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A Digital Twin Approach for Sustainable Territories Planning: A Case Study on District Heating

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***Abstract*—**The energy planning process is a very complex task that involves several stakeholders and requires the consideration of several local and global factors and constraints. In order to optimize and simplify this process, we propose a tool-based iterative approach applied to district heating planning. We build our tool with the collaboration of a French territory using actual district data and implementing the European incentives. We set up an iterative process including data visualization and analysis, identification and extraction of information related to the area concerned by the operation, design of sustainable planning scenarios leveraging local renewable and recoverable energy sources, and finally, the evaluation of scenarios. The last step is performed by a dynamic digital twin replica of the city. Territory's energy experts confirm that the tool provides them with valuable support towards sustainable energy planning.

***Keywords*—**Climate change, data management, decision support, digital twin, district heating, energy planning, renewables, smart city.

I. Introduction

SUSTAINABLE development scenarios are encouraged with important incentives to avoid the worst consequences of climate change. Drastic reductions in carbon emissions and in conventional energy consumption are targeted by 2050. New clean energy technologies taking benefit from solar, wind, geothermal are more and more encouraged by governments and citizens. Actions to mitigate environmental impact must be implemented at several levels, including encouraging technological innovations and using low-carbon energy resources.

Territories are involved in the urbanization decision while being driven by the net-zero emissions objectives. At the same time, they need to be attractive targets for investors and industrials. Both objectives can be considered as antagonist if a sustainable system is not widely adopted. For this purpose, it is necessary to change the way of urban planning by integrating the energy supply at the beginning of the process [1], [2]. For instance, according to the International Renewable Energy Agency (IRENA), District Heating and Cooling (DHC) is a good candidate to be upgraded from the dominating fossil fuel to renewables (solar, geothermal, biofuel, etc.). In a recent report [3], 21 real case studies all over the world are examined to determine the renewable potential up to 2030. IRENA [3] argues that renewables could supply more than one fifth of the energy needed all over the world for DHC, in a secure, efficient and low carbon emission manner. The impact on the environment would be reduced and the air quality improved.

Despite the confirmed potential of renewables, only a few countries such as Denmark, Sweden, and Switzerland are pioneers in promoting renewable-based district heating. In order to accelerate the renewables adoption, more encouraging policies and incentives are being promoted by Europe. For instance, the European Commission requires an annual increase of at least 1.1% of renewable energy in District Heating [4]. Consequently, each European country implements these high-level objectives into local climate transition laws. For instance, according to the law on Energy Transition and Green Growth in France, the renewable energies will have to represent 38% of the final consumption of heat by 2030 [5].

Accelerating the wide adoption of renewable-based DHC requires strong actions from national and city policy makers and a good understanding and promotion of the benefit-cost of the renewable technologies in several use cases (extension, creation, updating energy technology, etc.).

The energy planning problem has been referred to as "wicked problem" [4]. Actually, this problem is characterized by the involvement of many actors with different interests, values and objectives, conflicting solutions, dynamic context and scientific, political and administrative complexities [5]. Furthermore, local and global parameters such as the offer, the demand, the industrial needs, the future projects, the renewable energies, the existing networks, the potential synergies with other infrastructures, the cadastral specification, etc., need to be considered. An effective energy planning raises the following issues:

1) Coordinate the views of different stakeholders on the issue at hand.
2) Identify and collect information about the area where you want to implement an energy strategy.
3) Determine current and future energy needs.
4) Characterize the potential of renewables and recovered energy that can be exploited to meet local demand.
5) Find the optimal balance between the energy demand of the identified area and the locally available renewable and recoverable energy sources.
6) Compare different competing solutions (e.g., insulation or heating).

In this paper, we support a French territory implementing the climate transition objectives. We propose a systemic and generic approach dedicated to efficient and sustainable energy planning. We implement our work atop of a modeling and simulation platform. More specifically, we present a use case of

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District Heating network creation in an area situated in a southern suburb of Paris. Our main objectives are to assist the city decision makers to create or extend the district heating systems while increasing the use of renewables. The objective of our solution is to reduce the time spent for energy planning and put clean and local energies in the core of the decisions. The tool provides decision-makers with KPIs to assess whether climate transition goals are being met in terms of emissions reductions, increasing in renewable energy, user satisfaction and costs.

