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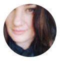

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Causal Loop Mapping of Emerging Energy Systems in Project TwinERGY: Towards Consumer Engagement with Group Model Building

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ABSTRACT

This paper outlines project TwinERGY's suggested approach to collaborative mapping of emerging energy systems with relevant stakeholders, including in particular participant consumers. The approach is based on the use of the established Causal Loop Diagram (CLD) from within the remit of System Dynamics/System Thinking techniques, as the basis of group model building. We explain how CLD is a relevant modelling technique for the problem domain of energy systems and why its qualitative nature that highlights interdependencies makes it suitable for use with participant stakeholders. Finally, we illustrate modelling examples relevant to actual project testbed deployments and initial experiment scenarios with the use of the online CLD tool LOOPY.

CCS CONCEPTS

• **Human-centered computing** → Collaborative and social computing; Collaborative and social computing theory, concepts and paradigms; Collaborative content creation.

KEYWORDS

Future Energy Systems, Causal Loop Diagram, Group Model Building, Consumer Engagement

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1 INTRODUCTION

Project TwinERGY aspires to create the underpinnings of the future European energy marketplace, by providing a transactive framework, process and platform that enables key stakeholders to leverage on emerging energy technologies [1]. Through the project developments such as micro- and local generation and storage, demand responsive systems, peer-to-peer trading, distributed ledger accounting and energy informatics are integrated in support of novel business models that democratise the future of energy and empower consumers and prosumers as cornerstones of the future energy market.

This is achieved through extensive stakeholder engagement and in particular of citizens and consumers of varied backgrounds, based on established practices derived by design thinking and systems modelling. The consortium explore key issues of the future energy marketplace across four pilot sites in Europe (Italy, Germany, Greece, UK), roll out and validate novel concepts and test their scalability and replicability within and across cities. The project will ultimately deliver a number of innovations that will enable better understanding of energy behaviours, provide stakeholders with feedback on energy generation and use, support energy trading in emerging markets and engage consumers in a meaningful way in the whole process.

Key outcomes of TwinERGY will contribute to service innovation in the energy sector by enabling deep insight development through large scale system modelling and analysis, scenario building and participatory experimentation, combining real time data feeds with advanced analytics and modelling. Guided by the principles of standard openness, data protection, ethics and public value TwinERGY is part of the initiatives that enable the next generation of energy systems and services to flourish within and outside the European Union.

The nature of participatory experimentation extends to consumer groups engaging with the project in a structured way to ensure maximum relevance and impact of local demonstration testbeds. Key stakeholders are asked to contribute and co-produce models of future energy systems allowing them to develop common understanding of challenges and system interdependencies. Key insights derived by such activities may influence TwiinERGY technology development and interventions in relevant Use-Cases.

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Engineered artefacts at the heart of the TwinERGY approach, such as Digital Twins and Distributed Ledger Technology, the notion of Transactive Energy or the use of Machine Learning/Artificial Intelligence, have the potential for transformational impact of the status quo in the energy sector. However, whatever definition one adopts for these, they represent an element of added complexity. Exploring the interdependencies of these technologies, their potential unintended consequences, identifying and articulating their benefits, whilst de-risking their use is thus a fundamental task.

As project pilots enter their enactment stage, volunteer participants are signing up and the technology is delivered across sites, the engagement process will be ongoing and based on collaborative methods and techniques. These are typical ones used to structure complex socio-technical problems and to develop common understanding, and hopefully purpose, between stakeholders (such as the participants, researchers, technology developers, municipalities, the state, other project consortia, industry representatives etc.) through a structured programme of collaborative interactions, including meetings and workshops.

Energy sector stakeholders come together in this context to explore energy futures through problem structuring, by reflecting on modelling artefacts that have been developed collaboratively. Working at local, national and international level a number of representative modelling artefacts provide the basis for examining real-world scenarios implemented in TwinERGY and understanding their value and impact. To that end a number of methods and tools from within the broad family of Systems Thinking will be used to facilitate the process and capturing the dynamics and interdependencies of the field. The following sections introduce an outline of the thinking framework and provide examples and a plan of engagement with stakeholders.

