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Farmer's willingness to adopt private and collective biogas facilities: An agent-based modeling approach

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ABSTRACT

Manure-based biogas may make an important contribution both to the energy transition and to the reduction in greenhouse gas emissions. Despite these benefits, in Switzerland the use of manure as an energy source is still very limited. The engagement of farmers in biogas production is low and the barriers to their participation are not well known. This study investigates the behavior of Swiss farmers towards anaerobic digestion and the potential impact of changing incentives. Based on a comprehensive survey, including a choice experiment, their willingness to participate in manure-based biogas production is investigated at different levels. An Agent-Based Model (ABM) is designed and used to simulate the development of biogas facilities under different framework conditions. The agent's' properties are derived from the farmers' survey. Simulation results show that revenue for produced energy is the main driver. An increase of 0.10 CHF/kWh energy revenues (compared to 0.45 CHF/kWh today) would enable the establishment of 10 additional biogas facilities (10% more than today) enabling the manure of an additional 4285 livestock units to be mobilized for biogas, (<1% of the total available manure). The influence of the availability of additional material (co-substrate) for digestion is visible but with even less impact, while a one-time remuneration grant has barely any influence. In this context, the mobilization of the full resources potential involves substantial changes at the technological, organizational, institutional, political, economic, and socio-cultural levels.

1. Introduction

Nowadays, fossil fuels supply more than 80% of the world's primary energy (IEA, 2020), which is one of the main causes of greenhouse gas (GHG) emissions from human activities (IPCC, 2014a). With the growing concern about the impact of GHG emissions on climate change, the demand for renewable energy is increasing (IPCC, 2014b). A well-known response to this demand is the production of energy from second-generation (non-food) biomass (Havlík et al., 2011; Naik et al., 2010; Schievano et al., 2009). In this regard, anaerobic digestion of animal manure can contribute to both reducing GHG emissions occurring during its storage and producing renewable bioenergy (Chadwick et al., 2011; Gerber et al., 2013). This practice is particularly promising at places where livestock farming is largely practiced (Cantrell et al., 2008; Cuellar and Webber, 2008).

This is the case of Switzerland, where anaerobic digestion of manure was recognized to offer significant opportunities for the country towards fulfilling its Energy Strategy 2050 objectives (Burg et al., 2018a; Kirchner et al., 2012) and achieving the goal of the Paris Agreement (Burg et al., 2018b). However, even though the amount of generated manure is substantial (about 21 M t/year) (Burg et al., 2018a), farmer's investment in biogas plants remains low. Similar to other countries, only 1440 TJ biogas, which corresponds to 7% of the total estimated collected manure, is currently produced by approximately 110 agricultural biogas units (BFE, 2019b). Several reasons are often mentioned for this low stakeholder involvement. High investment costs (Fenton and Kanda, 2017) (Ökostrom Schweiz - Anspach and Bolli, 2018), lack of heat customers and corresponding revenues from heat sales (Utiger

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et al., 2019), and the expiration of subsidies (SCCER CREST, 2017) are among the possible financial constraints. Limited energy output and public disapproval make biogas development even more challenging (Fenton and Kanda, 2017). Furthermore, Swiss farms are relatively small with on average 27 livestock units (LSU) per holding (1 LSU=equivalent to one adult dairy cow) (Burg et al., 2018a). Hence, a decisive limitation to guarantee efficient and sound bioenergy generation is the availability of sufficient local resources. In this context, collective biogas production represents an important model of participation. However, implementing cooperation between animal farmers is not easy (FOAG, 2015).

A number of studies have investigated farmer's adoption of new agricultural technology, (e.g. Feder and Slade, 1984; Sunding and Zilberman, 2001). There is an agreement that the adoption depends on a range of personal, social, cultural, and economic factors, as well as on the characteristics of the innovation itself (Pannell et al., 2006). Farmer's decisions are influenced by an interplay between internal and external factors in which the farmer operates (Prokopy et al., 2008). Hence, it is important to consider both the willingness and the ability of the farmers to adopt, in our case, anaerobic digestion of manure. However, few studies have investigated the cooperation dynamics among farmers within manure-based biogas production. Using empirical farm data from case studies in different regions of Europe, Regan et al. showed that cooperation between farms generally allows farmers to access additional local resources and, therefore, improves resource use efficiency (Regan et al., 2017). As a single actor often lacks the necessary resources, expertise, and experience to develop a biogas project without assistance, cooperation between actors is essential (Karlsson et al., 2017). Also, most challenges of adopting anaerobic digester technology can be faced more efficiently in a collective effort (e.g. enhancing economic feasibility of anaerobic digesters by lowering installation and operating costs, while allowing farmers to remain focused on milk production (Liebrand and Ling, 2009)). In this context, a way to overcome obstacles to the successful use of anaerobic digesters could be to follow one of two basic cooperative approaches: (1) an existing dairy cooperative providing services related to the adoption of anaerobic digester technology to its members, or (2) a group of dairy farmers forming a separate entity to address their specific needs. Moreover, the cooperation between farmers to invest and operate a biogas plant was shown to be particularly beneficial for smaller farms (Lauer et al., 2018). However, small-size farms have a weaker negotiating position for planned cooperation and require a comparably higher share of investments. Hence, to increase manure utilization policymakers could provide targeted support to smaller farms by encouraging cooperation.

A promising tool for understanding and forecasting the development of technologies is computer modeling. Among modeling methods, the appeal of agent-based models (ABMs) is that these allow the exploration of interactions between micro- and macro-level structures, e.g. at farmer's level and its wider environment (Schreinemachers and Berger, 2011). Thus, ABM is commonly used for studying complex system properties emanating from interactions among many agents (Berkes et al., 2008; Jager et al., 2000). Because biogas facilities emerge from a wide set of decisions taken at different scales, ABM appears well suited to study their market trends. Multiple studies have used ABMs to gain insight into market mechanisms of biomass value chains. For example, an ABM was used to study the adaptation of Miscanthus production by farmers in Illinois and the impact on biorefinery capacity and contractual agreements (Shastri et al., 2011). Also, an ABM was developed to assess the impact of market context on the supply of local biomass for anaerobic digestion plants (Mertens et al., 2016). Yazan et al. used an agent-based modeling approach to investigate the interactions between animal farmers and biogas producers in an industrial symbiosis case example to provide solutions to the manure disposal problem (Yazan et al., 2018). However, to our knowledge, no ABM-based studies have investigated the cooperation dynamics among farmers towards participating in biogas plant development. This aspect is particularly relevant in countries such as Switzerland, where the deployment of (individual or collective) biogas facilities mostly relies on the farmer's willingness. In particular, studies based on extensive empirical data about farmers' behavior have not yet been carried out. Typically, plausible agent characteristics are determined through literature searches and expert consultation (Yazan et al., 2018). The parametrization of the model should depend on the specific situation and the research question. As the results of this study could alter management practices, it is important to lean on data on farmers in the particular Swiss context. Hence, in this study, the base data was collected through an exhaustive survey of Swiss livestock farmers. A discrete choice experiment (DCE) was performed to elicit the farmer's preferences. The combination of DCE with ABM has been little explored until now. Some recent papers make use of DCE to enhance the predictive capability of ABMs, e.g. in the field of market dynamics (Holm et al., 2016) and diffusion of new technologies for renewable energy (Araghi et al., 2014).