The remainder of this paper is structured as follows. The next section presents some related work on decision support systems for energy planning in different cities around the world. Section III describes our tool-based approach for energy planning. The data collections leveraged in our decision support system are described in Section IV. Then, Section V is dedicated to the presentation of the Digital Twin. The software architecture and the description of our use case are presented in the Section VI.

II. Energy Planning Platforms

Digital platforms combined with expert knowledge are a powerful means of decision-support. The energy planning issue is a complex task because of its context-awareness and dependency to several aspects. Each country, city, district or area is subject to local and global demographic, climatic, geologic, geographical and political conditions. The aim of this section is to present some works that have been developed around the world towards sustainable energy planning.

"E-City" [6] is a web platform for planning energy balance applied in the city of Oeiras in Portugal. The objective is to assist decision-makers at the municipality level to define sustainable energy development strategies. For this purpose, the tool allows to explore the energy balance by articulating and visualizing energy consumption and solar energy supply for each zone.

SureCity [7] is a platform which aims to support cities to achieve their mid-to-long term sustainability objectives. The platform integrates urban policies and measures towards low carbon energy systems. It also provides the ability to create and visualize projects and scenarios. Several indicators are implemented, visualized and compared such as GHG emissions and energy efficiency performance.

In [8], the challenge of identifying suitable and eligible homes for energy improvement by retrofit measures is addressed. It is applied in the UK context as a data-driven geographical information system-based approach for quick and accurate spatial buildings identification. The goal is to bundle refurbishment actions to encourage mass deployment and reduce installation costs.

The authors in [9] propose an urban energy planning tool based on "GIS-BIM" (Graphical Information System, Building Information Model) system, which is able to provide the appropriate technical and policy solution to readjust city infrastructure. The proposed system has the following functionalities: leverage GIS based data, modeling the city, simulate energy conservation technologies and visualize the city in 3D. The case study concerns the city of Tokyo.

Our work exploits several collections of territorial data and facilitates their analysis, cross-referencing and visualization to implement a context-sensitive energy planning support system. In addition, we build our solution around a Digital Twin (DT) that allows real and live data provisioning. Furthermore, we enable our methodology to be extendable with artificial intelligence features including for instance prediction and optimization. The approach is applied to district heating upgrade, extension and creation.

III. Energy Planning Process

As discussed in the previous sections, the sustainable energy planning is a complex task. In order to make the best decision, the proposed interactive application helps the decision-maker to perform the following actions:

1) Visualization and analysis of the contextual data.
2) Identification, selection and extraction of relevant information about the area concerned by the operation.
3) Design of energy planning scenarios.
4) Evaluation and comparison of candidate scenarios.

A. Data Visualization and Analysis

In order to facilitate the contextual analysis, we mainly adopt cartographic visualization. Nevertheless, depending on the context, other types of visualizations are proposed. In order to display detailed information, we allow the navigability at the cadastral parcel level.

To improve the interaction with the tool, the available data sets are organized according to the following categories: territorial contextual information, energy consumption estimation, existing energy networks and local renewable energy potential.

B. Selection of the Zone

The selection of the area concerned by the operation requires the consideration of several parameters: the energy consumption estimation, the local renewable energy potential, the buildings thermal efficiency, the population density, the residential density, the city boundaries, etc. On the basis of the delimited geographical area, the application provides the user with a synthetic and detailed contextual information. This consolidated information is built thanks to several sources.

C. Design of Sustainable Energy Planning Scenarios

For the implementation of the scenarios, we are mainly based on the "EnR'CHOIX" methodology recommended by ADEME, the French Agency for Ecological Transition. This methodology gives guidelines whose objective is energy sobriety and efficiency, the grouping of requirements, the prioritization of local, recoverable and renewable energies for heating. The objective is to supply heat networks with renewable, recoverable and local energy. For example, in order to be exploited in the district heating, the source of waste heat must be in proximity of network [10].

According to the directive 2009/28/EC [11] of the European Parliament "geothermal energy means energy stored in the form of heat beneath the surface of solid earth". In order to use this resource in the form of heat, it is necessary to associate it with an extracting and a transfer device. In this context, the proposed application, powered by DT technology, allows to design and simulate energy planning scenarios. A scenario is defined by a set of actions associated with parameters and a trigger timestamp to apply it. Each scenario concerns one or a group of buildings. We can evaluate two types of operations:

1) Creation, extension and upgrade of a district heating. The proposed upgrades concern mainly the substitution of a production source by a renewable (geothermal, biomass, etc.) or recoverable energy source.
2) Refurbishment of buildings.

