Energy Cooperatives as an Application of Microgrids: Multi-Criteria Investment Decision Support

Completed Research Paper

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Abstract

The future of energy generation is expected to become increasingly decentralized. Today, many customers are already more than demand units, they also act as energy producers (prosumers) and thus participants in the energy market. The development of energy cooperatives with underlying microgrids in recent years undermines this observation. Information and communication technologies enable the management of energy cooperatives by incorporating data (smart meter, energy generation). We present a MAUT-based software tool to provide support for energy cooperatives when deciding about investments in new supply units. The findings of the literature analysis point out that energy cooperatives have economic, ecologic and social goals. Within our software tool we define measures for the fulfilment of the goals including available data. The utility for each goal is calculated and aggregated to an index. We test the developed software tool with real-world data. The results indicate that our artifact provides useful decision support.

Keywords: Energy Cooperative, Microgrid, Decision Support Systems (DSS), MCDA, Sustainability

Introduction

The Commission of the European Union released the Strategic Energy Technology Plan (SET) in 2007. One of its goals is the development of smart cities that manage local energy production and consumption in an efficient way (Commission of the European Communities 2007). So far, electricity markets are centrally organized, have high entrance barriers for individuals such as small consumption or supply facilities, and are complex. However, the transition towards decentralization is an ongoing process (Joskow 2008). Microgrids, also characterized as the “building blocks of smart grids”, are perhaps the most promising, novel network structure as they provide a chance for local optimization (Schwaegerl and Tao 2014b).

The meltdown of three nuclear power reactors in March 2011 in Fukushima was the initiation of ongoing discussions about the future of nuclear energy. In Germany, a huge shift in energy policy started: The government declared to shut down all nuclear reactors by 2022. One solution for overcoming the challenges is to focus on decentralized generation of energy in order to reduce grid expansion expenses and increase the security of supply. Along with the political decisions, regulatory programs were introduced to rise renewable energy production which encouraged customers to build own renewable power plants (Carley 2009). Concurrently, energy cooperatives were set up to “promote the use of renewable energy” (Viardot 2013). The expansion of microgrids can be observed in many parts of the world, as pilot sites were installed and explored in many countries (Kariniotakis et al. 2014; Viardot 2013). So far the topic of energy cooperatives as a form of operating a microgrid is rarely discussed in research. Energy cooperatives are one driver for decentralization and thus there is a need for research.

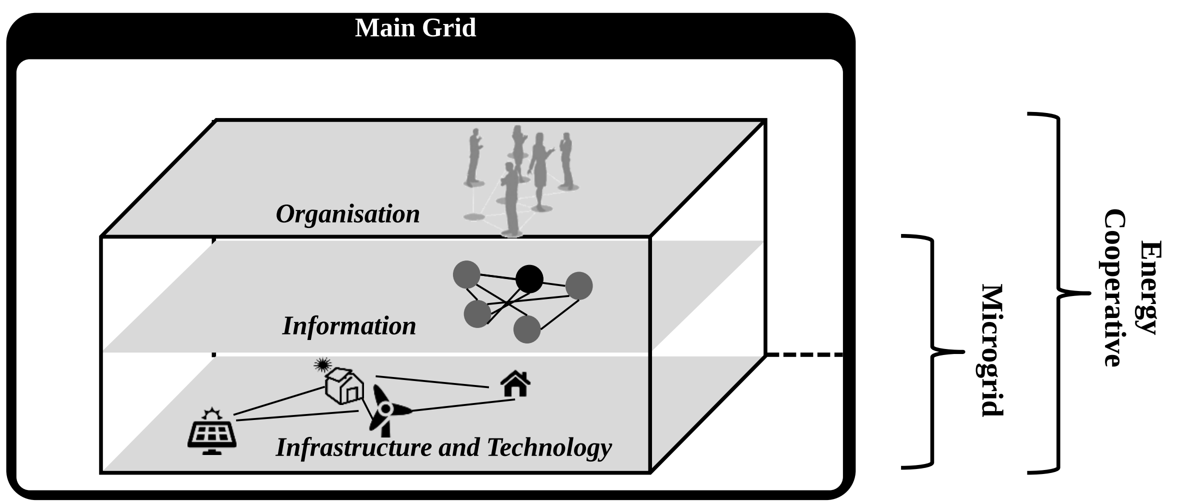

Figure 1. Schematic Diagram of Energy Cooperative and Microgrid

“Microgrids comprise (low voltage) LV distribution systems with distributed energy resources (DER) (micro turbines, fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads” (Hatziargyriou 2006-2009). A microgrid can have two modes, grid connected and islanded (or standalone) mode (Liang and Zhuang 2014). We define a microgrid to consist of infrastructure and technology which includes the internal low voltage grid, renewable generation and demand units (households) as well as information which mainly includes monitoring and control. The microgrid can be connected to the main grid or exist independently from the main grid. When it comes to the information layer, monitoring and control can only be realized by information and communication technologies (ICT). Those are influenced by the chosen organizational form. According to Krcmar (2005) ICT enables new business models. In the case of energy cooperatives the coordination and management of the infrastructure of the microgrid is enabled by ICT as diverse data sources can be collected and used for decision making. Figure 1 shows the relationship between the aforementioned terms.

The objective of this paper is to answer the following research question: *How should an energy cooperative based on a microgrid decide about investing in a new generation unit by incorporating available data?* To answer this question we develop an easy to implement data-driven software tool for decision-making incorporating multiple criteria. For the development of this artifact we follow design science research guidelines (Hevner et al. 2004).

Literature Review

In the following, we describe relevant literature regarding microgrids and energy cooperatives. The existing literature can be clustered in technology, economic and management-related literature. As microgrids are a technical concept, the literature in this area focuses on the feasibility and setting of microgrids whereas the economic literature analyzes the influence of microgrids on markets and regulation. Under management-related literature, we subsume the organizational form (i.e. energy cooperative) and the goals of a microgrid itself. As the goals of the cooperative form the basis for our software tool, we describe these in detail.

Microgrid as a technical concept was mostly developed in electrical engineering to overcome the challenges of increasing decentralization of generation (Lasseter et al. 2002; Lasseter 2002; Venkataramanan and Illindala 2002). According to Lasseter and Paigi (2004) microgrids are "a better way to realize the emerging potential of distributed generation". Technical microgrid literature can be split in conceptual literature and in research that focuses on operating concepts in pilot sites or laboratories. In terms of conceptual literature one focus is the implementation of new system concepts, e.g. control capabilities (Lasseter et al. 2002). Conceptually, a microgrid can be seen as an "integration platform for supply-side, storage units and demand resources, located in a local distribution grid", i.e. it is located at the low voltage level and focuses on local supply (Schwaegerl and Tao 2014a). Furthermore, the two-stage character of microgrids is vital to the concept, i.e. it must be capable to operate in both stages, grid-connected and islanded which is still a challenge. In terms of pilot sites, Kariniotakis et al. (2014) give an overview about various sites in Europe from a technical perspective. Soshinskaya et al. (2014) analyze projects around the world on a technical as well as regulatory perspective. Therefore, we conclude that the technical concept of microgrids is feasible even if there are still some challenges such as the operation in the dual mode or network constraints (Tao et al. 2011; Parhizi et al. 2015).

With regards to economic literature, much work focuses on the justification of the microgrid concept in different markets. Khalilpour and Vasallo (2015) point the trend towards "living off-grid" out which is amplified by decreasing cost for batteries and renewable energy sources. Thus, this could lead to a death spiral for utilites (transmission and distribution industries). They analyse the feasibility of leaving the grid from an economic viewpoint and conclude that it is best to remain grid connected but minimize the interaction with the main grid e.g. by installing a photovoltaic–battery system. Schwaegerl and Tao (2014a) evaluate and quantify technical, economic, environmental and social benefits of microgrids in different energy markets in Europe. Lo Prete et al. (2012) also assess and quantify different scenarios of microgrid integration in the Northwestern European energy market. They mainly quantify sustainability and reliability of microgrids in the market by incorporating multiple criteria. Matteson (2014) extends this approach by adding "experience curves, technological progress models, life cycle assessments, and thermodynamics within a dynamic multi-criteria optimization framework". In contrast to these authors, we focus on decision making of the cooperative internally and do not look at a market level but refer to the aforementioned analyses when identifying potential decision criteria.