The overall goal of this paper is to examine which characteristics could promote the development of manure-based anaerobic digestion in Switzerland. In particular, we aim at analyzing the impact of different incentives and key factors (e.g. change in revenue for the generated energy, one-off payment, availability of co-substrate) on the establishment of individual and collaborative agricultural biogas systems by farmers. This improved understanding shall enable policymakers to produce more effective policy instruments and engagement strategies. For this purpose, (i) the preferences of the farmers are determined within the framework of a survey and a discrete choice experiment, and based on this, (ii) an agent-based simulation model is developed. The data and model will also serve as a basis for further studies.

2. Data and methods

The adopted methodology and the structure of this chapter are illustrated in Figure 1. The conducted survey is described in the first part of this chapter (2.1). The survey's results enable a qualitative and quantitative understanding of the farmer's beliefs, social interactions, and behaviors. It is complemented by a DCE to investigate under which circumstances the farmers are willing to build and operate a biogas plant (Section 2.2). The ABM designed to simulate the development of manure-based biogas plants under changing boundary conditions (e.g. subsidies, substrate availability) is described in Section 2.3.

2.1. Survey: understanding farmer's behavior

The empirical data used in this paper to simulate the farmer's behavior was derived from an extensive survey. In the first step, a pilot study was undertaken during summer 2018 to gain first insights on farmers' motivation to participate in biogas plants (Akyol, 2018). In-depth, face-to-face interviews were conducted with 10 farmers already owning biogas plants (supplementary material S1.1). The interviews were semi-structured and lasted approximately two hours. The interviewees were selected to cover different regions of Switzerland and different biogas plant sizes. The goal was to learn about their original motives, the main factors that influenced their decision, and the main difficulties they faced during the process of building the plant. The information generated through this preliminary study provided the basis to construct the exhaustive quantitative questionnaire (Akyol, 2018). The questionnaire was designed to identify and quantify the key factors that affect the farmer's willingness and ability to participate in biogas plants. In the first part, general and biogas-specific questions covering the following aspects were asked (see full questionnaire in the supplementary material (S1.2)):

- Farmers' situations — e.g. their age, location, farm size, needs, opportunities, and constraints;
- Farmers' beliefs — e.g. what makes a good farmer, importance of manure, attitude towards renewable energy;

- Social and environmental behaviors – information channels, contact with other farmers;
- Perceptions and opinions of anaerobic digestion;
- Willingness (W) to have manure digested (whereby a distinction was made between W_1 "their general willingness to have their manure digested"; W_2 "to use external manure in an own biogas facility"; W_3 "to give their own manure to an external biogas facility".

The full survey was conducted from January 2019 until May 2019. Swiss farmers, both already involved and not yet involved in biogas plants were the target group of the survey. The farmers could participate either in a digital or "paper and pencil" version of the questionnaire, available in the country's most commonly used languages, German and French. Different communication channels were used to reach out to farmers throughout Switzerland (e.g. newspapers, associations, webpages — see also supplementary material (S1.1)). In addition, the survey was also specifically sent to a representative sample of 720 farms of different sizes across all Swiss regions. Our objective was to obtain coverage that would consider the individual heterogeneity of the farmers. Particular attention was set on the cantonal distribution to ensure the representativeness for the whole of Switzerland and take into account geographical particularities. A total of 186 farmers filled out the entire questionnaire.

2.2. Discrete choice experiment: quantifying farmer's willingness to build a biogas facility

The second part of the questionnaire was a Discrete Choice Experiment (DCE) to elicit the farmers' preferences to build a biogas facility. DCEs rely on Lancaster's characteristics theory of value, which states that attributes of the good or service determine the utility a decision-maker derives (Lancaster, 1966). During the experiment, farmers were confronted multiple times with different options of building a biogas facility, including an opt-out option. Therefore, by making multiple choices, the preferences of the farmers could be quantified and expressed as a utility.

2.2.1. Background

According to the random utility theory (McFadden, 1973), an individual chooses among different options based on their utility. The utility is the measure of relative desirability and can be described by the following function:

$$U = V + \varepsilon = \beta_1 c_1 + \beta_2 c_2 + \ldots + \beta_i c_i + \varepsilon \quad (1)$$

where U is the total utility of an option, $\beta_1 \ldots \beta_i$ are the part-worth utilities of the different decision criteria, $c_1 \ldots c_i$ are the numerical values of the corresponding decision criteria, and ε the error term. The error term describes the effects of all possible random factors on the individuals other than the main decision criteria

When the DCE includes an opt-out / None option, there is also the possibility to refuse the presented options and an additional part-worth utility is introduced, namely β_{None}. For accepting an option, the total utility must be greater than the part-worth utility of the None-option, resulting in ΔU to be positive:

$$\Delta U = U - \beta_{None} \quad (2)$$

During the development of the model, several strategies to convert observed utilities into behavior were tried out (supplementary material S4.1). In the multinomial logit approach used in this study, utilities are expressed as probabilities (McFadden, 1973, p. 110, Eq. (10); Bierlaire, 1998, Eq. (35)):

$$P_i = \frac{e^{U_i}}{\sum_{ji}^{k} e^{U_j}} \quad (3)$$

where P_i is the probability of choosing option i, e is Euler's constant, U_i is the utility of the option i and the number of presented options is k. In the ABM, the choice of the farmers whether to build or not a biogas facility is made according to this probability P_i (Section 2.4).

2.2.2. Experimental set-up

The options in the DCE were described by a set of attributes that represent important decision-criteria for building a biogas facility. Each attribute consisted of multiple levels that describe different options. The selection of the attributes and levels is crucial since all the following results depend on the selection. Too many attributes or levels can dramatically increase the complexity of the decision-situation and overwhelm the farmers, while also increasing the number of respondents needed to ensure representativeness. On the other hand, a too-small number may not cover the decision criteria space sufficiently. Typically, a DCE contains in practice fewer than 10 attributes, to ensure an acceptable degree of complexity (DeShazo and Fermo, 2002). It is also important to avoid inter-attribute correlation between two or more attributes, as this would prevent the accurate estimation of the independent effect of an attribute (Mangham et al., 2009).

The attributes and their levels were determined with the insights of the earlier mentioned pilot study (Akyol, 2018) and multiple sessions with local agricultural associations and experts.

Table 1 shows an overview of the attributes and levels used in this study. The choice of using two economic attributes was motivated by the importance of both the farmers and the experts attached to these aspects. The levels of the selling price represent the current range of energy selling prices with and without subsidies, as well as a higher level of subsidies. As this form of subsidy is likely to expire (SCCER CREST, 2017), it was important to also consider the potential of one-time remuneration grants. Furthermore, including both economic attributes reveals the preferred subsidy form. The willingness to collaborate with other farmers being a key factor for the establishment of agricultural biogas systems (Akyol, 2018; Lauer et al., 2018; Regan et al., 2017) the number of co-owners was defined as a significant attribute. The levels of co-owners used in the ABM reflect current practice (BFE, 2019a; Mutzner et al., 2019; Ökostrom Schweiz, 2019). Personal recommendations were frequently pointed out and were, therefore, recognized as another aspect to consider. Lastly, since most biogas facilities depend on co-substrate availability, this attribute was also included (BLW, 2019).

During the experiment, the attributes and levels were comprehensively described to the farmers (supplementary material S2). Here, partners represent other farmers which would co-own the biogas facility (hence participating in the financing and everyday operation). The personal recommendation is described as a recommendation from a farmer of trust, who owns a biogas facility, or from a qualified and trustful representative from the agricultural industry.

Table 1
Overview of attribute and levels in the discrete choice experiment.

