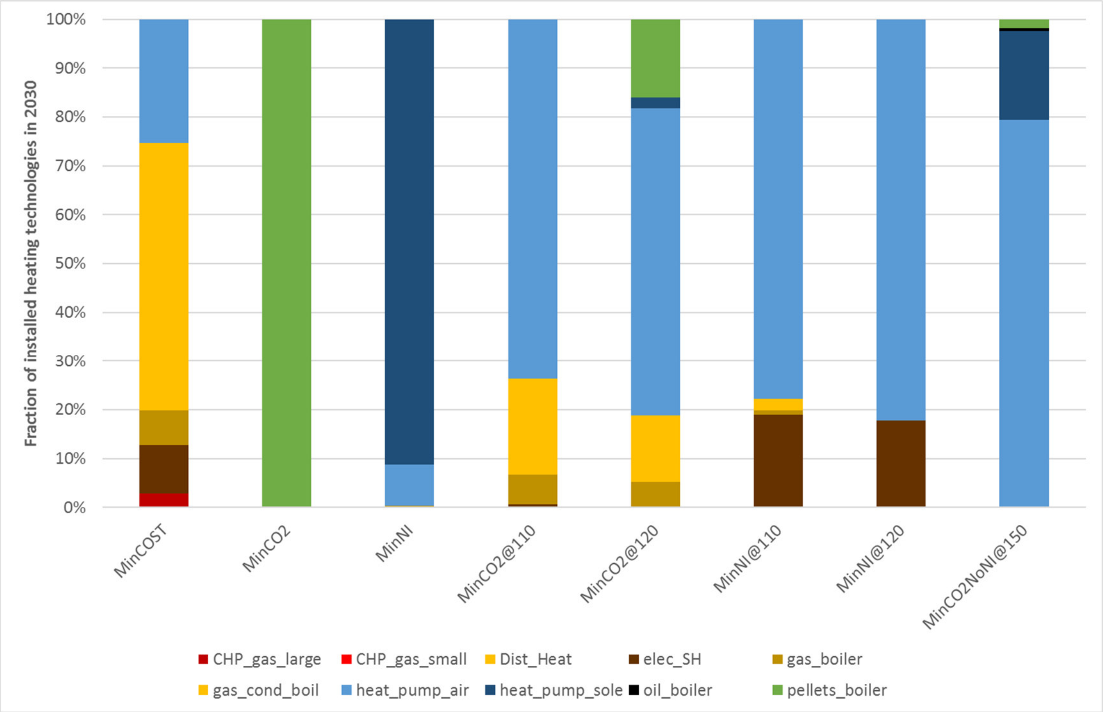

Figure 5: Overview of heating technologies installed for the 8 alternatives in 2030

It is thus possible to quantify the additional level of energy autonomy (i.e. reduced energy imports) and/or CO_2 emissions that can be achieved by increasing the total costs from the absolute minimum to 110%, 120% or even 150% of this value. It becomes apparent that significant emission reductions can be achieved with only minor additional costs. For example, allowing for 10% increase in total costs leads to 51% (of total achievable) emission reductions or to 27% of net import reductions, and allowing for 20% increase in costs leads to 64% (of totally achievable) emission reductions or to 36% of net import reductions. In addition, these relatively small relaxations in the permissible costs result in substantially different energy systems, as shown in Table 5 and **Fehler! Verweisquelle konnte nicht gefunden werden.**. The former shows the values of the global decision variables for the eight alternatives.

c. Multi-criteria evaluation of the considered alternatives

For the normalised means of the weight intervals elicited in the second workshop (see section 4.c / Table 2), Figure 6 shows the overall performance scores for the eight alternatives as they result from the energy system model, the values for which are summarised in Table 5. The results clearly show that the alternatives *MinCOST* and *MinNI* are outperformed by the other alternatives and that the remaining six alternatives achieve very similar performance scores, of which alternative *MinCO2NoNI@150* achieves the highest overall performance score of 0.65 for the elicited preference parameters.

Table 5: Decision table resulting from the energy system model for the 8 considered alternatives

Alternative #	Alternative name	Total costs (EUR)	CO2 emissions (kg CO_2)	Community net imports (kWh)	Primary energy imports (kWh)
1	MinCOST	8.77E+07	2.13E+08	5.96E+08	5.75E+07
2	MinCO2	1.42E+08	7.82E+07	4.82E+08	6.01E+07
3	MinNI	2.86E+08	1.15E+08	-9.27E+08	-9.91E+08
4	MinCO2@110	9.67E+07	1.44E+08	3.62E+08	7.65E+07
5	MinCO2@120	1.06E+08	1.27E+08	4.38E+08	5.45E+07
6	MinNI@110	9.67E+07	1.70E+08	1.79E+08	8.56E+06
7	MinNI@120	1.06E+08	1.62E+08	4.89E+07	-4.70E+07
8	MinCO2NoNI@150	1.32E+08	1.15E+08	0.00E+00	-8.29E+07

Beyond the overall performance scores, Figure 6 shows how the considered alternatives perform with respect to the different objectives. While the alternatives *MinCOST*, *MinCO2* and *MinNI* obviously perform best with respect to total costs, CO_2 emissions and community net imports respectively, the results also show that the alternative *MinCOST* performs worst with respect to emissions and imports, and alternative *MinNI* performs worst with respect to costs. The alternatives striving for a minimisation of emissions or imports at slightly increased costs in comparison to the *MinCOST* alternative all appear to be well balanced and perform reasonably well, with the alternative *MinCO2NoNI@150* somewhat ahead of the others. This suggests that alternative *MinCO2NoNI@150*'s performance loss with respect to costs is outbalanced by performance gains with respect to emission and imports for the "average preferences" of the community. However, as mentioned several times above already, the elicitation of preference parameters is inherently associated with uncertainties. We therefore explore the results' sensitivities with respect to variations of these preference parameters in the subsequent section below.

d. Exploring the impact of preference parameter variations through multi-dimensional sensitivity analysis

To explore the impact of simultaneous preference parameter variations on the MCDA results, SIMADA provides various options for carrying out multi-dimensional sensitivity analyses. Figure 7 shows the results of a multi-dimensional sensitivity analysis for 1,000 randomly sampled weights within the intervals given in Table 2.

The "spread of results" graph in the left part of Figure 7 shows the corresponding ranges of the overall performance scores for all alternatives. The tick marks at the ends of the vertical lines represent the minimum and maximum results, while the diamonds in the middle indicate the expected overall performance score for each alternative. For methodological details in relation to the sampling and the calculation of the expected overall performance scores, please see Bertsch & Fichtner (2016). The "spread of results" graph also shows that alternatives *MinNI@120* and *MinCO2NoNI@150* dominate alternative *MinNI*. Moreover, it illustrates that the highest possible overall performance score is attained by *MinCO2@120* (0.73), and that this alternative therefore maximises the upside potential of realising the highest possible overall performance score, while the lowest possible overall performance score is attained by *MinNI* (0.32). Finally, *MinCO2NoNI@150* attains the highest minimum score of all alternatives (0.58) This alternative therefore minimises the downside risk of obtaining a low overall performance score.

