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Research paper

# Design and assessment of energy infrastructure in new decarbonized urban districts: A Spanish case study

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ABSTRACT

New urban districts have great potential to reduce greenhouse gas emissions by electrifying energy demand in various sectors, such as transportation and buildings. This paper proposes a novel approach that combines different energy models to plan the infrastructure for supplying the energy demand of new, decarbonized, and highly electrified urban districts on a real-world scale. First, a model for energy management in buildings is used to plan and operate equipment for heating, cooling, and solar photovoltaic distributed generation. Second, a model that plans electric vehicle charging infrastructure determines the number and types of charging stations. Then, a large-scale distribution network planning model designs a cost-efficient electricity distribution grid to supply the district. A case study is presented for a new urban district in Madrid, Spain, to demonstrate how this approach can be applied to energy infrastructure planning in a real-world context. This case study presents different scenarios of energy efficiency performances in buildings and penetration levels of solar installations, electric vehicles, and heating and cooling systems. The results show that even in a high electrification scenario, improving energy efficiency in buildings through a district heating network based on heat pumps can lead to a lower peak electricity demand. This peak load reduction allows for integrating more electric vehicles, avoiding further investments in the electricity distribution network. In addition, the results confirm that a highly electrified scenario, which combines energy-efficient buildings with high integration of solar and electric vehicles, significantly reduces non-renewable energy consumption and greenhouse gas emissions.

## 1. Introduction

The Paris Agreement, adopted in 2015, aims to bring together all nations to hold the increase in global average temperature well below 2ºC. To accomplish this goal, parties to the agreement have committed actions to reach the global peak of greenhouse gas emissions. Urban areas, where around 75% of the global energy is consumed (Zhao and Jiang, 2024), offer a great potential to reduce greenhouse gas emissions, for instance, through energy efficiency in buildings and increasing the penetration of renewable energy sources in urban districts. Energy use in buildings and transportation could be further decarbonized through the deployment of distributed energy resources (DERs), such as electric vehicles (EVs) or heat pumps (HPs), coupled with a transition to clean energies in the electric power generation mix.

### 1.1. Literature review

In this context, the role of buildings in the energy transition has drawn the attention of researchers who have studied the benefits of active demand control to increase energy efficiency and energy savings in buildings (Kolokotsa, 2016). These benefits can be leveraged by implementing energy management systems (EMSs) to automate active demand control and optimize energy use. The scientific literature presents a broad spectrum of optimization algorithms for EMS models, including both mathematical optimization (e.g., mixed-integer nonlinear optimization algorithms (Wang et al., 2024)) and meta-heuristics (e.g., particle swarm optimization (Yelisetti et al., 2022) or genetic algorithms (Jiang and Xiao, 2019)). Moreover, integrating buildings in multi-energy systems, where energy demand is met through a combination of multiple energy vectors, can create synergies among the different energy sectors and reduce the overall costs of the system (Kolokotsa, 2016). Thus, power-to-heat devices, especially HPs, are

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**Nomenclature**

| | |
|---|---|
| BAU | Business as usual |
| CS | Charging stations |
| CTE | Spanish Building Technical Code |
| DG | Distributed generation |
| DER | Distributed energy resource |
| DHC | District heating and cooling |
| DHW | Domestic hot water |
| DN | (Electricity) distribution network |
| EMS | Energy management system |
| EV | Electric vehicle |
| GIS | Geographic information system |
| HP | Heat pump |
| LCOHC | Levelized cost of heating/cooling |
| LV | Low voltage |
| MV | Medium voltage |
| NRPE | Non-renewable primary energy |
| O&M | Operation and maintenance |
| OPE | Overall primary energy |
| PV | Photovoltaic |
| REBT | Spanish low voltage electrotechnical standard |

gaining more attention in recent years, given their ability to increase the system's flexibility. For example, the electricity generated by renewable energy sources can be converted into heat, stored, and used later at the right time to match the thermal demand (Nguyen and Candanedo, 2024). Consequently, the study of the efficient management of buildings has evolved into the efficient management of microgrids, modeling the aggregation of multiple buildings, adopting EMSs, and integrating DERs and multi-energy systems (Nawaz et al., 2022).

