TOWARDS SOCIAL DIGITAL TWINS – AN INTEGRATED SOCIOTECHNICAL APPROACH FOR THE URBAN ENERGY TRANSITION

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The urban energy transition is crucial for a sustainable future. To support this transition, Digital Twins are employed in an increasing fashion, providing decision makers with data-driven insights from mainly technological perspectives. Based on a case study of a neighbourhood in a Dutch municipality, we argue the need to address social perspectives more explicitly while employing Digital Twins. To this end, we identify three potential strategies for an integrated socio-technological approach for Digital Twins. These strategies are modelling social characteristics at a macro-economic scale, involving stakeholders in participatory approaches, and finally explicitly modelling stakeholder behaviour. Given its promise for our case study, we elaborate this last strategy with a conceptual method that aims to explicitly model citizens' decision-making processes through an agent-based modelling approach.

Keywords:
digital twin, urban digital twin, energy transition, simulation, socio-technical

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1 Introduction

Aligned with the 2015 Paris Climate Agreement (United Nations, 2015), The Netherlands has set targets to reduce greenhouse gases by 49 per cent by 2030 relative to 1990, aiming for a carbon-neutral energy system by 2050 (Government of the Netherlands, 2019a). To achieve the set targets, the Dutch government has defined the general energy transition guidelines in the Climate Agreement (Government of the Netherlands, 2019a), emphasizing that a collective effort from Dutch residents is needed to undergo an energy transition. The Dutch government has therefore chosen for a decentralized approach, where municipalities play the lead role in coordinating and supporting citizens within cities for the energy transition. Municipalities are therefore responsible to design and implement specific plans for their own city as defined in the Regional Energy Strategy plan (Government of the Netherlands, 2019b).

1.1 Urban Energy Transitions with Citizen Insights

To facilitate urban energy transitions, municipalities are already taking actions, for example implementing subsidies to make the shift financially manageable for energy users (Association of Dutch Municipalities (VNG), 2023). Despite these efforts, achieving public participation and engagement remains a challenge. Numerous barriers impede the energy transition, including gaps in knowledge and understanding of the process, conflicting interests and preferences among stakeholders, and challenges that extend beyond technological and financial constraints (Dorenbos et al., 2020).

The sustainable energy transition involves a complex interplay of interests among various stakeholders, where their objectives may sometimes align, and other times, diverge. Among the key stakeholders, municipalities could exhibit interests that significantly differ from those of local citizens (Buana et al., 2023). Municipalities may prioritize societal economic development, infrastructure improvements, and broader environmental goals set by the government. Whereas citizens prioritize personal benefits, with minimal regulatory and administrative burdens (Deng et al., 2023), and direct impacts on their daily lives, such as energy costs and savings (Bellos, 2018), ease and comfort (Wang et al., 2020), and potential property value enhancement (Selvakkumaran & Ahlgren, 2019).

The mismatch of interests between municipalities and citizens could create challenges in fostering engagement in sustainable energy initiatives. This underscores the imperative for local governments to incorporate a more nuanced understanding of the socio-psychological dimensions underpinning citizens' behaviour, ensuring a more holistic and effective approach to the sustainable energy transition process.

1.2 Digital Twins for Urban Energy Transitions

Employing a Digital Twin approach to model a neighbourhood's energy system (including buildings and technical installations) appears to be a promising strategy to support urban energy transitions. Digital Twins allow stakeholders to explore various scenarios with changing conditions and interventions in a digital world that is closely connected and linked to the real world including the physical living environment and people who live there, to finally support their decision-making processes.

The concept of Digital Twins is broad (Lehtola et al., 2022) and requires a further definition. In many industries and domains, the concept of Digital Twins has been employed. For example, a building's energy system (C. Li et al., 2023), the traffic situation on a highway (Saroj et al., 2021) or the status of a fleet of trains (Dimitrova & Tomov, 2021). In these situations, the concept is mainly employed to measure data from tangible real-world phenomena using various sensors to bring real-world data to a digital representation. Subsequently, the digital representation might also control actuators in the real-world system, to adjust or change its operations.

With a Digital Twin approach, various scenarios towards a more sustainable energy system can be explored. However, in these types of transitions, stakeholders, such as citizens, play a much more prominent role compared to when a Digital Twin is employed to monitor e.g. a fleet of trains. In our view, this requires a digital representation of these actors, their beliefs, capabilities, and decision-making strategies.

