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Modelling socio-ecological systems with MAIA: A biogas infrastructure simulation

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A B S T R A C T

Similar to other renewable energy technologies, the development of a biogas infrastructure in the Netherlands is going through social, institutional and ecological evolution. To study this complex evolutionary process, we built a comprehensive agent-based model of this infrastructure. We used an agent-based modelling framework called MAIA to build this model with the initial motivation that it facilitates modelling complex institutional structures. The modelling experience however proved that MAIA can also act as an integrated solution to address other major modelling challenges identified in the literature for modelling evolving socio-ecological systems. Building on comprehensive reviews, we reflect on our modelling experience and address four key challenges of modelling evolving socio-ecological systems using agents: (1) design and parameterization of models of agent behaviour and decision-making, (2) system representation in the social and spatial dimension, (3) integration of socio-demographic, ecological, and biophysical models, (4) verification, validation and sensitivity analysis of such ABMs.

1. Introduction

In the past decade we have witnessed dramatic developments in renewable energy production, which has led to a revival of decentralized local energy harvesting and use. The pace and scale of development in Germany and Denmark is already causing their centralized fossil based energy infrastructure systems to be adapted, if not redesigned, to accommodate the decentralized feed-in of renewable energy. Biogas infrastructures are an example of decentralized renewable energy production systems, which utilize local resources to produce biogas. The design choices of biogas infrastructures depend on locally available resources, local demand, stakeholder preferences, perceived uncertainty and risk avoidance. All these factors are influenced by existing and changing markets as well as policies and regulations. It is therefore unclear whether and what biogas infrastructure systems can or will emerge.

Biogas infrastructures are a type of socio-ecological system where social, institutional, technological and ecological dimensions co-evolve. Since socio-ecological systems are Complex Adaptive Systems (Rammel et al., 2007), agent-based models (ABMs) can be used to simulate and explore their characteristics. In particular, using the agent-paradigm, one can simulate stakeholder behaviour, institutional contexts and technical systems relevant for energy infrastructures and their ecological surroundings.

In this paper, we present an ABM of a biogas infrastructure in the Netherlands. The institutional aspects of such infrastructure systems has been a very important aspect for the analysis of its complexity, which is why we selected the MAIA framework (Modelling Agent systems using Institutional Analysis) (Ghorbani et al., 2013a) to build this ABM. MAIA is a conceptual framework which provides a template of concepts to model social systems with a particular focus on their institutional aspects. During the modelling process, we came to the conclusion, that besides facilitating institutional modelling, MAIA also provides an integrated solution to address major challenges for modelling socio-ecological systems as identified by Filatova et al. (2013) and Rounsevell et al. (2012).

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The goal of this paper is to show how these modelling challenges can be addressed with the MAIA framework by going through the modelling process of the biogas infrastructure in detail. We demonstrate our MAIA approach by presenting the decomposition, conceptualization and implementation of an ABM of a regional biogas system called the BioNet.

The structure of this paper is as follows. In Section 2, we briefly introduce the MAIA framework. In Section 3, we give an overview of the biogas infrastructure in the Netherlands. In Section 4, we present the biogas model conceptualized using the MAIA framework. In Section 5, we present the evaluation process of the model in particular with regards to stakeholder involvement and discuss the simulation outcomes. In Section 6, we discuss MAIA as an integrated solution to the modelling challenges by reflecting on our modelling process. Finally, in Section 7, we conclude our findings and reflect on future directions of research.

2. Modelling agent systems using institutional analysis

The MAIA framework (Ghorbani et al., 2013a), is an agent-based modelling framework which can be used to conceptualize and model socio-ecological systems. MAIA builds on the Institutional Analysis and Development (IAD) framework of the Nobel Laureate Elinor Ostrom (2011) by formalizing and extending its concepts. IAD has been applied in the analysis of many socio-ecological systems including ones with ABM, making it a reliable framework for studying such systems (e.g., ABM of Land change (Manson, 2005), ABM for Natural resource management (Bousquet et al., 1998), common pool ABM experiments (Deadman et al., 2000)). Furthermore, the MAIA framework has already been successfully applied, and evaluated, to study a number of diverse social systems (*see* Ghorbani, 2013). Finally, MAIA supports participatory model development, as its conceptual richness and structure allows domain experts to conceptualize a socio-ecological system with limited or no programming experience. Conceptual design is supported through a web-based application[1] facilitating collective development of models.