Attribute	Unit	Levels
Number of partners (co-owners)	[-]	0, 1, 5, 20
Selling price of generated energy	[Rp/kWh][a]	10, 25, 40, 55
Personal recommendation	[-]	Recommends against building, No recommendation, Recommends building
One-time remuneration grant	[%][b]	0, 25, 50
Local availability of co-substrate	[-]	Not available, Few and with effort available, Sufficient and effortless available

[a] The energy selling price is listed in the national currency (CHF), subdivided into 100 cents: "Rappen" (Rp) in Swiss-German. It is indicated per kWh of generated electricity or as equivalent bio-methane injected into the gas grid. At the time of this writing 1 CHF is equivalent to 1.03 USD and 0.93 Euros.

[b] The one-time remuneration grant is expressed as the ratio between remuneration grant and total investment costs for a biogas facility.

Based on the complexity of the decision-situation in our study, the number of options per choice set was limited to 2 (excluding the opt-out option) and the number of choice sets to 12 (Christofides et al., 2006; Hanson et al., 2005). This means that the farmer was confronted 12 consecutive times with a decision-situation, which included two options and one opt-out option. More information about the experimental design can be found in the supplementary material S2.

2.2.3. DCE evaluation

There are several methods for evaluating DCEs. In this study, the DCE was designed, tested, and evaluated with the Sawtooth software (Lighthouse Studio 9.6.0). Based on the data collected in the survey, we used a hierarchical bayes (HB) for the evaluation of the results. HB is an algorithm utilized for obtaining individual-level utilities, which is important for the ABM approach (Allenby and Ginter, 1995; Allenby and Lenk, 1994; Lenk et al., 1996). To do so, each respondent was smoothed toward the population's parameters. The evaluation of the DCE led to a part-worth utility value for each attribute level and one for the "don't build"-option: the none-option. The beta-coefficients of the utility function were obtained with a linear regression (cf. Eq. (1)). While the betas resulted from the DCE, the error term was randomly generated during the ABM simulation (for details see ODD, II.ii.c). It has a mean of zero and a variable standard deviation. This is represented in the model by drawing the error term from a normal distribution initialized with a random seed.

2.3. Data preparation for the agent-based model

Each respondent was described with a set of characteristics necessary to parametrize the agents in the model. These characteristics include: the farmers' situation (age, number of LSU, region), their communication radius (the number of farmers with whom they usually have an exchange, independently of their location), the utility parameters from the DCE, and their willingness to have manure digested (whereby a distinction was made between W_1 "their general willingness to have their manure digested"; W_2 "to use external manure in an own biogas facility"; W_3 "to give their own manure to an external biogas facility"). The interviewee's characteristics were compared with available Swiss governmental data, including the farmer's age, number of LSU, and region (2017). Whereas age and geographical distribution of the interviewees reflected fairly well livestock farmers as a whole, it was noted that small farms with less than 30 LSU were under-represented in the sample. Hence, for the integration in the ABM, the sample was adjusted to better reflect the Swiss farmer's population. For this purpose, a three-dimensional cross table was created with the variables age, location, and number of LSU. Related figures and additional information can be found in the supplementary material S3.

2.4. Agent-based model

This section briefly describes the main structure of the ABM. We developed our model with Netlogo 6.1.0, a program developed at the Center for Connected Learning (Wilensky, 2006). Readers interested in specific model details can have access to a complete model description following the ODD (overview, design concepts, and details) protocol (Grimm et al., 2006, 2010) in the supplementary material.

2.4.1. General description

The purpose of the model was to understand the farmer's decision-making process towards the establishment of agricultural biogas facilities, to develop a quantitative prediction of what could promote the development of manure-based anaerobic digestion in a context that resembles the features of the current Swiss agricultural scene. Social psychology theories of human behavior and more specifically the consumat approach (Jager et al., 2000) typified by multidimensional optimization were adapted to our local empirical findings on Swiss farmers' behavior. The model was meant to be used to observe the impacts of different incentives (e.g. change in revenue for the generated energy, one-off payment for the installation of the biogas facility) on farmer's behavior, as well as the influence of further key factors (e.g. availability of co-substrate).

Important aspects to be addressed by the model were the number and size of the built biogas facilities, as well as the organizational structure (centralized, decentralized). The model was designed for scientists, while the derived recommendations are relevant for the policymakers, local authorities and farmers' associations.

The ABM was initialized on a grid of 100×100 (=10,000) discrete cells (Fig. 2) as an abstraction of the real world. The aim of considering the spatial distribution in the survey (under 2.1) was merely to ensure the representativeness of the sample and hence of the farmers in the ABM. The communication radius corresponds to the number of farmers with whom they usually interact, independently of their geographical distance. The model environment is independent of any spatial scale and each grid cell represents one farm.

Two main kinds of objects were identified and integrated into the model: the farmers (responsible for the farm), which can also be defined as agents, and the biogas facilities. There is one farmer agent per cell (=10,000): the farm's manager. The farmers were characterized by empirical parameters according to the survey (Section 2.3 and Fig. 2). These parameters were complemented with variables that change during the simulation according to the evolving conditions (perceived utility and derived from this propensity to build, manure availability within the communication radius (measured in LSU), farmers' preferences within the communication radius, and recommendations of biogas owners in the wider neighborhood). Deliverers and owners can only contribute to one facility. However, biogas facility owners can make recommendations that might be helpful to agents, which start their decision-making process later.

Once established, the biogas facility objects are pure bookkeeping entities characterized by technical attributes (ownership type, capacity, information about founders and, if there are any, co-owners and deliverers). The exogenous factors are revenue for energy, one-time remuneration, a minimum amount of resources necessary to build a biogas facility (expressed in LSU), and co-substrate availability.

The model runs for 1800 steps. At each time step, one random farmer, who is not yet involved in a biogas facility (as an owner or deliverer) considers the possibility to plan and eventually build a biogas facility (alone or with others). With today's parameters, 1800 time steps were needed to simulate a number of facilities similar to those that have been built over the last ten years in Switzerland.

2.4.2. Process overview and decision process

The farmers' goal is to make the best decision regarding building a biogas facility in order to maximize their overall utility while considering their personal preferences (willingness W1-W3) and resources (LSU). If the utility of building such a facility is negative, they waive this idea and only return to it when they are asked to collaborate as feedstock deliverers. At each time step, the activities order of one randomly selected farmer is as follows (Fig. 3):

- decide whether to become active at all, depending on its personal preference (willingness W1-W3),
- find potential deliverers and/or potential co-owners (within communication radius),
- decide whether enough resources (LSU) are available to supply a biogas facility and whether the own contribution is high enough according to today's situation and available technology (Section 2.4.3),
- decide to build the facility if the overall utility is sufficient.

The decision process depends on the following hypotheses: The ability of farmers to build a facility is based on the assessment of their

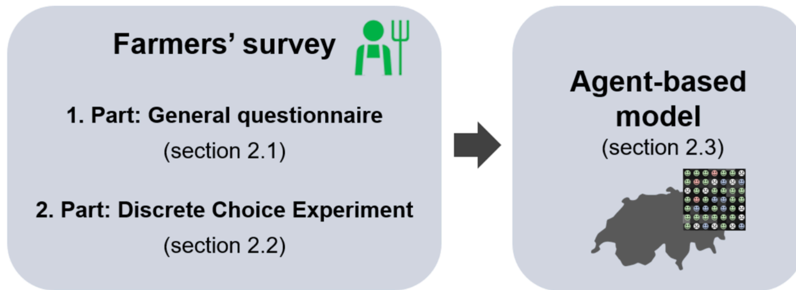

Fig. 1. Schematic overview of the adopted methodology and according sections.