2 THE SYSTEMS APPROACH

It will be helpful to analyse the system of interest (SoI) within a conceptual framework, to better understand how contextual developments and external drivers such as policy and regulation frameworks, new technology development and societal needs that stem from events such as climate change, the Covid-19 pandemic etc. influence it. We formulate an overall approach that enables collaborative exploration of the nature of energy demand and how TwinERGY innovation can shape developments in this landscape based on group model building practices, utilising Causal Loop Diagrams and the process of the Soft Systems Methodology.

As we discuss in more detail below, the nature of these models allows for multiple individual stakeholders to engage with their development, facilitating at the same time the development of common understanding of shared issues. This technique emphasises on qualitative and visual modelling, so it is appropriate for the engagement of stakeholders at any level (user/participants, industry representatives, project partners etc.). It is also relatively straightforward to convert such models to quantitative and data driven simulations (stocks and flows system models) that could complement the functionality of the Digital Twin and provide additional validation means for TwinERGY's key outcomes. Such models could be developed further upon consumption data generation from the pilots.

The planning, development and subsequent use of such models through-life of the project is coordinated through the use of an overall Systems Thinking framework, the Soft Systems Methodology, the brief background of which is provided in this section.

2.1 Thinking in Systems

A system can be defined as an arrangement consisting of physical components that are connected or related in such a way that they act as an entire unit [2]. Kump et al. [3] defines a system as an entity that is composed of diverse parts (components) that are interrelated. Together they function as a complex whole. A system may also exhibit adaptive, dynamic and evolutionary behaviour [4]. DiStefano et al. [2] go on to define a control system as being an arrangement of physical components that are connected in such a manner as to regulate itself or another system. Given this definition, it could be argued that the physical and build environments are abound with control systems. Note also that this is an idea central to the notion of the Viable System, where control is also a recognised element of it.

A systems approach can be applied in virtually any area of inquiry [3]. By studying the environment in systems terms and gaining an insight into its behaviour at a particular moment in time, it might be possible to build a more accurate picture of both the past behaviour of a physical system, whilst making more accurate predictions about the future. This can be especially important e.g., when considering the extent to which anthropogenic activity is responsible for modifications of the environment and the consequences of such change.

Components of a system interrelate in such a way as to determine the state of the system by allowing for the flow of information from one component to the next via links known as couplings [3]. Both positive and negative couplings can exist. In the case of a positive coupling, a change in one component, leads to a change in the same direction in the connected component, e.g., an increase in insolation could directly result in an increase in the Earth's surface temperature. Conversely, in a negative coupling, a change in one component would result in a change in the opposite direction in the connected component, e.g., an increase in surface albedo would directly result in a reduction of the Earth's surface temperature [3].

Couplings may also result in a feedback loop, which can be defined as a "self-perpetuating mechanism of change and response to that change" ([3], p. 22). Feedback loops may also be negative or positive, where negative loops reduce the effects of the disturbance and where positive loops amplify the effects.

A system is described as being in a state of equilibrium when it does not change until something creates a disturbance. Equilibrium may be either stable or unstable. In a stable state of equilibrium, a small disturbance to the system will result in responses that will quickly return the system to a state of equilibrium. In a system in an unstable state of equilibrium, however, a small disturbance may result in system adjustments that carry the system further and further from its original state until a new state of equilibrium, if such a state exists [4].

Looking, then, in a system with a single feedback loop, a negative loop demonstrates a state of stable equilibrium whilst a positive feedback loop demonstrates a state of unstable equilibrium. In the case of built environment and energy systems, such as in the domain of our project, however, the reality is considerably more complex. Systems such as these are typically made up of a combination of several subsystems that may consist of both positive and negative feedback loops.