1.3 Research Objective

Currently, it is still challenging to model a complex system, particularly one that incorporates human elements (Wan et al., 2019). We aim to provide a stepping stone for this challenge in the context of urban energy transitions by exploring the following research question in a Dutch context:

> *"How to incorporate social perspectives of citizens in Digital Twins that model the technical aspects of neighbourhood energy transitions to improve decision-making on urban energy transitions for e.g. municipalities and citizens?"*

In this paper, our objective is thus to outline relevant methods that can be used to capture, understand, and potentially steer social decision-making dynamics in sustainable energy transitions.

We acknowledge the argument that in a most truthful implementation to the concept, a Digital Twin should rely on (near) real-time data and control (Jafari et al., 2023; Sepasgozar, 2021), although others do not view real-time data as mandatory (do Amaral et al., 2023). In this work, we employ the notion of Digital Twins with an aim to achieve an accurate and truthful digital representation of our system-of-interest. This representation also entails monitoring and control, but on a longer time scale of e.g. policy implementations and subsequent monitoring of developments in a neighbourhood.

The focus of this work towards the Digital Twin concept is however aimed at the simulation aspects of the virtual model in a Digital Twin. We explore how to model and simulate both technical and social aspects in a single approach, expanding the potential application area for Digital Twins. Especially, this application provides a holistic view and supports strategy formulation, planning, and decision-making processes for energy transitions.

1.4 Paper Outline

In section 2, we discuss our case study and research approach. Section 3 presents further background to the social perspectives that we intend to address. Section 4 dives into the state of the art of Digital Twin modelling in urban, energy and transitional contexts. In section 5, we outline how these social perspectives can be included in Digital Twin approaches, resulting in "Social Digital Twins". Finally, a discussion and conclusion are presented in section 6.

2 Methodology

This section outlines our methodological approach. The context of the research through a case study is presented in section 2.1. Following this, our research approach is explained in section 2.2.

2.1 Case Study Background

The specific area that is subject of the research project "Sustainable and Social Local Energy Systems" (Hogeschool Utrecht, n.d.) is the "Heuvel-Amstelwijk" district in the city of Leidschendam-Voorburg in the Netherlands. This neighbourhood can be characterized as a relatively low-income and multi-cultural area with a large share of high-rise apartment buildings (Alle Cijfers, 2024).

On a strategic level, the general action plan of the city has been outlined in the document Transition Vision Heating (Municipality Leidschendam-Voorburg, 2021) as part of Regional Energy Strategy (Government of the Netherlands, 2019b). It has been identified that each neighbourhood could require different approaches and that the choice for each approach depends on several factors, among which technological, financial and organisational (Municipality Leidschendam-Voorburg, 2021).

2.2 Research Approach

To uncover relevant social perspectives, which are presented in section 3, we employ a three-fold approach. This approach is based on both previous and forthcoming work in the context of our wider research project and aims to gives context for subsequent sections in this work. The first part of the approach consists of a qualitative literature review. Secondly, we have employed a coded-interview approach with various relevant stakeholder. The subsequent analysis and results are published in previous work (Peng, 2023) and have enriched the discussion presented in section 3. Lastly, we distributed surveys among residents. Data acquisition in the survey is still ongoing but preliminary insights are used in a qualitative manner in this work.

To assess the current state and usage of Digital Twins for urban energy transitions we have employed a literature review in section 4 with the following keywords "Digital Twin" or "Digital Twinning" and “District” or “Urban” or “Neighbourhood” or “Neighbourhood” and “Energy System” or “Energy Transition”. We have compared various scientific databases from 2015 until now and determined that Google Scholar delivered the most extensive results (n = 293). We then performed a qualitative analysis of these results and present the most relevant results in section 4.

Section 5 then discusses the inclusion of social perspectives based on a qualitative literature review using the terms “Socio-technical” or “Social” and “Digital Twin” and “Energy Transition”.

3 Social Perspectives for Digital Twins

Financial considerations (Bellos, 2018) and environmental concerns (Selvakkumaran & Ahlgren, 2019) are commonly recognized factors influencing individuals' energy consumption decisions. Research from the fields of economics and psychology indicates that behavioural interventions are an effective tool that can significantly reduce the energy consumption of private households (Andor & Fels, 2018). Consequently, it is crucial to explore and elucidate how social behavioural factors impact residents' energy decisions. Research has revealed that in addition to individual personality traits (Selvakkumaran & Ahlgren, 2019; Tanveer et al., 2021), social factors such as peer effects (Palm, 2017; Wolske et al., 2020), social norms (Tanveer et al., 2021), social altruism (Selvakkumaran & Ahlgren, 2019), concern for own children and others (Ataei et al., 2021; Wang et al., 2020) could all potentially impact one's behaviour and decisions in sustainable energy adoption and usage.
While these social factors may function as direct predictors and motivators for decision-making (Ataei et al., 2021; Selvakkumaran & Ahlgren, 2019), another perspective is that their influence goes beyond direct causation, serving instead as complex moderating and mediating variables in the decision-making process. It is conceivable that an individual's environmental concern might be influenced or moderated by social factors. In other words, a person's interest in environmental

issues and willingness to adopt sustainable energy solutions can be shaped by their social surroundings.