In terms of management science, one major focus of research is internal coordination and pricing of microgrids (Chenrui and Ghosh 2011; Dimeas et al. 2014; Maity and Rao 2010). However, this is not the scope of our work as we concentrate on decision making. In this context, for example Morris (2012) summarizes the arising cost of developing and operating a microgrid and presents the results in a framework. Furthermore, the author evaluates the framework in a case study. This provides an overview but no explicit decision support. Liang and Zhuang (2014) focus on utilization of existing methods in stochastic modeling and optimization to ensure "efficient, reliable and economic planning, operation and control of microgrids". They give an overview on existing methods that can be applied for microgrids and also point out that the main challenge in optimizing microgrids is the computational complexity because of the number of stochastic elements, e.g. weather. Beshr (2013) analyzes the question of extending an autonomous microgrid with photovoltaic or wind from a technical perspective but he solely focuses on operation quality (avoiding interruptions) and does not include other criteria such as investment expenses. He et al. (2013) also concentrate on the composition of a microgrid, as they aim at identifying the optimal size of the microgrid by considering the energy price equilibrium. The results indicate that the optimal size based on the levelized cost of electricity changes depending on the starting point of the analysis (seasonality of generation). Both analyses focus on specific criteria but we did not find multi-criteria decision support for microgrids when it comes to investment decisions.

A microgrid can be organized in various ways, by a distribution system operator, by energy utilities or by a prosumer consortium which highly influences the decision setting and goals (Schwaegerl and Tao 2014b). In the latter form, consumers benefit from the microgrid directly. In this case "consumers own and operate multiple micro source units as an aggregated prosumer entity" (Schwaegerl and Tao 2014a). The prosumer consortium is very likely to be organized as an energy cooperative.

The International Co-operative Alliance (ICA) has framed seven core principles that are the basis for cooperatives around the world. According to ICA "a co-operative is an autonomous association of persons united voluntarily to meet their common economic, social, and cultural needs and aspirations through a jointly-owned and democratically-controlled enterprise" (ICA 1995). The core principles of cooperatives are voluntary and open membership; democracy; economic participation of members; autonomy and independence; education, training and information; co-operation among co-operatives; and concern for community. Therefore cooperatives have specific characteristics. Most cooperatives are cooperatively owned which means that there are no external investors (ICA 2007). The general concept of cooperatives developed by ICA serves as one basis for deriving potential values and goals of an energy cooperative. However, energy cooperatives are a special form of cooperatives and therefore their inherent goals might differ from the goals stated by ICA, therefore we also analyze specific literature on energy cooperatives in the following. Empirical results of renewable energy cooperatives in Germany also imply that founders and members are driven by various goals, that are of "economic, ecologic, social or financial" nature or a combination of these factors (Yildiz et al. 2015). The topic of energy cooperatives becomes increasingly important but accordingly, no multi-criteria decision support has been applied so far. There exist theoretical studies on, for example, the decision making process of traditional cooperatives from the field of social psychology, socio-economics and socio-ethics (Cass et al. 2010; Park 2012).

The recent development of energy cooperatives in Europe and the US indicates that customers start to search alternatives to the traditional energy supply model where the whole value chain is controlled by utilities. This can be undermined by the fact that many cooperatives are founded in order to promote the use of renewable energies (Viardot 2013). This development is strongly related to the rise in decentralized generation of energy, mainly promoted by renewable energy generation, i.e. PV or wind power and supported by subsidies. In Germany, for example only 1% of the 635 generation energy cooperatives is engaged in conventional energy, probably influenced by the German feed-in tariff system that is advantageous for renewable energy (Yildiz et al. 2015). Another reason for acting in a group is the advantage as a group to get more flexible contracts and eventually price advantages due to a higher volume and especially a flat aggregated demand curve (Veit et al. 2013).

Microgrid operation by an energy cooperative goes beyond the pure analysis of technical optimization and technical benefits as the interest of the members of the cooperative are taken into account as well. Veit et al. (2013) suggest a central coordinator for the cooperative, which can be seen as a social planner that manages the individual demand decisions of the members of the cooperative. According to Ketter et al. (2010) such group coordinators in regional markets are called trading agents which act as self-interested "brokers" who also build a portfolio of supply and demand and aim at maximizing profit. This is not necessarily the case for energy cooperatives, as energy cooperatives also contribute to a higher adoption of renewable energy, especially via transparent communication (social marketing initiatives) (Viardot 2013). Our analysis of literature indicates that energy cooperatives are set up to follow the idea of a more sustainable energy system (Schreuner 2012). According to Alanne and Saari (2006) a sustainable energy system is characterized by "(cost-) efficiency, reliability and environmental-friendliness". Thus, we argue that an energy cooperative has various economic, ecologic, and social goals that can be measured by different criteria (Zarghami and Szidarovszky 2011).

The economic goals of an energy cooperative can roughly be categorized in providing locality benefit and selectivity benefit (Schwaegerl and Tao 2014a). Locality benefit for example includes the reduction of transport losses as the distance between generation and demand unit is short. The selectivity benefit includes "optimization of real-time dispatch decision" (Schwaegerl and Tao 2014a). It can be argued that in the case of cooperative-owned production facilities, the energy can be sold at cost of generation, which is lower than retail or even wholesale prices. Another economic advantage is lower overhead cost. Nevertheless it has to be stated that these benefits highly depend on local characteristics such as energy tariffs (Morris 2012). In the US for example, the Fox Islands Cooperative reduced energy costs by setting up own wind mills (Borst 2010).

The ecologic goals of an energy cooperative can be of different nature, the most known ones are the integration of renewable energy and thus the reduction of conventional energy consumed. "In recent years, cooperatives have been created to promote the use of renewable energy most notably in Canada, the US, UK, Denmark or Germany" (Viardot 2013). Microgrids also enable increased energy efficiency and help to reduce emissions (Parisio and Glielmo 2012). Lasseter and Paigi (2004) highlight that from the technical perspective the potential of renewable energies can just be exploited by building subunits, i.e. microgrids. However, increasing the amount of decentralized generation, i.e. PV or wind, influences the stability of the grid and thus the security of supply (Vogt et al. 2010). Due to more renewable energy sources in the microgrid, there are fluctuations in the generation, but when adding energy-storage devices to the microgrid, this can absorb fluctuations and thus lead to a cost reduction (Chenrui and Ghosh 2011).

The social goals of an energy cooperative are of a very broad nature, they reach from creating employment to "electrification of underdeveloped areas" (Schwaegerl and Tao 2014a). *Own Energy*, a community wind developer, states that for regions it is important that projects "create [...] jobs, wages, business income and local pride" (Borst 2010). However, authors agree that one major goal is security of supply as modern society critically depends on a secure supply of energy (Schreuner 2012; Schwaegerl and Tao 2014b). A sustainable energy system benefits of independency of main grid (electricity distribution) (Alanne and Saari 2006; Allard et al. 2013). There are energy cooperatives for which autonomy is the most important goal, i.e. cooperatives that are located in rural areas where it is difficult to secure energy supply. However, autonomy in the case of energy cooperatives is mainly connected to the independence from the main grid and not to the autonomy as described by the ICA principles. Besides technical security of supply, the development of energy cooperatives also aims at a more independent supply of energy, i.e. independence of the energy utility, which is an idealistic goal (Khalilpour and Vassallo 2015).