DER expansion planning and operation optimization for systems connected to the electrical grid have been addressed in the literature. For instance, the DER-CAM model (Mashayekh et al., 2017) developed by the Lawrence Berkeley National Laboratory determines the optimal investment and dispatch of DERs (Gallego-Castillo et al., 2021) while minimizing costs or emissions. This is achieved by considering several inputs, such as consumption profiles, DER technology characteristics, tariff data, and weather conditions (DeForest et al., 2014). URBANopt, from the National Renewable Energy Lab (NREL), is able to model energy districts (Wang et al., 2022) and leverages REopt to assess the impact of DER (El Kontar et al., 2020). There are also platforms to quantify and analyze the potential photovoltaic (PV) generation that can be installed in urban areas (Massano et al., 2023). Another popular model for planning hybrid renewable energy systems is the Hybrid Optimization Model for Electric Renewables (HOMER), which was also developed by NREL (Thirunavukkarasu et al., 2023). This software has been widely used to plan renewable energy systems in urban areas around the world, including the United States (Khosravani et al., 2023) and the Maldives (Mohamed et al., 2024). Optimal planning of DERs and configuration of multi-energy systems has also been addressed in Huang et al. (2019). However, these studies typically do not plan the electrical grid, which is given as an input for the optimal power flow and remains unchanged despite increases in DER penetration levels. Ignoring the electricity grid infrastructure can lead to sub-optimal scenarios for the adoption of DERs in urban districts, as the additional investments required to integrate them into the electricity grid are not considered. Therefore, the optimal planning of DERs and electricity grids should be combined to plan new decarbonized urban districts efficiently.

On the other hand, multiple studies have evaluated how the planning of electricity distribution networks (DNs) is impacted by the shift towards a more decarbonized energy system with higher adoption rates of DERs. Active DN planning aims to minimize investments in new installations, network reinforcements, and DER assets to comply with network requirements (Picard et al., 2021). Several researchers have proposed models for active DN planning considering the integration of DERs, such as wide deployments of controllable loads (Ziegler et al., 2024), distributed generation (DG) (Alipour and Askarzadeh, 2024) and EVs (Sun et al., 2020). A model for incremental DN planning to minimize the cost of network reinforcements required to allow higher penetrations of DGs and EVs is proposed by Shi et al. (2019). Besides, Anastasiadis et al. (2019) analyzes the possibility of increasing EV penetration on the DN by applying different smart charging strategies. However, these studies do not combine multiple energy models that account for other aspects, such as building EMSs. Analyzing the various aspects of energy modeling in urban areas separately, without considering their interdependencies, risks overestimating investments in DNs. For example, an increase in load peaks resulting from the adoption of EVs and HPs can be mitigated through self-consumption and increased energy efficiency in buildings.

Few authors have developed models to evaluate how integrated planning of electricity and thermal systems could enhance the efficiency of the overall energy system in urban environments (Heise et al., 2023). For instance, Abbasi and Seifi (2014) aims to find the optimal expansion planning for a DN, which also supplies the heating demand through HPs, achieving minimum investment costs, energy losses, and voltage deviations. However, these models have only been applied to relatively small test networks, usually consisting of only a few buses. The scalability of these methodologies and results from small test systems to real large-scale urban districts has not been sufficiently analyzed in the existing literature. In a previous conference paper (Rosa et al., 2021), some of the authors outlined the initial steps to integrate the synthetic distribution network tool RNM-US (Mateo et al., 2020) with the district-scale thermal and electrical buildings and energy systems model URBANopt. However, the study in Rosa et al. (2021) did not evaluate the impacts of decarbonization policies such as energy efficiency measures or the adoption of PV, HPs and EVs. This paper presents an integral approach to energy system planning and assesses the impact of various decarbonization options in a real case study of a new urban district in Spain.

### *1.2. Research gaps and main contributions*

Although several authors have analyzed different aspects of energy modeling in urban areas, to the best of the authors' knowledge, the literature still lacks an integrated planning approach that considers multi-energy systems when planning real-scale urban districts. As aforementioned, models that focus on optimization of DER expansion planning and operation typically consider the electrical grid as an input, i.e., these models do not plan the electricity DN required to supply these areas. On the other hand, active DN planning models typically focus on the impacts of a selection of DERs and do not combine multiple energy models. In the scientific literature, only a few authors have developed integrated planning models of multi-energy systems, and these models have only been applied to small test systems. Therefore, the interdependencies and synergies between different aspects of energy modeling have not been sufficiently analyzed, especially in real-world case studies. The main contributions of this paper are:

- This paper presents a novel approach that combines multiple energy aspects for planning and sizing the energy infrastructure needed to supply energy demand in modern decarbonized and smart urban districts. The literature review reveals a need for comprehensive energy infrastructure planning models that can be applied to large-scale urban areas. This integral approach considers energy efficiency, EMSs, multi-energy systems (e.g., HPs and district heating and cooling networks), solar PV, EVs, and electricity DNs.
- An actual case study is analyzed: Madrid Nuevo Norte, one of Europe's largest and most innovative ongoing urban regeneration

projects. The case study illustrates how this comprehensive approach can improve energy infrastructure planning in a real-world context.
- The proposed approach is also used to evaluate, from a techno-economical perspective, the synergies that arise from combining building energy efficiency, multi-energy systems, PV generation, EV charging, and smart grids in a real-world case study.