A perturbation of a system is a temporary disturbance of a system, whereas a forcing mechanism is a more persistent disturbance. Kump et al. [3] give as an example of a perturbation in natural systems such as the volcanic outgassing of sulphur dioxide into the atmosphere during a terrestrial (Earth) eruption. As SO2 reacts to form sulphate aerosols in the atmosphere in the period following the eruption, it prevents a small amount of insolation reaching the Earth's surface, lowering average global temperatures. Forcing mechanisms, on the other hand, such as increasing levels of sunlight received by the Earth over billions of years, are more persistent in nature.

2.2 Causal Loop Diagrams

We referred to how thinking in systems is comprehensive in terms of providing the ability to encounter both the natural, but also the built reality. The ideas of feedback loops, control, mechanisms of disruption and forcing etc. can be fundamental to describe the behaviour of engineered systems. As an example, Shepherd outlines the fundamental principles and possibilities for application of system dynamics in transportation modelling [5]. System dynamics is a methodology that uses a standard causal loop approach to develop qualitative models of a system which could be used to develop dynamic hypotheses before a more quantitative stock-flow model is developed [5].

The approach can be used to model various transportation scenarios, such as the uptake of alternative fuel vehicles, highway maintenance and construction, and airlines and airports. This approach is particularly suited to problems with feedback and recurrence, e.g., in particular of the 'problem symptom – quick fix – problem growth' type, such as the interrelated transport variables 'congestion – capacity – car use'. The potential problematic nature of increasing the capacity to fix issues of congestion, is that it could then lead to increased car use. This then aggravates the initial problem of congestion, resulting in a repetitive and non-progressive cycle occurring within this loop. Figure 1 demonstrates this idea; the positive polarity label indicates an increase in one variable as the variable at the start of the arrow increases, and the negative polarity label indicates a decrease in one variable as the variable at the start of the arrow increases.

The causal loop shown in Figure 1 can be included as a fundamental or archetypal loop within a detailed model of a broader transport system. The variables of congestion, capacity and car use have a significant influence on the feasibility of transport improvements, and the potential for reducing air pollution. The relative levels of these variables could also have a large impact on many others involved in a typical transport system, such as traffic rate, active travel use, and travel time etc.

2.3 Soft Systems Methodology

The use of Digital Twins, blockchain applications and other innovations developed in TwinERGY address sociotechnical problems that cross the boundary between human activity systems and engineering artefacts. These often involve many interested parties with different perspectives (world views), where ill-defined issues could cause difficulty in agreeing objectives (success requires stakeholder consensus). Being able to bring stakeholders on tha same page and allowing the development of common understanding of the challenges is therefore crucial.

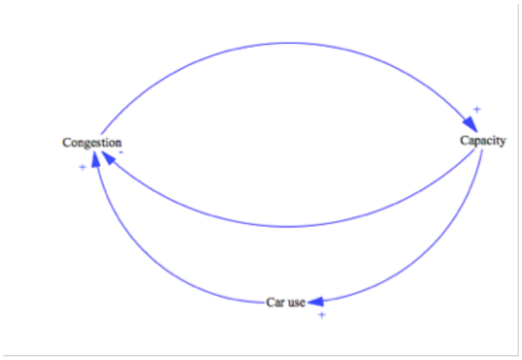


Figure 1: Causal loop diagram of the congestion–capacity–car use problem.

Several Systems-oriented methodologies could be applied to facilitate collaborative energy problem exploration and solving. They can be differentiated between those based on systems thinking (ST) and rely on diagramming and analysis, versus those that work in a systemic way and rely on action research and allow for emergence. Although many of these are flexible enough to be adapted to an energy-focused intervention, we will particularly adopt principles of soft systems methodology (SSM) as a method that integrates naturally with Systems modelling techniques. These include System Dynamics which has been selected for facilitating the Systems modelling of TwinERGY's interventions for the development of common understanding between involved groups of stakeholders. This is gradually developing through activities and relevant dissemination actions (academic publications, workshops etc.), broadly planned under the principles of SSM.

Checkland's SSM [6] is a ST method that establishes a learning system for investigating messy problems and enables practitioners to 'bring to the surface different perceptions of the problem and then structure these in a way that all involved find fruitful' [7]. It has been demonstrated useful for collaborative behaviour change within organizations.