D. Evaluation and Comparison of Scenarios

To simplify the comparison and the refinement, once the zone is selected, the candidate scenarios are designed in an iterative and hierarchical way. They can be compared through the following Key Performance Indicators (KPIs): energy consumption, renewable energy production, Greenhouse Gas Emissions (GHG) and investment and exploitation costs.

IV. City Data Collection and Management

Data management is a central task for our decision-making system. In the context of energy planning, several heterogeneous data sets must be collected, processed, linked and visualized to allow the assessment of the current situation and the design of a relevant planning scenarios.

A. Territorial Contextual Information

Relevant energy planning requires both general and context-specific information. In our tool, several datasets are used and visualized: the city boundaries, the population density, the building density, the information about the planned urban projects, the land registry data, etc. Indeed, several information about the parcels is extracted from the land registry, including the area, the year of construction, the number of floors and the number of apartments.

B. Existing Energy Networks

The decision-making process for district heating requires the awareness of the existing energy networks in the territory. The application displays the different energy networks (gas, electricity and heat) in a centralized and overlapping manner. Therefore, the decision-maker can get an overview of the existing networks.

C. The Potential of Renewable Energies

In order to drive the design of scenarios, we capture the potential of renewable energies from different data sources and display them with the right level of granularity, for example: the geothermal potential and the solar potential of roofs.

Based on the data provided by BRGM (French Geological Survey) and the ADEME (French Environment and Energy Management Agency), the application allows visualizing on a map the different geothermal layers with indications of the potential level of each layer from very low to very high. The following properties are used to describe a geothermal layer: depth of the basin and temperature of the geothermal fluid. In the Paris region, there are several layers of geothermal energy:

1) Dogger: Located at a depth of 1,500 to 2,000 meters with a temperature ranging from 55 °C to 80 °C.
2) Lusitanian: Located at a depth of about 1,300 m and with a temperature of about 50 °C.
3) Neocomian: Located at a depth of 900 to 1,000 meters with a temperature of about 38 °C.
4) Albian: Located at a depth of about 600 m and with a temperature of about 28 °C.

We can notice that the temperature increases with the depth of the layer. It is obvious that the economic cost of extraction also increases with the depth. The geothermal energy is suitable to supply tertiary or residential buildings with temperature requirements below 100 °C and a continuous demand without too strong intermittence. For district heating, if the temperature is similar to that of the network, it can be used directly; otherwise, the temperature can be raised by installing heat pumps.

The data related to the solar energy potential of the roofs are obtained thanks to the Regional Agency Energy-Climate of the Paris Region Institute. The methodology is based on a modeling at the scale of each building whose objective is to estimate the potential energy production of each roof measured in kWh/year. Solar energy can be used either to produce electricity (photovoltaic) or heat (thermal). Within the framework of the urban heating network, solar energy can directly feed the network or provide electricity to power the heat pump.

D. Estimated Energy Consumption

The modeling of energy consumption is a key element in urban planning [12], it allows to better evaluate the demand, to adapt the development projects and to propose recommendations for supply or insulation. Several data sets are available at the territory level to allow the modeling of electricity, gas and heat network consumption. However, these data do not cover the whole territory and are generally provided at aggregated spatial and temporal scales for regulatory and technical constraints.

The approach taken to estimate energy consumption is to leverage the available high-level data (city, district or the street) to estimate the consumption at the level of a dwelling. Then, from a representative subset of dwellings, the consumption is extrapolated to a larger area.

In the context of urban heating, we used data collected from an existing urban network. The consumption for heating and domestic hot water is provided at the scale of a group of dwellings for one year. In order to obtain the characteristics and to refine the estimation, it was necessary to match these data with the land register. The information used to refine the estimation model is the following: type of use (residential, tertiary or industry), area, number of floors, date of construction, heating mode, and indications about the energy performance of the building (energy class).