To include these varied perspectives in a full approach for urban energy transitions, Kourtit et al. (2023) advocate the use of a five-dimensional model, which includes hardware, infoware, finware, socioware and software. Translating this to our case in the Heuvel-Amstelwijk, the hardware represents the building stock and energy systems. The infoware dimension captures the perceptions and preferences of inhabitants. The finware dimension addresses financial viability, which is a challenge in this generally low-income neighbourhood. The socioware dimension comprises social interactions such as common energy initiatives. This links for example to the complex decision making of owners' associations in the many apartment buildings in the district. These decision-making processes have been recognized as a significant inhibitor of the energy transition in the Netherlands (RTL Nieuws, 2024). Finally, software relates to advanced tools to monitor and guide the urban energy transition, which in our case is the development of a Social Digital Twin. The related work of Nijkamp et al. (2023) presents a participatory concept with a diabolo model in which an energy broker acts a mediator between citizens and government. In this process, they argue that "*the use of modern advanced statistical and digital research and visualisation tools seems to be indispensable for successful urban energy transitions*" (Nijkamp et al., 2023, p. 14).

4 Current Advancements in Digital Twins

Given the sentiment expressed by Nijkamp et al. (2023) in the previous section, it is a logical next step to outline the role of Digital Twins in this process. The use of Digital Twins is growing in the field of urban energy transitions (Strielkowski et al., 2022; Weil et al., 2023). In this work, we focus on applying Digital Twins to facilitate decision making in urban energy transitions. Based on this focus, we present our findings in three perspectives. These perspectives are Urban Digital Twins (4.1), Energy Digital Twins (4.2) and finally, Digital Twins for strategic decision-making (4.3).

4.1 Urban Digital Twins

Weil et al. (2023) present a comprehensive literature review identifying a wide range of challenges for Urban Digital Twins (UDTs). UDTs collect information from a wide array of sources to cover a multitude of relevant aspects in an urban context, such as transportation, energy, water management, crowd management, noise pollution and climatology (Alva et al., 2022; Lehtola et al., 2022). In certain developments, the aim is even to offer an open data ecosystem for urban data (Cureton & Hartley, 2023). Caprari et al. (2022) present several Digital Twin implementations that utilize urban Digital Twins in the context of urban planning and conclude among others that although participatory approaches are employed, further work is needed for a full representation.

Weil et al. (2023) also highlight that UDTs are not only for decision-making support but also for fostering trust between public and governance. A main and prevalent concern is ongoing lack of proven effectiveness in decision-making, particularly for long-term planning and decisions in the context of dynamic changes. In this sense, one could argue that a neighbourhood energy transition falls in this category of being both long-term and dynamic.

Finally, Nochta et al. (2021) raise the notion that UDTs represent a "paradigm shift in urban modelling", since more abstract models are exchanged for exact mirrors of the physical system.

4.2 Energy Digital Twins

The energy system is one of the key infrastructure elements of a smart city and often the singular focus of Energy Digital Twin (EDT) implementations (Martinelli, 2023). Ghenai et al. (2022) identify a growing interest into Digital Twins in the energy sector. Current EDTs are often used to monitor systems and determine optimization strategies (Bortolini et al., 2022; Ghenai et al., 2022; B. Li & Tan, 2023). B. Li & Tan (2023) conclude that a real-time Digital Twin approach enables faster and more accurate prediction of system performance. The increased availability of smart meter data further accelerates this process (Bayer & Pruckner, 2023; Martinelli, 2023).
A systematic literature review of EDTs presented in the work of do Amaral et al. (2023) identifies the most common approaches to model the system as numerical

methods and data-driven (machine learning) approaches. They also identify several advantages, issues, and opportunities in the application of EDTs. One of the opportunities is *"Handle with multi-objective problems, considering the divergent stakeholders' interests"* (do Amaral et al., 2023, p. 12). However, the work does not delve into specific examples of these divergent interests. Bortolini et al. (2022) have conducted a review for EDTs focusing on building energy efficiency and identified a relatively small number of publications, indicating that this field is still novel. Their findings highlight four distinctly different application goals of EDTs, being design optimization, occupant comfort, building operation and maintenance and energy consumption simulation.