SSM is an action-oriented process of inquiry in which stakeholders formulate a solution strategy from a systemic understanding of the problem situation and take action to improve it [8]. SSM has had considerable success as a problem structuring methodology and has been applied to learning systems [9] and information system design [10]. SSM addresses unstructured ('soft') problematic situations where there may be little consensus among stakeholders (even about the actual problem). SSM aims at accommodating different perspectives through conceptual models of human activity systems. These models are then used to decide on interventions for the resolution, or improvement, of the situation.

SSM focuses on the development of a conceptual model (a view of what could exist) with the aim to express stakeholder mental models

Table 1: N-Square diagram showing intra-system interactions within the Energy Management System of a building.

Energy Management	HVAC		•Increase conditions to the greatest values within a specified range which allows energy usage to be shed during peak hours.	•HVAC can 'outsource' a needed increase in temperature, without drawing more energy from the grid.
		Lighting	•Maximise the amount of natural light, to minimise the energy used.	•If more light is required, and the grid energy cost is high, generators can provide electricity, the heat from which can be used in the HVAC system.
			Electrical Load Shedding	
	•If high grid power cost occurs, then the heat from the generators can be fed into the HVAC system.		•Reduce need for grid power in HVAC system during periods of peak energy cost.	Cogeneration of Electricity

of the problem and gain consensus on objectives and issues. A problem may even disappear as the result of stakeholder consensus on a number of key issues. A concept model does not describe what exists but is modelling a view of what exists within a human activity system. When models are used in the design of information systems intended to support physical processes, a comparison between the models and the physical world is required. During SSM analysis, a 'soft' problem will be expressed to provide a perspective that can be considered a 'hard' problem to be solved by a variety of traditional methods. Checkland argues that SSM could be used to address systems engineering problems, as the ability of SSM to address 'soft' problems is akin to Operation Research which solves structured 'hard' problems [9]. SSM can be an iterative process to drive continuous improvement [11].

2.4 N-Square Charts

Decomposition into subsystem entities can facilitate handily the analysis of interdependencies, both in terms of identifying such and in designing for robustness. A simple but powerful technique to do this is to place all such entities on a diagonal and identify all item flows between them. Traditionally we can identify outputs in the horizontal dimension and inputs in the vertical. Then we can reorder these to group tightly coupled elements (i.e., where there is heavier interaction occurring). In this way, nodes of interest (critical functions, nodal points etc.) become clearer to identify. Key environment for energy use in the context of TwinERGY is the domestic and commercial built environment.

For example, in modelling a building as a system, a N-Square diagram exploring the interdependencies of four key energy management subsystems (HVAC, Lighting, Electrical and potential cogeneration) could look like Table 1 [12].

3 MODELLING TWINERGY TESTBEDS AS SYSTEMS

Systems modelling methods and techniques as described here can provide advanced insights into complex issues. We utilise the techniques throughout the project to understand the developing dynamics and impacts of TwinERGY's interventions. The first step however is to develop *archetype* systems capturing the essence of TwinERGY's testbeds. To that end we will use causal loop diagrams (CLD) to model the participant household testbeds, working collaboratively with local pilot partners and selected pilot participants, in order to co-develop models built upon common understanding of the system and its interdependencies.

Key environment for energy use in the context of TwinERGY is the domestic and commercial built environment.

- Within the system boundary there are five main categories of components:
  - people (consumers/prosumers),
  - energy service demand (need for warmth, light, motor power, etc.),
  - energy-using equipment that provides services (boilers, light bulbs etc.),
  - low-carbon energy generating or storage equipment (solar PV, CHP, batteries etc.), and intervention strategies (energy behaviour change, energy efficiency upgrades, etc).
- The SoI sits within the Operating Environment of wider society, made up of many components which affect how it operates, as well as providing inputs that allow the system to function. The outputs from the SoI are the emissions associated with energy use. This is the metric that typically most interventions seek to reduce.