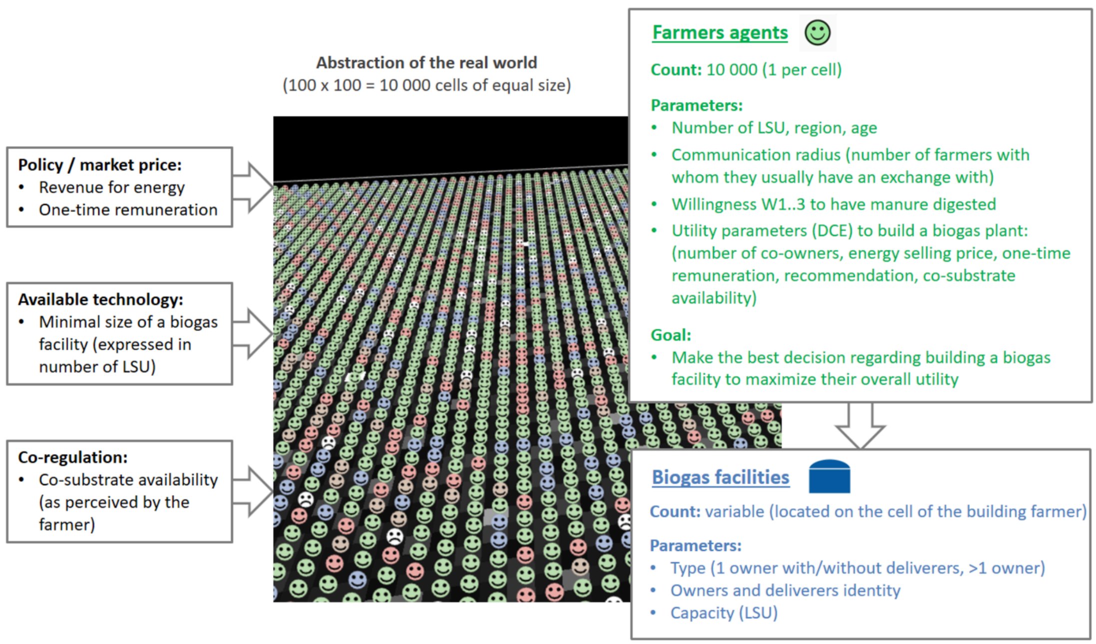

Fig. 2. Schematic overview of the ABM.

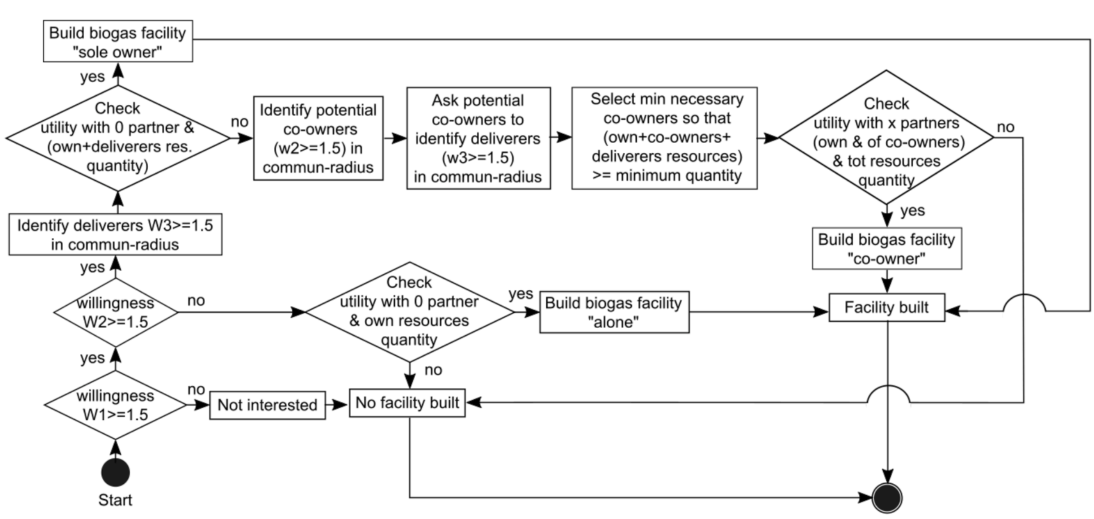

Fig. 3. Flowchart depicting a farmer's decision and its consequences during one time step.

own resource availability (own number of LSU), their willingness to use manure from other farmers (W2), and their communication radius (number of LSU in their communication radius according to the questionnaire, only considering farmers which are not involved in a biogas facility yet). Their willingness to build a biogas facility results from the DCE. If the farmers have enough resources with no co-owner, they will preferentially choose this way. If they are willing to use external manure, they will accept all possible deliverers in their communication radius, while limiting their total contribution to 80–85% (by first discarding the smaller contributors). If more resources are necessary, they will choose all potential co-owners in their communication radius, so that they still have a minimum share of 15% (again by first discarding the smaller contributors). Hence, three different types of biogas facilities are distinguished: namely "alone" with one farm (run by one person or by one family) as owner and no deliverers, "sole owner" with one owner and at least one deliverer and "co-owner" with more than one owner. The biogas facility will be built on the site of the largest owner.

2.4.3. Initialization

Distribution of farmer's attributes is drawn stochastically from distribution characterizing the population according to the empirical data. Thus, depending on how the random number generator is used (with a constant or random seed), the model can be started with fixed initial conditions (to analyze how changes e.g. co-substrate availability or revenue for generated energy impact results) or with different initial conditions (to learn about how sensitive the model is to the randomly determined part of the initial state, and particularly to the artificial topography of the model).

The utilities obtained from the DCE were used to model farmer's decision whether to build a biogas facility or not. In this study, utilities were converted into a probability p (Section 2.2.1 and more information in the supplementary material S4.1). We then draw a uniformly distributed random number r between 0 and 1. A facility is built if $p > r$ and the total manure capacity is expected to be sufficient.

Distinguishing between farmers who only want to build a facility by themselves while accepting manure from deliverers ("sole owner"-facilities) and those who prefer to build a facility together with other investors ("co-owner"-facilities) with the help of the willingness questions is impossible, but one output of the DCE allows for such a distinction. All participants were asked for the influence of the number of possible partners for their utility considerations; this led to a regression equation for the partner related influence on the observed utility $U_p=\alpha + \beta\ n_p$ where n_p is the number of partners at the time of decision. Survey participants who had a positive β see the situation as a win-win situation when the risk is distributed over more than one investor, whereas those with negative β seem to believe that it is better not to share any profit with other colleagues. Hence it was decided to split the group of farmers who were willing to build a facility with deliverers and/or co-owners at β=0.

For every farmer the following attributes are randomly allocated during the initialization:

- minimal share of the manure that should come from the farm where the facility is installed (randomly at least 5%, 10%, 15%, or 20%).
- minimal capacity of a biogas facility (randomly 75–101 LSU for biogas facilities without deliverers "alone", 350–601 LSU for alone owned facilities with deliverers "sole owner" and 600–851 LSU for co-owned facilities "co-owner").

The goal of the random allocation was to respect the observed heterogeneity of the already installed biogas facilities (Section 2.4.4).

2.4.4. Calibration (status quo) and sensitivity analysis (Monte Carlo)

To compare simulation results to empirical data, we compiled a list with data from different databases (BFE, 2019a; BLW, 2019; Mutzner et al., 2019; Ökostrom Schweiz, 2019), which contains information about 102 biogas facilities out of the 111 existing as of 01/01/2019 all over Switzerland (BFE, 2019b). For 40 of them, it was possible to determine all the following characteristics: capacity, number of manure deliverers, ownership, and type of biogas facility as defined in the model (namely "alone", "sole owner" and "co-owner"). The exact figures can be seen in the supplementary information (S4.2). These sample characteristics were used to calibrate the simulation model: among the runs with varying parameters, those providing results near the sample values will best replicate the reality in Switzerland by 2019.

