Integrating Urban Digital Twins and Agent-Based Models for Strategic Grid Expansion in Evolving Urban Energy Networks

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***Abstract*—Efficient planning of energy supply networks is crucial for communities and energy suppliers. We present an innovative toolchain that assists distribution system operators (DSOs) in modelling current and future building energy demands using a data-driven approach. The toolchain integrates detailed building data with agent-based modelling to assess the temporal evolution of each building's energy characteristics, such as envelope quality and heating systems. It consists of three main components: an urban digital twin model, an agent-based refurbishment decision model,and a district heating model. The urban digital twin comprehensively represents buildings' technical attributes and owners' economic and socio-demographic factors. The agent-based model simulates future energy demand by considering building owners' refurbishment decisions and their willingness to invest. With a focus on heat pump adoption, the toolchain helps DSOs anticipate increased electrical loads and evaluate district heating options. A case study in Aalen, Germany, demonstrates its effectiveness.**

***Index Terms*—Agent-based modelling, Urban Digital Twin, District Heating , Building energy demand**

I. Introduction

The decarbonisation of the heating sector necessitates advanced planning of energy supply networks. Distribution system operators (DSOs) face the challenge of creating accurate models to predict energy demand in residential buildings, considering the diverse nature of building structures, ownership, and individual behaviours. To address these complexities, we introduce an innovative toolchain that integrates detailed building data from an Urban Digital Twin with agent-based modelling. This integration allows for a precise assessment of the temporal evolution of building energy characteristics, facilitating data-driven determinations of current energy demands and projections of future developments based on refurbishment decisions. The toolchain comprises three core components: a highly detailed Urban Digital Twin model (UrbanTwin), an agent-based refurbishment decision model (AgentHomeID), and a district heating model. The Urban Digital Twin serves as a detailed digital representation of buildings, incorporating both their technical attributes and their owners' economic and socio-demographic characteristics. The agent-based model builds on this foundation, projecting future energy demand by simulating how building owners make refurbishment decisions and assessing their willingness to invest in energy-efficient technologies. The district heating model not only assesses network expansion feasibility but also sets boundary conditions for the agent-based model, identifying buildings eligible for district heating connections. A key aspect of the toolchain is its focus on heat pump adoption, allowing distribution system operators (DSOs) to anticipate rising electrical loads and explore district heating solutions.

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II. State of Art

The integration of new electricity consumers and producers into distribution networks has been extensively studied in the literature. Research such as Love et al. [1] and Navarro-Espinosa and Ochoa [2] examines the impacts of heat pumps on distribution grids, while studies such as Richardson [3], S. Alshahrani et al. [4], and Agora Verkehrswende [5] focus on the effects of electric vehicles. Additionally, the integration of rooftop photovoltaic systems and their implications for grid stability are addressed in Anaplan PV [6].

In recent years, the combination of Urban Digital Twins (UDTs) and Agent-Based Models (ABMs) has gainedtraction, offering significant potential for urban planning and strategic grid expansion. UDTs provide a realistic virtual representation of urban environments, enabling the simulation of complex urban processes. When integrated with ABMs, which model the behaviour of autonomous agents, these tools offer a deeper understanding of dynamic urban phenomena and support informed decision-making.

Abbasabadi and Ashayeri [7] explore the development of Digital Twins for city-wide energy modelling and management, emphasising the role of UDTs in understanding urban energy flows and reducing carbon emissions. Their study highlights the importance of incorporating socio-economic data into digital twin frameworks to refine energy demand modelling and better account for consumer behaviour. Similarly, Værbak and Billanes [8] designed a Digital Twin framework to effectively simulate Distributed Energy Resources (DERs) within distribution grids. Their framework consists of four key modules: DERs, the electricity distribution grid, the energy management system, and consumers. This structure facilitates comprehensive simulations of grid topologies and demand-side management, contributing to more efficient and resilient energy distribution systems. Collectively, these studies illustrate the transformative potential of combining UDTs with ABMs in urban energy planning. By leveraging high-resolution data and simulating individual behaviours, this integrated approach provides a wide framework for analysing current urban dynamics and predicting future developments. These methods are particularly relevant for Distribution System Operators (DSOs), as they enable more accurate modelling of energy demand evolution and incorporate detailed socio-economic and behavioural factors into infrastructure planning. This is especially pertinent in light of recent regulatory developments in Germany (EnWG §14d) [9], which demand more precise and data-driven planning methodologies.