V. Digital Twin

In order to evaluate and compare scenarios, we use a dynamic DT. A similar approach was applied to mobility [13]. For energy planning, the used DT includes a relevant replica of the city, with its resources, constraints, processes and data. It offers decision-makers the possibility to virtually evaluate several energy action plans before starting the project. Our DT brings the following properties:

1) It can take the input data from the business system or from a deployed Internet of Things (IoT) infrastructure.
2) It offers the possibility to virtually apply modification on the city studied.
3) It has the ability to be simulated. The city's behavior is predictable in a given time frame.

The simulation allows to run the "what-if" scenarios on a set of copies of the DT. It delivers invaluable insights on how to execute the energy plans and also allows to predict the impact of the plans on the KPIs.

Our DT integrates all the models required to represent virtually an urban heating infrastructure and its environment. Each model has its entities (corresponding to real-world subsystems, or to any abstract component), with their own state and their own list of rules describing the dynamics of the underlying systems, i.e., the way it evolves, the causal rules, and all the interactions of its present and future components and constraints.

Fig. 1 represents the conceptual model of our DT. It is composed of three sub models, heat network, building upgrade and technology adoption. The conceptual model structure is simple and flexible; for instance, we can simulate an experimental modification on the heat network without using the underlying dynamics generated by the technology adoption model.

A. Heat Network

The heat network model allows to find the best deployment considering the deployment schedule, energy price and the incentive policies. For example, it is possible to support the deployment of the district heating network with a pricing policy that encourages building managers to replace their heating equipment and connect to the urban network. The optimal network must meet the robustness criteria including seasonal trends and economic and demographic development. To do that, it provides three main computational features:

Compute Heat Demand: This feature estimates the monthly heat demand of building. To address the unavailability of data at a detailed spatial and temporal scale, we use a standardized electrical consumption profile which is based on the following parameters:

1) Surface of building in m^2.
2) Energy class of building in $kWh/m^2/year$.
3) Standard housing surface in m^2.
4) Average yearly energy demand for the studied area, expressed in kWh/year.
5) Standard energy consumption of a building in $kWh/m^2/year$.
6) Consumption profile: The variation of the consumption profile for each month of a year.

In order to compute the parameters, we mainly use the land register data.

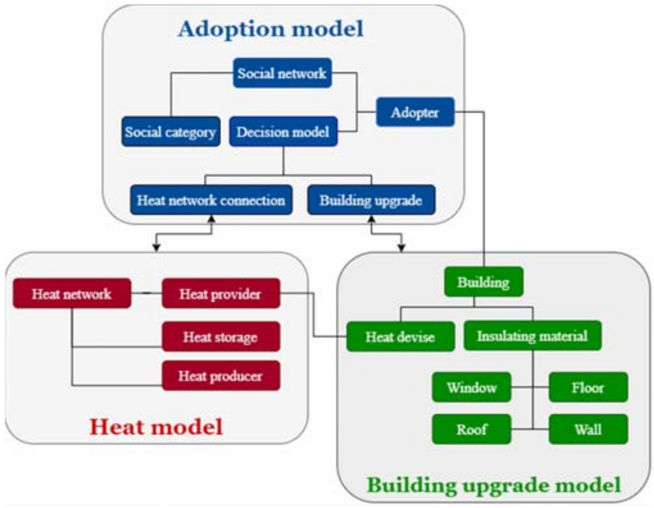

Fig. 1 The conceptual model of DT

Adapting Heat Production: This feature performs the balance of the heat network producers and consumers. It updates the energy level in heat storage, and the power delivered by heat producers. The total demand is computed first, followed by the total quantity of power coming from non-controllable producers. If there is not enough heat available, it can be decided to use controllable heat producers or heat storage, based on the priority defined.

Computing Heat Network Profit: This feature computes the sum of revenues coming from every consumer of the heat network. Every fixed and variable bill is computed knowing the actual consumption of each consumer. The total expenses of the heat network are deducted from the total revenues which gives the profits value of the current month.

Heat Network Connection - Economic Utility: This feature computes the economic utility of heat network connection. It compares the price currently paid by the building for heating purposes and price proposed by the heat network using a desirability function, varying from 0 to 1 and expressing the household's satisfaction. To encourage the household to replace their heating device and connect to the heat network, the pricing policy of the heat network operator is a variable parameter that should be find according to the area studied.