The MAIA framework (i.e., meta-model[2]) consists of five interrelated structures that categorize various concepts of socio-ecological systems. These are briefly discussed below:

- **Social[3] Structure**. This structure captures all the relevant properties, behaviours and internal decisions of the actors and allows for the implementation of heterogeneous agents.
- **Institutional[4] Structure**. This structure consists of roles and institutions. “A role is an abstract representation of a set of activities that are performed according to some rules in order to reach social objectives” (Ghorbani, 2013, p32). Depending on the roles they assume, agents follow various institutional rules. Institutions are decomposed and conceptualized using ADICO grammar of institutions as introduced by Crawford and Ostrom (1995). Agents pursue different objectives based on their roles. For example, some mainly maximize profit, while others focus on maximizing social welfare or environmental performance. Agents' dependencies on each other is also related to these objectives.
- **Physical Structure.** The Physical Structure is used to conceptualize the ecological and technological environment for the ABM. Besides physical goods, physical infrastructure is required to produce, convert, transport and consume products or services. Agents may own different parts of the physical infrastructure and their physical assets, whether natural or man-made, can either be open to everyone or only accessible to them.
- **Operational Structure.** The Operational Structure describes the dynamics of the simulation by modelling agents' behaviours and interactions which are grouped into different action situations (e.g. market situation, production situation).
- **Evaluative Structure.** This structure links the expected outcomes of the model to agent behaviour and interaction. This structure allows an external observation for analysis of the model outcomes and model validity. The MAIA framework summarized in Fig. 1 provides formal concepts to populate the model with heterogeneous agents and various social, institutional and physical aspects. MAIA is not a prescriptive framework, providing flexibility for modellers to ground agent behaviour and decision making in the theories that are most relevant for the particular domain of study.

3. The Dutch biogas system

Biogas has been attracting much interest from the Dutch government, because it can contribute to achieving the Dutch CO_2 emission reduction and renewable energy production targets. Kaparaju and Rintala (2011) and Massé et al. (2011) show that biogas has the potential to reduce CO_2 emissions by replacing fossil fuels and fertilizers since it is produced from renewable organic material. Most of the biogas in the Netherlands is produced by agricultural firms who use anaerobic (co-)digestion to convert manure and other biomass to biogas. Water treatment facilities are also large producers of biogas through silt digestion, which is often integrated in their water treatment process.

Biogas production is profitable for waste water treatment facilities because the production costs of biogas from silt are estimated at 0.05 €/m^3 (Lensink et al., 2012, p.26), which is well below the natural gas price of 0.33 €/m^3 (CBS, 2015). Agricultural firms experience significantly higher costs, however, due to the cost of biomass co-feed, digestate (waste product) processing and transport. Nevertheless, biogas production can be a lucrative business when subsidized or when a local solution can be found to sell the gas. The effects and development of biogas production from co-digestion and water treatment facilities in terms of CO_2 emissions and replacements of fossil fuels is given in Table 1 (CBS, 2014).

The majority of the produced biogas in the Netherlands is combusted in a technology called combined heat and power (CHP) which generates electricity and heat. The large share of CHP units is due to the fact that this technology was eligible for subsidies. However, The CHP units suffer from conversion losses, and in many cases the heat produced cannot be completely utilized locally. Existing agent-based simulation studies focus on CHP and biogas upgrading technologies, which allows the biogas to be used in existing electricity and natural gas networks (Delzeit et al., 2012; Madlener and Schmid, 2009; Sorda et al., 2013). All three studies use a GIS information system to simulate and compare the diffusion of biogas technologies in various regions. Furthermore, these studies assume economic (rational) agents. Finally, these studies do not include policy evaluations, apart from feed-in tariff (FIT) policies (Madlener and Schmid, 2009; Sorda et al., 2013).

BioNet (Fig. 2) is a new biogas distribution network solution by Alliander, a Dutch Distribution Network Operator, which is piloted

[1] http://maia-tool.github.io.

[2] “A formal description of this set of concepts that describe a model is called a meta-model” (Ghorbani, 2013, p27; Schmidt, 2006).

[3] In previous versions of the MAIA framework, this structure was referred to as the Collective Structure.

[4] In previous versions of the MAIA framework, this structure was referred to as the Constitutional Structure.