III. Methodology

In this section, we present the toolchain developed in this study, which integrates an Urban Digital Twin, agent-based modelling, and district heating modeling to support strategic grid expansion planning. As shown in Fig. 1, the methodology captures the current state of the building stock and simulates its future development, considering district heating network development. To represent the existing building stock, various data sources are combined within the Urban Digital Twin model. This model provides a very detailed representation of the building physics of residential buildings at the individual building level. Moreover, representative surveys and census data further refine the digital building representation, creating a comprehensive digital cityscape that offers insights into both building energy consumption and residents' demographic and economic characteristics.

Building on this digital cityscape, we employ the agent-based model AgentHomeID to simulate the temporal evolution of renovation and heating technology decisions. A key factor shaping the future development of the building stock is the role of district heating and local heating systems. In order to accurately capture the complex interplay between central energy suppliers (e.g. municipal utilities) and individual building owners, we integrate district heating modelling. Combined

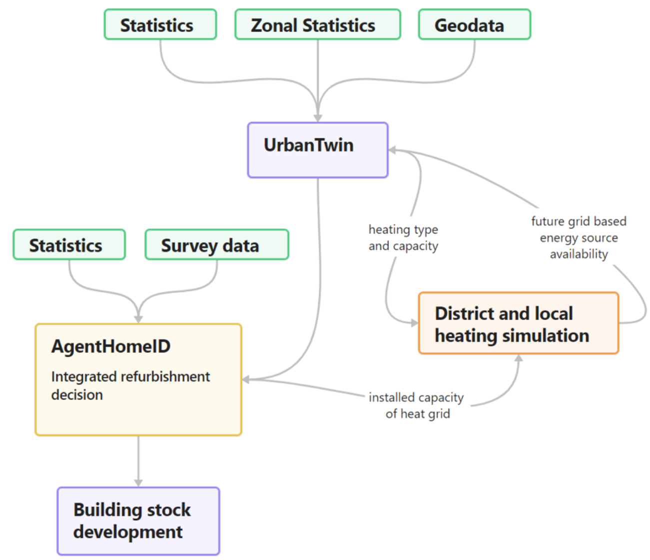

Fig. 1. Flow chart of the modelling pipeline.

with the agent-based framework, this approach enables the improved identification of future district heating areas.

A. Data

The basis of the proposed model chain is a diverse and comprehensive set of data sources that together provide a high-resolution understanding of the building structure, demographics, socioeconomics, and behavioural economics of its occupants. These data sets include geographic information, building physics, socioeconomic and demographic statistics, and regulatory frameworks. By synthesising these different data points, the model chain enables a detailed and dynamic assessment of the development of buildings over time.

The core of this analysis is based on high-resolution 3D building models that provide a detailed representation of urban structures and their physical characteristics. These models are enriched by additional geographical data. Information on building physics and census statistics thus contribute to a more detailed description of the buildings and their occupants and form the basis for understanding decision-making processes in relation to refurbishment and energy efficiency improvements. Legal and regulatory frameworks ensure compliance with national and local energy policies, while econometric surveys that capture property owners' willingness to pay help to predict investment decisions for refurbishment and heating technology upgrades. Table I provides a structured overview of the primary data sources used in this study. The integration of these datasets into the agent-based modelling and digital twin framework enables realistic simulations of the evolution of heating demand and infrastructure change, supporting strategic decision-making for energy-efficient urban development.

B. Urban Digital Twin (UrbanTwin)

The Urban Digital Twin represents a detailed digital reconstruction of the urban building stock, integrating geospatial

TABLE I
OVERVIEW OF DATA SOURCES USED FOR THE MODELLING APPROACH

Data Source	Description
3D Building Model	Level of Detail 2 (LOD2) model [10], provides geo-referenced 3D data for buildings, including building function
Geographical Data	Geo-referenced data: addresses data [11] and households and population Data [12]
Construction Physics	Scientific databases for building physics in residential structures [13]
Census Statistics	Census data: Scientific Use Files (2018) [14] and Grid-Based Census (2022) [15] linked with building information
Laws and Regulations	German laws (GEG [16], BEG [17], WPG [18]), energy pricing policies [19], federal subsidies, DIN standards for energy demand
Willingness to Pay	Econometric survey data assessing private owners' refurbishment investment preferences

and socio-economic data to enable precise energy demand modelling. This urban twin is derived by combining high-resolution 3D building models with additional geographic data sources. These data sources provide crucial insights into building structure, material composition, and thermal performance, forming the foundation for energy simulations.