Three decarbonization scenarios with increasing energy efficiency in buildings, flexibility from intelligent multi-energy systems, and higher shares of PV generation, EVs, and HPs are assessed in the case study. The results of this study inform on the reduction of greenhouse gas emissions and non-renewable energy consumption, as well as the infrastructure required to meet the energy demand. Moreover, it is analyzed whether higher levels of electrification would lead to higher investments in DNs.

The remainder of this paper is organized as follows. Section 2 presents the proposed methodology for integrated planning combining multiple energy aspects. The case study for a new urban district in Madrid, Spain, is introduced in Section 3, which also describes the three scenarios evaluated for the future development of the new district. Then, Section 4 analyses energy consumption and distribution network planning results from both a technical and an economic point of view. Finally, conclusions are drawn in Section 5.

## 2. Methodology

This paper proposes a multi-energy approach that combines different energy models to plan the infrastructure needed to supply the energy demand of new decarbonized and highly electrified real-scale urban districts. The proposed approach is based on geographic information system (GIS) data (e.g., street layout, building types, and locations, etc.) and combines three different energy models, as represented in Fig. 1. First, a model for energy management in buildings is used to design the equipment for heating, cooling, domestic hot water (DHW), lighting, appliances and solar PV production in buildings. In addition, the EMS optimizes the hourly energy profiles for each building. The second model for EV charging estimates the future needs of charging stations