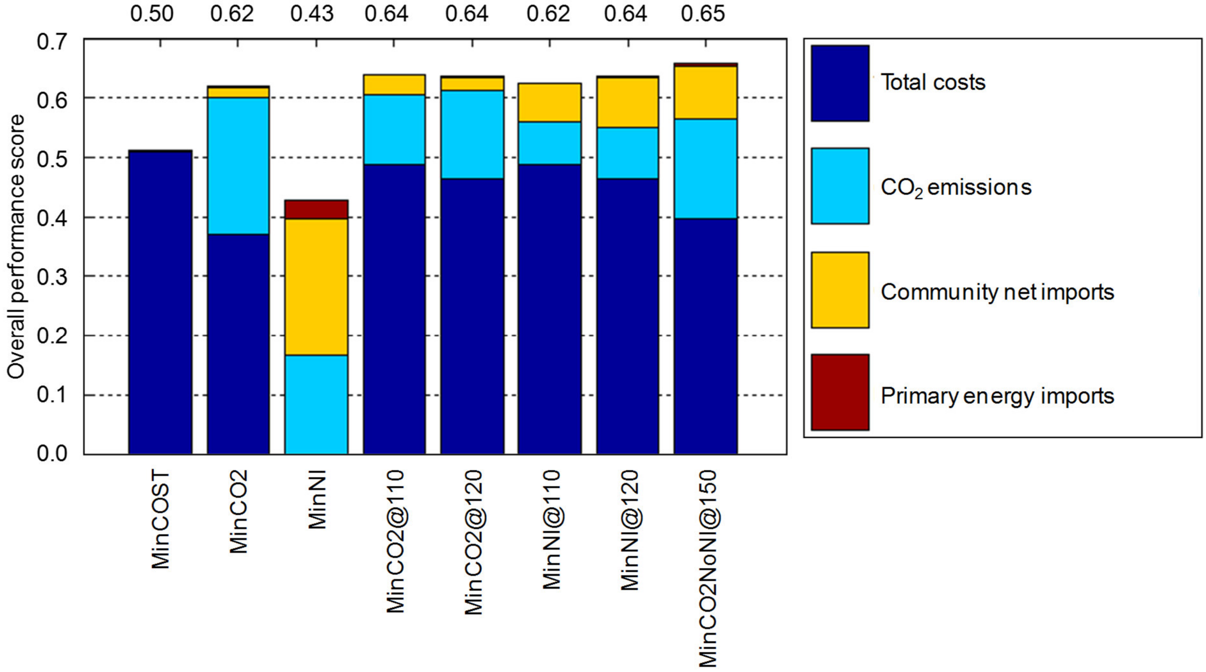

Figure 6: Overall performance scores for the 8 alternatives

The "cumulative performance" graph in the right part of Figure 7 shows the relative frequency of the overall performance scores of the different alternatives by plotting the overall performance scores against the cumulative percentage (of the 1,000 preference parameter samples). This representation of results is based on Butler et al. (1997) and provides detailed information of the complete distribution of the results. Whilst the "spread of results graph" also shows the ranges in which the scores of each alternative vary, the "cumulative performance" graph additionally provides insight into the distribution of the alternatives' scores within these ranges. For instance, while the left diagram shows that *MinCO2* has the highest range of score variation from min to max, the right diagram shows that the range between the 5th and the 95th percentile of the same alternative is much smaller and that *MinCOST* and *MinNI* actually have higher variation ranges between these percentiles.

However, since the performance scores in the right diagram of Figure 7 are plotted in increasing order for each alternative individually, i.e. the different scores at an imaginary perpendicular cut through the diagram do not necessarily belong to only one (valid) preference parameter combination. the diagram does not reveal information on rank performances. For this purpose, the natural language generation module in SIMADA supports the production of the following Table 6, showing the percentages for which each alternative attains a certain rank. For instance, the table reveals that *MinCOST*, *MinNI* and *MinNI@110* are never ranked first and that *MinCO2*, *MinCO2@110*, *MinCO2@120*, *MinNI@110*, *MinNI@120* and *MinCO2NoNI@150* are never ranked last. Moreover, it shows that *MinCO2NoNI@150* achieves the highest percentage of No. 1 ranks (55.4%). Finally, in the far right hand column, Table 6 shows the expected rank for each alternative, with *MinCO2NoNI@150* achieving the best expected rank (2.04) and *MinNI* achieving the worst expected rank (7.71) out of the eight considered alternatives.

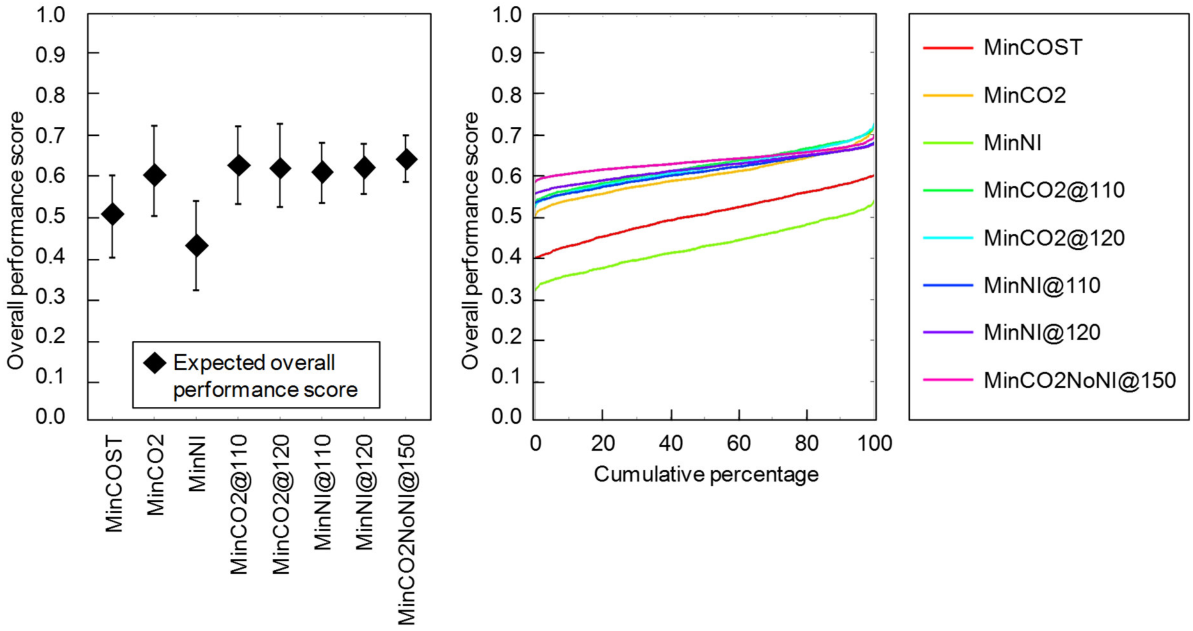

Figure 7: Multi-dimensional sensitivity analysis for the 8 alternatives

In addition to the multi-dimensional sensitivity analyses above, SIMADA allowed us to explore the "weight space", i.e. to identify which criteria and weights are most important in determining the ranking and optimality of the first-ranked alternative. We find that for weights of total costs above 0.54 (complete interval: 0.4-0.6) as well as for weights of community net imports below 0.16 (complete interval: 0.1-0.35), *MinCO2NoNI@150* never achieves the first rank. This information allows the discussion to be focused on the weights for these two criteria. This is also highlighted by the excerpt of the text output of SIMADA's natural language generator provided in the box below.

- Criterion total costs is most sensitive for the ranking of *MinCO2NoNI@150* as preferred alternative followed by criterion community net imports.
- The relative importance of criteria CO_2 emissions and primary energy imports only has a minor impact on the ranking of *MinCO2NoNI@150* as preferred alternative.

The natural language generator also provides very insightful information in relation to (stochastic) dominance relationships (see excerpt in box below) which go beyond the dominance relationships explainable on the basis of Figure 7 above.

MinCO2NoNI@150 dominates…

- … *MinCOST* and *MinNI* in 100 % of the simulation runs.
- … *MinCO2* in 89.3 % of the simulation runs.
- … *MinNI@110* in 86.3 % of the simulation runs.
- … *MinNI@120* in 79.6 % of the simulation runs.
- … *MinCO2@120* in 74.4 % of the simulation runs.
- … *MinCO2@110* in 66.3 % of the simulation runs.

Table 6: Rank performances

Alternative	**#1 rank**	**#2 rank**	**#3 rank**	**#4 rank**	**#5 rank**	**#6 rank**	**#7 rank**	**#8 rank**	**Expect. rank**
MinCOST	0 %	0 %	0 %	0 %	0 %	0.7 %	***72.3 %***	27 %	7.26
MinCO2	4.7 %	18.2 %	6.3 %	9.9 %	3.8 %	***55.4 %***	1.7 %	0 %	4.63
MinNI	0 %	0 %	0.3 %	0 %	0.1 %	0.6 %	26 %	***73 %***	7.71
MinCO2@110	20.2 %	18.8 %	25.6 %	***31.8 %***	3.6 %	0 %	0 %	0 %	2.80
MinCO2@120	7.6 %	16 %	24 %	16.5 %	***35.4 %***	0.5 %	0 %	0 %	3.58
MinNI@110	0 %	4.8 %	20.2 %	15.4 %	21.6 %	***38 %***	0 %	0 %	4.68
MinNI@120	12.1 %	***30.8 %***	10.2 %	13.1 %	29 %	4.8 %	0 %	0 %	3.30
MinCO2NoNI@150	***55.4 %***	11.4 %	13.4 %	13.3 %	6.5 %	0 %	0 %	0 %	2.04

Overall, the above analyses show that alternatives *MinCOST* and *MinNI* can be eliminated from the discussion. The *MinCOST* alternative is interesting insofar as the criterion total costs was given the highest weight (interval). In fact, further sensitivity checks assuming weight intervals of 1-99% for each of the four criteria show that the *MinCOST* alternative turns out to be optimal in less than 1% of the randomly sampled weight combinations within these intervals. The alternative only turns out to be optimal if the weight of total costs is at least 70% and, at the same time, the weights of CO_2 emissions and Net imports are smaller than 7% and 5% respectively. These findings provide evidence that the community should not pursue the *MinCOST* alternative.