Specific implementations of EDTs are for example developed for a combination of PV installations, EV charging systems, battery storage systems, heat pumps, heating grids or smart meter data (Agostinelli et al., 2022; Bayer & Pruckner, 2023; Zinsmeister & Perić, 2022). EDTs with a focus on optimal energy price discovery or energy trading are also being explored (Andriopoulos et al., 2023; Dulaimi et al., 2022; Fathy et al., 2021; Tsado et al., 2022). Another angle is to uncover energy demand, e.g. at district level (Huang et al., 2022; Rovers et al., 2022), to provide smart grid control (Mourtzis et al., 2022) or to assess the sustainability of an area (Calabuig-Moreno et al., 2022).

4.3 Digital Twins for Energy Transitions

Lesnyak et al. (2023) categorize the application scale of Digital Twins in urban energy transitions into three levels: building, campus, or urban. In this work, we focus on a neighbourhood level, which can be characterized as a large campus. Lesnyak et al. (2023) also discuss that for energy transitions and heating transitions several challenges remain. At the building level the objective is to address the heterogeneity of individual housing units, questioning the feasibility of a one-fits-all approach. At a campus or neighbourhood level, the objectives shift to integrating outcomes from the building level to enhance energy system operation, utilize predictive maintenance, and facilitate proof-of-concept for proposed solutions. This latter aspect is most relevant for our work.

Bocullo et al. (2023) provide a concrete example of a neighbourhood level approach where a Digital Twin of a city block is developed and subsequently simulated to evaluate various renovation scenarios. They state that "*the concept of a Digital Twin in deep renovation is a novel approach*" (Bocullo et al., 2023, p. 3) and it serves a more holistic view on a renovation process. They evaluate scenarios comprising various renovation packages that utilize different technologies, and within those scenarios, they compare two alternatives with varying heat and electricity prices. However, Bocullo et al. (2023) do not elaborate on the context in which this design approach is applied. Similarly, HosseiniHaghighi et al. (2022) offer a comprehensive solution for evaluating energy transition scenarios using an extensive UDT approach, delivering detailed models of the housing stock. Through abstract modelling of the energy systems, they evaluate various energy system scenarios. However, they do not consider social perspectives in decision-making to select specific energy systems, so in that sense it remains a solely technical, although very impressive, exercise.

Piaia and Frighi (2022) provide insight into application context with a social-technical approach, that includes monitoring health, comfort and wellbeing of residents. Piaia and Frighi (2022) suggest a six step approach based on (1) doing a baseline analysis case study, (2) modelling the baseline case, (3) simulating to test and monitor different design scenarios, (4) decision-making, (5) employing a multi-criteria decision-making (MCDA) approach to determine thresholds of interventions, and (6) employing a the Digital Twin as a guideline for the ongoing energy transition. In the sixth step, the Digital Twin could be employed to for example guide residents in learning about the effect of their behaviours, or to monitor progress of the transition (Calabuig-Moreno et al., 2022). They also note that the energy (or sustainable) transition cannot be seen separate from the digital transitions, referring to the concept of the 'twin transition/transformation' (Fouquet & Hippe, 2022; Graf-Drasch et al., 2023) or 'dual transformation' (Kürpick, Kühn, et al., 2023; Kürpick, Rasor, et al., 2023).

5 Towards Social Digital Twins

As stated in section 3, an urban energy transition involves a multitude of stakeholders. Therefore, it is key to ensure a relevant representation and involvement of those stakeholders in their decision-making processes, and thus also in the Digital Twin designed to support these processes. Wan et al., (2019, p. 23) state that "*system-*

level optimization, though being the explicit purpose of some Digital Twins in the engineering sphere, may not be an effective approach to address "wicked" urban problems". They further argue that Digital Twin developers who typically have technical expertise are not equipped to address non-technical factors, therefore diminishing the meaningfulness of the subsequent model-based optimizations. We therefore propose a Social Digital Twin which can provide a municipality an overview of both social and technical variables that influence the urban energy transition.

5.1 Social Perspective Inclusion Strategies

Based on our literature review, we have identified three strategies to include a social perspective in Digital Twins and will discuss these below.

The first strategy addresses social characteristics at a macro-economic scale. For example, Savage et al. (2022) explore social inequality within the energy transition. Yossef Ravid and Aharon-Gutman (2023) introduce the concept of a Social Urban Digital Twin (SUDT) and highlight the lack of social considerations in smart city developments. Their implementation allows for the analysis of detailed demographic characteristics, such as the accessibility of amenities for certain demographic groups.