Methodology

According to Gregor and Hevner (2013), design science research in information systems "involves the construction of a wide range of socio-technical artifacts, such as decision support systems (…)". In line with this approach, our paper answers the research question by developing and evaluating an artifact, a data-driven software tool that supports an investment decision process. Hevner et al. (2004) propose an information systems research framework based on relevance and rigor. Thus, IS research applies existing knowledge on a relevant problem. The available information e.g. smart meter data has not been incorporated in the decision making of energy cooperatives so far. We evaluate our software tool by example. Therefore we set up randomly generated energy cooperatives based on real-world data and conduct analyses to different sensitivities of the decision. Our artifact is also based on existing knowledge, which is a multi-criteria decision analysis (MCDA). So, we contribute to knowledge through extending the existing MCDA methods by applying and tailoring them to the field of energy cooperatives. See Table 1 for an overview of the seven design science guidelines (Hevner et al. 2004) and how they are addressed in this paper.

In order to decide on the basis of the identified goals, an energy cooperative needs to define criteria for the goals and find a suitable hierarchy of criteria. Therefore, in the following we assign a criterion to each goal, which reflects the impact of an investment in a new power plant best. These are: Increase of profit (*economic criterion*), promotion of renewable energy (*ecologic criterion*) and independence from the main grid (*social criterion*). As it is crucial for our decision tool to ensure that we identified the right criteria we verified them by interviewing two cooperatives and one local energy utility. We chose a local utility as well as they consider managing and supporting cooperatives as a possible future business model. However, the criteria might not be exhaustive and there might be individual criteria for different cooperatives to include.

Table 1. Design Science Research Guidelines (Hevner et al. 2004) and Application in Paper		
Guideline	**Description**	**Application in Paper**
Guideline 1: Design as an Artifact	"Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation."	We develop a decision support tool as our artifact which can be applied by energy cooperatives easily (see Artifact Description section).
Guideline 2: Problem Relevance	"The objective of design-science research is to develop technology-based solutions to important and relevant business problems."	Energy cooperatives and microgrids become increasingly important and current research has not focused on decision support so far. In our research, we enable the utilization of various data sources by a software tool. The output provides a solid foundation for decision making of an energy cooperative (see Motivation section).
Guideline 3: Design Evaluation	"The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods."	We test the decision support artifact with real world data. We furthermore construct randomly generated examples from our data set to get a broader idea of the utility our artifact provides. In addition, the enlargement of our sample allows for a sensitivity analysis (see Evaluation section).
Guideline 4: Research Contri-butions	"Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies."	Decision support for microgrids and especially energy cooperatives is a fairly new topic. MCDA enable the involvement of multiple criteria in decisions. The paper explains and evaluates a possible application of MCDA to microgrids and energy cooperatives (see Motivation and Artifact Description).
Guideline 5: Research Rigor	"Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact."	The decision support tool is presented in an under-standable way to enable application. The tool is based on past research in the field of MAUT that has been developed by Keeney and Raiffa (1976). The applicability and utility of MCDA was often illustrated for energy issues (Hahn 2014; Klein and Whalley 2015; Mavrotas et al. 2003; Polatidis et al. 2006). Still, the use in information systems research is still rare. By implementing MCDA in a software tool we bridge this gap and allow the MCDA method to be applied to our problem for which various kinds of data need to be processed (see Methodology).
Guideline 6: Design as a Search Process	"The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment."	We utilize the method MAUT of MCDA to develop our decision support artifact. Before selecting MAUT we defined requirements and tested those against other MCDA methods (see Methodology).
Guideline 7: Communicat ion of Research	"Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences."	We work together with cooperatives to proof our concept and aim at publishing results on conferences and research journals. The focus on simplicity and automation through a software tool underline the practical applicability of our tool.

Table 1. Design Science Research Guidelines (Hevner et al. 2004) and Application in Paper

Cooperative 1 is based in southern Germany and exists since 1923, it has 350 members. The cooperative owns and operates its grid and also renewable power plants. The cooperative currently serves 60% of energy supplied by renewable sources and aims to increase this fraction (*ecologic criterion*). They explained that they aim at becoming independent from the main grid in the long term (*social criterion*). Currently this is not possible due to regulation in the German electricity market.

Cooperative 2 is based in the U.S. and located on an island, it was founded in 1974. The main reason was autonomy from the main grid (*social criterion*). In recent years, they invested in a wind project and now 100% of the electricity is generated by wind power (*ecologic criterion*). However, they are still connected to the main grid. The reason for setting up its own wind farm was, that the electricity bill could be lowered with this project (*economic criterion*).

The energy utility we spoke to is located in the south-east of Germany. It supplies the region of Nuremberg and the surrounding areas. The utility believes that decentral solutions become more important in the future. Especially for the integration of renewable energies, decentral solutions need to be designed according to the interview (*ecologic criterion*). Thus, the energy generated should be used in the same region to generate advantages also when it comes to tariff design (*economic criterion)*.

To conclude, the three criteria we identified for energy cooperatives are visible in existing energy cooperatives as well. Two cooperatives and one regional utility are a very small sample, therefore this is subject to future research.

However, the three criteria can be of different importance for each cooperative. Thus there exists no average or "typical" cooperative (Schwaegerl and Tao 2014a). Therefore, the decision method which evaluates the benefits coming from a new supply unit should allow a weighting of goals for different types of cooperatives. The internal and external factors that determine the individual weights of a cooperative can be characterized by three main points: Geographic location, time and sensitivities (market) (Schwaegerl and Tao 2014a). One possible type of cooperative can be an energy cooperative that focuses on renewable energy integration; security of supply and economic value is less important for this type. However there also exist energy cooperatives which focus on security of supply as a main goal due to their geographic location (e.g. island, rural area).

The described goals and thus decision criteria of the cooperative can be of conflicting nature, therefore the decision of including or not including a new supply unit in the energy cooperative is extremely complex as manifold criteria need to be incorporated. For such multi-criteria decisions with conflicting goals the concept of MCDA is an expedient approach (Polatidis et al. 2006; Zarghami and Szidarovszky 2011). MCDA was introduced in the mid-1960's since when it has been applied in Management Science many times since then and still is a field which is further developed (Dyer et al. 1992; Ehtamo and Hämäläinen 2001; Wallenius et al. 2008). Figueira (2005) gives an extensive state of the art survey of MCDA methods. Especially for energy and sustainability issues methods of MCDA are expedient (Hahn 2014; Klein and Whalley 2015; Mavrotas et al. 2003; Polatidis et al. 2006). In the IS community the method has also been applied, for example in terms of value focused process engineering (Churliov et al. 2006). Multi-criteria assessments were also already applied to microgrids but from a market perspective (Lo Prete et al. 2012; Matteson 2014).

The approaches of MCDA can be categorized in utility-based methods, where every decision alternative gets a single score and outranking methods which base on pairwise comparison of decision alternatives (Polatidis et al. 2006). The methods of MCDA thereby follow a general procedure. Following the selection of the appropriate MCDA method comes the collection of relevant criteria and data for the decision. Finally, decision criteria are calculated and results are aggregated. Especially the last step differs in each MCDA method. Based on the aggregated value the method recommends the alternative that fulfils the decision criteria best (Guitouni and Martel 1998). No MCDA method fulfils all needs, i.e. there is no perfect method for all problems but some methods fit better to our problem than others. In the decision making process of the energy cooperative a ranking of the alternatives is appropriate in order to decide about the investment in a new supply unit. Furthermore, the cooperative requires an easy to implement decision despite incorporating various criteria.

For our research question, we identified the MCDA method MAUT (multi attribute utility theory), which is part of the utility-based method family, as an appropriate method. MAUT was introduced by Keeney and Raiffa (1976), it allows to take into account the individual utility of the decision maker (DM). The method suggests the definition of a utility function for each decision criterion, which is constructed such that the utility generated by the criterion is between the interval of 0 and 1. The utility reflects the preferences of the DM. After the calculation of the respective utility values for the criteria, they are weighted and aggregated for each alternative. Then the alternatives can be compared, the one with the highest utility is recommended. There are reasons for favoring MAUT. First, we aim for a simple approach and results, which are easy to understand. Furthermore we are interested in reflecting compensatory effects of the criteria as they can run in opposite directions (Montis et al. 2000) and we perceive the measure of utility as the basis of a decision very useful. Hahn (2014) uses MAUT in order to rank decision alternatives in sustainable projects at a university. In the aforementioned case, the DMs were surprised by the result of MAUT, which leads to the assumption that the intuition of the decision maker was incorrect, probably due to the complexity of the decision. This underlines the helpfulness of MAUT as a decision support method.