During the calibration, the grid was randomly generated whereby each of the 10,000 agents are instantiated using values from one of the 186 survey participants in a way that the multivariate distribution of these variables is the same both in the survey and in the NetLogo world. The parametrization that lead to the best fit of the situation in Switzerland in 2019 with today's input parameters ("RevenueForEnergy" = 0.45 CHF/kWh "OneTimeRemuneration" = 0%, and "LocalCoSubstrate" = 1) was used for the subsequent sensitivity analysis. Here, "best" is considered in terms of the biogas facility distribution (median capacity of the three types of facilities) and the proportion of manure stemming from the facility site.

Besides the status-quo, a wide variety of alternative scenarios (instead of only a handful of arbitrarily selected scenarios) were generated in a Monte-Carlo parameterization of the input parameters (whose value ranges can be found in the upper part of Table 2). 1200 of these were used for a sensitivity analysis, using linear regression (see Table 3) to yield information about the influence of changes in these parameters on the output parameters listed in the lower part of Table 2. Depending on the order in which the farmers are "asked" to make their decisions, the output metrics follow a more or less normal distribution. The alternative scenarios are Monte Carlo parameterizations of the input parameters (Table 2). The different sensitivity analysis runs started with an identical random seed for the initialization combined with run-wise random seeds with the varying input parameters "OneTimeRemuneration", "RevenueForEnergy" and "LocalCoSubstrate".

3. Results

The results of the DCE are described in the first part of this chapter (3.1). The main findings of the ABM are presented thereafter (3.2).

3.1. Discrete choice experiment

The box plots of the utilities in Fig. 4 show how the different preferences with regard to individual decision criteria are distributed. The chart is scaled so that, for each attribute, the sum of all positive values equals the sum of all negative values. Hence, a negative number does not mean that a given level has "negative utility" - it just means that this level is on average less preferred than a level with an estimated utility

Table 2
Input variables varied in the sensitivity analysis (Monte Carlo) of the agent-based model and observed output variables.

Input variable	Description	Range
OneTimeRemuneration	The one-time remuneration grant is expressed as the ratio between remuneration grant and total investment costs for a biogas facility.	0–50%
RevenueForEnergy	The selling price of the produced energy	0.10–0.55 CHF /kWh
Local Cosubstrate	The availability of local-co-substrate, as estimated by the farmer.	0–2 (Not available, Few and with effort available, Sufficient and effortless available)
Output Variable	Description	
All_Facilities	Total number of biogas facilities	
Facilities_type 1, 2, 3	Number of built biogas facilities of type 1 (sole owner, no deliverers), type 2 (sole owner, with deliverers), type 3 (with co-owners)	
All_Involved	Total number of farmers involved in a biogas facility (all owners + all deliverers)	
Owners_type 3	Number of owners of a biogas facility type 3 (owners_type 1 and 2 = the number of facilities of these types)	
All_Deliverers	Total number of manure deliverers	
Deliverers_type 2, 3	Number of manure deliverers to type 2 facilities (sole owner, with deliverers) and type 3 (with co-owners)	
Total_capacity	Total capacity of built biogas facilities (expressed in LSU)	

Table 3
Regression coefficients between input parameters and selected output metrics [1].

Output metric	R^2	Standardized regression coefficients			Unstandardized regression coefficients[2]			
		One Time Remuneration	Revenue for Energy	Local Co-Substrate	Constant	One Time Remuneration	Revenue for Energy	Local Co-Substrate
Number of facilities (depending on their type)								
All facilities	0.94	0.32	0.90	0.23	11.42	0.33	97.45	5.82
"Alone" (type 1)	0.53	0.34	0.66	0.05	1.91	0.08	15.41	0.30
"Sole owner" (type 2)	0.92	0.31	0.89	0.26	5.70	0.25	75.08	5.26
"Co-owner" (type 3)	0.19	0.05	0.43	0.07	3.812	0.01	6.96	0.26
Number of involved farmers								
All involved	0.89	0.28	0.89	0.24	181.68	2.83	961.59	60.57
Co-owners (owners type 3)	0.14	0.00	0.38	0.03	32.88	0.01	47.16	0.97
All deliverers	0.91	0.29	0.89	0.25	141.19	2.50	823.94	54.05
Deliverers to facilities with sole owners (type 2)	0.90	0.30	0.88	0.26	79.65	2.36	720.71	50.95
Deliverers to facilities with co-owners (type 3)	0.19	0.06	0.43	0.06	61.55	0.14	103.23	3.10
Total capacity (LSU)	0.92	0.29	0.90	0.25	5974.58	−133.27	42,846.57	2783.55
R^2 (coefficient of determination [3])		0.18	0.80	0.22				

[1] See Table 2 for more information about the output metrics.
[2] The unstandardized regression coefficient is expressed in the unit of the output metric per unit of the input metric. An example: 42846.57 means that per 1.00 CHF increase in revenue for energy the expected value of the total capacity is increased by 42846.57 LSU (thus at 0.10 CHF more, 4284.66 LSU equivalents more).
[3] R-squared is a statistical measure of how close the data are to the fitted regression line. 0 indicates that the model explains none of the variability of the response data around its mean.

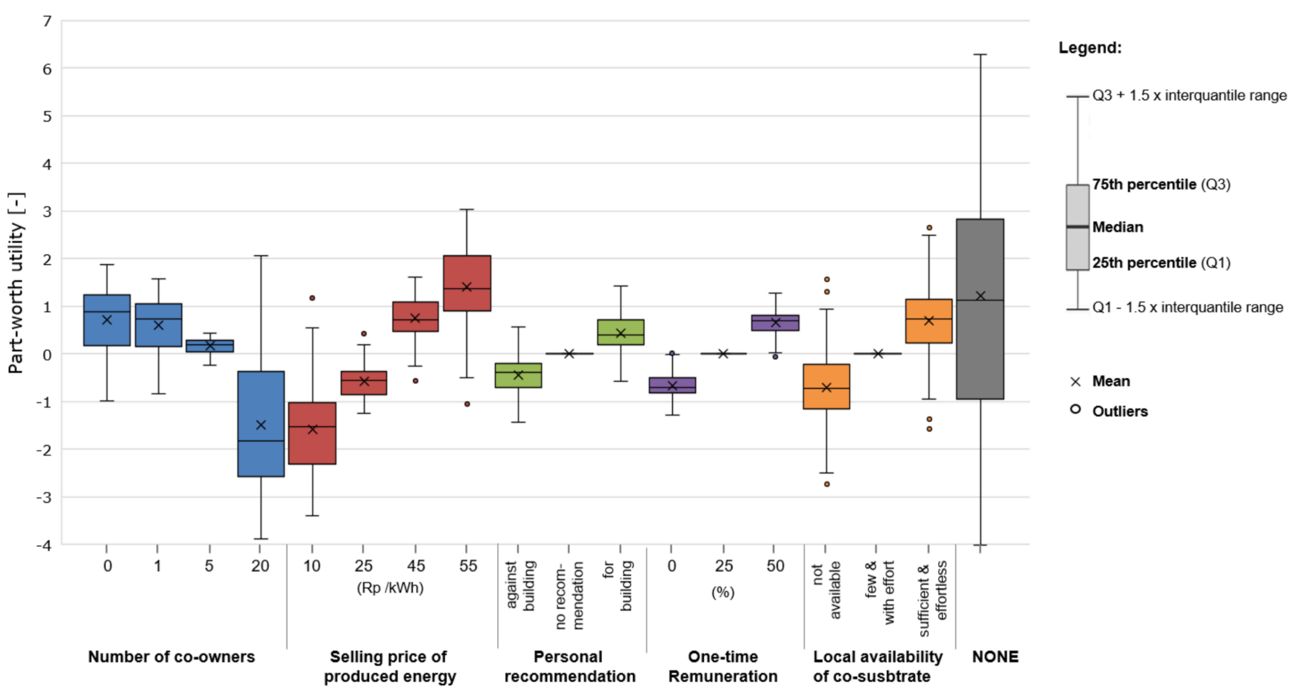

Fig. 4. Box plots of the part-worth utilities from hierarchical bayes analysis.

that is positive. Especially the option not to build a biogas plant (None) shows a great deviation. In 44% of all choices (number of participants multiplied by the number of tasks), the participants chose not to build a biogas plant.