At this level, a unit of analysis could be perceived the single household or organization, and the components of the system are of two types: hard or soft. Hard subsystems are the physical building(s) and energy using equipment in them; soft subsystems are the (one or more) collection of people that buy and operate that equipment. Presented here are ways to identify meaningful subsystems and some of the ST methods that could be used to work with them. Depending on use-case focus, the system boundary can be recognised around such unit (e.g., a single household) or a collection of households that form a community (and is built upon multiple collaborating units).

Development of basic testbed models and scenarios based on CLDs started with internal group meetings considering individual components and their interdependencies, e.g., a battery that is charged through a photovoltaic panel (PV) exposed to sunshine etc. Figure 2 shows a preliminary hand-drawn model on an online whiteboard during a hybrid meeting to consider the boundaries of the local testbed in relation to each household and the energy market.

In turn, this model produced a Systems Archetype (Figure 3) of our specific testbed, i.e., a basic manifestation of how the assembly PV/battery/TwinERGY will behave as an integrated system producing the desired effects. On this model, certain features have been recognised as input parameters (e.g., occupancy, level of sunshine, appliance efficiency) and others as interrelated variables that cause complex behaviour (e.g., PV generation, battery charge, consumption, grid imported energy and ultimately cost). In the scenario captured in Figure 3 we have assumed use of a simple fixed tariff (hence there is no input for the cost of a unit of energy). It is easy however to represent a variable tariff via the addition of another input representing unit cost (and affecting positively the overall Cost variable).

The TwinERGY logic is represented via the existence of the balancing loop between *Consumption* ↔ *Grid import* ↔ *Cost,* which causes the testbed to ensure measures are taken when appropriate (e.g., shifting demand, switching appliances off).

This simple archetype can then be used as a building block to model a series of more complex scenarios, e.g., the occasion where energy assets are shared between dwellings, or the peer-transactive operation of a local community energy scheme. The potential combinations are numerous allowing us e.g., to model the scenario where N households form a community but do not share energy assets, may be on different tariffs etc. We will not provide the entire range of such variations here, and they can be further developed in support of use cases when the latter are realised in our testbeds with the delivery of software applications.

Having developed the basic archetype, other model instances are easy to be considered and may include a community of an arbitrary number of N households join up in a virtual power plant transacting with the Grid, communities transacting between them and the Grid etc. We will continue identifying such scenarios and capturing them in simple CLD models through the project.

The models have been developed with the online CLD tool LOOPY [13], because the platform allows for sharing of a web canvas during a collaborative online session. Participants are able to see and share the models and to contribute to their development. LOOPY is also ideal to provide qualitative understanding of the effected behaviour of the modelled system, as it can run elementary simulations based on rough estimates of initial values for inputs (expressed as ballpark graphical 'quantities'). The visualisations include colour and movement and are therefore engaging for participants to understand, without burdening them with formalities of more formal simulation platforms.

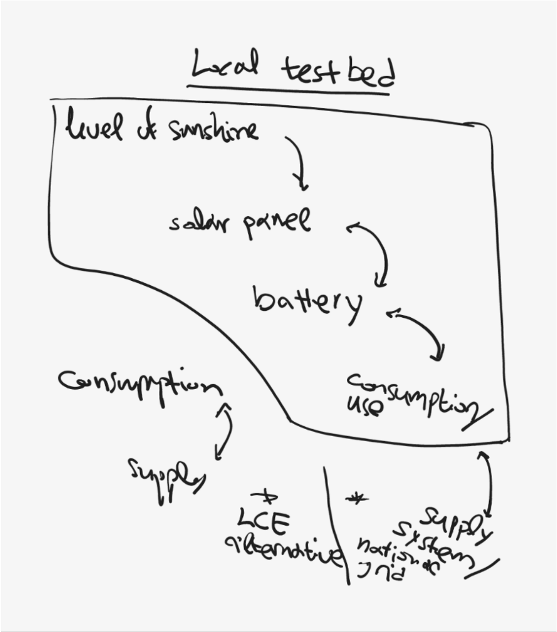


Figure 2: Collaborative online whiteboard sketch from initial hybrid group model building session.

