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Anaerobic digestion: a prime solution for water, energy and food nexus challenges

Ismail Haltas[a]*, James Suckling[b], Iain Soutar[c], Angela Druckman[b], Liz Varga[a]

[a]*Cranfield University, Cranfield, Beds MK43 0AL, UK*
[b]*University of Surrey, Guildford, Surrey, GU2 7XH, UK*
[c] *University of Exeter, Penryn Campus, Cornwall, TR10 9EZ, UK*

Abstract

We solve the problem of identifying one or more optimal patterns of anaerobic digestion (AD) installation across the UK, by considering existing installations, the current feedstock potential and the project growth of the potential via population, demography and urbanization. We test several scenarios for the level of adoption of the AD operations in the community under varying amounts of feedstock supply, which may arise from change in food waste or energy crops generation via other policies and incentives. For the most resilient scales of solutions, we demonstrate for the UK the net energy production (bio-gas and electricity) from AD (and so the avoided emissions from grid energy), the mass of bio-waste processed (and avoided land-fill), and the quantum of digestate produced (as a proxy for avoided irrigation and fertilizer production). In order to simulate the AD innovation within WEF nexus we use agent based modelling (ABM) owing to its bottom-up approach and capability of modelling complex systems with relatively low level data and information.

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Keywords: Nexus; water-energy-food; complexity; agent based model; case study; governance; technology

* Corresponding author. Tel.: +44-123-475-1122.
E-mail address: ismail.haltas@cranfield.ac.uk

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1. Introduction

1.1. WEF Nexus challenges

The water-energy-food (WEF) nexus is a contemporary framing of the challenges associated with a sectoral focus. These challenges arise because each sector has interdependencies with each other, the consequences of which are poorly understood, managed or exposed. Furthermore, the stresses created by the interdependencies result in major impacts on our global systems i.e. environment, economy, society, which can result in greater sectoral pressures.

Infrastructure systems provide products which are considered a public good: users have an expectation that water, energy and food is available, affordable, safe and secure. However the production of water, energy, and food is highly interdependent in a non-linear manner. Each product is reliant, directly or indirectly upon each other: they need each other. And the context of growing population growth, and in particular the rising expectations of the growing middle classes, are creating increased demand in each of the sectors, exacerbating interdependency stresses.

The consequent impacts of WEF nexus systems on our global systems are evidenced by legislation and regulation attempting to control carbon emissions, water abstraction and contamination, air pollution, and food insecurity, and in general to work toward United Nation Sustainable Development Goals. The core challenge for the global economy is to decouple economic growth from resource constraints [13] and more significantly to find strategies toward sustainable resource use [8].

1.2. Governance in the nexus

The lack of interconnectivity between water, food and energy systems is frequently framed as a governance issue, that is, a consequence of the lack of integrated organization, thinking and practice between systems [11]. Broadly defined, governance concerns how actors (i.e. the individuals, households, communities, firms, government departments, regulators and other organizations with interest or influence), their institutions (e.g. the norms, rules, conventions and values shaping the behavior of such actors) and their practices (i.e. the actions of actors, such as consumption behaviors or processes of policymaking) influence outcomes in systems. The articulation and appraisal of governance arrangements is thus of central importance in understanding the human factors shaping current WEF systems and their interconnections, as well as how future systems might be enabled and/or constrained [17].

One specific way in which governance affects outcomes at the nexus is by shaping processes of innovation and inertia within systems. Innovation comprises multiple actors, in multiple roles, interacting towards the development of solutions to address specific problems, while inertia is concerned with the role of actors in resisting such processes. Innovation is relevant to the nexus in terms of the development of both problems (i.e. the degree to which problems are framed as addressing single system objectives) and solutions (i.e. the impact of specific instances of innovation activity across systems). Taking an innovation-centric view of nexus issues can thus help to draw light the efficacy of both existing and future frameworks of governance in shaping processes of change.