Moreover, particularly as far as the optimality of the most “promising” alternative *MinCO2NoNI@150* is concerned, the weights of total costs and community net imports are more important to focus on than the weights of the other criteria. In addition, the analyses show that, for the same cost increase compared to the *MinCOST* alternative, the performance gain of the *MinCO2@110/120* alternatives with respect to emissions is larger than the gain of the *MinNI@110/120* alternatives with respect to net imports. In other words, an equivalent performance gain with respect to net imports (autonomy) comes at higher costs than the same gain with respect to emissions.

e. Third workshop: towards implementation

Thus far this section has focused on the macro-level results from the perspective of a central planner within the municipality. But as already mentioned in the introduction, most decisions relating to the implementation of concrete measures in the context of community energy are reached, at least partly, at the micro-level within households and the minds of individuals. The analysed alternatives must therefore be broken down into individual measures if useful recommendations are to be derived at the local level.

The optimisation model outputs in terms of installed capacities of different technologies are shown above for the whole of Ebhausen (cf. Table 4 and Figure 5). These results are also available at the district level, and within each district for a building type, i.e. a combination of building type, size and age (100 in total). Hence it is possible to derive concrete recommendations for specific building types within a district, based on these results.

Due to the fact that the optimisation model takes a “central planner” perspective (cf. section 3.b), its results are not necessarily economical from an individual user’s (i.e. household’s) perspective. In other words, there could well be a gap between what an individual household finds economical and what this study recommends for a particular building type in the context of one of the eight alternatives. This gap could be partly or wholly closed through financial incentives from the community or external sources. In order to assist the community in identifying and measuring this gap, we developed a simple Excel tool to carry out a simple economic and environmental assessments of investments in building insulation and heating system upgrades. In addition, the tool enables an assessment of the potential for PV on an individual building, the only part of the model input which is actually generated at the building (as opposed to building type) level. The tool is based on a lifecycle costing approach that employs standard methods of economic assessment to determine the Net Present Value (NPV), dynamic payback period and internal rate of return, as well as related environmental indicators as shown in Appendix 2.

Hence the administration within the community can use this tool to analyse the situation for individual building types and thereby identify those in which a switch of heating system, insulation of the building fabric or an installation of a PV system could be economically attractive to the household. For cases in which it is not, the administration will first have to identify the size of the "gap" between the required measures and the economic investments for individual households. Secondly, it could attempt to "bridge the gap" through its own funding or external sources, if it wishes to implement the one of the eight alternatives as defined here.

The recommendations to the community, as discussed in the context of a final workshop in late November 2016, can be summarised as follows. The three extreme scenarios can be rejected outright because of their low overall performance scores; instead the community should select one or more of the intermediate scenarios (referred to as numbers 4-8 above). Within these five scenarios, the identified measures are similar, for example, a dominance of air-source heat pumps for heating, a moderate to deep insulation of buildings, a universal application of LEDs and high-efficiency electrical devices, and a strong development of PV capacities. Based on the simple micro-level tools made available to the community, the economic case for each of these measures should be analysed for individual buildings and/or types. In addition, and in order to spread awareness and educate the community about the opportunities for emission-reduction measures within their own buildings, it is recommended to organise information events to which the general population could be invited. Further work from a research perspective is highlighted in the following section.

6. Discussion of the method

a. The methodological framework

This section briefly discusses the method developed and employed in this paper, beginning with a general discussion before addressing the cost-potential analysis/optimisation model and MCDA aspects respectively. Firstly, the selection of the community for the case study could be criticised, being based on communities that are already involved in the EEA and therefore are already active in terms of climate/energy projects. On the other hand, exactly for this reason the response to the enquiry amongst these municipalities was so positive, especially compared to similar enquiries amongst local municipalities where contacts previously existed. The identification and recruitment of the relevant stakeholder groups was in the present case left up to democratic processes, i.e. the project and workshops were publicised but the active involvement was ultimately left up to the individuals. An equal representation of all relevant stakeholders could have been achieved through a more pro-active engagement strategy (Bohunovsky et al. 2011), but this is clearly resource-intensive as was not feasible due to a lack of funding in the present case. It is certainly fair to state that the active cooperation, and to a certain extend enthusiasm, within and from the community has played an important role in this research. The study as carried out here relies upon an effective cooperation between researchers and communities, which requires both initiative and a certain degree of open-mindedness on the part of the "test subjects".

Another general point about the method is the uncertainty surrounding some of the input data and certain aspects of the methodology. For the optimisation model and the MCDA, the uncertainties in the input data are at least partly addressed by the sensitivity analyses. The existing renewable energy potential study (Krauss et al. 2011) indicates per capita CO_2 emissions of around 2 tCO_2, which is roughly equal to the results obtained here for 2015 in most of the examined alternatives. The method relies on standardised building types and load profiles, so that the results for heating and electricity demand on the individual building level are almost certainly wrong but serve as an orientation. For the municipality as a whole, the results are reasonably robust as they match frequency distributions from published statistics, hence why the latter should be used to derive direct insights rather than the former (except for PV, see above). However, some more specific limitations apply to the PV potential estimation method. Currently, the method is only able to identify partial areas for saddle roofs on square buildings. Flat roofs are often not correctly identified and shading, e.g. from other buildings, cannot yet be considered with this method. It is also not possible to extract the roof inclinations, which is why empirical distribution functions have been used here. Looking to the future, the analysed alternatives also represent quite ambitious target systems for the community, which also raises the question whether such a rapid transition could be feasible.

In terms of the MCDA approach, we are aware that the use of an energy system model to generate input for the MCDA, as employed in this paper, is not the only possible option. Alternatively, there are approaches that directly integrate energy system modelling and MCDA, such as multi-objective optimisation. We acknowledge that there are advantages and drawbacks for both types of approaches and that an "overall optimum" in a continuous solution space can only be derived from a multi-objective optimisation. Our main reasons for using an energy system model to provide input for an MCDA, however, are the following. In our opinion, one of the main purposes of using MCDA is not just the calculation or identification of an optimal solution but rather the enhancement of the decision makers' understanding through interaction and carrying out (multi-dimensional) sensitivity analyses. In that sense, the absolute optimality becomes a side-issue to some extent (cf. Rios & French 1991). We are also aware that some interactive procedures exist for certain continuous approaches. Their practical application (concerning the computational effort) to realistically-sized multi-objective energy planning problems, however, has not been demonstrated so far. Decoupling energy system modelling and MCDA leads to a significant reduction of the computational intensity in this case. Moreover, we are not aware of approaches for (online) multi-dimensional sensitivity analyses in multi-objective optimisation. Given the importance of multi-dimensional sensitivity analysis to address the inherent uncertainty and subjectivity related to the preference parameters, this would be problematic.

In terms of the MCDA results, note that by nature the elicited weight intervals used in the MCDA are the key drivers of our results, which is crucial to consider when attempting to transfer the results to other communities. Moreover, the elicited preferences may vary over time and should be monitored from time to time. Finally, note that it was agreed in the second workshop to use linear value functions and we did not elicit any intervals in relation to these intra-criteria preference parameters. The analyses in this paper therefore focus on inter-criteria preference parameter variations.

b. The employed criteria

The general approach presented here involved identifying important criteria together with stakeholders from the case study community, and optimising the energy system with respect to these criteria. Hence the wishes and objectives of the community interactively shaped both the overall objectives and the research design of the study. Whilst these criteria seem to be appropriate for this individual community, there is a more general question about their compatibility with high level energy-political goals and policies. For example, the community clearly identified costs as the most important criteria, but there is some evidence that some communities rank other criteria such as employment, local added value and air quality higher (Bohunovsky et al. 2007).