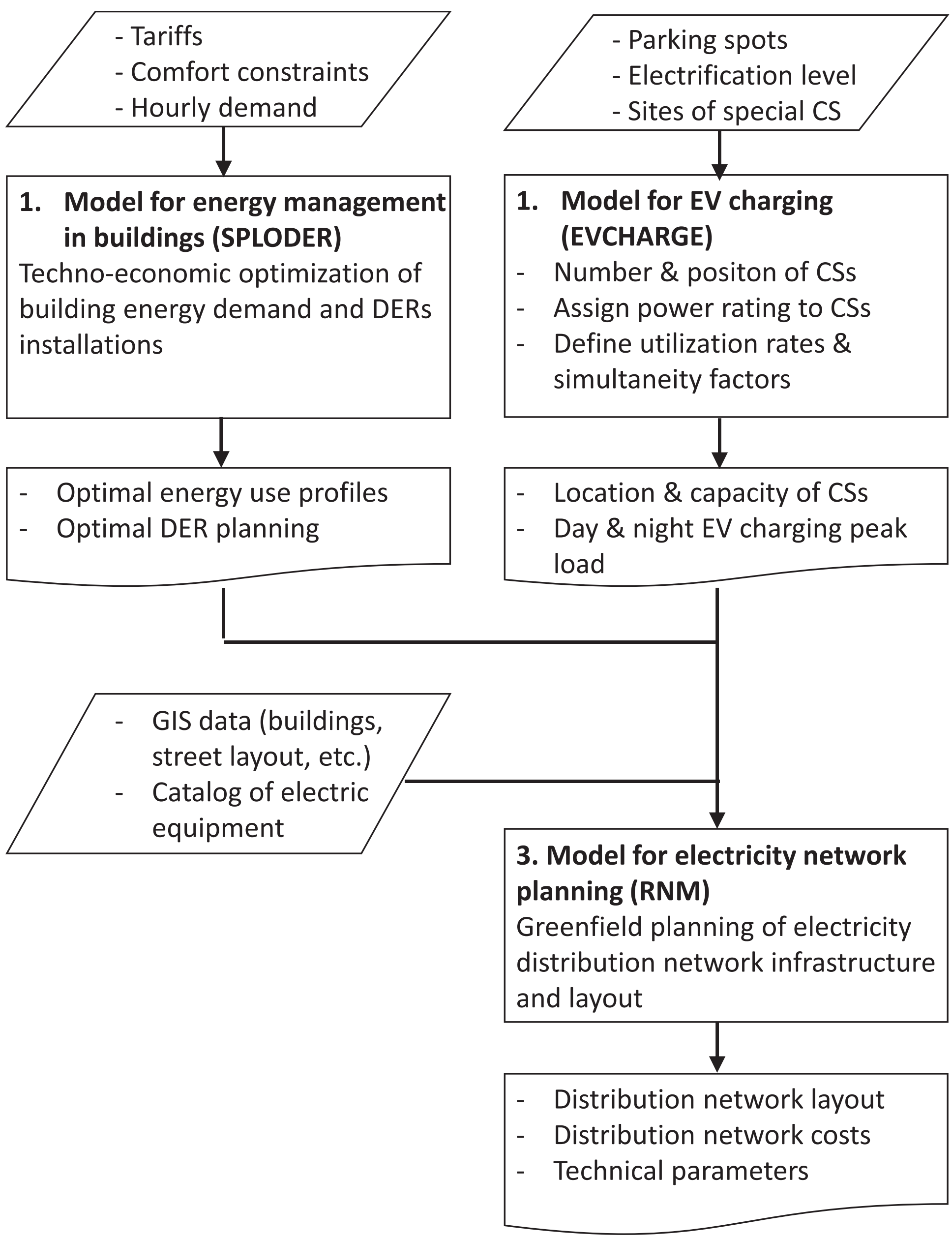


**Fig. 1.** Flowchart of the proposed methodology for multi-energy system planning in urban areas.

(CSs) in the district and provides the number, types, and total capacity of CSs and the hourly demand profile for each CS. Lastly, the third model for electricity network planning designs the least-cost electricity DN required to supply the peak demands at each supply point, considering the hourly consumption profiles obtained by the previous two models.

### 2.1. Energy management in buildings

First, energy use in buildings is planned and optimized based on the methodology presented in Martín-Martínez (2017). The energy management model (SPLODER) focuses on residential buildings (e.g., apartments, households, etc.) and tertiary buildings (e.g., shops, offices, etc.). This model optimizes the thermal and electric energy consumption for each building within the district under different energy efficiency and DERs' investment and operation scenarios (Martín-Martínez et al., 2016). The model receives weather forecasts, user preferences (e.g., comfort temperatures), energy tariffs, and hourly energy demand data as input. Energy demand is classified into two categories: uncontrollable and flexible or controllable. Uncontrollable demand refers to energy consumption whose operation is fixed and cannot be optimized (e.g., lighting and other electric appliances). On the other hand, controllable demand is comprised of heating/cooling and domestic hot water consumption that is managed to achieve the most cost-effective operation considering meteorological data and comfort constraints.

For instance, the EMS could start the operation of heating/cooling systems during off-peak hours to exploit the thermal inertia, thereby reducing their consumption at peak hours. Moreover, considering tariffs, the model manages the energy demand from heating/cooling and DHW and integrates the optimal amount of PV and storage. Besides managing the building's energy use, this model also decides on investment in different DER technologies, such as PV or batteries. The outputs of this model are the optimal energy consumption profiles and DER investments per building.

### 2.2. EV charging stations

This section describes the methodology followed to determine the CSs required to meet the EV charging demand and the contribution of EV charging to the peak load of the district. The EVCHARGE model calculates the total number of CSs to be deployed following the required standards according to national or municipal policies. For instance, in our case study centered in Madrid, Spain, the following standards apply: i) low voltage electrical installations, including EV charging stations (Ministry of Science and Technology, 2002), hereinafter REBT by its Spanish acronym, ii) construction and thermal installations in buildings (Ministry of Development, 2019), hereinafter CTE by its Spanish acronym, and iii) local urban development plans, in particular for our case study, the General Urban Development Plan of the considered urban area in Madrid (Madrid City Council, 2020).

First, the number of CSs for electric cars is determined as a percentage of the total number of parking spots for each building, which will be defined for each scenario. Besides, both the number and installed power of the CS for each building would depend on where they are placed, e.g., residential buildings, tertiary buildings, public parking on streets, or short/long-term parking lots. Moreover, specific CSs are allocated for charging electric buses or e-bikes. The sites of those CSs are given as input to the model.