We modify the approach of MAUT for our decision artifact with regards to the aggregation of the different utility values over time. According to Hajkowicz (2006), we construct an index, which can be used for comparing decision alternatives, using various input data over a period of time and deciding for one alternative. In contrast to Hajkowicz (2006), our index is based on different aggregated utility values in different periods of time. The advantages of an index are for example that a multitude of different indicators are integrated and aggregated to one decision variable.

By applying this MAUT-based approach, we implicitly assume mutual preference independence (Keeney and Raiffa 1976). This means that the DM does not change the chosen utility function of one criterion according to the actual utility of another criterion. Although preference independence does rarely exist in reality, this assumption is vital for our decision artifact in order to make MAUT applicable.

Artifact Description

Our artifact is suitable for the following setting: It is applicable for those cooperatives which do not have any other generation capacity besides renewable energies, as this is one of the main goals of an energy cooperative (Schwaegerl and Tao 2014a). Furthermore, due to reasons of simplicity we model an energy cooperative that does not feature storage devices and means of flexible generation (e.g. biogas). In our setting, the microgrid is always connected to the main grid. We assume that the cooperative does not exceed a critical size, therefore it is a price taker. Neither will the main grid be unable to supply the cooperative or take their overcapacity nor will the external market prices be affected. Each household is equipped with a smart meter. The concept of the energy cooperative is to maximize average common welfare among the members of the cooperative. According to ICA (1995) a cooperative is an independent organization which focuses on cooperation among members. We therefore conclude that internal demand is served first, as a basic economic advantage of a cooperative is the ownership of the production facility and therefore the pricing of electricity at cost of generation (Schwaegerl and Tao 2014a). Most likely, the cost of generation and the avoidance of grid usage charges will never fall short to wholesale or retail prices. A new supply unit is characterized by its individual supply profile.

For applying MCDA, the role of the DM needs to be defined in order to set assumptions and model preferences appropriately. In our setting, the cooperative itself acts as the DM. Therefore, the cooperative tries to fulfil its major goal: Maximizing the overall utility of the cooperative. Individual interests of members might lead to different decisions, but with regards to the cooperative setting the maximization of overall utility is realistic (ICA 1995). Thereby, the DM can choose between two decision alternatives $a0$ and $a1$, i.e. not to invest or to invest in a renewable energy source (e.g. a photovoltaic plant).

Concept of Net Supply

For calculating the value of a new supply unit to the cooperative, the difference between supply and demand, measured in kWh over a given period needs to be taken into account. In order to model this difference, we introduce the concept of net supply. The measure net supply is a characteristic value for a cooperative and heavily influences the benefits that can be generated. Therefore we base all criteria of our decision model on this measure. However, according to Keeney and Raiffa (1993), there are various conditions that criteria need to fulfil, they should be complete, operational, decomposable, non-redundant and minimum size. Non-redundancy addresses the need for independency of the criteria. As in our tool all criteria are derived from the net supply this could harm the prerequisite of non-redundancy. Therefore we test for the correlation of the criteria with real-world data (see Evaluation) and as they are not correlated, we find that the prerequisite of non-redundancy is fulfilled.

For determining the net supply, we suggest to use past supply and demand data as an approximation for future supply and demand. This was used before e.g. for a decision support tool concerning the "feasibility of leaving the grid" (Khalilpour and Vassallo 2015). Furthermore, it is easy applicable as no further transformation on the data is required.

Formally, we define the net supply as follows: f is the number of all elements in the cooperative, i.e. all supply and demand units. In the case of a cooperative consisting of two households and a solar power plant, f equals three. As it is important to consider demand and supply during different time periods, we model net supply in every period t. Each unit of the cooperative has its own net supply S_t^f, the sum of all S_t^f of the cooperative equals S_t (1). A demand unit is therefore characterized by $S_t^f \leq 0$, whereas an energy supplier is characterized by $S_t^f \geq 0$. It is important to note that prosumers exist as well, e.g. a private household with a solar panel on the rooftop. Every prosumer serves own demand first which means that every prosumer has an own net supply S_t^f as an output variable which can be positive or negative for different t. We write the equation as follows:

$$S_t = \sum_{f=1}^{F} S_t^f \quad \text{with } t = 0,1,\dots,T \tag{1}$$

The shorter the time periods t, the more precise is the load profile. This choice mainly depends on the availability of data. We define $\vec{S}$ to be a vector containing all S_t.

Decision Process

The software tool supports a decision process that is described in Figure 2. The process illustrates the determination of different input parameters which are required for defining the thresholds of the utility functions and for calculating the utility of the decision criteria. The goal is to build a decision index out of the utility values in order to enable a simple decision based on the comparison of these utility indices (Hajkowicz 2006). The decision process is embedded in an information system and therefore integrates available data and preferences of the DM.

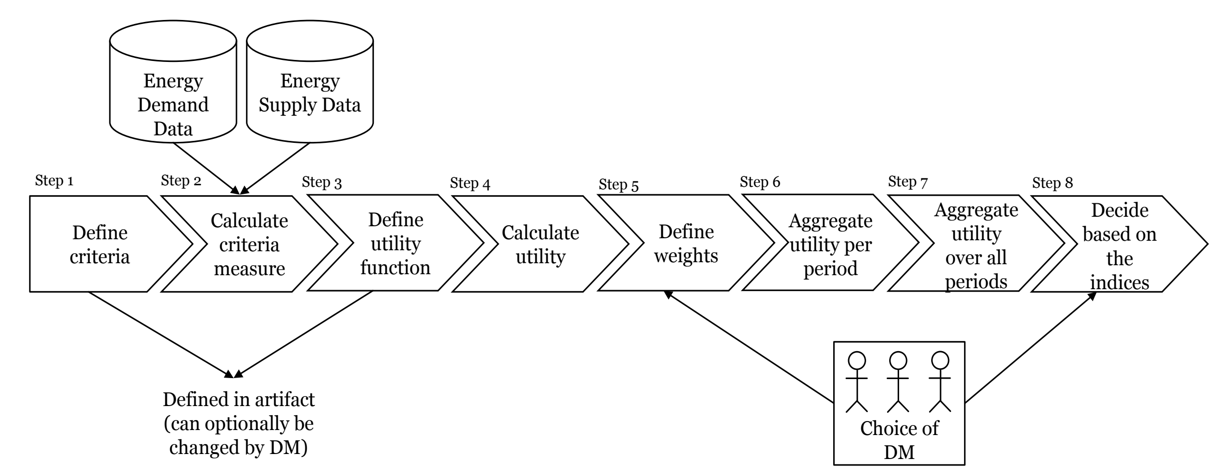

Figure 2. Investment Decision Artifact for Energy Cooperatives

The DM, i.e. the cooperative follows every step of the process in Figure 2. In our artifact we suggest decision criteria (Step 1) and corresponding utility functions (Step 3) depending on S_t. The proposed criteria cover the three generic goals of cooperatives, i.e. economic, ecologic and social goals. The degree of adaptation of the criteria and especially the utility functions is subject to the DM. If there are further cooperative-specific goals an extension of criteria is possible. When seeing the indices as an objective support for making a decision, it is recommendable to use our proposed criteria and utility functions. The utility functions are suitable for a risk-neutral DM and follow an objective approach by considering monotonicity (Neumann and Morgenstern 2007). Step 2 contains the calculation of the criteria themselves, as they are the input parameters for the utility functions. Based on historical supply and demand data the utility for every alternative and every criterion is calculated (Step 4). This step is exercised for every time period t. In Step 5, the DM assigns weights to the three criteria, which are necessary for the aggregation of the utility values. Finally, the resulting indices for every time period (Step 6) need to be aggregated over all time periods (Step 7). The result is an index for every alternative, reflecting the DM's preferences through the weights. The indices can be used for providing a ranking of the two alternatives and thus a decision for the one with the top position in the ranking (Step 8).