The relative importance of an attribute was derived from the difference between the minimum and maximum utility of that attribute divided by the sum of the utility ranges for all attributes for every respondent. Therefore, it highly depends on the definition of the levels within an attribute. Although the relative importance values show a distinct preference profile, a minority of participants varies greatly from the mean. This variability is illustrated in the box-and-whisker plot shown in Fig. 5. As expected, the energy selling price is one of the most important factors. More surprising is the similar importance of the number of partners (co-owners), which clearly demonstrate the farmer's preference to own a biogas facility alone rather than in co-ownership with other farmers. On the other side, the value of a one-time remuneration grant, personal recommendation, or local co-substrate availability were not very high.

After the DCE, the farmers were asked to directly rank the importance of the attributes. The results are similar to the ones of the hierarchical Bayes analysis, herewith confirming that the DCE questionnaire was well-understood by the farmers (supplementary material S2.3).

3.2. Agent-based model

The simulation results below present the averages of 1200 runs for the results of the calibration model. This number of runs is necessary to capture stochastic effects and to provide general estimations. The status-

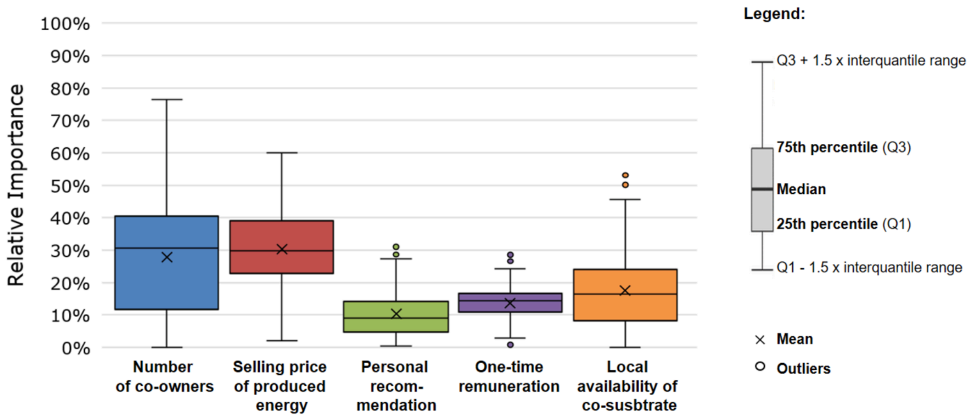

Fig. 5. Box plots of the relative attribute importance from the hierarchical bayes analysis.

quo scenario with today's parameters ("OneTimeRemuneration" 0, "RevenueForEnergy" 0.45 and "LocalCoSubstrate" 1) was run 1000 times. Its results for most output metrics were normally distributed around the values of their empirical counterparts, but with a considerable variance due to the random order in which the agents make their decisions and determine the decision conditions for agents coming later.

The results of the sensitivity analysis (Table 3) show that the output metrics that describe the overall state of the simulated situations are highly dependent on the input parameters. A sensitivity analysis was carried out to simulate the effects of selected input variables on the most interesting output variables (Table 2). The effects on further output variables can be found in the supplementary material S4.3.

As far as the distributions of "facilities", "owners", "deliverers", and "capacities" of the three biogas types are concerned, the explanatory power — and consequently the effect — of the input metrics and the measures taken with these inputs is considerably lower. Yet the effect still exceeds one third (measured as standardized regression coefficients) for output metrics such as the numbers of facilities of the three separate types and their owners and deliverers (see the coefficients > 0.3 in the columns with standardized regression coefficients in Table 3). These two observations make clear that political measures, such as the amount of the revenue for energy, control the overall capacity and number of facilities.

3.2.1. *Revenue for energy as the most important input parameter*

The influence of the input parameter "revenue for energy" is the highest with respect to nearly all output metrics — it shares about 80 percent of its variance with all output metrics together. This is particularly true for output metrics describing the overall effect: the number of all farmers involved, the number of deliverers involved in facilities which allow deliverers, the total capacity, and the number of facilities, as in all these cases the standardized regression coefficient is above 0.9, and the respective overall variance reductions are more than 90 percent. From the right-hand part of Table 3 we can even estimate that a rise in revenue for energy by 0.10 CHF/kWh (compared to 0.45 CHF/kWh today) would enable the establishment of ten additional facilities (see Table 3 and footnote 2) compared to 100 today. The unstandardized regression coefficient suggests that 98 additional facilities would be created if the revenue for energy increased by 1 CHF (second column from the right) or consequently round 10 facilities for 0.10 CHF. The next three coefficients in the same column reveal the type of facility one can expect for 0.10 CHF: 7 to 8 facilities would be sole-owned, 1 to 2 without deliverers, and at most one would be co-owned. The establishment of these ten facilities would enable the manure of an additional 4285 livestock units to be mobilized for biogas (<1% of the total available manure). The same 0.10 CHF rise would lead to an estimated additional 96 farmers owning or delivering to biogas facilities (961.59 farmers per 1.00 CHF, multiplied with 0.10 CHF and rounded).

The strong influence of the energy price for biogas on the total capacity of potential Swiss biogas facilities is visible (Fig. 6): for 0.50 CHF, we expect a total capacity of 30,000 LSU equivalents or 6 MW of electrical capacity, for 0.10 CHF about 10,000 LSU or 2 MW. In all cases, the confidence interval would be plus/minus 5′000 LSU equivalents or 1 MW of installed electrical capacity.

3.2.2. *Availabilit of local co-substrate*

The standardized regression coefficients of the input parameter "local co-substrate" are considerably lower, so the influence of the availability of additional material from sources other than manure still exists but with less effect. This input parameter shares 22 percent of its variance with all the output metrics. In the discrete choice experiment, this parameter was only given qualitatively (as unavailable, as few and difficult to come by or as sufficient and easily exploited), but in the simulation, this three-point scale was converted into a metrical scale from 0.0 to 2.0. Fig. 7 shows a positive correlation between input parameter (local co-substrate) and total LSU (output metric). The mean total capacity (in LSU) is about 17,500 or 3.5 MWel without any co-substrate whereas it could be 23,000 LSU (or 4.6 MWel from manure only) with co-substrate, with a broad confidence band. The model suggests that co-substrate availability does only marginally influence the farmer's preferences. This can be the consequence of the big differences in the farm size of initiators, potential co-owners, and deliverers such that the overall level of availability is not one-to-one applicable to the situation of the individual farm or cooperative.