To ensure a realistic representation of energy demand patterns, the Urban Digital Twin incorporates synthetic population reconstruction methods, and combinatorial optimization approaches. Synthetic reconstruction generates realistic populations by randomly assigning individual characteristics from the census statistics, while combinatorial optimization ensures that local demographic economic and building conditions are accurately reflected [20]. By leveraging detailed socio-economic and environmental data sets, this model enables highly precise infrastructure planning.

C. Agent-Based modelling (AgentHomeID)

Building on the UrbanTwin framework, our research employs AgentHomeID—an agent-based model that simulates homeowner investment decisions to project building stock development over time. The model classifies building owners into two main groups: private individuals and corporate entities, each operating under distinct decision-making mechanisms. Individual owners are modelled via a personal random utility approach, while corporate entities are assumed to optimise economically and are further segmented into private property companies, cooperatives, and public authorities. In contrast, private individuals—comprising landlords, owner-occupiers, and homeowners' associations—are characterised by empirical data that inform their respective willingness to pay, drawing on socio-demographic and economic factors such as income, gender, education, community size, and past refurbishment behaviour.

AgentHomeID also incorporates behavioural uncertainty, effectively capturing the variation in decision-making across owner types. The integration of willingness-to-pay surveys enhances the accuracy of investment simulations, ensuring realistic representations of owner responses to market changes. Moreover, the model supports scenario-based analysis, enabling DSOs to assess the impact of different policy instruments and economic incentives on the uptake of energy-efficient renovations.

Decisions within the model are triggered by critical events, e.g. changes in ownership or tenancy, maintenance needs, or new regulatory requirements, while continuously evolving factors, including cost trends, fuel prices, and policy updates, further influence investment behaviour.

By including various economic constraints and local regulatory frameworks, the model ensures that the simulated decisions align with real-world investment behaviours.

D. District Heating Model

The district heating model complements the Urban Digital Twin and AgentHomeID by assessing the potential expansion of district heating networks. It evaluates heating demand density, economic feasibility, and regulatory constraints to determine viable district heating areas. The approach incorporates:

- Spatial analysis of existing and potential district heating zones,
- Restricted areas (e.g. water protection areas),
- Demand clustering to identify high-potential expansion areas, and
- Policy-based constraints, such as municipal heating roadmaps and investment incentives.

As a foundation for grid expansion, we use the existing district heating network, which is primarily derived from Census grid cell data. The network is expanded using convolution with square kernels that adjust in size based on the scenario year. The expanded systems are then filtered using heat demand density as well as various restriction areas, such as water protection zones.

The district heating model operates iteratively with AgentHomeID, where initial results inform agent decisions on heating technology adoption. Buildings projected to connect to district heating networks are identified, and their impact on local grid infrastructure is assessed. The model also evaluates the potential for decentralised energy hubs, considering the feasibility of integrating large-scale heat pumps and cogeneration plants into district heating systems. Furthermore, it incorporates land-use planning data to ensure compatibility between proposed district heating zones and urban development plans.

To enhance spatial resolution, the model integrates high-resolution spatial data, improving the granularity of district heating expansion analysis. By considering multiple infrastructure development scenarios, it provides DSOs with a robust decision-making tool that balances economic, regulatory, and technical constraints in district heating expansion. Our integrated approach ensures a realistic representation of future heating demand distribution and its implications for strategic grid expansion. By combining Urban Digital Twin modelling, agent-based simulation, and district heating expansion analysis, the proposed toolchain provides a comprehensive framework for DSOs to make informed investment decisions in evolving urban energy networks.

IV. Results

The following sections present the results of the applied toolchain using Aalen, a mid-sized city in Baden-Württemberg, Germany, as a case study. The Urban Digital Twin provides an overview of the current status of the city's building stock and heating infrastructure, serving as the baseline for scenario-based expansion strategy. This strategy explore potential development paths for the years 2030 and 2040, evaluating how different policy measures and technological advancements could shape the energy landscape in the region.

A. City Structure (UrbanTwin)

In the region of Aalen, the UrbanTwin identified in the year 2020 17.046 residential buildings covering a total living area of approximately 24,83 km^2. The building stock consists of 2.781 multi-family homes, while the remaining structures include single-family and two-family houses, as well as terraced houses with one or two dwellings. The distribution of the primary heating energy source per household and the corresponding total heat demand were estimated based on the building typology as mentioned in Table I. The calculation of the usable floor space was derived from LOD2 building data. Information about which heating technology is used in which building is a result of the synthetic population reconstruction of the UrbanTwin. The results are summarised in Tab. II. The data highlights a continued reliance on fossil fuel-based

TABLE II
Actual Heat Demand by Energy Carrier in 2021

Primary Heating Energy Source	Number of Households	Total Heat Demand (GWh/a)
District heating	483	64
Gas	9952	941
Electric (without heat pump)	487	42
Heating oil	4592	423
Biomass/wood	1047	86
Heat pumps	465	36
Other sources	20	3

heating, with gas and heating oil remaining the predominant energy sources. Despite increasing efforts to transition towards sustainable heating, renewable options such as heat pumps and biomass remain underrepresented, and district heating, though available, has limited coverage.