The second strategy engages residents and other social actors through a participatory approach. With respect to stakeholder involvement, Cureton and Hartley (2023) discuss the use of various user interfaces (VR, apps) within a City Information Model (or UDT). They conclude that virtualization and gamification of these models are "essential areas to build the socio-technical relationships". In addition, Cureton and Hartley (2023) state that such a model "requires the engagement of stakeholders in the schematic design of these systems, including providing suitable training to attain the new opportunities described above".

The third strategy includes explicit modelling of the behaviour of these actors. Andriopoulos et al. (2023) propose a Consumer Digital Twin (CDT) that models a "human-oriented, simplified virtual replica that represents the entity of an electricity consumer". For each consumer or user, preferences can be indicated through a user interface for various energy appliances. Subsequent results can be presented in a consumer-oriented Digital Twin dashboard.

Given our case study, we would characterize the abovementioned first "macro-economic" strategy too superficial for a comprehensive understanding of decision-making processes. A deeper insight into decision-making and relevant behavioural characteristics of decision makers is essential. This, in principle, requires an additional layer on top of the Digital Twin information system that models the behaviour of these actors, as proposed in the third strategy. Of course, a blend between these strategies might be feasible as well.

5.2 Conceptual Implementation Approach

To enable a Digital Twin approach that supports decision-making, we follow the strategic approach offered by Nochta et al. (2021), who identify three key aspects that should be addressed.

Firstly, it should be possible to translate high-level policy goals into practical policy challenges for which potential solutions can be developed. In the case of Leidschendam-Voorburg, the municipality aims to transition neighbourhoods from gas-based to renewable energy systems. However, to support the day-to-day execution of the energy transition, it is crucial to provide information and guidance to residents, owners' associations, and other energy renovation decision makers about specific renovation options suitable for their energy systems and housing situation. The model should include factors for municipality decision-making, such as their own prior decisions, stakeholder disposition and relevant local events, in addition to the more traditional "technical" state and renovation options for the neighbourhood. Furthermore, the model should provide concrete recommendations on where they can act, like subsidy support, information campaigns, timing of decisions, stakeholder engagement, and setting sustainable performance goals (KPIs), etc.

Secondly, it is important to reflect the local governance structures appropriately. In our context, this entails accurate understanding the decision-making processes of the involved social actors. We suggest moving beyond traditional rational and individual decision-making and instead acknowledge the complex decision-making processes involved in e.g. owners' associations by explicitly modelling a more complex group-based decision-making processes for those associations.

Thirdly, they argue that it is necessary to address both individual and organizational learning. A solely technology-focused approach often lacks human centricity, overlooking the diverse needs of individual and organizational (group) learning required to adopt and integrate CDTs into policy decision-making structures and processes. The municipality needs to learn how to apply these tools to encourage citizen participation in the process, understand how individuals interact, influence, and change their behaviour within the complex system, and facilitate this evolutionary process towards a collective sustainability goal at a macro level.

Our intent is to implement this strategic approach into a simulation environment that utilizes a characterization of the built environment and its energy systems combined with an agent-based model that simulates people's actions to understand their behaviour change in transition scenarios. We aim to characterize the agents in the model by abstraction of both quantitative and qualitative survey data among involved stakeholders into an actionable decision-making model. To this end, we build upon our previous approach (Haveman et al., 2020), which is based on the prevailing notion that "*the agent-based approach is found to be uniquely suited for the complex adaptive sociotechnical systems that must be modelled*" (Hoekstra et al., 2017). The basis of the decision-making model employed in our approach is the Theory of Planned Behaviour (Ajzen, 1991), which provides a widely understandable reference to understand decision-making and ultimately the social dynamics of an urban energy transition.

6 Discussion & Conclusion

This work has given an outlook on potential strategies to include social perspectives in decision-making for urban energy transitions when employing Digital Twins. We have discussed three areas within the field of Digital Twins, being UDTs, EDTs and the usage of Digital Twins in energy transitions in general. This discussion provides an applicable background for extending urban energy transitions with social perspectives. We identified and discussed three strategies for incorporating social perspectives and elaborated the most relevant approach for our case study involves explicitly modelling decision-making through agent-based representations.

In this discussion, we would like to note that in general, when working with Digital Twins, data security and privacy are relevant themes to consider (Yossef Ravid & Aharon-Gutman, 2023). This will of course be only more prevalent when working with social perspectives that include more "social data".

This work is part of an ongoing research project, and future work in the project aims to further elaborate, verify, and validate the approach in our current case study as well as in potential other case studies.

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