In addition, there has been a strong discussion in Germany in the recent past about the fairness of redistributing the costs of renewable energy development mainly onto households and commercial consumers (with the exception of heavy industry and rail transport), who currently pay around 6 €ct/kWh for this. This redistribution of costs in this manner means that exactly those consumers who install renewable energy locally stand to benefit, compared to those who do not, who must then co-finance developments elsewhere.

Other important criterion in the present case were CO_2 emissions and energy autonomy, both of which are closely interrelated with a local energy supply through renewables combined with a balancing out from the electricity grid over the year. The same argument as above applies, to a certain extent, to the network fees: the network has to be extended and/or strengthened especially there where increased renewable capacities are installed, but end-consumers have to cover the redistributed costs. Hence there is a key question in the context of the energy transition relating to the burden sharing for this renewable expansion including the associated costs for grid expansion (Jägemann et al. 2013).

There are also other key interaction effects between the community and the overarching energy systems. These relate amongst other things to the energy and carbon implications of the electricity that is replaced by feed-in or “used” for imports. In a fully renewable energy system, energy imports are environmentally attractive, but at present (with around 30% renewable electricity in Germany), the local renewable generation and use and/or feed-in is more attractive. If one municipality installs a lot of renewable capacity and becomes (partly) energy autonomous, it has very little impact on the emissions factor at the margin. But when hundreds or thousands of communities do this, it obviously does. Whilst the applied method is able to capture the implications at the municipal, and indirectly through the supplied tools also at the building level, it has a weakness in overlooking some of the implications at the level of the national energy system.

CO_2 emissions were employed here to operationalise environmental sustainability. Whilst there is a clear trend towards/of community energy in many countries, most of the efforts/projects within this context seem to focus on energy and/or carbon dioxide (CO_2). Communities attempt to increase their supply of energy from renewable sources, improve their energy efficiency, and reduce their CO_2 emissions, with an implicit assumption that this is a good thing. Several studies have quantitatively examined the impacts of such endeavors, but few if any have assessed the sustainability implications within a holistic framework. Sustainability indicators could be developed for each alternative by employing the sustainability assessment framework of Santoyo-Castelazo & Azapagic (2014). This and other aspects remain areas for further work, as addressed in the subsequent section.

c. Outlook and further work

From the beginning, the system boundary for this study was defined as the administrative boundary around the municipality. There was a distinct focus on the residential sector, whilst the transport sector and energy infrastructure were largely ignored (energy flows between districts were modelled). For this particular community, the industrial and services sectors are not significant in terms of energy use and CO_2 emissions (Krauss et al. 2011), so in this respect the focus on the residential buildings is justified. But the transport sector is significant, as the municipality contains a large proportion of commuters who use internal combustion engine driven vehicles. These vehicles are responsible for an estimated 60% of the total CO_2 emissions in the community in 2010 (ibid.) and are therefore a prime target for measures aiming at reducing greenhouse gas emissions. Especially electric vehicles, which can in principal offer each household a mobile electric battery storage, and thereby enable better integration of self-produced electricity (higher energy autonomy), could be analysed in this context. They are not considered in the present study because it goes beyond the scope and the data basis was not available, nor was it gathered, on the number of vehicles, passenger-km, age of the fleet etc. Especially in rural municipalities the allowable penetration of electric vehicles is typically lower than in urban ones (Neaimeh et al. 2015), which would only be exacerbated with a high PV penetration. Such an analysis could provide much scope for further work in Ebhausen, ideally in collaboration with the local distribution grid operator (Netze BW), in order to simulate the resulting distribution grid power flows.

The presented method is in principle highly applicable to other contexts. Its application depends upon the availability of data, which in Germany is relatively good, but in other European countries is less satisfactory. OpenStreetMap data and data relating to the installed capacity of (renewable) power plants is now widely and freely available[8], but the availability of other data surrounding the local building stock

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[8] E.g. http://data.open-power-system-data.org/

and the installed heating technologies is very much a national or regional issue. In addition, there is quite a diverse picture across Europe in terms of the populations attitude towards the environment (European Commission 2008), for example between the countries Germany, France and UK, and barriers to wind energy are much higher in France than Germany, due to different support frameworks and planning restrictions (Jobert et al. 2007). Hence the scope for active engagement of a community, which is a prerequisite for such a study, is also quite context-specific.

In the context of considering an application of this method elsewhere, it seems helpful to think about the user and the target audience. The methodological framework is principally aimed at scientists and researchers, who are experts in the field, and would apply it, perhaps in adapted form, to their own context. Whilst the approach is suitable for such applications, this research has demonstrated that this sort of participative exercise with stakeholders is a resource-intensive process, which in this case ran over nine months and involved several full time researchers. Whilst thinking about a large scale application to many small communities, it seems neither feasible nor desirable to restrict applications to those undertaken by experts.

Instead, it should be a medium term vision to develop these approaches further, so that as much as feasible the process can be automated. Partly, such developments could be achieved by further research, especially in the fields MAVT and automated output generation. But some factors are beyond the researchers' control, such as the available data about the local energy system and/or the renewable resources in a given community. Nevertheless, a reasonable medium term objective could be to develop these and similar methods into a toolkit that can not only be employed by experts, but also by the communities themselves. By masking the complexity of integrated methods behind a comfortable interface with which non-experts can work, it might just be possible to enable these communities to "help themselves".

7. Conclusions

Researchers and practitioners are increasingly attempting to combine qualitative and quantitative methods in order to deal with the complexity and heterogeneity associated with decision-making in the context of community energy systems. This paper presents an integrated participatory methodological framework that combines cost-potential assessments, optimisation modelling, MCDA/MAVT and structured alternative-formulation and preference-elicitation workshops with key stakeholders in order to derive feasible energy concepts/alternatives for small communities. This approach goes beyond existing work in this area especially in terms of the direct interaction with the community, the sourcing of input for the MCDA from the optimisation model, the sourcing of input data for the optimisation itself from open source data and the explicit consideration of uncertain stakeholder preferences in a multi-dimensional sensitivity analysis. Through its interactive nature and the use of natural language generation techniques as well as open data, our approach contributes to increasing the accessibility (methodologically and in terms of data needs) of complex OR methods for smaller communities with limited resources. In this sense, it also increases the accessibility and exploitability of sustainable energy for these communities.

The application of this method in the context of a case study for a small community of 5000 inhabitants in southwest Germany has demonstrated its feasibility and delivered indispensable decision-support in terms of clearly-defined alternative energy systems in 2030 as well as concrete measures to reach this aim. The impact of this research within the community ultimately rests with the stakeholders themselves, but it has at least provided a sound basis for which future decisions relating to the energy system can be made.

Whilst the general approach is highly transferable for experts, the feasibility of its application in other contexts will rely largely on the active engagement of target communities as well as the availability of detailed data on the existing energy system. Due to the resource-intensive nature of such expert-driven initiatives, it is highly desirable to further develop this framework into one that can be effectively employed by non-experts within the community and thus reduce the required expert input to a minimum. In particular, this would mean integrating the distinct aspects of this approach (i.e. workshops, optimisation model, MCDA and simple building-level tools) into one unified interface aimed at decision makers at the local level. Such an interface would require a pre-definition of likely criteria for the system optimisation, would make extensive use of automated natural language outputs, and might even be made available as open source for the purposes of dissemination. To begin with, such an interface would require expert intervention in order to moderate the process, but with an intensive learning period it could find stand-alone application within individual communities and thus enable them to at least be autonomous in their energy concept development.