3.2.3. *Investment subsidies least important*

Finally, the incentive of investment subsidies plays a minor role — it shares its variance with only 18 percent with all the output metrics. Moreover, Fig. 8 shows that the distribution of the respective simulation run results depends on this input parameter, but even less than on the co-substrate parameter. It is not so much the availability of the funds needed for an investment that controls farmers' decision but the profit that can be gained while the facility is running — and this profit depends mostly on the price of the energy that can be sold and of the availability of manure and co-substrate. From the fact that the (standardized) regression coefficients are higher for the output metrics describing the numbers of facilities with only one owner, one can conclude that investment subsidies are relevant only for single owners, not for co-owned facilities. As in the case of the co-substrate availability, the small influence of investment subsidies is due to the different importance individual farmers and cooperatives attribute to this incentive.

4. Discussion

The results of the study allow us to gain insights into how the three aspects i) farmers willingness ($W_{1..3}$. utility parameters from the DCE) ii)

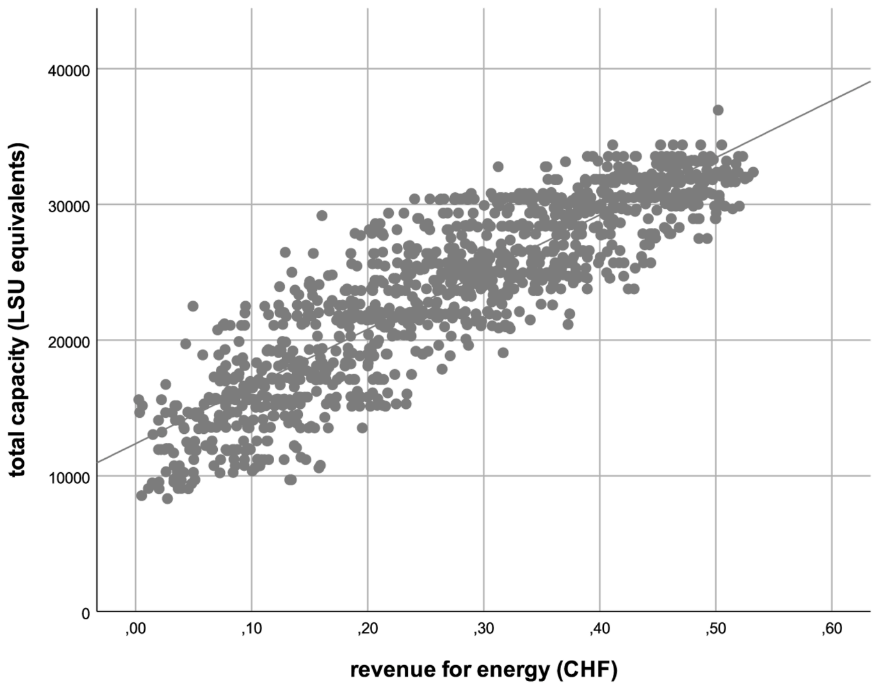

Fig. 6. Scatterplot of total capacity (LSU equivalents) against revenue for energy (CHF) per kWh.

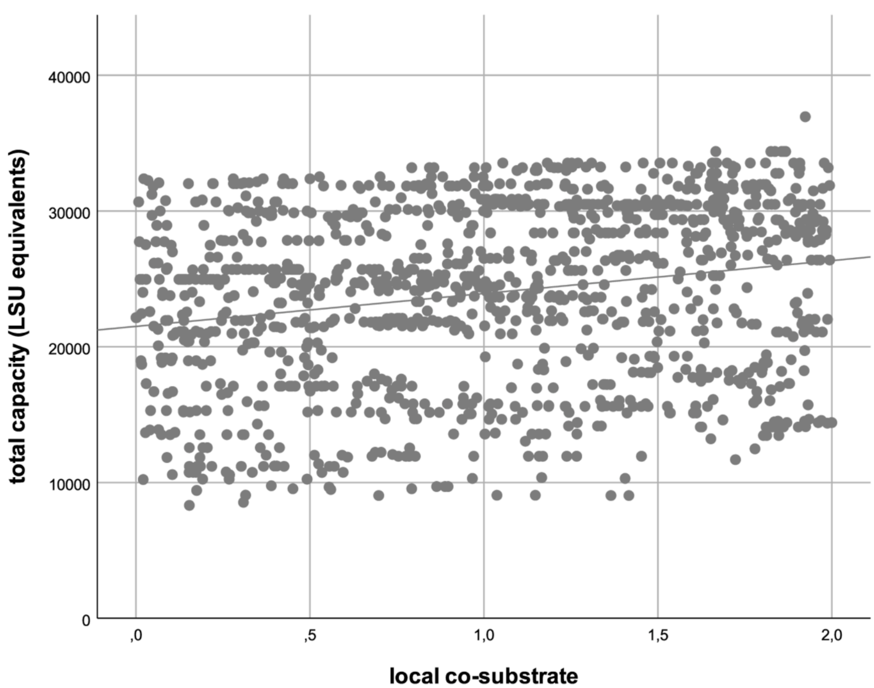

Fig. 7. Scatterplot of total capacity (LSU equivalents) against local co-substrate availability (0: unavailable, 1: available with some effort and medium quantity, 2: plenty and available without effort).

farmers ability (manure amount, availability of co-substrate), and iii) external conditions (first of all the revenue for energy, but also the attitude and behavior of other farmers) influence the process of developing additional biogas facilities. Furthermore, they reveal the complex interplay between these factors. The model was constructed, not to produce results at the individual level, but rather to better understand the mechanisms that influence and contribute to the adoption of biogas facilities by farmers in general. Our results are relevant to policymakers and associations with an interest in biogas development, as they highlight the impact of different incentives and further key factors (e.g. availability of co-substrate) influencing the farmer's willingness to participate in biogas investment. The findings provide both insights for the specific case of agricultural biogas in Switzerland or similar regions, and also more general insights valuable for actors interested in the development of collaborative agricultural value chains beyond biogas production. Indeed, the effectiveness of many types of agri-environmental schemes is also often dependent on the scale of participation among neighboring landowners, as for example wetland reconstruction (Zemo and Termansen, 2018).

Farmers prefer to build alone — in the discrete choice experiment,

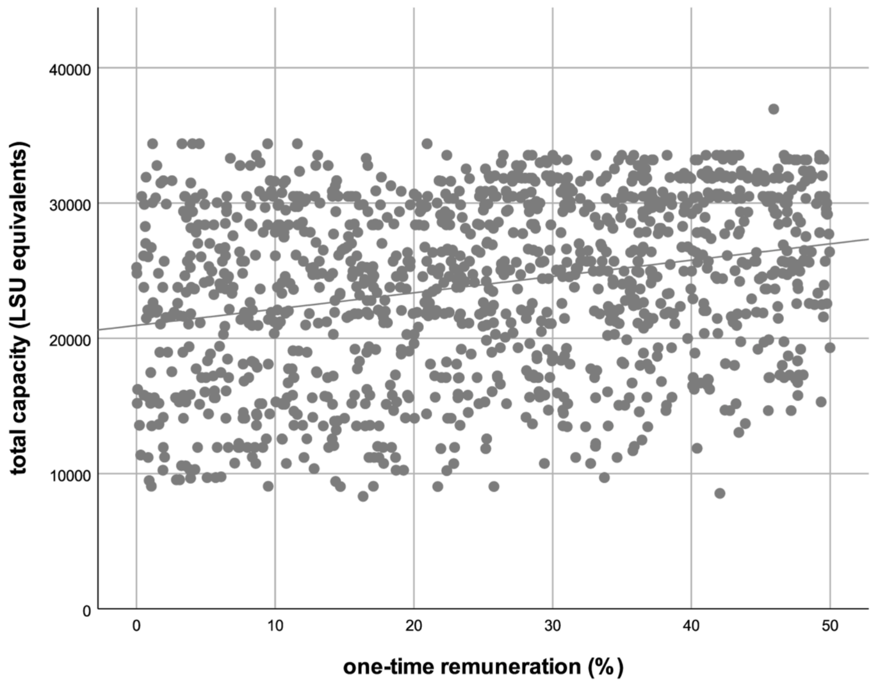

Fig. 8. Scatterplot of total capacity (LSU equivalents) against one-time remuneration (%).

only a minority of the interviewees found that the utility of installing a biogas facility rises with the number of partners, and consequently the simulation showed that cooperative facilities are less widespread than facilities owned by just one farm. This result is in line with the structure of the existing biogas facilities in Switzerland but shows the challenge of initiating collaboration, whose importance has been highlighted by previous studies (Karlsson et al., 2017; Liebrand and Ling, 2009).

