A BOTTOM-UP SUPPLY-SIDE SIMULATION MODEL OF RESIDENTIAL AND COMMUNITY ENERGY SYSTEMS USING SYSTEM DYNAMICS

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ABSTRACT

Increasing interest in distributed generation of energy, increasing number of participants in energy planning, and the interdisciplinary nature of energy planning, provide an opportunity for new tools to model energy systems from bottom-up. This paper presents bottom-up supply-side models of residential and community energy systems based on a case study using System Dynamics. The simulation models are constructed to facilitate Systems Thinking, which can enable interdisciplinary and transdisciplinary approaches, whilst performing analyses expected from similar models. The modelling process is presented followed by discussion on the outcome of the process. The paper concludes with future work on the model.

Keywords: System Dynamics, Energy System, Simulation, Systems Thinking

1 INTRODUCTION

Centralised electricity generation has been facing many challenges like constraints to efficiency and capacity, which can be resolved by Distributed Generation (DG) (Mendes et al 2011; Takahashi et al 2005). There is a trend in research and industry towards more distributed generation, especially from renewable sources (Sadeghi et al 2017). Global trends like liberalisation of energy markets, environmental protection and sustainable development have increased interest for energy planning at smaller geographic scales (Cormio et al 2003). Moreover, the main trends in energy planning include: growing interest in DG based on renewables; growing community awareness on environmental issues; increasing number of decision makers in energy planning (Mirakyan and De Guio, 2013). These trends may also explain the rise of the “prosumer” (Rathnayaka et al 2015), who is both producer and consumer of energy. Since the implementation of energy system depends on whether the user is a producer or consumer (Project SENSIBLE Partners, 2015), the prosumer presents a challenge to implementation of energy systems, and consequently energy planning. In distributed residential and community energy systems, any individual can be a planner.

Energy planning involves many areas of problem, activities and participants, which makes it unavoidably interdisciplinary, or even transdisciplinary. Modelling the operations of energy systems is essential in energy planning of different scales especially communities and cities (Huang et al 2015; Mirakyan and De Guio, 2013). Based on the review in (Huang et al 2015), it seems that at the heart of bottom-up energy planning is techno-economic assessments, techno-ecological assessments and what-if (scenario and sensitivity) analyses. Accordingly, it has been observed in (Manfren et al 2011) that there is a need for energy planning tools that can facilitate communication in an interdisciplinary or transdisciplinary manner whilst carrying out expected analyses. This would also benefit researchers taking an interdisciplinary or transdisciplinary approach.

This study aims to demonstrate creation and possible uses of System Dynamics (SD) models for bottom-up supply-side simulation models of residential energy systems and community energy systems. Some of the contributions of this study include the use of discrete feedback in SD to model energy systems, as well as the use of a diagrammatic transdisciplinary method for simulation.

The next section provides a background to the study by looking at relevant aspects of System Dynamics, followed by a literature review of similar models in light of System Dynamics. Then there is a brief section on methods followed by a section on results and discussion, in which the modelling process, outcomes and validity considerations are presented. Finally, there is a concluding section.

2 BACKGROUND

2.1 System Dynamics

System Dynamics (SD) is a method of modelling and simulation of complex systems – with features such as feedback, nonlinearity, delay – that can analyse dynamic behaviour over time based on the principles of system structures (Forrester, 1961; Sterman, 2000). SD provides a common means of representation and communication across several disciplines and beyond formal disciplines which makes it an interdisciplinary, as well as a transdisciplinary, method. This is achieved by using the generic language of systems as outlined in the system principles (Forrester, 1997); making SD a systems approach. In addition, SD meets the four minimum criteria (system hierarchy; means of communication; adaptation; emergent properties) for Systems Thinking according to (Checkland, 2012; Checkland, 1981).

All System Dynamics models have at least one of two general aims which can be achieved via a variety of architecture (which includes but not limited to Ordinary Differential Equations, Agent Based Modelling, Discrete Event Simulation, or a combination) (Rahmandad and Sterman, 2018; Sterman, 2000): improve understanding of a system by explaining its dynamics; virtually simulate and analyse possible configurations of the system. Some models have both aims. Improving understanding is applicable to continuous feedback, whereas virtual simulation and analysis is applicable to both continuous and discrete feedback. SD also has other benefits that are characteristic of the method which all SD models can benefit from. These include being a: method of structural realism; quantitatively rigorous soft method; diagrammatic simulation method; method based on systems language. These properties make SD a suitable method for interdisciplinary and transdisciplinary approaches to research or projects.