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10 Appendix 1: Mathematical model formulation

10.1 Sets and Subsets

	Description
$\boldsymbol{AY}$	all years (1880 – 2030)
$\boldsymbol{MY}$	model years {2015, 2020, 2025, 2030}
$\boldsymbol{TS}$	timeslices, i.e. continuous groups of hours (72 per year)
$\boldsymbol{DY}$	days (8 groups of timeslices)
$\boldsymbol{DS}$	all districts
$\boldsymbol{DS^{en}}$	endogenous districts
$\boldsymbol{DS^{ex}}$	exogenous districts (outside the regions' boundaries, for energy import)
$\boldsymbol{ST}$	sectors
$\boldsymbol{BI}$	building instances (of a building type)
$\boldsymbol{TC}$	technologies
$\boldsymbol{TC^{ss}}$	small (building) scale technologies
$\boldsymbol{TC^{ls}}$	large (district) scale technologies
$\boldsymbol{TC^{fx}}$	technologies with a given generation profile, e.g. PV
$\boldsymbol{TC^{ht}}$	main heating technologies
$\boldsymbol{EC}$	energy carriers
$\boldsymbol{EC^{b}}$	balanced energy carriers, e.g. electricity
$\boldsymbol{EC^{n}}$	non-balanced energy carriers, e.g. ambient heat
$\boldsymbol{EC^{d}}$	day-balanced energy carriers, e.g. room heat
$\boldsymbol{EM}$	emissions

10.2 Parameters

	Description
$\boldsymbol{NH}$	number of hours per timeslices
$\boldsymbol{NT}$	quantity of a timeslice per year
$\boldsymbol{NB}$	number/quantity/scalefactor for this building type
$\boldsymbol{NY}$	number of years that are represented by a model year
$\boldsymbol{CF}$	fuel costs
$\boldsymbol{CE}$	emissions costs
$\boldsymbol{CT}$	transmission costs

$\boldsymbol{CD}$	distribution costs
$\boldsymbol{CV}$	variable costs
$\boldsymbol{CX}$	fix costs
$\boldsymbol{CI}$	installation costs, e.g. for a scaffolding for building insulation
$\boldsymbol{UI}$	investment per unit
$\boldsymbol{IO}$	input-/output-rates for technology processes
$\boldsymbol{ER}$	emission rate
$\boldsymbol{PEF}$	primary energy factor
$\boldsymbol{DF}$	discount factor
$\boldsymbol{AF}$	annuity factor
$\boldsymbol{RL}$	remaining lifetime of an installed technology
$\boldsymbol{HG}$	geographical hierarchy
$\boldsymbol{IS^{BI}}$ / $\boldsymbol{IS^{DS}}$*	initially installed number of units (stock)
$\boldsymbol{DM}$	demand for energy services
$\boldsymbol{UA^{BI}}$ / $\boldsymbol{UA^{DS}}$*	maximum number of allowed units
$\boldsymbol{EM^{ex}}$	model-exogenous emissions (e.g. from the transport sector)
$\boldsymbol{AL^{fx}_{y,t,tc}}$	activity level for technologies with given profiles, e.g. PV
$\boldsymbol{FD^{max}}$	maximum energy flow between districts
$\boldsymbol{FB^{max}}$	maximum energy flow from district to building level
$\boldsymbol{FB^{min}}$	maximum energy flow from building to district level
$\boldsymbol{ZC^{max}}$	maximum allowed costs
$\boldsymbol{ZE^{max}}$	maximum allowed CO_2 emissions
$\boldsymbol{ZI^{max}}$	maximum allowed net energy imports
$\boldsymbol{ZP^{max}}$	maximum allowed primary energy use

*BI denotes a building-level, DS a district-level parameter

10.3 Variables

	Description
$\boldsymbol{al^{BI}}$ / $\boldsymbol{al^{DS}}$*	activity level of a technology
$\boldsymbol{fl^{d}}$	energy flow between districts
$\boldsymbol{fl^{b}}$	energy flow from district to building level
$\boldsymbol{uc^{BI}}$ / $\boldsymbol{uc^{DS}}$*	commissioned units
$\boldsymbol{ud^{BI}}$ / $\boldsymbol{ud^{DS}}$*	endogenously decommissioned units
$\boldsymbol{uda^{BI}}$ / $\boldsymbol{uda^{DS}}$*	all decommissioned units (including those from the stock that fade out over time)
$\boldsymbol{us^{BI}}$ / $\boldsymbol{us^{DS}}$*	units in stock / installed units

$\boldsymbol{bni^{BI}}$ / $\boldsymbol{bni^{DS}}*$	whether a new investment is made (binary)
$\boldsymbol{bti^{BI}}$	whether a technology is installed (binary)
$\boldsymbol{z}$	combined objective
$\boldsymbol{z^{c}}$	total discounted system costs
$\boldsymbol{z^{e}}$	total discounted CO_2 emissions
$\boldsymbol{z^{i}}$	total discounted net energy imports
$\boldsymbol{z^{p}}$	total discounted primary energy use
$\boldsymbol{c^{ei}}$	energy import costs
$\boldsymbol{c^{et}}$	transmission grid costs
$\boldsymbol{c^{ed}}$	energy distribution costs
$\boldsymbol{c^{ia}}$	investment annuities costs
$\boldsymbol{c^{fx}}$	fix unit costs
$\boldsymbol{c^{vr}}$	variable unit costs
$\boldsymbol{c^{em}}$	emission costs
$\boldsymbol{em}$	endogenous emissions
*BI denotes a building-level, DS a district-level variable	

10.4 Equations

The objective function z of the model (10.1) is comprised of the four indicators total discounted system costs z^c (10.2), emissions z^e (10.3), net energy imports z^i (10.4) and primary energy demand z^p (10.5) as well as the associated weighting factors w for these indicators. The binary characteristic of the weighting factors is used to easily switch between the different objective function indicators for the analysed alternatives.

$$\min z = (w^c * z^c + w^e * z^e + w^i * z^i + w^p * z^p)$$
$$\text{with } w^c, w^e, w^i, w^p \in \{0; 1\}\, ; (w^c + w^e + w^i + w^p) = 1 \tag{10.1}$$

$$z^c = \sum_{y \in MY} \left(DF_y * NY_y * \left(c_y^{ei} + c_y^{et} + c_y^{ed} + c_y^{ia} + c_y^{fx} + c_y^{vr} + c_y^{em} \right) \right) \tag{10.2}$$

$$z^e = \sum_{y \in MY, d \in DS^{en}, m \in \{"CO2"\}} \left(DF_y * NY_y * \left(\sum_{t \in TS} \left(NT_t * em_{y,t,d,m} \right) + EM_{y,d,m}^{ex} \right) \right) \tag{10.3}$$

$$z^{i} = \sum_{y \in MY} \left(DF_{y} * NY_{y} * \sum_{t \in TS, e \in EC} \left(NT_{t} * \sum_{d1 \in DS^{ex}, d2 \in DS^{en}} \left(fl^{d}_{y,t,d1,d2,e} - fl^{d}_{y,t,d2,d1,e} \right) \right) \right)$$

(10.4)

$$z^{p} = \sum_{y \in MY} \left(DF_{y} * NY_{y} * \sum_{t \in TS, e \in EC} \left(NT_{t} * PEF_{y,e} * \sum_{d1 \in DS^{ex}, d2 \in DS^{en}} \left(fl^{d}_{y,t,d1,d2,e} - fl^{d}_{y,t,d2,d1,e} \right) \right) \right)$$

(10.5)

The total discounted system costs are comprised of cost factors for energy import c^{ei} (10.6), use of the transmission grid c^{et} (10.7), local energy distribution c^{ed} (10.8), investment annuities c^{ia} (10.9), fixed c^{fx} (10.10) and variable c^{vr} (10.11) operating costs as well as emissions c^{em} (10.12). Taxes and subsidies are explicitly not considered, i.e. the model incorporates a macro-economic perspective where these are considered merely as a redistribution of costs with no impact on total welfare.

$$c^{ei}_{y} = \sum_{t \in TS, e \in EC} \left(NT_{t} * CF_{y,t,e} * \sum_{d1 \in DS^{ex}, d2 \in DS^{en}} \left(fl^{d}_{y,t,d1,d2,e} - fl^{d}_{y,t,d2,d1,e} \right) \right)$$

(10.6)

$$c^{et}_{y} = \sum_{e \in EC} \left(CT_{y,e} * \sum_{t \in TS, d1 \in DS^{ex}, d2 \in DS^{en}} \left(NT_{t} * \left(fl^{d}_{y,t,d1,d2,e} + fl^{d}_{y,t,d2,d1,e} \right) \right) \right)$$

(10.7)

$$c^{ed}_{y} = \sum_{e \in EC} \left(CD_{y,e} * \sum_{t \in TS, e \in EC, d1 \in DS^{en}, d2 \in DS^{en}:\ d1 \neq d2} \left(NT_{t} * \left(fl^{d}_{y,t,d1,d2,e} + fl^{d}_{y,t,d2,d1,e} \right) \right) \right)$$