Define and Calculate Criteria (Steps 1 and 2)

We identify three goals of energy cooperatives. Based on them, we define one measurable criterion for each goal. The criteria we define are directly affected by the investment decision, so they all reflect the changes in the net supply through a new power plant. There might be further criteria which can be directly assigned to one of the three goals of cooperatives, e.g. due to individual characteristics of energy cooperatives. So our choice of criteria is not exhaustive. Still, we use the convention economic, ecologic and social criterion for our defined criteria to express their assignment to one of the three goals.

The economic benefit can be measured by the following *economic criterion*: Cost of producing and buying energy as well as the revenue from selling energy to the wholesale market, i.e. profit. Thus, we choose profit maximization as the relevant economic decision criterion of the energy cooperative. The cooperative tries to materialize an economic benefit (Borst 2010; Morris 2012; Schwaegerl and Tao 2014a). There are two possible cases: The first one is the case when $S_t > 0$, here the energy cooperative produces more than it demands, the superfluous energy is sold to the main grid. The second case, i.e. $S_t < 0$ arises when there is more demand in the cooperative than supply, such that the cooperative needs to buy energy from the wholesale market. Consequently, the cooperative's benefits depend on the current market prices on the respective external market but also on the cost of the new and existing supply units (investment expenses, fixed cost, variable cost) This approach also allows for negative prices, e.g. if the cooperative sells surplus energy to the wholesale market and contributes to a current supply peak in the main grid (van der Veen, Reinier A.C. et al. 2012). We suggest to measure the criterion by the product of the estimate of S_t, which is either positive or negative, and the price for one unit of energy p_t, which also can also be positive or negative. $\vec{p}$ is the vector of all prices for every time period. k_t is the average overall cost of all supply units in the cooperative k_t^f over their lifetime in period t. $\vec{k}$ is the vector of all average cost for every time period observed. Formally, the input for the economic criterion is written as it follows in (2).

$$(S_t \cdot p_t) - k_t \; with \; t = 0,1,\ldots,T \;\;,\;\; p_t \in \mathbb{R} \qquad (2)$$

The criterion for the ecologic benefit can be described by the enforcement of renewable energy, which is one major motivation for setting up an energy cooperative (Viardot 2013). We already included this indirectly by addressing cooperatives that only consist of renewable generation capacity. However, as mentioned before there are periods with energy deficit in the cooperative, causing the purchase of electricity from the wholesale market. Yet, the energy available in the wholesale market is not solely generated by renewable sources (Schaber et al. 2012), which violates the cooperative's ecologic objective. The mix of generation in the main grid differs in every period of time. We measure the aforementioned violation by the amount of electricity bought and consumed from conventional sources. To derive this, the measure S_t is multiplied with c_t, which is the portion of conventional generation in the electricity mix of the main grid for every period t. $\vec{c}$ is a vector of the portion of conventional generation for every time period. This measure only makes sense when more demand than supply occurs in the cooperative. In times of less demand than supply the cooperative fully serves its demand from own generation and does not consume electricity from the main grid. In times of less supply than demand, the cooperative consumes electricity from the main grid, which might not be exclusively generated by renewable energy sources. Therefore we introduce the indicator function $1_{S_t<0}$. By doing this, the value of the *ecologic criterion* is set to zero as soon as S_t is negative, i.e. as soon as the cooperatives demand is fulfilled completely by own supply, regardless of the value of c_t. When introducing utility functions in the following we need the indicator function because in case the ecologic criterion is zero, the utility function returns the highest possible utility of 1 (see equation (9)).

$$\mathrm{S_t} \cdot \mathrm{c_t} \cdot 1_{\mathrm{S_t}<0} \quad with\ t = 0,1, \dots, T, \mathrm{c_t} \in [0, 1] \tag{3}$$

We are aware that the way we define the ecologic criterion might not suit all cooperatives, e.g. there might be cooperatives that mainly focus on producing as much renewable energy as possible regardless of their own consumption. Then there is no need for an indicator function and also not for multiplying the net supply with c_t. In that case the utility function has different parameters but it still is monotonically increasing. However, the threshold differs and is not derived from the net supply anymore.

We define the *social criterion* of the energy cooperative as autonomy from the main grid which can be described as independent energy supply (Khalilpour and Vassallo 2015; Schreuner 2012). Although the energy cooperative is always in grid connected mode, it nevertheless tries to be independent from the main grid as often as possible (Allard et al. 2013). A high degree of autonomy is given if the net supply is zero in most periods of time. Having supply and demand close to each other reduces the dependency on the main grid. This also implies the avoidance of charges for grid usage. So, a measure is required, which reflects how close the net supply can come to zero. For this, we introduce the following criterion: Variation around zero $|S_t|$. In accordance with the other criteria, it is calculated for each time period t.

$$|S_t| \tag{4}$$

Define and Calculate Utility Functions (Steps 3 and 4)

The value for the cooperative regarding each criterion can be expressed by the utility that is delivered to the cooperative. For each criterion, we suggest a suitable utility function that later forms the basis of the decision index. It is common to use linear utility functions for MAUT-applications on environmental and energy issues (Klein and Whalley 2015). We further support the application of linear functions by assuming a risk-neutral DM. Figure 3 illustrates the proposed utility functions.

The utility of the *economic criterion* is maximal, i.e. 1, when the maximum observed profit is generated from operating supply units and buying or selling energy from/to the wholesale market. Therefore we describe the utility function of the economic criterion by a monotonously increasing linear function. There are thresholds q and d that have to be defined, q is the maximum profit for which the utility is 1, i.e. the maximum utility according to MAUT whereas d is the loss which marks the lower bound with a utility of 0, i.e. the minimum utility according to MAUT. We derive the thresholds by comparing the maximum profit achieved over all periods of time by the two different alternatives. The same applies to the losses. From (5) and (6) we see that the thresholds are functions of the wholesale price and generation cost. $\vec{p}$ is multiplied component-by-component ($\otimes$) with the time series of net supply $\vec{S}$ for each alternative $a0$ and $a1$, i.e. $\vec{S}_{a0}$ and $\vec{S}_{a1}$. $\vec{k}_{a0}$ and $\vec{k}_{a1}$ are the respective vectors of generation cost of the alternatives $a0$ and $a1$ where all entries have the same value and reflect the average overall cost of all supply units in the cooperative over their lifetime. By setting the thresholds d and q like this, we reflect characteristics of both alternatives in the utility function. The comparability of the alternatives is therefore better as with a utility function with thresholds that are set independently of the underlying data.

$$d(\vec{p}, \vec{S}, \vec{k}) = \min\left(\min\left((\vec{p} \otimes \vec{S}_{a0}) - \vec{k}_{a0}\right), \min\left((\vec{p} \otimes \vec{S}_{a1}) - \vec{k}_{a1}\right)\right) \tag{5}$$

$$q(\vec{p}, \vec{S}, \vec{k}) = \max\left(\max\left((\vec{p} \otimes \vec{S}_{a0}) - \vec{k}_{a0}\right), \max\left((\vec{p} \otimes \vec{S}_{a1}) - \vec{k}_{a1}\right)\right) \tag{6}$$

For the suggested utility function we set up a system of linear equations, solving for the slope and the intercept we derive the closed-form expression.

$$u_{economic}(S_t \cdot p_t) = \frac{(S_t \cdot p_t) - d}{q - d}, \ d \leq S_t \cdot p_t \leq q \tag{7}$$

We suggest to measure the *ecologic criterion* by the portion of conventional energy bought in times when there is a surplus of demand in the cooperative. This implies that our exemplary cooperative gains utility from the consumption of electricity from renewable energy. One can also imagine a cooperative, which gains utility from producing electricity from renewable energy, still in our artifact we focus on consumption. When there is no conventional electricity e.g. it is just internal (renewable) sources that serves the demand, the utility is 1. The less "ecofriendly" the energy is produced, the less utility results for the energy cooperative. The utility can therefore be described as a monotonously increasing linear function (9). The threshold d is the maximum possible amount of electricity from fossil sources, caused by one of the two alternatives at any period of time t. $\vec{c}$ is a vector with the components being the relative portion of conventionally generated energy in the main grid. The multiplication is again component-by-component.