Then, a power rating is assigned to each CS. The following charging speed rates associated with different power ratings are defined based on the standard IEC 61851–1: i) slow AC charging (3.6–7.3 kW), ii) semi-fast AC charging (7.3 kW single-phase and 22 kW three-phase), and iii) fast DC charging (50 kW). It is assumed that most EVs will be charged at home at night, as confirmed by previous literature on CS planning in urban environments (Hardman et al., 2018). Therefore, the model prioritizes the installation of CSs in residential buildings, followed by the installation of CSs in tertiary buildings and public parking sites. Lastly, the slow charging points installed in public parking sites on streets have a marginal role, given the low level of probability of their usage by EV owners, due to the increase in EV battery capacities (Helmus et al., 2018).

Finally, an estimation of the utilization rate for each CS is carried out by the model. As a result, a simultaneity factor, modeling the contribution of each CS to the peak demand, is applied to the installed power of each CS to avoid oversizing the infrastructure of the DN. The simultaneity factors depict the maximum power consumed simultaneously by all the individual CSs connected at the same network location. The model differentiates between day and night simultaneity factors since EV charging sessions depend on the building types. For instance, night charging has a higher simultaneity factor for CSs located in residential buildings. As a result, the overall peak coincident demand from EV charging can be obtained, which is used as input in the following section to design the DN.

### 2.3. Electric distribution network

The DN is planned based on the RNM model presented in Mateo Domingo et al. (2011), which designs a cost-effective DN to supply all consumers in a particular area while complying with voltage and thermal limits and geographical and reliability constraints. This type of DN planning model, known as the Reference Network Model (RNM), has been used to build European synthetic distribution grids for large and mid-scale smart-grid projects. Moreover, RNM has been applied to analyze the impact on DNs of high penetrations of DERs, such as energy storage (Mateo et al., 2016), DG (Mateo et al., 2018), and EVs (Martínez et al., 2021). However, this is the first time this type of DN planning model has been used to simulate a highly decarbonized district to evaluate different electrification scenarios, combining high energy-efficient buildings with deep penetrations of EVs and PV installations.

This paper uses RNM in a greenfield mode, i.e., RNM plans the DN from scratch. As input from the SPLODER model, RNM receives hourly energy profiles for each building. In addition, the location, installed capacity, and peak loads of the CS calculated with the EVCHARGE model are also inputted to RNM. Based on the REBT, simultaneity factors have been applied to the estimated loads. These simultaneity factors model the utilization rate of loads in the peak hours of demand. On the other hand, the installed PV for each building is defined considering a maximum installed power of 100 kW, based on Ministry for the Ecological Transition (2019), which regulates the technical, administrative, and economic norms for electricity self-consumption in Spain. Besides, a street-map layout and the locations of buildings, CSs, and PV installations are provided as GIS input data to RNM, which are used to determine the geographic constraints for the DN layout in the area. A catalog including the technical and economic parameters of the electric equipment (e.g., power lines, transformers, etc.) is also provided as input to RNM. The technical parameters have been collected from catalogs of electric equipment manufacturers for DNs. On the other hand, reference unitary investment and operation and maintenance (O&M) costs for electric equipment in Spanish DNs are defined in MINETUR (2015).

The RNM follows a bottom-up approach to plan, sequentially, the low voltage (LV), medium voltage (MV), and high voltage (HV) networks. At each voltage level, the supply points (e.g., transformers, substations, etc.) are located and sized. Then, power lines are planned in the greenfield RNM based on an initial configuration: the minimum spanning tree connecting the substation with all consumption and DG nodes. However, this initial configuration is not necessarily feasible, so power lines are planned to account for geographical constraints and technical requirements, i.e., reliability indices and voltage and thermal limits. Given that the case study is particularized for Spain, the load-based reliability indices used are TIEPI and NIEPI, which are equivalent to the Average System Interruption Duration Index (ASIDI) and the

Average System Interruption Frequency Index (ASIFI) defined in ("IEEE Guide for Electric Power Distribution Reliability Indices," 2022). These reliability indices are defined by Ministry of Economy (2000) in Spain. Furthermore, the cost of energy losses is calculated using the methodology for calculating the remuneration of electricity distribution companies (CNMC, 2019). Finally, the RNM outputs are the graphical layout of the DN and the techno-economic results for each DN component.

## 3. Case study: scenarios

In the case study, the proposed methodology is applied to plan, under different decarbonization scenarios, the energy infrastructure required to meet the future energy demand in a new urban district in Madrid, Spain. The new district, Madrid Nuevo Norte, will cover an area of approximately 3.5 $km^2$ and is one of Europe's largest ongoing urban regeneration projects. The project for the new district includes the development of about 150 buildings distributed in residential (1048,535 $m^2$) and tertiary (1307,796 $m^2$) uses. For this study, the authors had access to the district's GIS data, including coordinates and other geo-referenced data for buildings and streets.