The socio-economic and demographic structure of the population plays a crucial role in modelling future heating demand and investment decisions using AgentHomeID. Therefore, we summarise key population parameters for Aalen. The average age of household heads in Aalen is 47 years. Ownership patterns indicate that 9.587 buildings are owner-occupied, while 7.218 buildings are rented, and 241 buildings belong to homeowners' associations with at least one resident owner. The average monthly net household income ranges between 4.000 € and 4.500 €, with 38 % of the population holding an Abitur (higher education entrance qualification). These socio-economic factors influence renovation willingness and energy efficiency investments and were derived from the Census 2022 grid-cell data, the 2018 Microcensus Scientific Use File, and household statistics as mentioned in Tab. I. All data are stored and analysed within a geographical information system (GIS), with results aggregated for this study.

These findings provide a concise overview of Aalen's existing heating landscape, exposing the need for targeted energy efficiency strategies and the expansion of renewable heating solutions. The significant reliance on gas and oil presents an opportunity for policy-driven incentives to accelerate the adoption of heat pumps and district heating, thereby reducing carbon emissions and enhancing energy system resilience.

B. District heating

Based on the census data and the building structure, the simulated district heating expansion in Aalen is shown in Fig. 2. The dark blue areas indicate the existing district heating network, while the light blue to red gradient indicates heating demand. Hatched areas denote additional district heating potential identified for expansion in 2030 and 2040, respectively.

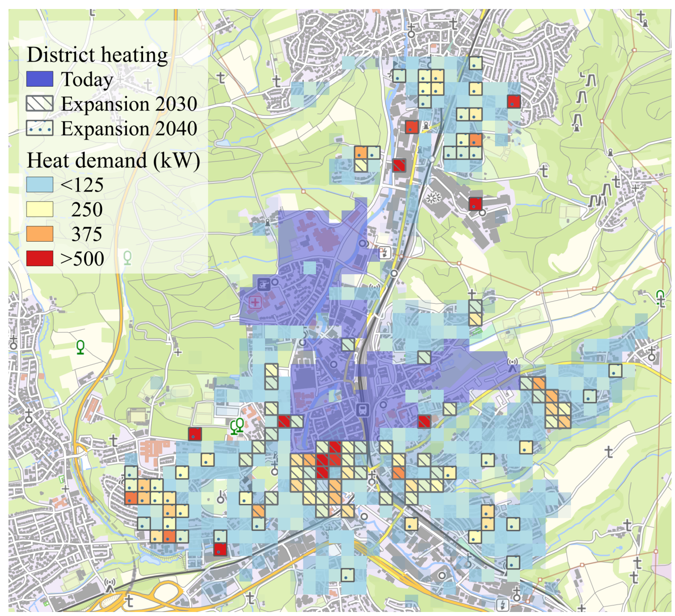

Fig. 2. Expansion of district heating potential

The extent of the current district heating is derived from city-provided data and, after aligning with the census grid, covers around 159 ha in the upper city center. The modelled expansion identifies a total potential of 450 ha by 2040. These areas were filtered with the heat demand of the encompassed buildings applying a threshold of 180 kW per census grid cell. With this approach, only cells with a sufficient demand are available in the agents' decision portfolio. As a result, the filtering process identifies 58 ha of additional potential areas by 2030 and 54 ha by 2040. Based on data-driven simulation outcomes, the process chain allows for the incorporation of supplementary constraints, expert assessments, and location-specific infrastructure planning decisions. This methodology was exemplified in the municipality of Aalen, resulting in a more conservative estimation of the district heating potential.