(10.8)

$$
\begin{aligned}
c_y^{ia} = & \sum_{d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}:\, HG(d,s,b)} \Bigg(AF_{tc} \\
& * \sum_{y_1 \in MY:\, y_1 \geq y_0, y_1 \leq y, RL_{tc,y_1,y} > 0} \Big(min\big(RL_{tc,y_1,y}, NY_y\big) * NB_{y_1,d,s,b} \\
& * \big(bni_{y_1,d,s,b,tc}^{BI} * CI_{tc,y_1} + uc_{y_1,d,s,b,tc}^{BI} * UI_{tc,y_1}\big)\Big) / NY_y \Bigg) \\
& + \sum_{d \in DS^{en}, tc \in TC^{ls}} \Bigg(AF_{tc} \\
& * \sum_{y_1 \in MY:\, y_1 \geq y_0, y_1 \leq y, RL_{tc,y_1,y} > 0} \Big(min\big(RL_{tc,y_1,y}, NY_y\big) * \big(bni_{y_1,d,tc}^{DS} * CI_{tc,y_1} + uc_{y_1,d,tc}^{DS} * UI_{tc,y_1}\big)\Big) \\
& / NY_y \Bigg)
\end{aligned}
\tag{10.9}
$$

$$
c_y^{fx} = \sum_{d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}:\, HG(d,s,b)} \big(NB_{y,d,s,b} * us_{y,d,s,b,tc}^{BI} * CX_{tc}\big) + \sum_{d \in DS^{en}, tc \in TC^{ls}} \big(us_{y,d,tc}^{DS} * CX_{tc}\big)
\tag{10.10}
$$

$$
\begin{aligned}
c_y^{vr} = & \sum_{t \in TC, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}:\, HG(d,s,b)} \big(NT_t * NB_{y,d,s,b} * al_{y,t,d,s,b,tc}^{BI} * NH_t * CV_{tc}\big) \\
& + \sum_{t \in TS, d \in DS^{en}, tc \in TC^{ls}} \big(NT_t * al_{y,t,d,tc}^{DS} * NH_t * CV_{tc}\big)
\end{aligned}
\tag{10.11}
$$

$$
c_y^{em} = \sum_{t \in TS, d \in DS^{en}, m \in EM} \big(NT_t * em_{y,t,d,m} * CE_{y,t,m}\big)
\tag{10.12}
$$

Emissions are comprised of model-endogenous emissions em (10.13) and model-exogenous emissions EM^{ex}, that can be supplied by the user (e.g. to incorporate emissions from currently not covered sectors such as transport).

$$
\begin{aligned}
& em_{y,t,d,e} = \sum_{s \in ST, b \in BI, tc \in TC^{ss}:\, HG(d,s,b)} \big(NB_{y,d,s,b} * al_{y,t,d,s,b,tc}^{BI} * ER_{tc,m} * NH_t\big) + \sum_{tc \in TC^{ls}} \big(al_{y,t,d,tc}^{DS} * ER_{tc,m} * NH_t\big) \\
& \forall\, y \in MY, t \in TS, d \in DS^{en}, m \in EM
\end{aligned}
\tag{10.13}
$$

The decommissioned units uda are calculated as a combination of model-endogenous decommissioning ud as well as units from the initially provided stock IS and units that have been built by the model uc that reach the end of their respective lifetimes (equations (10.14) and (10.15)).

$$uda_{y,d,s,b,tc}^{BI} = \sum_{y_1 \in AY: y_1 < y, RL(tc,y_1,y-1) > 0, RL(tc,y_1,y) \leq 0} \left(IS_{y_1,d,s,b,tc}^{BI}\right) + \sum_{y_1 \in MY: y_1 < y, RL(tc,y_1,y-1) > 0, RL(tc,y_1,y) \leq 0} \left(uc_{y_1,d,s,b,tc}^{BI}\right) + ud_{y_1,d,s,b,tc}^{BI}$$

$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}: HG(d,s,b)$$

(10.14)

$$uda_{y,d,tc}^{DS} = \sum_{y_1 \in AY: y_1 < y, RL(tc,y_1,y-1) > 0, RL(tc,y_1,y) \leq 0} \left(IS_{y_1,d,tc}^{DS}\right) + \sum_{y_1 \in MY: y_1 < y, RL(tc,y_1,y-1) > 0, RL(tc,y_1,y) \leq 0} \left(uc_{y_1,d,tc}^{DS}\right) + ud_{y_1,d,tc}^{DS}$$

$$\forall\, y \in MY, d \in DS^{en}, tc \in TC^{ls}$$

(10.15)

The current stock of each technology us is calculated using the initial stock of units as well as all commissioned and decommissioned units (equations (10.16) and (10.17)).

$$us_{y,d,s,b,tc}^{BI} = \sum_{y_1 \in AY: y_1 < y} \left(IS_{y_1,d,s,b,tc}^{BI}\right) + \sum_{y_1 \in MY: y_1 < y} \left(uc_{y_1,d,s,b,tc}^{BI} - uda_{y_1,d,s,b,tc}^{BI}\right)$$

$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}: HG(d,s,b)$$

(10.16)

$$us_{y,d,tc}^{DS} = \sum_{y_1 \in AY: y_1 < y} \left(IS_{y_1,d,tc}^{DS}\right) + \sum_{y_1 \in MY: y_1 < y} \left(uc_{y_1,d,tc}^{DS} - uda_{y_1,d,tc}^{ds}\right)$$

$$\forall\, y \in MY, d \in DS^{en}, tc \in TC^{ls}$$

(10.17)

Equations (10.18) and (10.19) are used to fix the activity level al for technologies such as PV to their pre-determined activity levels AL^{fx}, scaled to the number of installed units.

$$al_{y,t,d,s,b,tc}^{BI} = us_{y,d,s,b,tc}^{BI} * AL_{y,t,tc}^{fx}$$

$$\forall\, y \in MY, t \in TS, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{fx}: HG(d,s,b)$$

(10.18)

$$al_{y,t,d,tc}^{DS} = us_{y,d,tc}^{DS} * AL_{y,t,tc}^{fx}$$

$$\forall\, y \in MY, t \in TS, d \in DS^{en}, tc \in TC^{fx}$$

(10.19)

Additionally, the model contains a number of constraints that have to be fulfilled. These can e.g. be used to constrain the four objective indicators z^c, z^e, z^i, and z^p to certain values (equations (10.20), (10.21), (10.22) and (10.23)), which is used to create different alternatives/scenarios.

$$z^c \leq ZC^{max} \tag{10.20}$$

$$z^e \leq ZE^{max} \tag{10.21}$$

$$z^i \leq ZI^{max} \tag{10.22}$$

$$z^p \leq ZP^{max} \tag{10.23}$$

Some of the most important constraints are the energy balance equations ((10.24) for building level, (10.25) for district level), that state that the energy service demand has to be matched by an equivalent supply at all times.

$$\begin{aligned} &\sum_{tc \in TC^{ss}} \left(al^{BI}_{y,t,d,s,b,tc} * IO_{tc,e} * NH_t \right) + fl^{b}_{y,t,d,s,b,e} - DM_{y,t,d,s,b,e} * NH_t \\ &= 0 \\ &\forall\, y \in MY, t \in TS, d \in DS^{en}, s \in ST, b \in BI, e \in EC^{b}\colon HG(d,s,b) \end{aligned} \tag{10.24}$$

$$\begin{aligned} &\sum_{tc \in TC^{ls}} \left(al^{DS}_{y,t,d,tc} * IO_{tc,e} * NH_t \right) + \sum_{d1 \in DS: d1 \neq d} fl^{d}_{y,t,d1,d,e} - \sum_{d1 \in DS: d1 \neq d} fl^{d}_{y,t,d,d1,e} \\ &\qquad - \sum_{s \in ST, b \in BI\colon HG(d,s,b)} \left(NB_{y,d,s,b} * fl^{b}_{y,t,d,s,b,e} \right) \\ &= 0 \\ &\forall\, y \in MY, t \in TS, d \in DS^{en}, e \in EC^{b} \end{aligned} \tag{10.25}$$