In SD, variables are mainly categorised into stocks or flows; others are auxiliary variables and constants. In stock and flow diagrams, links can be material links or information links represented as double arrows or single arrows respectively. The direction of material links indicate the movement of the same quantity between two variables, but information links simply indicate dependence. Stocks are accumulations, while flows are the rate of accumulation.

2.2 Literature Review

Energy models have been classified in (Van Beeck, 1999; Timmerman et al 2014; Hall and Buckley, 2016) along similar dimensions. However all their classifications are limited to software packages, excluding generic modelling methods like MATLAB and System Dynamics. This study is primarily about a modelling method, not specific problems of the modelled system, even though efficacy of the model will be demonstrated via examples of problems. The models of interest are bottom-up energy supply models of (the operation of) microgrids; which can be found in (Ravindra and Iyer, 2014; Hong et al 2017; Mukherjee et al 2017; Aguilar-Jiménez et al 2018; Kitson et al 2018; Dhundhara et al 2018; He et al 2018; Adefarati and Bansal, 2019; Nnaji et al 2019; Raji and Luta, 2019; Xu et al 2019; Astriani et al 2019; Bukar et al 2019; Castillo-Calzadilla et al 2019; Cornélusse et al 2019; Ge et al 2019; Griego et al 2019).

Given the varied purposes of the models listed, their capabilities will not be compared. It is sufficient that the tools or methods have been demonstrated to carry out what they aim to do in their respective studies. Therefore the use of SD in this study is not to improve on analytic capabilities where other methods fail, but to highlight its other beneficial features, in addition to its analytic

capabilities. To the knowledge of the authors, there has been no bottom-up supply-side simulation of an energy system using System Dynamics.

The main limitation of SD in this study is the inability to implement programming concepts that may be required for metaheuristic algorithms without a third party integration. SD can be understood as a modelling method that can present a model with three layers of complexity: the diagram layer; the equations layer; the programming layer/add-on. In the case of Energy Planning, different participants may be interested in the different layers, respectively: the public and prosumers; management; industry partners. Researchers may be interested in any of the layers. It has been observed that bottom-up energy models are characterised by the first two thermodynamic laws, economic and environmental constraints (Huang et al 2015). The thermodynamic laws can be implemented in the SD model of this study as energy conservation and energy conversion loss, whilst the constraints can be simulated via impact assessments. In addition, SD can offer more realism via the principle of causal connectedness; which aims to ensure that causal links in the model must be justified by evidence from the real system.

2.3 Project SENSIBLE

The case study to be modelled is Project SENSIBLE (Storage Enabled Sustainable Energy for Buildings and Communities). The aim of SENSIBLE “is to understand the economic benefits that energy storage can bring to households, communities, and commercial buildings” (<https://www.projectsensible.eu/> accessed 1 July 2018). SENSIBLE explores the use of energy storage at residential and community levels implemented in real communities. One of the communities is in The Meadows, Nottingham, UK. The plan was to implement a Community Energy System and several Residential Energy Systems made up of power electronic and communication devices; a smart grid. The project has been well documented and available at the website (<https://www.projectsensible.eu/downloads/> accessed 1 July 2018).

3 METHODS

Equivalent processes of system dynamics have been outlined in Table 1 based on (Randers, 1980; Richardson and Pugh III, 1981; Roberts et al 1983; Sterman, 2000). In addition, the corresponding parallel validity tests have been outlined in (Sterman, 2000; Shreckengost, 1984; Qudrat-Ullah and Seong, 2010). The main method of sourcing data is via archival research, and the data sources include project deliverables, quantitative data from operational devices, and specification sheets of devices.