B. Building Upgrade

The building upgrade model aims to improve the energy efficiency of buildings by decreasing energy consumption and GHG emissions. This model helps local authorities evaluate and compare several incentives policy to encourage building upgrade. For example, the evaluation of the effectiveness of a government assistance policy with regard to its impact on the reduction of electricity consumption and GHG emissions. The incentive can be focused on sub set of buildings or house-holders satisfying some conditions (construction year, energy efficiency, dwelling type, energy improvement rate, income situation, family composition, etc.). This model provides two main computational features:

Compute Building Energy Efficiency: This feature computes the building energy efficiency diagnostic (EED) [14] of the building. The EED gives a single number for the rating of building energy efficiency, and a recommended value of the potential for improvement. The EED is a conventional method used to compute building consumption, i.e., it is based on a standardized building usage for an average climatic condition. In other words, EED provides the information of building consumption which overcomes the occupant behavior (number of people occupying the building and their behavior regarding the winter). The main criteria characterizing the conventional method are:

1) The whole living area of building is considered heated continuously during the heating period.
2) Heating needs are computed based on average degree-hour over 30 years.
3) The internal rapports (occupation, electrical equipment, lighting, etc.) are considered through a fixed contribution of 1 °C. This allows to achieve the desired temperature of 19 °C.
4) The need of hot water is fixed according to the building living area.

Building Energy Upgrades - Economic Utility: This feature computes the economic utility of the building energy upgrades. To do that, the model establishes all possible combinations of building energy upgrades based on the thermal envelope of the building that is eligible for improvement (not yet improved). For each possibility upgrade the cost, expected profit and potential improvement are combined to compute the net present value. The upgrade that has the smallest net present value with payback not exceeding the lifetime is selected to be proposed to adoption models.

C. Technology Adoption

The adoption model aims to describe the technology adoption process. It allows to test consumer and social dynamics for the adoption of different technologies such as heat network building connection or building renovation. To adopt a new technology, a household computes a score expressing the probability to be prone to adopt a new technology based on different criteria:

1) Economy: It represents the cost and risk related to the technology.
2) Personal: It captures the personal satisfaction associated with the technology (for instance, environmental sensitivity aspect like the amount of GHG reducing by adopting a technology).
3) Social: It represents the influence of the social environment.

VI. Decarbonized City Application

A. Software Architecture

The tool we created is a web application that leverages a DT technology in order to support the energy planning approach described above. The global software architecture is described in Fig. 2.

We use the Azure Digital Twins (ADT) platform to create a digital representation of the city's physical environment. The ADT platform brings an open modeling language (Digital Twins Definition Language) to create custom models of a connected environment. Once the model is created, the ADT platform provides useful connectors to feed data into the DT from the business systems or real time through the IoT.

Once our connected DT instance is created, we add to it the capability to be simulated. To achieve this, we use the CosmoTech platform that allows us to augment the DT by adding the dynamics of the underlying systems (see Section V).

We use the multi-model database Azure Cosmos DB to store user-generated what-if scenarios as well as the geospatial data used by the application. For instance, when a geographic area is selected by drawing a polygon, the application performs a geospatial query to obtain information about the selected area.

We use React as a front-end framework and Power BI to create the dashboards used for presenting the results of the simulation. The application is managed (hosting, deployment, integration and scaling) using Azure Static web apps service. The application back-end is based on serverless architecture leveraging azure functions.

We use Azure Data Explorer and Azure Event Hubs to ingest and process the generated simulation results.

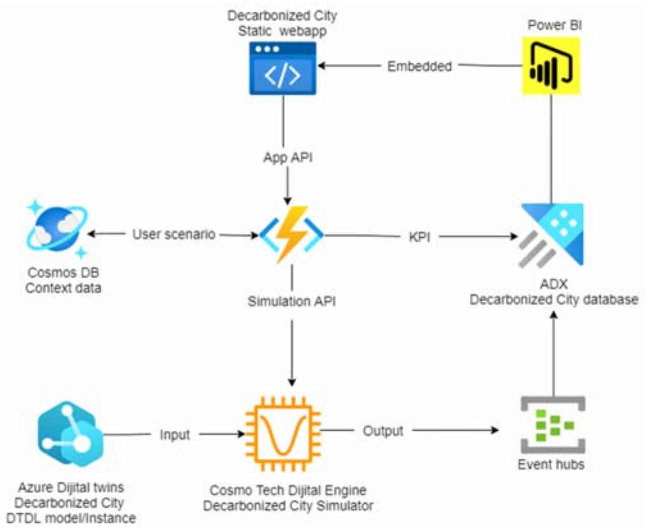

Fig. 2 Global software architecture

B. Case Study

Our use case concerns a city in the Paris-Saclay Agglomeration Community that includes 27-city area situated in the south of Paris. More specifically, the former hospital must be transferred in a new area to make way for the realization of a Concerted Development Zone (CDZ). This situation gives the opportunity to rethink the energy options.