$$d(\vec{c},\vec{S}) = \min\left(\min\left((\vec{c} \otimes \vec{S}_{a0}) \cdot 1_{S_t<0}\right), \min\left((\vec{c} \otimes \vec{S}_{a1}) \cdot 1_{S_t<0}\right)\right) \quad (8)$$

We derive the closed-form expression in (9) analogously to the utility function of the economic criterion (7).

$$u_{ecologic}(S_t \cdot c_t) = \begin{cases} 1 - \frac{S_t \cdot c_t \cdot 1_{S_t<0}}{d}, & d \leq S_t \cdot c_t \cdot 1_{S_t<0} < 0 \\ 1, & S_t \cdot c_t \cdot 1_{S_t<0} = 0 \end{cases} \quad (9)$$

The utility that can be created by the social criterion reflects the level of autonomy of the cooperative, which is maximal when $|S_t|$ is 0, i.e. when it is completely autonomous. The minimum utility, i.e. 0 is reached at a maximum deviation from zero. Therefore, the utility is measured by a linear function that is monotonically decreasing. The lower $|S_t|$, the better for the social criterion. If the threshold d is reached, which reflects the maximum possible net supply from one of the two alternatives, the utility becomes 0 (11). We have to consider the absolute values of the net supply when calculating it, as we want to measure the distance from zero, no matter if it is positive or negative.

$$d(\vec{S}) = \max\left(\max\left(|\vec{S}_{a0}|\right), \max\left(|\vec{S}_{a1}|\right)\right) \quad (10)$$

$$u_{social}(|S_t|) = 1 - \frac{|S_t|}{d}, \; 0 \leq |S_t| \leq d \quad (11)$$

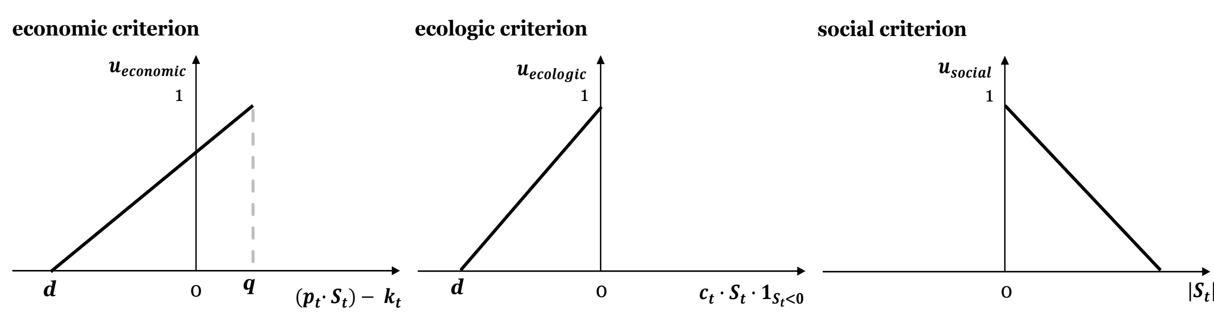

Figure 3. Utility Functions of Economic, Ecologic and Social Criterion

With the thresholds and the input vectors for the utility functions, the utility vectors $\vec{u}$ of every single criterion is calculated. The vectors have T entries, for every period t one. Formally we express this as it follows:

$$u_{economic}(\vec{p} \otimes \vec{S}) = \vec{u}_{economic} \quad (12)$$

$$u_{ecologic}\left((\vec{c} \otimes \vec{S}) \cdot 1_{S<0}\right) = \vec{u}_{ecologic} \quad (13)$$

$$u_{social}(|\vec{S}|) = \vec{u}_{social} \quad (14)$$

For every alternative, these vectors exist, indicating the utility delivered by choosing one of the two alternatives.

Define Weights (Step 5)

The goals among the DM might differ, i.e. the criteria might not have the same importance. Depending on the preference of the DM, i.e. the cooperative, the weights can be chosen individually in order to account more or less for some criteria. For example, a cooperative with high interest in security of supply and profit generation can set the weight for the ecologic criterion to zero and therefore the vector $\vec{u}_{ecologic}$ is not of any importance for the decision of this cooperative. Formally, the weights are defined in (15).

$$w_{economic} + w_{ecologic} + w_{social} = 1 \quad \text{with} \; w_{economic}, w_{ecologic}, w_{social} \in [0,1] \tag{15}$$

Within our decision artifact there is no recommendation on how to set the weights, as this is a subjective decision of the respective DM (Keeney and Raiffa 1976). We are not able to derive common properties for the weights, as it is the case for the utility functions where a monotonic increase is easy to assume, according to common theorems (e.g. Von–Neumann-Morgenstern 2007). A survey or the empirical determination of the weights does not make sense in case of this artifact, as this would tailor it to the preferences of the examined cooperatives. As our goal is to provide energy cooperatives with an easy-to-use artifact for decision-making, we cannot provide generic weights, as they would not reflect their subjective preference. Therefore it is up to the DM to choose the weights according to subjective importance.

Aggregation and Decision Making (Steps 6, 7 and 8)

In order to make a simple final decision an understandable aggregation method is required. The first step is the aggregation of the vectors $\vec{u}_{economic}$,$\vec{u}_{ecologic}$ and $\vec{u}_{social}$ over all components, which represent the utility values for each period t. They are aggregated additively by multiplying every vector with its related weight and building the sum of all vectors:

$$w_{economic} \cdot \vec{u}_{economic} + w_{ecologic} \cdot \vec{u}_{ecologic} + w_{social} \cdot \vec{u}_{social} = \vec{u}_{total} \tag{16}$$

Each component of the resulting vector $\vec{u}_{total}$ represents the aggregated utility from one alterative in a certain period of time t. This can be used for the determination of a dominant alternative i.e. if one alternative has a higher utility in each entry of the vector, compared to the other alternative. As this is rarely the case for all entries, we propose to make the decision based on the average total utility of an alternative. Furthermore we aim at decision support that is easy to interpret and to communicate by the DM. This leads to the construction of an index by averaging all entries of the utility vector $\vec{u}_{total}$. In this step we go beyond the classical MAUT-approach as we aggregate the utility values to get a single utility index over all periods, i.e. the software tool returns utility values for each period in Step 7 (according to MAUT) that need to be aggregated over all periods as well.

$$u_{total} = \frac{\sum_{total,t=0}^{T} u_{total,t}}{T} = \frac{u_{total,1} + .. + u_{total,t} + .. + u_{total,T}}{T} \tag{17}$$

For every alternative there is one such index. They can be compared and the decision can be made based on the highest index, as this indicates the highest utility on average (Step 8) and is in line with the general concept of MAUT which requires the utility to lie in a closed interval between zero and one (Keeney and Raiffa 1976).

Evaluation

We evaluate our decision artifact by applying it to 1,000 fictional energy cooperatives constructing those, we use real-world data. For the application of our software tool, we use further data from various sources. The examined period for all data sets is from June 2011 until September 2014. The smart meter profiles and generation profiles were collected for every 15 minutes within the mentioned period.

- 20 smart meter demand profiles from Germany
- Electricity generation profile from a wind turbine (installed capacity: 1 MW) from Baden-Wuerttemberg, Germany
- Electricity generation profile from a photovoltaic plant (installed capacity: 1 MW) from Baden-Wuerttemberg, Germany
- Electricity spot prices from the EPEX for the market area Germany

- Feed-in information regarding renewable and conventional electricity generation from the Transmission System Operator for Baden-Wuerttemberg, Germany
- Cost information on photovoltaic plants and wind turbines, including fixed cost, variable cost and depreciation from Kost et al. (2013)

In Figure 4 we illustrate the generation profiles of the photovoltaic plant and the wind turbine during October 1, 2011. From the joint generation profile we can recognize the complexity of the decision, as the profiles do not give any hint about the contribution of the additional generation unit to the three goals of a cooperative. In order to ensure this, incorporating the various available data sources for the decision is vital. Furthermore, we observe the variability of the profiles over time, so it is reasonable for a decision method to reflect this variability.