C. Building stock development according to AgentHomeID

Simulations with AgentHomeID yield a diverse range of outcomes that can be analysed in detail. Building owners' decisions regarding envelope refurbishment and system replacement form the basis for evaluating key technical parameters on an individual building level. These parameters include heating demand, final energy demand, system installation, CO_2 emissions, installed capacity, and the employed energy carrier, along with various cost parameters related to installation, fuel, and CO_2. Such detailed, building-level assessments allow for subsequent aggregation across different spatial scales—from individual settlements or neighbourhoods to the entire municipality—or grouping according to specific characteristics, such as owner type, building type, or building age class. This granularity enables a targeted analysis of trends, facilitating the early identification of critical developments within particular building types and owner groups, and thereby supporting the formulation of measures tailored to specific challenges and target groups.
As an evaluation example, the aggregated development of the technology shares of heating systems for Aalen is presented in Fig. 3. The stacked area chart illustrates the projected distribution of heating systems in residential buildings from 2020 to 2045. In Germany, a fundamental transition is taking place from fossil-fuel-based heating systems to renewable energy supply systems, driven by regulatory requirements governing system replacements. According to current legislation, any newly installed heating system must derive at least 65 % of its heat from renewable energy sources. However, there remains uncertainty regarding which renewable technologies will be adopted and at what pace the transformation will occur. Over time, fossil-fuel-based heating systems, including constant temperature, low-temperature, and condensing boilers, exhibit a significant decline after 2025. Condensing boilers, in particular, decrease sharply after 2035 and disappear entirely by 2040, in alignment with the City of Aalen's plan to decommission its gas network. Consequently, the remaining boilers are exclusively oil-based.
In contrast, renewable and high-efficiency heating technologies, particularly heat pumps (air-source and ground-source), experience substantial growth, emerging as the dominant heating systems by 2045. Biomass boilers also increase in prevalence, with some supplemented by solar thermal systems. While district heating expands slightly, its overall contribution remains limited in potential as described in the district heating section (refDH).
Overall, the Fig. 3 underscores the transition of Aalen's heating sector toward a predominantly renewable energy-based system by 2045, characterised by a significant shift toward air-source heat pumps and biomass boilers, while a residual share of oil-based heating systems persists.

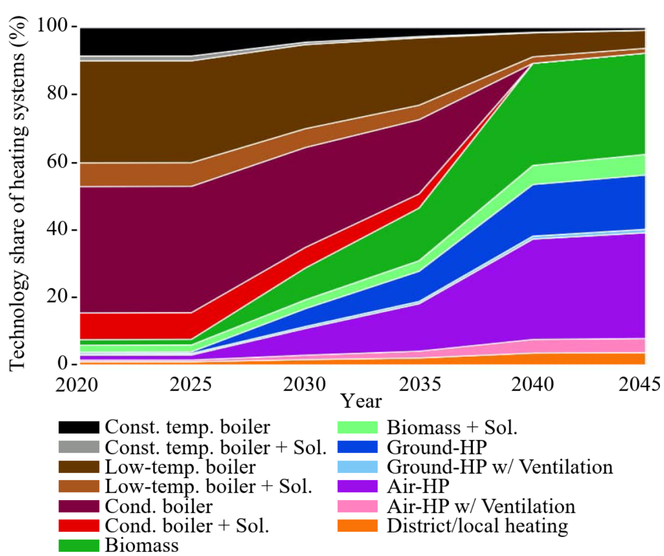

Fig. 3. Development of technology shares in the building stock over time.

V. Conclusion

We demonstrate the potential of integrating urban digital twins, agent-based modelling, and district heating modelling for strategic grid expansion in evolving urban energy networks. By leveraging high-resolution building data, socio-economic factors, and modelling refurbishment decisions, the proposed toolchain enables distribution system operators (DSOs) to effectively predict and plan future energy demand.

The case study in Aalen serves as a practical demonstration of the toolchain's capabilities, beginning with a detailed analysis of the existing building stock and heating infrastructure based on data from urban digital twins. This provides a sound basis for future energy system simulations. The results indicate a clear shift toward heat pump adoption and the expansion of district heating networks, driven by evolving energy policies and consumer preferences. For DSOs, the spatial distribution of heat pump systems is particularly critical, as it directly impacts electricity grid planning and load forecasting. The agent-based model offers valuable insights into the refurbishment and investment behaviour of individual households.

Future research should focus on enhancing the Urban Digital Twin by integrating data on the building refurbishment status to improve energy consumption modelling. The district heating model could be refined by incorporating economic boundary conditions such as energy price trends, investment incentives, and operating costs to enhance feasibility assessments. Additionally, the agent-based model should be continuously updated with real-world refurbishment trends and new survey data to reflect evolving consumer preferences and regulatory changes. Implementing these improvements will further enhance the toolchain's predictive capabilities, support data-driven decision-making, and enable more effective decarbonised urban energy infrastructure planning.

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