Using the application, we can select the area which includes the future CDZ with a group of neighboring buildings. Based on the energy estimation approach and the data integrated, the application displays (see Figs. 3 and 4) several relevant information about the selected area, for example, the number of dwellings, the global energy consumption, GHG emissions, the repartition of the number of floors, the years of construction, etc.

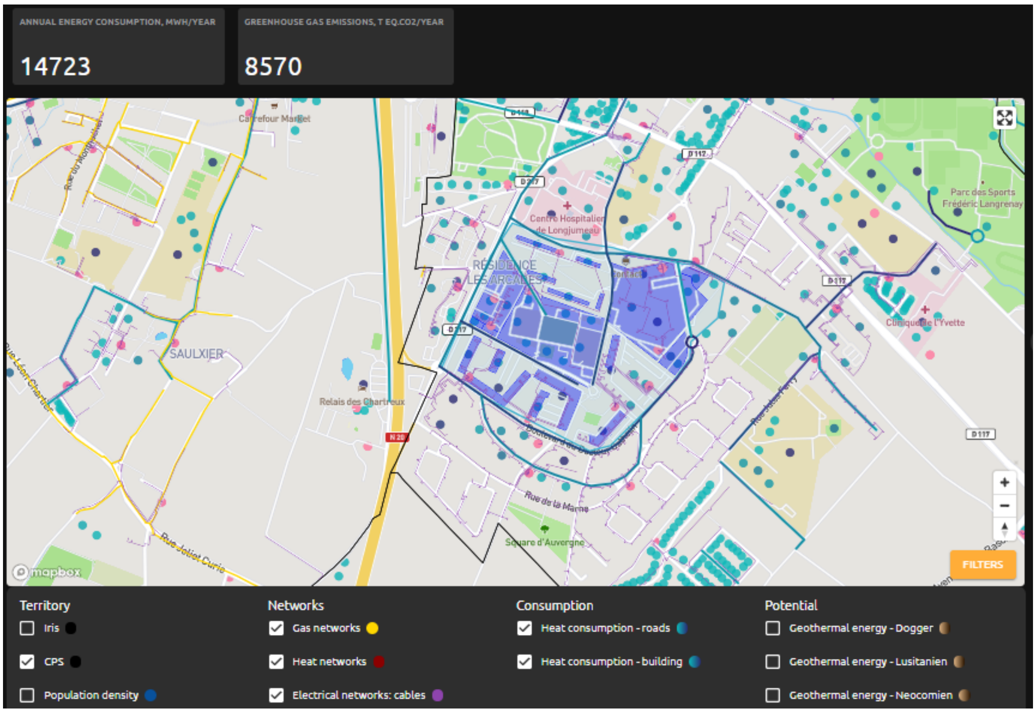

Fig. 3 Scenario setting: zone selection and contextual information visualization (consumption, etc.)

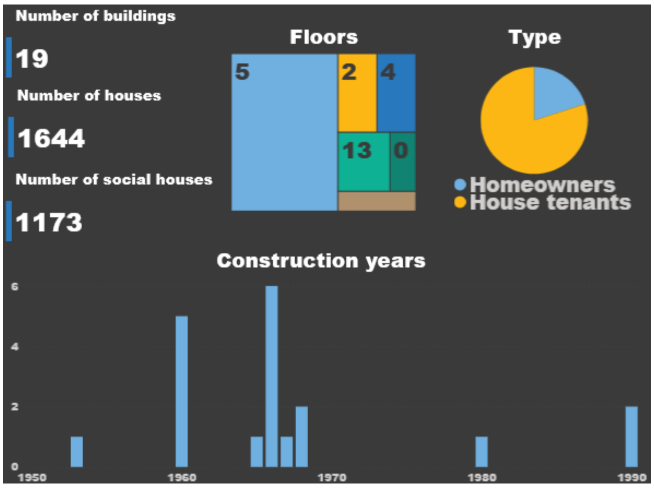

Fig. 4 Display of contextual information about the selected area

Based on the several data sets integrated and visualized by the application, we notice that no heat network is available near the area and the city has an interesting potential in geothermal energy especially at the layers of Albian and Dogger. With the support of the application, the objective is to evaluate the opportunity to create a district heating by leveraging geothermal energy.