Table 1 *Stages of System Dynamics process, tools, expected outcome and corresponding validity tests*

Order	Stage	Tool(s)	Expected Outcome	Validity Test
1	Problem articulation	Model Boundary Chart	Problem theme; Problem statement; Time scale and range; Key variables and concepts.	Boundary Adequacy
2	Construction of conceptual model	Stock and Flow Diagram	A conceptual model	Structure Verification Dimensional Consistency Parameter Verification Extreme Conditions Behaviour Reproduction Sensitivity Analysis
3	Formulation of simulation model	Stock and Flow Diagram	A simulation model	
4	Conclude Validity Test	-	Confidence, or means to establish confidence, in the model's structure and behaviour.	<i>Not Applicable</i>
5	Analyses	-	Answers to questions about the real system via the simulation system	<i>Beyond the scope of this research.</i>

4 RESULTS AND DISCUSSIONS

The discussion that follows is based on the stages of the System Dynamics process and their corresponding validity tests. The validity tests will be addressed in form of responses to the questions they pose, as outlined in (Sterman, 2000). For brevity, each question will not be dedicated a subsection. Moreover, the discussion that follows is not limited to the questions of the validity tests.

4.1 Problem Articulation

The purpose of the System Dynamics exercise is to create simulation models of residential and community energy systems from Project SENSIBLE to demonstrate scenario analysis, techno-economic impact analysis, and techno-ecological impact analysis. Therefore the focus is on the operational, economic and environmental dimensions of the system. The time resolution of the simulation model is minutes because the field devices measure in minutes, and the time range is the duration of a day in order to make system behaviour visually distinguishable in a time-series graph. Table 2 is the model boundary chart showing variables from the real system that will be modelled (endogenous and exogenous) and those that will not be modelled (excluded). Forecasting, storage optimisation and energy market services are modules within SENSIBLE that rely on proprietary algorithms (which include machine learning and genetic algorithms) and stored data. The outcome of these modules are signals to the energy systems which have been represented as exogenous variables.

Table 2 *Model Boundary Chart*

Endogenous	Exogenous	Excluded
<ul style="list-style-type: none"> • Consumption • Battery State of Charge (SoC) • PV Consumption • PV Loss • Power Import • Power Export • PV Charging • PV Charging Loss • PV Discharging • PV Discharging Loss 	<ul style="list-style-type: none"> • Load demand • PV production • Storage efficiency • Conversion efficiency • Signal to charge battery from grid • Signal to supply load from grid without battery discharge • Signal to sell to grid without battery charge • Signal to limit maximum battery SoC from grid • Power ratings 	<ul style="list-style-type: none"> • Reactive power • Battery lifetime • Auto discharge

4.2 Conceptual Model

Data about structure of the system was obtained from project documents: SENSIBLE Deliverables (<https://www.projectsensible.eu/downloads/> accessed 1 July 2018). The residential and community energy systems are made of devices with a variety of capabilities. Each system could be modelled as an electricity system or information system, depending on the level of abstraction; as an electric circuit or information network. The systems as information system is better suited for the purpose of this study. The chosen level of aggregation is to model power in Watts and energy in Watt-minutes because most of the monitoring devices measure power in Watts.

A conceptual model of a Residential Energy System is shown in Figure 1, created using Vensim. The conceptual model can facilitate Systems Thinking because it is a diagram that explicates the interdependence in a system with feedback (Richmond, 1993; Forrester, 1994; Sterman, 2000). In addition to causal dependency indicated by all arrows, other observable features of the material links (double arrows) are energy conservation and energy conversion loss. The simulation model is built on the conceptual model.

Figure 1 Conceptual Model of a Residential Energy System showing causal dependencies among system elements using Stock and Flow Diagram. Dotted arrows indicate connections to and from the Energy Management System.

4.3 Simulation Model

For moments where load demand exceeds the combined rated values of all power sources, the unserved load is monitored separately as a validation measure. The simulation models implement the following in fidelity with the real system:

- Nonlinear efficiency and loss of energy during energy conversion by the power inverters.
- Energy conservation such that energy can be accounted for from source to load and loss.
- Enforcement of causal connectedness such that decision making elements make decisions using only information realistically available to them.

All system rules have been derived from description of three use cases applicable to the Nottingham Demonstrator of SENSIBLE (<https://www.projectsensible.eu/downloads/> accessed 1 July 2018). The discrete feedback of the system is determined by the system decisions. The model was checked using the integrated Units Checking tool in Vensim and there are no errors, which confirms dimensional consistency. All parameter values are obtained from the same project documents used for conceptual model, as well as device specification documents. Extreme values are handled within equations, for example, using rated values of devices. Only one normaliser variable in the model has no real world counterpart but it is used in order to balance the units. It is called “Energy to Power Normaliser”, which has a value of 1 and a unit of 1/time. This is used in equations of the following variables where a power value is to be determined from energy values: Charge Power to Max; Discharge Power to Min; and Grid Charge Limit.