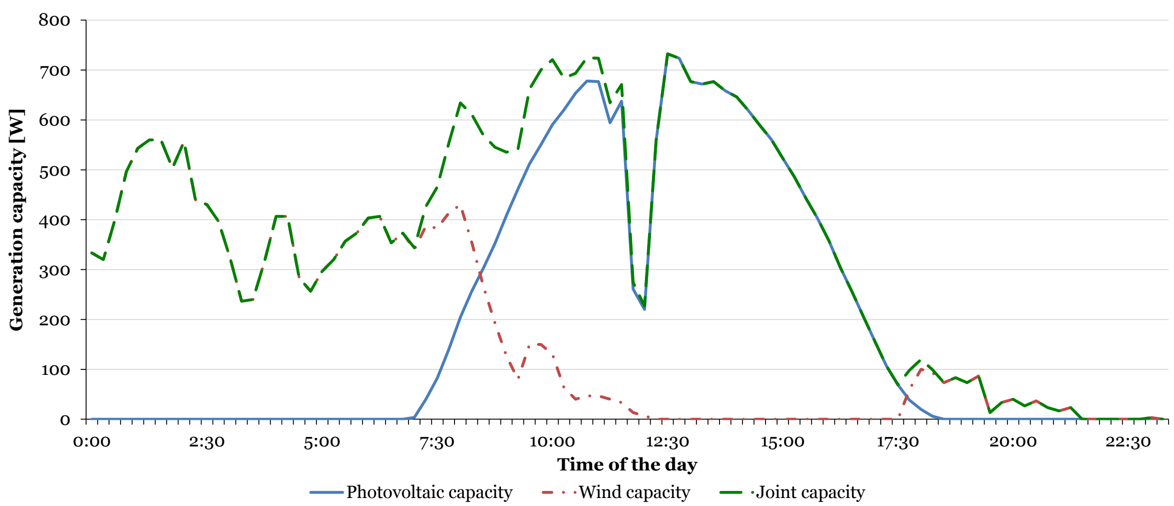

Figure 4. Generation Profiles of Photovoltaic Plant and Wind Turbine for October 1, 2011

According to Step 2 of the process, we need to calculate the three criteria. First, we compute the *economic criterion* by calculating the revenues and the cost for every 15 minutes. The calculation of the *ecologic criterion* requires information about the portion of renewable energy in the main grid. We rely on data from the transmission grid for the region of Baden-Wuerttemberg, as our generation data comes from there we assume the cooperatives to be located there as well. From the total amount of electricity in the grid and the feed-in information of renewables in this area, we can calculate the fraction of renewables for every 15 minutes interval. The calculation of the *social criterion* does not require any further data but the absolute values of the net supply of both alternatives.

We compute the utility of every alternative in every 15 minutes for all of the 1,000 cooperatives. For the evaluation, we do this for 300 different weight combinations, in order to account for a variety of preferences. For constructing the weights, we apply the following procedure: We start for one criterion with a weight of 0 and increase it in steps of 0.01 until 1, while reducing the other two criteria's weights equally. This is done for every criterion. All weight combinations in Figures 5,6 and 7 are derived this way. Finally, we aggregate the utility values for every 15 minutes to one single index. Over all weight combinations and all alternatives, the highest utility value observed is 0.9991, the lowest is 0.0973. The mean of the utility is 0.5892 with a standard deviation of 0.1776. The skewness is -0.2085, which indicates a low deviation from a symmetric distribution. The excess kurtosis is also close to zero.

We define a naïve DM as a DM that either always conducts or always rejects the investment in the photovoltaic plant. In order to evaluate the artifact, we compare the utility generated by applying our software tool to naïve cooperatives that do not apply the tool. In Figure 5 we see the maximum utility improvement compared to a DM who always rejects, observed for the weight combinations mentioned above. The highest improvement of 26.8% is observed for a cooperative with a purely social objective.

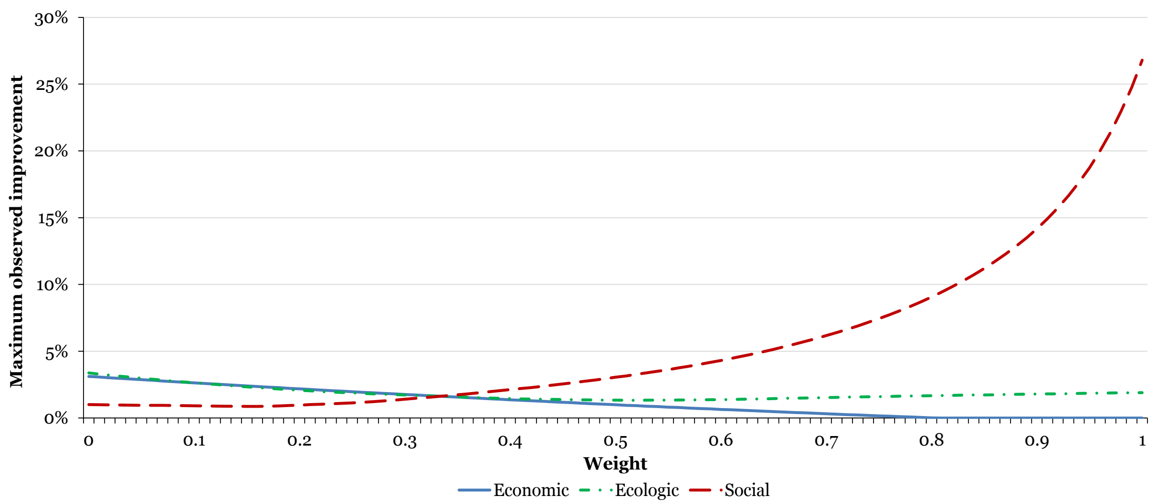

Figure 5. Maximum Utility Improvement Compared to a Naïve DM (Reject Investment)

Compared to a DM always conducting the investment in the photovoltaic plant, the maximum utility improvement is lower. The cooperative, which would invest with a solely social objective, would suffer most from naïvely conducting the investment, i.e. the utility improvement from considering social criteria is 6.75% (Figure 6). We further see that a cooperative with weights below 0.31 on the ecologic criterion also faces high losses of utility when naïvely conducting the investment.

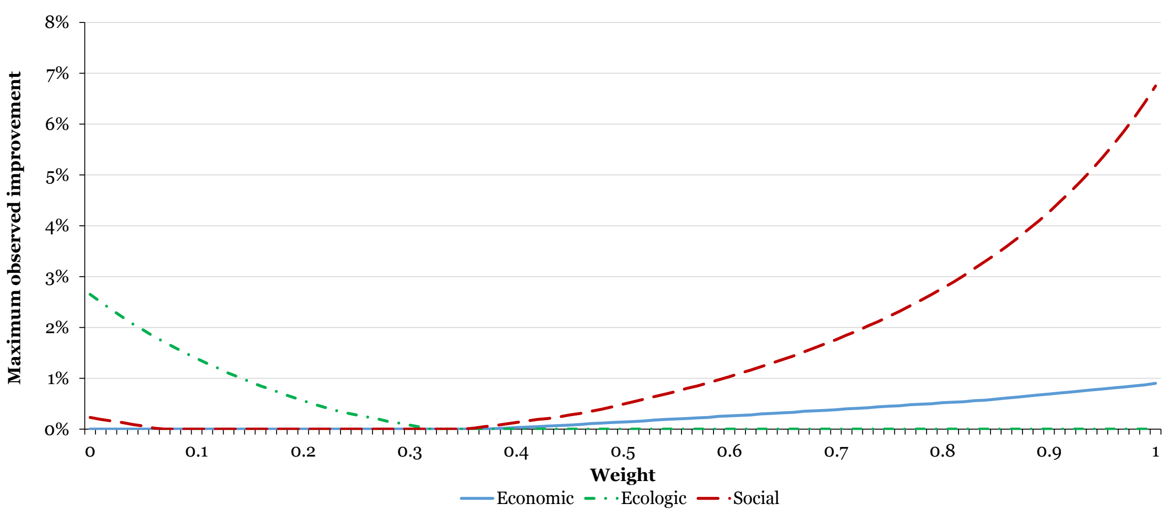

Figure 6. Maximum Utility Improvement Compared to a Naïve DM (Conduct Investment)

We want to cover three independent objectives of a cooperative, so correlation among the criteria is undesirable. As all criteria are based on S_t, we test for correlation in order to make a statement about the dependencies among the criteria. We use the Bravais-Pearson correlation coefficient to depict the linear correlation between the three criteria based on the results from the evaluation. The results indicate that the criteria are not highly correlated, i.e. the economic and the ecologic criterion show a correlation of 0.11, the economic and social criterion are slightly negatively correlated (-0.07) and the ecologic and social criterion have a correlation of 0.13. Thus it can be argued that the transformation of S_t for every criterion heavily influences the value of the criterion. We cannot exclude the fact of non-linear correlation among the criteria. Exhaustive testing is not possible and total independence will never occur in reality. We interpret the results from the correlation analysis as a good indicator for the robustness of our model.