1.3. The role of anaerobic digestion at the nexus

Anaerobic digestion (AD) is the decomposition of biodegradable matter by microbes in an oxygen-free environment. The principal outputs are biogas, which is composed primarily of methane and carbon dioxide, and nutrient rich digestate which is comprised of water and the remaining undigested solids. Digestate has the potential to be used as a fertilizer and the methane as an energy source, and both capable of replacing fossil fuel based energy sources. AD is often implemented in order to treat wastes and residues from the food supply chain and, when considering the environment, compares favorably with other disposal techniques such as composting [5] or landfilling [7], even if electricity production from methane captured from a sealed landfill is considered. The relative benefit of producing methane from AD increases with future decarbonisation of the UK electricity grid [22].

Anaerobic digestion has the potential to reduce the environmental impact of energy production through such displacement of fossil fuels [2]. Benefits have been observed not only to replace fossil fuels for heat, but also for electricity generation and transport fuel [21]. Since bio-gas can be stored, or upgraded for insertion into gas grid infrastructure, AD may contribute to energy security by offering a demand orientated solution to the erratic nature of other renewable energy sources such as wind or solar [6,16].

With respect to energy generated from specially grown crops, AD is still has lower negative impact on the environment than fossil fuels, even when considering the effects of indirect land use change required to make up the resulting shortfall in food production [21]. However, such use of energy crops can come with severe ramifications for water use, with bio-fuels requiring 70 to 400 times more water per GJ than fossil fuel equivalents [9].

As a fertilizer for growing crops [14], the use of digestate to replace mineral fertilizer can reduce the emissions associated with food cultivation, one of the main sources of emissions in the supply chain [4]. Finally, AD has the potential to mitigate the emissions associated with slurry produced by animals reared for food [1].

1.4. Agent Based Modelling

Agent Based Modelling is a bottom up approach where the overall behavior of a system emerges from the behaviors and interactions of autonomous agents within the system [12]. ABM allows the disaggregation of systems into individual components that can potentially have their own characteristics and rule sets. As such, evolution of the system over time can be simulated by simply populating the agents, defining their behavior rules and letting them act in the landscape of the system. ABM provides significant advantage especially in modelling nonlinear complex systems, because all the complexity and nonlinearity of the system is mapped by the complex and nonlinear collective behavior and interaction of agents with relatively simple set of rules [3]. In agent based modelling no prior information about the dynamics of the overall system -which may be impossible to have for an integrated system like a nexus- is required for modelling the system. The heterogeneity in the system can also easily be modelled as each agent type in the system is populated with its set of parameters and heterogeneity is revealed in the different values of the parameters and the resulting agent population [12]. The behavior rules of an agent can be designed in a way that the agent can learn from consequences of previous actions and update its behavior to achieve its own goals [18]. Its methodological approach and capability of modelling complex systems with relatively low level data and information makes ABM an ideal tool for modelling AD innovation within nexus context.

In this article we discuss the consequences of adopting AD, but recognize that tackling WEF nexus challenges requires a palette of diverse solutions, each of which must be economically, socially and environmentally viable.

2. Case Study: Anaerobic Digestion

Anaerobic digestion plants have been operating within the UK for decades, but it is only recently that the number of plants has increased considerably, in part due to support from subsidies, namely the Feed-in Tariff (FiT), the Renewable Heat Incentive (RHI) or the Renewables Obligation (RO). The ability of AD to offer solutions aligned with energy system interests (low carbon electricity and heat) means that growth in the sector can now largely be associated with energy policy [20]. This has allowed the number of AD plants to grow from 424 to 540 between 2015 and 2016 alone [15]. Currently in UK AD plants with a wide range of types and sizes operates on multiple different feedstocks and generates 708 MWe of energy. It is estimated that in 2015 2TWh of biomethane was injected into the national grid, out of a potential 35TWh which could be generated from wastes and residues: this potential production would make up approximately 4-12% of the projected UK gas needs in 2050 (300 – 800TWh) [19].