Three scenarios are considered accounting for different decarbonization energy policies. These scenarios have been obtained as a combination among different penetration levels of CSs for EV charging, with different energy efficiency levels and integration of PV installations in buildings:

1. *Business as usual*: this scenario considers the CSs mandated by current legislation and a BAU energy model for buildings. The BAU energy model applies a decentralized heating/cooling system for apartments within residential buildings and a centralized heating/cooling system for tertiary buildings. Moreover, this scenario also reflects a low penetration of rooftop PV because this is not a requirement in the CTE.
2. *Existing policies*: this scenario models moderate progress towards decarbonization. An intermediate EV penetration is combined with the decentralized energy model for buildings, consisting of a central heating and cooling system per building, residential or tertiary. The PV generation target for this scenario aims to install 100 kW per building rooftop, based on (Madrid City Council, 2020).
3. *Sustainable development*: in this scenario, decarbonization efforts are maximized through the widespread adoption of novel technological solutions to achieve very high levels of electrification. This scenario considers the highest energy efficiency standard for residential and tertiary buildings. For instance, EMSs take advantage of the thermal inertia of the buildings to optimize their energy demand. This innovative building energy model is based on a centralized district heating and cooling (DHC) network consisting of multiple loops with geothermal HP stations deployed throughout the district. Moreover, it combines this innovative centralized building energy model for this region with an extensive smart EV charging infrastructure. Furthermore, maximum PV penetration is considered, including unconventional PV installations in public areas such as parks and gardens.

Table 1 summarizes the main assumptions for the three scenarios, providing the peak power consumption and the EV and PV penetration levels for the residential, tertiary, and municipal services building categories.

### 3.1. Scenarios of energy demand in buildings

Energy demand in buildings is modeled considering Madrid's climatic conditions characterized in the Spanish CTE. The *sustainable development* scenario follows *passivehaus* standards, reaching the minimum thermal demands contemplated in the CTE. The CTE also defines sustainability indicators used to assess and compare the buildings' energy consumption results for the different scenarios in this case study. These indicators are calculated per surface unit of the building, considering the consumption from all heating, ventilating, air conditioning, and DHW installations. For tertiary buildings, lighting consumption is also added.

**Table 1**
Peak power consumption, number of CSs and PV penetration per building type and scenario.

| | | Business as usual scenario | Existing policies scenario | Sustainable development scenario |
|---|---|---|---|---|
| **Residential** | Peak power consumption [kW/apartment] | 9.20 kW | 6.90 kW | 5.75 kW |
| | CS/parking spots [%] | 10% | 60% | 100% |
| | PV systems | - | Target 100 kW | Max. rooftop surface available |
| **Tertiary** | Peak power consumption [kW/m2] | 0.1 kW/m2 | 0.1 kW/m2 | 0.08 kW/m2 |
| | CS/parking spots [%] | 10% | 20% | 30% |
| | PV systems | Based on CTE (Ministry of Development, 2019) | Target 100 kW | Max. rooftop surface available |
| **Municipal Services** | Peak Power Consumption [kW/m2] | 0.1 kW/m2 | 0.1 kW/m2 | 0.08 kW/m2 |
| | CS/parking spots [%] | - | 10% | 20% |
| | PV systems | Based on CTE (Ministry of Development, 2019) | Target 100 kW | Max. rooftop surface available |

The building energy consumption in the *business as usual* scenario is based on the conventional energy model, which consists of using natural gas boilers for heating and solar thermal collectors with natural gas boilers as a backup system for DHW. Decentralized heating/cooling systems are used in residential dwellings, while centralized systems are employed in tertiary buildings. This results in a high peak power consumption, particularly in residential buildings, as shown in Table 1.

The *existing policies* scenario assumes a central thermal system per building. While tertiary buildings maintain the same installations as the *business as usual* scenario, thermal energy demand in residential buildings is met by a central air/water HP using underfloor heating and cooling plus a dedicated air/water HP for DHW. As a result, the peak power consumption in residential buildings is reduced compared to the *business as usual* scenario.