Sensitivity Analysis

We examine the sensitivity of the investment decision to different weights of the criteria. For doing this, we conduct the same weight construction procedure as in our evaluation on each of the 1,000 cooperatives: We start for one criterion with a weight of 0 and increase it in steps of 0.01 until 1, while reducing the other two criteria's weights equally. This is done for each of the three criteria (see Figure 7).

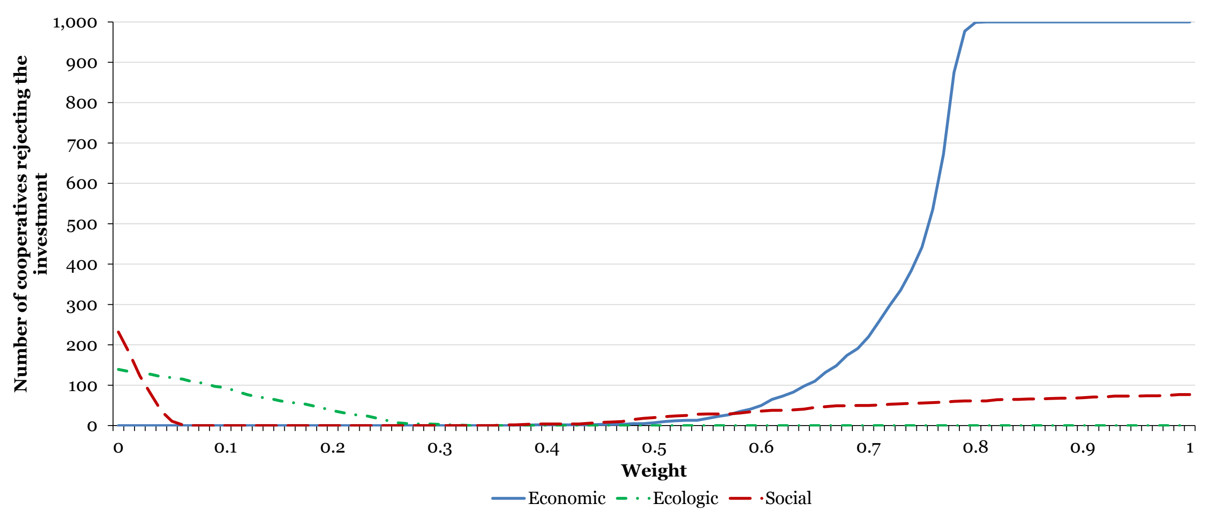

Figure 7. Sensitivity of Investment Decision to Different Weight Combinations

In Figure 7 we see how many of the 1,000 cooperatives reject the investment decision for a certain set of weights. The blue (solid) line represents the weights we derive from conducting the weight-combination procedure mentioned above on the economic criterion. For a weight from 0 to 0.47 on the economic criterion, all cooperatives are investing. This is due to the ecologic and social criterion which compensate the lower utility from the economic criterion for *a1*. For a weight of 0.48 to 0.8, some cooperatives reject the investment decision. For a weight of 0.8 and beyond on the economic criterion all cooperatives reject the investment as the increasing cost from the photovoltaic plant cannot be covered sufficiently by the revenues. The opposite is true for the ecologic criterion. For a weight of 0.31 and beyond every cooperative does invest in the photovoltaic plant. This is mainly because of the higher independence from the main grid due to the additional generation capacity. For a weight of zero on the ecologic criterion, 139 cooperatives reject the investment. These cooperatives already cover their demand very well by the existing supply capacity, such that the investment decreases independence from the grid heavier than the utility from additional revenue. The behavior of the red (dashed) line reflects the need for our decision support tool best, as the red line is not monotonous. For a weight of 0 to 0.07 on the social criterion, most cooperatives benefit from the photovoltaic plant, as it increases the utility from the ecologic criterion heavily. For a weight of 0.08 to 0.35, all cooperatives decide in favor of the investment. In this case, the social criterion can compensate for the reduced economic utility from the investment. For a weight of 0.36 and beyond on the social criterion, some cooperatives reject the decision, as the influence from the ecologic criterion is low and those cooperatives are more autonomous without the additional photovoltaic plant.

We observe a strong but comprehensible sensitivity of the decision towards the different criteria what makes our software tool useful in the case of the examined cooperatives. Furthermore, the possible loss of utility for cooperatives with strong emphasis on the independency from the main grid might be very high. So we can illustrate the benefit of our decision artifact in the case of 1,000 fictive cooperatives.

Main Results, State of Research and Future Outlook

In this paper we present a data-driven software tool for supporting investment decisions in energy cooperatives. The development of energy cooperatives is strongly related to ICT, as only by incorporating available data, new management possibilities arise. The complex decision of investing in a new supply unit is not just made on the basis of a net present value approach as know from many other investment decisions. We develop and evaluate a software tool for making a decision based on three criteria, reflecting the utility dimensions of a cooperative.

The criteria we identify are not exhaustive but one relevant aspect of each of the goals when it comes to an investment decision. There might be further criteria e.g. when a cooperative also values production and not only consumption of electricity from renewable energy sources or when it has a broader understanding of the social impact an investment decision might have. So even though our artifact cannot cover all criteria, it allows for a simple extension. This is subject to future research.

The utility functions we propose are intuitive and reflect rationality, which is suitable for the construction of an index. Our evaluation shows, that for the exemplary cooperatives, a decision based on the identified criteria and utility functions is recommendable, as the sensitivity of the decision is high to the ecologic and social criterion and the utility improvements from applying our decision software tool are remarkable. A solely economic focus might lead to a different decision and less utility for the cooperative. Nevertheless, the criteria and the utility functions might differ among cooperatives individually. It could also be possible that there exist more than three criteria. Therefore, the artifact is not exhaustive. However, our software tool allows for extension, e.g. other criteria can be included. The utility functions for each criterion reflect risk-neutrality and try to imply objectiveness. Nevertheless, it can be interesting to interview existing cooperatives and find out how their individual utility functions look like, as this might improve individual decisions.

As the focus on this paper is not the calculation of expected energy generation and demand we assumed that historical data is an adequate basis for the decision. Therefore the decision is based on the assumption that future demand and production will be similar to past demand. This does not entirely consider the fact that S_t highly depends on weather data and also on other input factors. In order to specify the results, the decision should be based on expected data, e.g. expected supply, demand, and prices. However, future work could focus on integrating appropriate estimates in the software tool.

According to design science research we tried to not just contribute to knowledge by filling the research gap, but also tested the artifact with real-world data. We constructed fictional cooperatives from the data available. Future research also aims at applying the artifact to real cooperatives and to different decisions, i.e. decisions about the investment in storage or means of flexible generation.

Our artifact enables microgrid based cooperatives to make the complex investment decision by taking available data as well as sustainability criteria into account. The evaluation indicates that the software tool automates and improves the decision process of the cooperative by increasing the utility generated by the investment decision. Therefore, our paper might be of high relevance for cooperatives in the future.

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