However, AD expansion is currently facing headwinds within the UK. At present it only receives subsidies for the energy which it generates. The subsidy levels are in the process of being reduced, and are at the point where many consider a significant proportion of future plants not to be feasible [15]. This must be compared against already high perceived barriers of cost to installing AD [23]. This is compounded by the lack of value of the digestate, which receives no support from subsidy or policy. In fact it is seen often a burden to the plants producing it, with many paying for it to be taken away [24]. Hence, the number of new plants coming online is predicted to reduce dramatically in the coming years [15].

In order to understand the potential for AD to grow against these headwinds and capture all of the available feedstock it is necessary to understand the motives of the actors involved in the AD industry. For this purpose, the research is working with case studies of AD plants at different scales, types of operation and phases of development.

The plants range from a small scale, not-for-profit community plant (< 1kW) taking food waste from local restaurants, to a medium scale crop based plant (50kW) built using novel construction techniques, up to large commercial plants (> 1MW) operating over multiple sites and operating their own food waste collection logistics. Further case studies include a planned on-farm plant as part of an integrated agricultural model and a company making containerized, modular systems for waste treatment. The drivers behind the different plants vary as does the importance of subsidies: some are fully dependent on FiT as the main source of income; some hold a power purchase agreement with the local distribution network operator; others benefit from the savings made from avoided waste disposal costs or purchased fertilizer costs. These and other varying attributes of the case studies allow us to understand the variety of motivations of AD plant operators and potential acceptance of other incentives to promote the uptake of AD.

With respect to some of the feedstock streams used within AD, it is not always those that install or operate the AD plants that have ultimate control over the source of the feedstock. For example the collection and disposal of domestic food waste is ultimately controlled by the regional authority (local, district, or county council) AD innovation affects and is affected by actors, institutions and practices from throughout water, energy and food systems. The need to manage waste from farming, food production, and water treatment means that much of AD innovation takes place by actors traditionally associated with food and water systems. The potential for a wide range of environmental, social and economic impacts, both positive and negative, means that a diverse group of stakeholders hold interest and influence in the development of AD projects and the sector more widely, as illustrated in Figure 1.

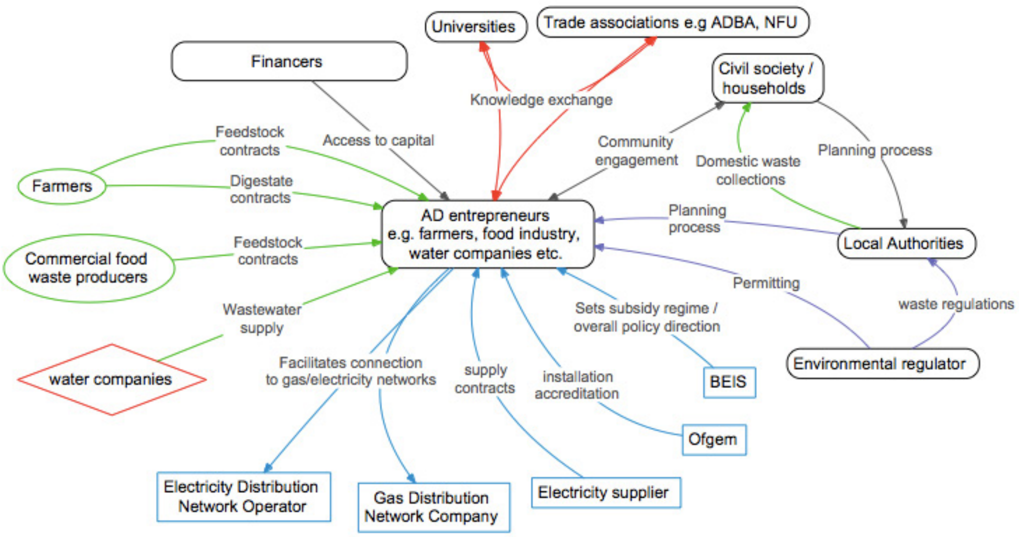

Fig. 1. Simplified representation of key stakeholders and interactions affecting AD developments.