A DHC geothermal network is implemented to supply the heating and cooling demand of both residential and tertiary buildings under the *sustainable development* scenario, increasing the overall energy efficiency of the district. The DHC network is split into 19 loops, each with its own HP, with a total peak-load demand of 23.3 MW. The HPs are recuperative geothermal units. Therefore, each loop consists of two rings for hot and cold water, respectively. The HP employs the heat removed by the cold ring as a thermal source for the hot ring, taking or releasing the required heat to the ground to complete the energy balance. The thermal energy for the DHW is taken, in the first stage, from the hot ring powered by the centralized geothermal HP, and in the second stage, from a decentralized water/water HP located in each building. Moreover, thermally activated structures in buildings are used as heating and cooling storage installations, taking advantage of the thermal inertia to manage their energy demand. As a result, peak power for residential buildings, including both dwellings and common areas, and tertiary buildings is considerably reduced with respect to the *existing policies* scenario.

### 3.2. Electric vehicles scenarios

Three EV scenarios have been defined, accounting for different penetration rates. Each scenario is differentiated in terms of the number of CSs installed at each building category, as shown in Table 1. Moreover, the share of each type of CS, i.e., slow, semi-fast, and fast charging) varies among the three scenarios, considering higher shares of fast CSs in the scenarios with higher EV penetrations. The number of CSs in the *business as usual* scenario is strictly defined to comply with the Spanish REBT that established the required number of CSs as 10% of the total parking spots available in residential, tertiary buildings, and public parking spots in streets. This scenario is characterized by a low deployment of EVs, with mostly slow CSs (3.6–7.3 kW). The simultaneity factors for CSs in this scenario are close to one, given the slow charging speed and assuming that few CSs would count with smart charging systems.

The *existing policies* scenario assumes a medium penetration of EVs. Thus, the percentage of CSs installed per parking spot is increased to 60%, 20%, and 10% for residential, tertiary, and public parking lots, respectively. Besides, this scenario introduces semi-fast charging CSs in residential and tertiary buildings, accounting for 20% of their total. Finally, in the *sustainable development* scenario, the number of CSs in the district is maximized in residential buildings, considering a CS is installed in every parking spot. The grade of electrification of parking spots in tertiary buildings has also increased to 30%. Moreover, the share of semi-fast CSs is extended to 30%. The simultaneity factors considered in the *existing policies* and *sustainable development* scenarios are lower than the ones used for the *business as usual* scenario, assuming a higher deployment of smart charging infrastructure. Additional information about the data used under each scenario is provided in (De Rosa et al., 2023).

## 4. Results

This section presents the results obtained by applying the developed approach to the selected case study. First, the energy demand in buildings is assessed under the three scenarios. Second, the peak coincident power corresponding to electric vehicle CS is calculated for the three scenarios. Then, the peak load of the district corresponding to all the energy uses per scenario is determined. Finally, the techno-economic parameters that characterize the three obtained DN for the three scenarios are compared.

### 4.1. Building energy demand

The following indicators are considered to assess the buildings' energy performance under the three scenarios: i) the overall primary energy (OPE) consumption per conditioned area, ii) the non-renewable primary energy (NRPE) consumption per conditioned area, and iii) the carbon dioxide emissions ($CO_2$) per conditioned area. In addition, the levelized cost of heating/cooling (LCOHC) systems is used to compare the economic performance of the designed energy infrastructure. The LCOHC accounts for all thermal infrastructure, including heating, cooling, and DHW. Table 2 compares the obtained results for the three scenarios.

Under the *existing policies* scenario, Table 2 shows that introducing HPs for heating and cooling in residential buildings halves non-renewable primary energy consumption and $CO_2$ emissions with respect to the *business as usual* scenario. Overall primary energy hardly varies due to the inclusion of low-temperature heat from the environment. Moreover, a 71% reduction in the LCOHC is achieved by replacing solar thermal collectors for DHW with an air/water HP and centralizing thermal systems in each building. However, tertiary buildings in the *existing policies* scenario maintain the same centralized heating and cooling systems used for the *business as usual* scenario, so there are no reductions in NRPE or $CO_2$ emissions in these buildings. Under the *sustainable development* scenario, the DHC network significantly reduces non-renewable primary energy consumption and $CO_2$ emissions. Nevertheless, the *sustainable development* scenario has a greater LCOHC, especially for tertiary buildings, due to the high investment costs of the DHC network. High investment costs of DHC networks could be mitigated through public support, considering the better efficiency achieved with this technology.