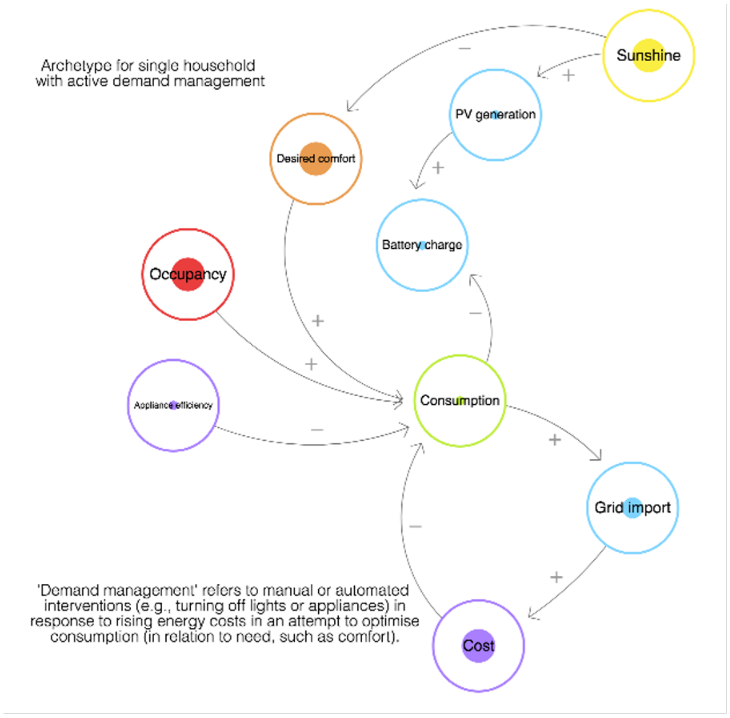
These simple but powerful CLD models have been initially developed and sanity-checked with the contribution of Bristol local partners and selected participants. With the completion of the testbed deployment phase and upon generation of operational data from the relevant system components (PV inverter, battery, smart plugs) of the TwinERGY platform, models will be further turned into stocks-n-flows in the Vensim modelling tool (more detail in [14]). This will give us the ability to run more accurate simulations based on the real-life data.

4 CONCLUSIONS AND FURTHER WORK

In this paper we introduce Systems Thinking and its related modelling practices as utilised in the context of project TwinERGY to model aspects of future energy systems, energy behaviours and anticipated impacts of project interventions. These techniques have been and will continue to be used in a collaborative setting through-life of the project, to allow project partners, participants and industry stakeholders to come together and develop a common understanding of related issues via group model building practices.

We adopted Causal Loop Diagrams, used through semi-structured interventions, such as workshops and 'action' case studies, i.e., impromptu experimentation with volunteering participants, planned under the general principles of the Soft Systems Methodology approach. CLDs offer an engaging way not only to partners but also to project participants to contribute to scenario building with regards to the use of innovations, as experienced through the local demonstration testbeds. The engaging graphical output of online tools like LOOPY allows for developing deeper insights and understanding jointly.

We also employ the technique of N-Square charting analysis, in order to understand better the interdependencies of subsystems, especially from an informational exchange perspective. By developing an initial N-Square diagram reflecting on Bristol's local testbed and applicable use-cases, the pivotal role of software modules of the project becomes clear, even across demonstrator sites. Indeed, a high-level instance of this model captures at broad scale interactions applicable to all pilots.


Archetype for single household with active demand management

'Demand management' refers to manual or automated interventions (e.g., turning off lights or appliances) in response to rising energy costs in an attempt to optimise consumption (in relation to need, such as comfort).

Figure 3: Bristol Pilot's TwinERGY testbed System Archetype, developed as a CLD model of participant households.

In the future, other Systems Thinking approaches will be considered including the Multi-Level Perspective approach [15] for evaluation of impact of key outcomes and whether these could shape market paths (e.g., as impactful innovation does). We also plan to investigate the use of the Viable System Model, a cybernetic approach for the modelling of organisations [16], for a more elaborate 'un-packaging' of the subsystems featuring along the N-Square chart in a way that would allow interdependencies at lower levels to become clearer when the pilot set ups are fully operational.

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