The wider group of stakeholders are engaged in the project to understand their motivations. In order to supplement information from case studies, stakeholders who represent wider bodies are also engaged in the project, including trade associations for AD (such as the Anaerobic Digestion and Bioresources Association), and representatives of farming bodies or food waste producers.

3. Agent Based Model of Anaerobic Digestion

In the agent based modelling of the anaerobic digestion, stakeholders are modelled as agent types, therefore understanding stakeholders' characteristics and behaviour is crucial to be able to define the correct set of rules for the agents. Furthermore besides understanding the behaviour of stakeholders under the existing conditions, estimating their response and updating agents' behaviours for future conditions is important in order to develop a dynamically evolving ABM. The AD ABM employ both the qualitative and quantitative data attained through the stakeholder interviews. The behaviour rules of agents rely on both narratives and numerical data from the stakeholders. While within the overall architecture of the ABM, states and transitions of each agent are designed based on the qualitative data, the parameters and variables of agent populations are assigned based on the quantitative data. An ABM of a system can be designed at various spatial and temporal levels of abstraction. The flexibility in the level of abstraction helps to tailor the ABM easily in a way that the model output provides the necessary insight for the targeted decision support tool. In the AD ABM the components are modelled at the micro or operational level where agents are defined as individual objects with exact sizes, distances, velocities and timing. For example; each individual truck/tanker, their exact route and speed are simulated in the AD ABM. The model unit time -ticks- are hourly.

The stakeholders in the anaerobic digestion process are basically the AD Plants, the feedstock sources, the collection/transportation contractors, and the governing bodies such as council. There are wide range of AD Plants in terms of type, size, capacity, feedstock type, and output process in UK [25]. AD Plants are simply classified by Environment Agency as farm-fed or waste-fed, yet there are a range of different types of feedstock (Table 2) from various types of source (Table 1).

Table 1. Feedstock Source Types

ID	Description
1	House
2	Farm
3	Wastewater Treatment Plant
4	Food Factory
5	Restaurant
6	Food Store
7	Slaughterhouse
8	Municipal

The feedstock types are classified as solid or liquid as the storage, transportation and digestion of solid and liquid feedstock vary. The AD innovation process is modelled using Plant, Source, Contractor, and Trucks/Tankers (Transportation) as physical agents and Collection Request as information (soft) agent. All physical agents in the model are placed in GIS environment. Therefore the geographic coordinates of all the physical agents are needed to populate the agents. The information agent facilitates the exchange of information (i.e. need for scheduled or unscheduled collection) between the other agents as massages.

Table 2. Feedstock Types

ID	Description	S/L

1	Food Waste from Houses	Solid
2	Green Waste from Houses	Solid
3	Green Waste from Municipality	Solid
4	Energy Crops From Farms	Solid
5	Crop Residues from Farms	Solid
6	Slurry from Farms	Liquid
7	DAF sludge from Wastewater Treatment Facility	Liquid
8	Food Waste from Food Factories	Solid
9	Food Waste from Restaurants	Solid
10	Food Waste from Food Stores	Solid
11	Animal by-products (Category III) from Slaughterhouses	Solid

The AnyLogic software, which is a simulation tool that supports all the most common simulation methodologies such as System Dynamics, Discrete Event, and Agent Based modelling [10], is used to develop the ABM. In AnyLogic agent based modelling, the behaviour rules of an agent are defined as state charts (Fig. 2). A state chart is composed of possible states (such as producing, consuming, transporting, idle etc.) of the agent and transitions between the states.