For room heat ((10.26) and (10.27)), the demand does not have to be matched at each timeslice, but for the sum over each day. This represents the fact that heating technologies in buildings are usually equipped with sufficiently sized thermal storages that can temporarily decouple supply and demand. This simplification allows the model to forgo the explicit consideration of the thermal storage level for each timeslice, which greatly reduces model complexity and computational effort.

$$\sum_{t \in TS:\,DAYSTSMAP(dy,t)} \left(\sum_{tc \in TC^{ss}} \left(al^{BI}_{y,t,d,s,b,tc} * IO_{tc,e} * NH_t \right) + fl^{b}_{y,t,d,s,b,e} - DM_{y,t,d,s,b,e} * NH_t \right)$$
$$= 0$$
$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, e \in EC^{d}, dy \in DY: HG(d,s,b)$$

(10.26)

$$\sum_{t \in TS:\,DAYSTSMAP(dy,t)} \left(\sum_{tc \in TC^{ls}} \left(al^{DS}_{y,t,d,tc} * IO_{tc,e} * NH_t \right) + \sum_{d1 \in DS: d1 \neq d} fl^{d}_{y,t,d1,d,e} - \sum_{d1 \in DS: d1 \neq d} fl^{d}_{y,t,d,d1,e} - \sum_{s \in ST, b \in BI:\, HG(d,s,b)} \left(NB_{y,d,s,b} * fl^{b}_{y,t,d,s,b,e} \right) \right)$$
$$= 0$$
$$\forall\, y \in MY, d \in DS^{en}, e \in EC^{d}, dy \in DY$$

(10.27)

For certain energy carriers, such as ambient heat, an excess of energy is allowed.

$$\sum_{tc \in TC^{ss}} \left(al^{BI}_{y,t,d,s,b,tc} * IO_{tc,e} * NH_t \right) + fl^{b}_{y,t,d,s,b,e} - DM_{y,t,d,s,b,e} * NH_t$$
$$>= 0$$
$$\forall\, y \in MY, t \in TS, d \in DS^{en}, s \in ST, b \in BI, e \in EC^{n}: HG(d,s,b)$$

(10.28)

$$\sum_{tc \in TC^{ls}} \left(al^{DS}_{y,t,d,tc} * IO_{tc,e} * NH_t \right) + \sum_{d1 \in DS: d1 \neq d} fl^{d}_{y,t,d1,d,e} - \sum_{d1 \in DS: d1 \neq d} fl^{d}_{y,t,d,d1,e} - \sum_{s \in ST, b \in BI:\, HG(d,s,b)} \left(NB_{y,d,s,b} * fl^{b}_{y,t,d,s,b,e} \right)$$
$$>= 0$$
$$\forall\, y \in MY, t \in TS, d \in DS^{en}, e \in EC^{n}$$

(10.29)

Further constraints limit the allowed energy flow between districts (10.30) and from district to building level (minimum and maximum energy flows for all buildings in a district as well as for each single building: (10.31), (10.32), (10.33), (10.34)).

$$fl^{d}_{y,t,d,d1,e} / NH_t <= FD^{max}_{y,d,d1,e}$$
$$\forall\, y \in MY, t \in TS, d \in DS, d1 \in DS, e \in EC: d1 \neq d$$

(10.30)

$$\sum_{s \in ST, b \in BI} \left(NB_{y,d,s,b} * fl^{b}_{y,t,d,s,b,e} \right) / NH_t <= FB^{max}_{y,d,e}$$

$\forall\, y \in MY, t \in TS, d \in DS^{en}, e \in EC$

(10.31)

$$\sum_{s \in ST, b \in BI} \left(NB_{y,d,s,b} * fl^{b}_{y,t,d,s,b,e}\right) / NH_t >= FB^{min}_{y,d,e}$$

$\forall\, y \in MY, t \in TS, d \in DS^{en} e \in EC$

(10.32)

$$fl^{b}_{y,t,d,s,b,e} / NH_t <= FB^{max}_{y,d,e}$$

$\forall\, y \in MY, t \in TS, d \in DS^{en}, s \in ST, b \in BI, e \in EC \colon HG(d,s,b)$

(10.33)

$$fl^{b}_{y,t,d,s,b,e} / NH_t >= FB^{min}_{y,d,e}$$

$\forall\, y \in MY, t \in TS, d \in DS^{en}, s \in ST, b \in BI, e \in EC$

(10.34)

The following inequalities formulate the restriction on the maximum allowed quantities of certain technologies (e.g. due to potential restrictions or due to a technology not being available yet at a certain point of time: (10.35) and (10.36)).

$$us^{BI}_{y,d,s,b,tc} <= UA^{BI}_{y,d,s,b,tc}$$

$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss} \colon HG(d,s,b)$

(10.35)

$$us^{DS}_{y,d,tc} <= UA^{DS}_{y,d,tc}$$

$\forall\, y \in MY, d \in DS^{en}, tc \in TC^{ls}$

(10.36)

Other constraints are concerned with inner model logic, e.g. the restriction of the activity level for technologies to the installed numbers: (10.37) and (10.38).

$$al^{BI}_{y,t,d,s,b,tc} <= us^{BI}_{y,d,s,b,tc}$$

$\forall\, y \in MY, t \in TS, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss} \colon HG(d,s,b)$

(10.37)

$$al^{DS}_{y,t,d,tc} <= us^{DS}_{y,d,tc}$$

$\forall\, y \in MY, t \in TS, d \in DS^{en}, tc \in TC^{ls}$

(10.38)

The binary variables bni^{BI}, and bni^{DS} express whether a new investment is undertaken and are required e.g. for the calculation of installation costs. The binary variable bni^{BI} expresses whether a technology is installed in a building or not. It is used to state that only one type of main heating technology is allowed per building. These variables are defined using the Big-M-method through the inequalities (10.39) to (10.45).

$$bni^{BI}_{y,d,s,b,tc} \geq uc^{BI}_{y,d,s,b,tc}/10.000$$
$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}: HG(d,s,b)$$

(10.39)

$$bni^{BI}_{y,d,s,b,tc} \leq uc^{BI}_{y,d,s,b,tc}$$
$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ss}: HG(d,s,b)$$

(10.40)

$$bni^{DS}_{y,d,tc} \geq uc^{DS}_{y,d,tc}/15.000$$
$$\forall\, y \in MY, d \in DS^{en}, tc \in TC^{ls}$$

(10.41)

$$bni^{DS}_{y,d,tc} \leq uc^{DS}_{y,d,tc}$$
$$\forall\, y \in MY, d \in DS^{en}, tc \in TC^{ls}$$

(10.42)

$$bti^{BI}_{y,d,s,b,tc} \geq us^{BI}_{y,d,s,b,tc}/1.000$$
$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ht}: HG(d,s,b)$$

(10.43)

$$bti^{BI}_{y,d,s,b,tc} \leq us^{BI}_{y,d,s,b,tc}$$
$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI, tc \in TC^{ht}: HG(d,s,b)$$

(10.44)

$$\sum_{tc \in TC^{ht}} bti^{BI}_{y,d,s,b,tc} \leq 1$$
$$\forall\, y \in MY, d \in DS^{en}, s \in ST, b \in BI: HG(d,s,b)$$

(10.45)

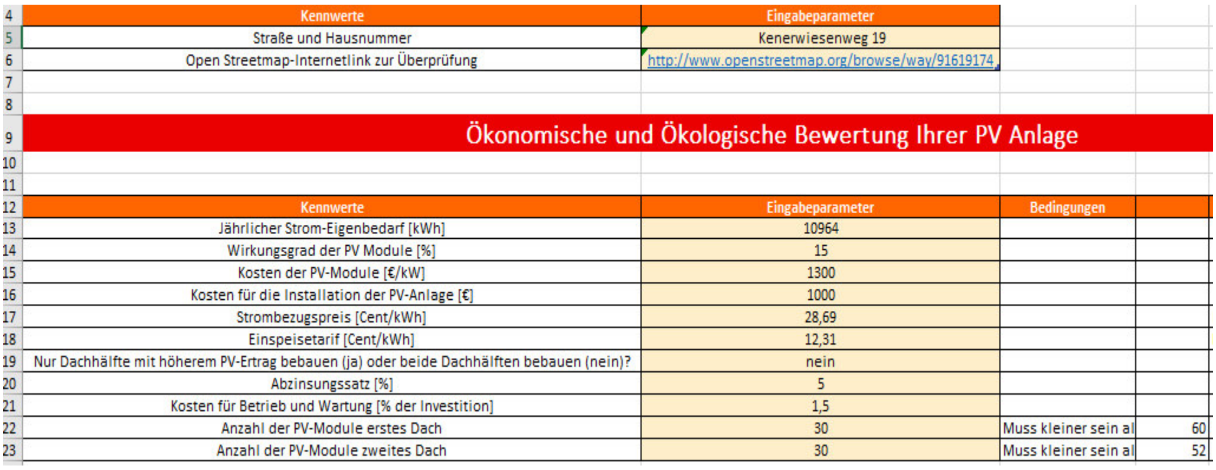
11 Appendix 2: description of Excel tool