According to the number of dwellings, the consumption estimation and the geothermal potential, the exploitation of the intermediate depth Albian layer is more adapted to this project. This layer has been successfully exploited in a similar project in the Paris region in the "Fort Numérique" district in Issy-les-Moulineaux city. In order to design this scenario, the application allows us to instantiate a new CDZ and a new heat network associated with two producers: a geothermal producer and a gas backup producer. The latter will be mainly useful to meet the heating needs in winter.

Given the significant variability of investment, operation and maintenance costs depending on the technology and location, the application allows the user to enter the contextual economic and energy parameters of each scenario.

Once the parameters of the simulation and the time horizon are set, the user can launch the simulation which produces the following KPIs: energy consumption, renewable energy production, GHG emissions and the cost. Other KPI related to the heat network performance are also provided: energy mix, customer satisfaction and heat network efficiency (see Fig. 5). In a similar way, the application allows simulate an unlimited number of strategies and to evaluate the impacts of the decisions taken. For example, we can consider evaluating the biomass exploitation scenario or leveraging the deep geothermal layer (Dogger) while extending the concerned area by the operation over several cities.

VII. Conclusion and Perspectives

District heating is a relevant means to mutualize the infrastructure, reduce the costs and supply the maximum number of users. Moreover, it is a vector for the exploitation of renewable, recoverable and local energies. In addition to heating, urban refurbishment is an efficient way to reduce consumption by improving the frame insulation.

In this paper, given the complexity of energy planning in an urban environment, we have proposed a tool-based iterative approach which is organized in several steps: urban data analysis and visualization, selection of the area, design of sustainable energy planning scenarios and the evaluation of candidate scenarios. The last step is performed using a DT technology that requires scalable deployment and systemic modeling. The latter relies mainly on the territory data.

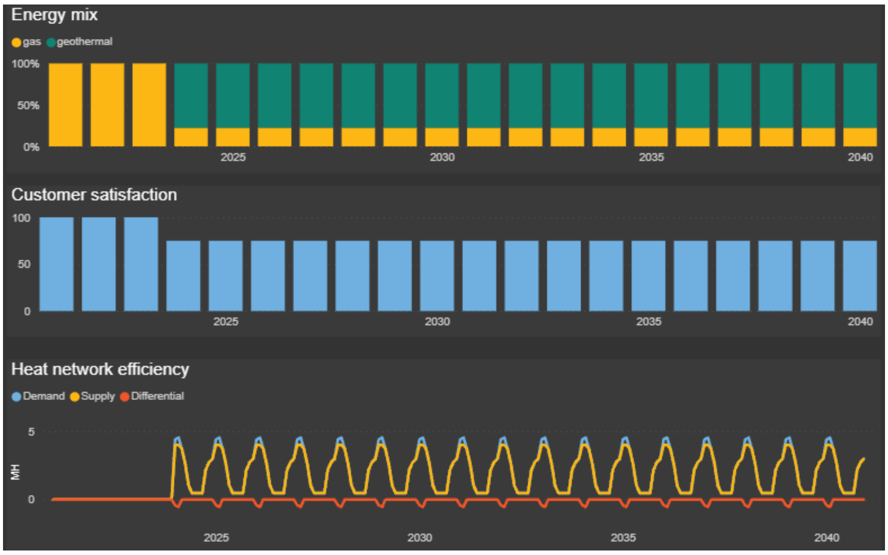

Fig. 5 Dashboard of heat network performance

In order to improve our tool, we plan to support decision making in energy planning based on data-driven optimization approach, as described in [15]. For example, in our system, optimization can help in the selection of the most suitable perimeter (subset of buildings) based on the available energy potential, the grouping of several districts for a heat network project, the selection of the most suitable geothermal layer based on the surface energy demand, etc. To achieve this goal, it is necessary to integrate accurate economic models and to be able to run optimization algorithms within the application. These algorithms can select the best energy planning scenario while taking into account several criteria.

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