The model can be applied to any study area (from the catchment area of a single AD Plant to nation-wide) in UK as long as the minimum required data set including the location attribute of the agents are available. Simulation can be performed for any real time span (i.e. 2017 – 2030). The AD ABM incorporates the population raise based on the trends in the historical census data. The increase of the population within the study area is modelled as increase in the number of feedstock sources and in the feedstock generation rate.

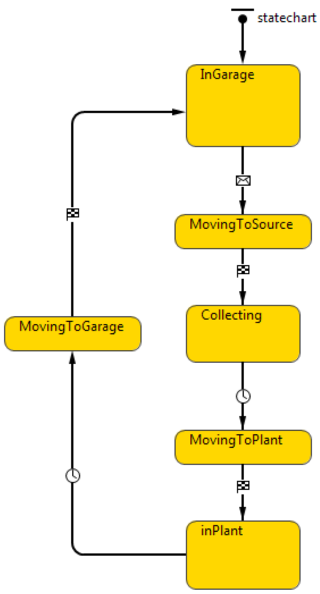

Fig. 2. Example state chart of transportation (truck/tanker) agent.

4. Discussion and Conclusions

Anaerobic digestion has the potential to contribute to mitigation of challenges at the water energy food nexus. Through the use of appropriate feedstocks it has the potential to help decarbonize the energy market, and to improve the security and sustainability of food production through land management practices, such as reduction of crop monocultures and reducing use of fossil based fertilizers. Furthermore, it is capable of treating, stabilizing and valorizing wastes by turning them into an energy source and fertilizer.

The multi-purpose nature of AD is evident in the application of the technology at a variety of scales, employing diverse feedstocks, producing a range of products, with value for a range of practitioners across water, energy and food spaces. As such, AD can be regarded as an example of a 'boundary crossing' innovation, i.e. it not only crosses systemic boundaries in terms of inputs and outputs, but also alters the interconnections between systems, with implications for its future. For example, the opportunities AD offers has encouraged farmers and food producers to become engaged with multiple innovation functions around AD, not least in terms of entrepreneurship, knowledge development and knowledge exchange, and the mobilization of resources. The capacity to engage with these functions varies among actors, particularly as a function of scale, which affects, among other things, the availability of resources (and the availability of economies of scale) and organizational capacity.

The UK has a long standing, but somewhat immature AD industry. At present only a small fraction of the potential feedstocks are utilized, leading to a rate of energy generation nationally that is much lower than theoretically possible. The industry has seen strong growth in recent years, but that is predicted to rapidly tail off with reductions in the main mechanism of support: subsidies for energy generation. Through exploring case studies that are involved in different aspects of AD, utilizing different feedstocks and business models, and who are at different stages of development, it is possible explore the likely size of the industry under these conditions and how it may flourish under other policy regimes.

In the current stage of the research a prototype of AD ABM model has been developed. In this model there are several assumptions about the behaviour rules of the agents yet to be validated and also the initialization of the model parameters are based on semi-pseudo data. In the following stages of the research the prototype model with validated assumptions and actual data will be applied to a pilot study area at county scale. Eventually an UK scale AD AMB model will be developed. Multi-agent models such as AD ABM usually require an extensive set of input data. Acquiring such data sets particular to each individual agent may not be possible especially for large scale models. In the absence of particular data sets some statistical extrapolations and data aggregation techniques are commonly used. After all, the primary purpose of the AD ABM modelling exercise is to simulate the average emerging behaviour of AD innovation within a nexus perspective. The AD ABM model parameters are currently defined as deterministic values, yet in order to account the uncertainty in the data some of the parameters will be assigned random variables and a Monte-Carlo simulation will be conducted. The ensemble average of the simulation results will provide an average emerging behaviour of AD innovation impact on WEF nexus. Several global indicator variables such as cumulative generated food waste, cumulative produced energy crop, cumulative collected feedstock, cumulative produced biogas and power etc. will be the output of the simulations. The project will thus be able to inform industry actors and policy-makers about the potential for AD to increase the sustainability of food practices and energy generation, and the policies under which the AD industry may flourish.

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