In the context of this study, an Excel tool was created that allows the inhabitants of Ebhausen to evaluate the profitability of PV systems on their own houses. Furthermore, changes in heating systems and insulation measures can be economically and ecologically assessed. Fundamentals for the calculations can be inserted and results looked at in the first spreadsheet *Input Table*. The second spreadsheet *Graphical Results* illustrates the results of the calculation in graphically. The results of the Excel tool and the optimisation model can only be compared to a certain extent. This is due to different approaches used. In the case of the optimisation, the community as a whole is being considered, meaning a central plan for the community is identified, whereas the Excel tool examines only single houses. The view of each household is considered independently, meaning the individual measures of PV systems, insulation and heating systems are evaluated individually based on a lifecycle costing approach. In addition, reciprocal effects of the individual measures can be taken into account in the optimization model by using a combined consideration of the installation of PV-systems, insulation and heat system changes. In the Excel tool, however, the various measures are being evaluated independently from each other. Furthermore, the Excel tool can only analyse the current situation, and in contrast to the optimization model it does not consider future investments. Consequently, the Excel tool can lead to different results than the optimization model. The deviations between the centralized results of the optimization model and the decentralized results from the household's point of view must be rectified by supplementary financial incentives.

11.1 Economic and ecological evaluation of PV systems

For the economic/ecological evaluation of PV systems, the address of the house must be first selected from the list (cf. Figure 1). If some houses are not listed, their addresses could not be identified by the approach applied to determine the addresses.

The correlation between address and building can be verified on the webpage www.openstreetmap.org. Subsequently, consumption data need to be inserted including but not limited to annual demand for electricity and prices. If quotations from installers have been obtained, individual costs can be adapted as input parameter. If not, average values should be used for the calculation. In addition, the tool allows the selection of only one (the one with the highest yield) or both sides of the rooftop to be covered with PV systems. After the selection of the address, the number of potential PV modules on each roof top half will be determined. However, the user can also enter a smaller number of PV modules. Figure 1 shows an example with 30 PV modules being installed per roof half, instead of the maximum values of 60 or 52. At this point it is important to point out that a reasonably (high) number of modules on each roof top half should be selected to avoid falsified results (e.g. share of PV electricity consumed by the household itself). This is due to the fact that the household demand for electricity using the option of both roof top halves will be divided up into both roof halves.



4	Kennwerte	Eingabeparameter
5	Straße und Hausnummer	Kenerwiesenweg 19
6	Open Streetmap-Internetlink zur Überprüfung	http://www.openstreetmap.org/browse/way/91619174
7		
8		

9 Ökonomische und Ökologische Bewertung Ihrer PV Anlage

12	Kennwerte	Eingabeparameter	Bedingungen	
13	Jährlicher Strom-Eigenbedarf [kWh]	10964		
14	Wirkungsgrad der PV Module [%]	15		
15	Kosten der PV-Module [€/kW]	1300		
16	Kosten für die Installation der PV-Anlage [€]	1000		
17	Strombezugspreis [Cent/kWh]	28,69		
18	Einspeisetarif [Cent/kWh]	12,31		
19	Nur Dachhälfte mit höherem PV-Ertrag bebauen (ja) oder beide Dachhälften bebauen (nein)?	nein		
20	Abzinsungssatz [%]	5		
21	Kosten für Betrieb und Wartung [% der Investition]	1,5		
22	Anzahl der PV-Module erstes Dach	30	Muss kleiner sein al	60
23	Anzahl der PV-Module zweites Dach	30	Muss kleiner sein al	52

Figure 1: Input parameters of the Excel tool for economic and ecological evaluation of a PV system

After specifying all relevant data, the result will indicate amongst other things the net present value (NPV), the payback period and the annual CO_2 emissions reduction. The timeframe for the calculations is 20 years.

11.2 Economic and ecological evaluation of changing the heater system

Besides the PV system, the tool can also economically and ecologically evaluate a change of heating system. Therefore, the user can select the building type (single-family house, semi-detached house, etc.), the year of construction or the year of the last renovation, and the existing heat technology (cf. Figure 2). In order to consider the residual value of the heat technology, the age of the existing heat technology must be indicated. Subsequently, the new heating technology can be determined through the given list.

42	Kennwerte	Eingabeparameter
43	Gebäudetyp	Einfamilienhaus
44	Baujahr/Jahr der letzten Sanierung	1949 - 1957
45	Bestehende Heiztechnologie	Luft-Wärmepumpe
46	Alter der bestehenden Heiztechnologie [a]	18
47	Wechsel zu Technologie	Gas-Kondensationskessel
48	Abzinsungssatz [%]	5

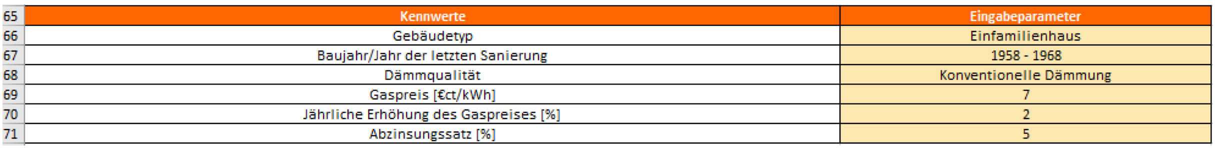
Figure 2: Input parameter in the Excel tool for an economic and ecological evaluation of changing the heating system

Amongst other things, as results form the data given, the change of life-cycle costs and the annual emissions as well as the payback period (over 20 years) can be viewed.

11.3 Economic and ecological evaluation of insulation measures

In contrast to the evaluation of PV systems and changing heating systems, the economic and ecological evaluation of insulation measures is based on a 50-year timeframe due to the longer lifetime of those measures. To determine the results, the heating system with a gas boiler is used as the reference system.

That is why the input data includes, besides the building type and the insulation quality, also the price of gas and its annual increase (cf. Figure 3). Conventional or deep insulations are both options that can be chosen for the desired insulation quality. Due to the fact that the costs for deep insulation cannot be estimated in relation to the initial state, this initial state of the house cannot be indicated in the tool. If conventional insulation is in place, e.g. double glazed windows still need to be replaced by triple glazed windows. Hence, independent of the initial state, the same costs for a deep insulation would accrue.



65	Kennwerte	Eingabeparameter
66	Gebäudetyp	Einfamilienhaus
67	Baujahr/Jahr der letzten Sanierung	1958 - 1968
68	Dämmqualität	Konventionelle Dämmung
69	Gaspreis [€ct/kWh]	7
70	Jährliche Erhöhung des Gaspreises [%]	2
71	Abzinsungssatz [%]	5

Figure 3: Input parameter in the excel tool for an economic and ecological evaluation of insulation measures

11.4 Limits of the Excel tool

The Excel tool is not able to evaluate to what extent the results change if all measures would be combined. Using an electric heat pump in a household would change the evaluation of the PV system, for example. In that case, using both rooftop halves could be more economically viable since more PV power could be used to run the heat pump. Therefore, in order to make real investment decisions, all three measures must be considered.

Furthermore, for some calculations, the dynamic perspective is missing. Thus, some parameters (e.g. costs and feed-in remuneration) are only considered statically. Further, averaged values for consumption lead to uncertainties in the calculations.

The results of the evaluation of PV systems can be considered as sound assessments, but the results of the evaluation of changing heating systems and insulation measures should only be considered as a rough first guideline, however. All in all, no investment decisions based on the results of the Excel tool should be made without further analyses.

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