However, manure amount is often a limiting factor, which results in the acceptance of the participation of other farmers who only deliver their manure without being co-owners, thus sharing neither profit nor losses. Both in our simulations and in the current Swiss situation, the facility owner or manager contributes only a small part (20 percent) of the facility feedstock capacity (averaged over all three types “alone”, “sole owner”, “co-owner”; as in the literature (BFE, 2019a; BLW, 2019; FOEN, 2016), including the farms which do not accept deliverers at all).

The most important input parameter is the revenue for energy — this finding was first revealed by the discrete choice experiment (Fig. 5). However, there the difference in importance toward building a facility between the number of partners and the energy selling price was less obvious and the ABM made this point clearer. The quantified relationships can provide indications for the design of incentive systems. The expected success of political measures supporting the energetic exploitation of manure in the eyes of potential investors lies in the price they can get for their output. Hence, it may be expected that an additional revenue (e.g. in form of CO_2-certificates or for using the produced digestate as valuable fertilizer) could be a promising strategy to develop biogas plants. Today, Switzerland counts 1.309×10^6 LSU (FOAG, 2019), whereby approximately half of the produced manure was assessed as sustainable for energy (Burg et al., 2018a) (representing the manure of round 750′000 LSU). Even with a rather high revenue of 0.55 CHF / kWh less than 5% of this potential would be mobilized (Fig. 6).

The influence of a one-time remuneration grant and the availability of additional material (co-substrate) for digestion seems to have much less impact (Figs. 7 and 8). Hence, it remains an open question, how much administrative or political measures to support the availability of co-substrate or to support one-time investment into biogas facility are effective. This lesser significance was also visible from the DCE, where little importance was attached to these attributes. The least important attribute according to the DCE was the personal recommendation. The overall impact on the simulation results is hence expected to be small but could not be quantified as personal recommendation between agents exists (as it is not a global input parameter like selling price, investment grant, and availability of co-substrate).

To fully harness the energy and GHG mitigation potential of converting manure to biogas, other strategies need to be developed at different levels and policymakers should look beyond conventional biogas deployment systems. At the organizational level, the initiative to build larger plants (with many deliverers) cannot be expected (only) from the farmers. This point supports the first approach described by Lauer suggesting that existing dairy cooperatives could provide services related to the adoption of biogas technology (as opposed to sole farmers forming a joint entity) (Lauer et al., 2018). Further initiatives could come from municipalities or energy companies becoming active in this domain. However, the willingness of farmers to deliver their manure to such external biogas facilities and the willingness of these stakeholders to establish biogas facilities would need to be explored within a completely new study. While combining DCEs with ABMs has been recognized to be a suitable method to enhance the empirical foundation of ABMs (Holm et al., 2016), this approach also brings a certain rigidity to the model. Indeed, attribute selection and levels have to be defined beforehand and DCE can only be applied to participants with a general understanding of the choice context. Hence, the use of the DCE approach would need to be reexamined for this new purpose, requiring preliminary research that includes consultation of the new stakeholders.

Improvement at the technical-economic level could lead to smaller plants becoming cheaper and easier to run for the farmers. Accordingly, policymakers should consider reducing administrative work linked to the building and running of agricultural biogas facilities. At the legal level, anaerobic digestion could become obligatory as part of manure management, eventually with the corresponding subsidies or measures to avoid CO_2 emissions. At the economical level, we have tested compensation rates of max 0.55 CHF / kWh but it remains open what would happen with higher rates such as 1 CHF / kWh. Furthermore, incentives and enabling measures to support collaboration between farmers to overcome the small-scale production structures can also be an approach to be investigated. Previous studies already encouraged policymakers to provide targeted support to promote farmers' cooperation in this sector (Lauer et al., 2018; Liebrand and Ling, 2009).

To improve confidence in the findings, it is necessary to assess how model assumptions and parameters alter the results. On the one hand, we might underestimate the development of biogas facilities, as we only simulated the establishment of biogas facilities by farmers. However, we have seen from the data (Section 2.4.4) that approximately 15% of the existing biogas facilities are linked to a non-agricultural actor (e.g. municipality or energy company). On the other hand, we might overestimate the development as further barriers are not considered (e.g. locally limited availability of co-substrate, administrative process, objections from neighbors).

In this study, manure is processed in agricultural biogas facilities through anaerobic digestion. Following previous studies, we assumed typical average yields for Swiss manure (Burg et al., 2018b), which allowed us in this study to consider only the amount of livestock units. Several factors such as dry matter, organic content, or lignin existing in the biomass might influence the biogas yield. In Switzerland, the resulting biogas is usually burnt to produce electricity and heat. Biogas can also be purified into bio-methane and injected into the natural gas grid. At the moment, this technology is not common in Switzerland (< 5% of all the existing facilities (BFE, 2019b)) but the proportion is growing. Any change in the resource properties or in the technology may influence the assumptions of the model and hence outcome (e.g. via changing the minimal feedstock amount (LSU) to run a biogas facility). Similarly, if farmers' attitudes change in the future, the sample of respondents would no longer be appropriate for modeling farmer's attitudes. However, the developed model could still be used as a basis but would need to be adapted and recalibrated to suit to this new environment.

5. Conclusions

Here, we investigated the diffusion of manure-based biogas facilities in Switzerland. An agent-based model of farmers' willingness to participate and invest in biogas facilities was developed. The agent-based model was based on a DCE to quantify the preferences and readiness of the agents (farmers) to act. According to the ABM results, the most influential factors affecting farmers' decisions are energy prices, the initial setting of the neighborhood, and the number of partners needed to reach the minimal resources amount. Generally, the farmers who are predicted to be more likely to adopt biogas technology were those who interact more with other farmers (larger communication radius) and who possess more resources (manure feedstock). Although other approaches have been recognized at e.g. the technological, organizational, or institutional level, these were not further investigated in the frame of the study. Hence, further research could investigate the decision-making and adaptation process of farmers through role-playing games. Indeed, the mobilization of the full resources potential involves substantial changes at e.g. the technological, organizational, institutional, political, economic, and socio-cultural levels - a small increase in revenue for the generated energy is by far not sufficient.

CRediT authorship contribution statement

Vanessa Burg: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Klaus G. Troitzsch:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Deniz Akyol:** Conceptualization, Resources, Writing - original draft, Visualization. **Urs Baier:** Conceptualization, Resources, Validation, Writing - original draft. **Stefanie Hellweg:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision. **Oliver Thees:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105400.

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