To run a simulation, a time series of electric load is provided as input. Data from real residences with four different composition of devices were obtained.

4.3.1 Validity Test - Behaviour Reproduction

The aim is to investigate if a model reproduces historical behaviour in the system. See Figure 2a for example. In general, for the same 24 hour period, the behaviour of the simulation models of the four residences matches data from the real system; for the variables of battery charging, battery discharging, power import, power export, and battery state of charge. The exception is in the case of import and export for the residence with Grid + Battery + PV, but more significant in the export. The discrepancy in export follows behaviour that does not match what has been documented.

Additionally, the error may be explained by one of three reasons: the real data is erroneous; or the documents did not capture properly the system's rules; or the rules were not properly applied in the simulation. The error is likely to be from the real data because other simulations resulted in reasonable match, including variables of the same residence (charging, discharging and battery state of charge), and the rules are from the same sources. Also, the use of optimisation signals (to export power or not), does not explain the error. At the moment, efforts are being made to obtain real data from other residences with the same configuration in order to verify.

4.4 Analyses

4.4.1 Scenario Analysis

The aim is to simulate and compare the dynamic behaviour of different compositions of the system. See Figure 2b for examples; it visually compares power import from simulations of Community Energy Systems with and without a community battery. During daylight hours, there is significant import from the grid in the scenario where there is no community battery because there is no stored energy that may have been obtained at night when energy is cheaper.

Figure 2 a) Example of behaviour comparison between SD simulation and the real system for different residences. b) Example of Scenario Analysis comparing the same Community Energy System with and without community battery.

4.4.2 Environmental Impact Analysis

Figure 3 estimates and compares CO₂ (Carbon Dioxide) equivalent footprint and savings of different system compositions of the real system. The conversion factor is 0.28307 kg of CO₂ saved for each kilowatt-hour (kWh) produced from a carbon free source, based on RenSmart (<https://www.rensmart.com/Calculators/KWH-to-CO2> accessed 1 July 2019). Within a 24 hour period, a residence fitted with PV panels has an additional impact of about 400 grams of CO₂ equivalent of imported power when it does not have a battery. However it appears there is no difference within the same 24 hour period with regards to CO₂ savings from export; given the state of other variables. These values are influenced by the battery state of charge at time 0.

Figure 3 Example of Environmental Impact Analysis: a) Comparing cumulative CO₂ equivalent footprint from power import between the same residence with two different compositions; b) Comparing cumulative CO₂ equivalent savings power export between the same residence with two different compositions.

4.4.3 Economic Impact Analysis

Figure 4 estimates and compares monetary costs and savings of a residence with and without battery, when it is fitted with PV panels. The cost per kWh is based on Green Energy's TIDE tariff for weekdays (https://www.greenenergyuk.com/PressRelease.aspx?PRESS_RELEASE_ID=76 accessed 1 July 2019). Within a 24 hour period, a residence fitted with PV spends in excess of about 25 pence from imported power when it does not have a battery. On the other hand the residence earns about 10 pence in the same period from exporting excess power generated from PV. These values are influenced by the battery state of charge at time 0. Other system compositions of the real system that can be explored include: Community Energy System with and without battery; centralised community battery and individual residential batteries.

Figure 4 Example of Economic Impact Analysis: a) Comparing cumulative money spent on power import between the same residence with two different compositions; b) Comparing cumulative money earned from power export between the same residence with two different compositions.

5 CONCLUSION AND FURTHER WORK

System Dynamics has the capability to model supply-side of residential and community energy systems using a bottom-up approach. The simulation model facilitates systems thinking by being diagrammatic, modular and having multiple layers of detail. In addition, the model features energy conservation, nonlinear conversion efficiency and causal connectedness. Though the model considered the sophisticated optimisation of the real system as exogenous, it behaved like the real system, by mainly relying on the descriptions of use cases. Finally, the model could be used for a number of analyses, and examples have been presented.

Simulation models like the one presented in this paper could be a step towards allowing the public and prosumers to take part in transdisciplinary Energy Planning, as well as researchers in interdisciplinary and transdisciplinary research. In the future, the model could be expanded to include electric heating and Electric Vehicles (EV). In its current state, the model can be readily integrated with other System Dynamics models that have common variables. An issue worth exploring is the scalability of the community energy systems when it is made up of many residences beyond the few presented in this paper.

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