Tertiary and residential consumptions in Table 2 are not fairly compared since they have different demand profiles. A better comparison is achieved when they are referred to the maximum allowed NRPE indicator. Such limitation is established by local regulations (Madrid City Council, 2020) depending on residential or tertiary buildings. Fig. 2 shows the ratio of the NRPE consumption to the maximum allowed value for each building typology against the LCOHC. In the *business as usual* scenario with conventional thermal solutions, NRPE consumption is close to the maximum allowed consumption for residential buildings or even exceeded in tertiary buildings. Fig. 2 illustrates that switching from conventional systems to collective central air/water HPs for underfloor heating and cooling plus a dedicated air/water HP for DHW in the *existing policies* scenario almost halves NRPE while the LCOHC is reduced drastically. In the *sustainable development* scenario, shifting to a DHC network results in an important reduction of the NRPE

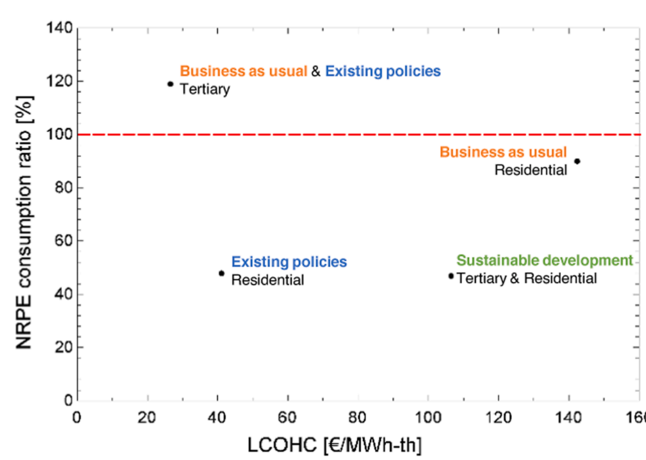


**Fig. 2.** Comparison of energy and economic performance of the district in the three scenarios.

**Table 2**
Energy and economic performance indicators in buildings.

| Scenario | Business as usual | | Existing policies | | Sustainable development |
|---|---|---|---|---|---|
| **Building** | **Residential** | **Tertiary** | **Residential** | **Tertiary** | **Residential & Tertiary (*)** |
| **OPE [$kWh/m^2$]** | 41.6 | 69.6 | 46.3 | 69.6 | 49.0 |
| **NRPE [$kWh/m^2$]** | 24.0 | 48.5 | 12.7 | 48.5 | 16.3 |
| **$CO_2$ [$kg/m^2$]** | 5.1 | 9.6 | 2.2 | 9.6 | 2.76 |
| **LCOHC [€/MWh-th]** | 142.4 | 26.5 | 41.1 | 26.5 | 106.5 |

(*) Residential and tertiary buildings are coupled by DHC network in the sustainable development scenario.

consumption of tertiary buildings. However, this is achieved at the expense of a higher LCOHC.

### 4.2. Charging stations

Applying the sizing criteria for EV CSs, explained in Section 3.2, the total CS installed power obtained per building category and charging speed is shown in Fig. 3. This figure highlights the predominance of slow charging in the *business as usual* scenario and an increasing installed power of semi-fast and fast chargers in the *existing policies* and *sustainable development* scenarios where CSs are also installed at municipal service buildings.

Table 3 compares the peak coincident demand for EV charging in the district after applying simultaneity factors to the installed power of CS shown Fig. 3. As aforementioned, simultaneity factors consider both the utilization rate of the CS and the adoption of smart charging. Given that the prominent use of night residential EV charging is assumed, a higher simultaneity factor for night charging leads to a greater coincident night peak demand. In contrast, day charging is primarily applied in tertiary and commercial charging points, translating into a higher day-simultaneity factor. Moreover, in Table 3 it is observed that the simultaneity factor of EV loads decreases, moving from the *business as usual* to the *sustainable development* scenario, due to the adoption of more smart charging infrastructure that can respond to signals that incentivize to shift EVs charging needs to off-peak hours.

### 4.3. Peak load

The total peak load of the district per scenario is compared in Fig. 4. In this figure, the peak load consumption for buildings is classified as LV and MV, depending on the size in kW of the connection points. The EV charging demand is considered separately. A reduction of the peak demand of LV consumers in the *existing policies* scenario compared to the *business as usual* one can be observed in Fig. 4. In Table 1, the *existing policies* scenario was established considering a higher energy performance of residential buildings than the *business as usual* scenario. Moreover, implementing a DHC network in the *sustainable development* scenario allows a further reduction of peak energy consumption in residential and tertiary buildings, which is reflected in a 9% reduction in the aggregate peak load from LV and MV consumers with respect to the *business as usual* scenario. On the other hand, the peak demand from EV charging is approximately tripled and quadrupled from the *business as usual* scenario to the *existing policies* and *sustainable development* scenarios, respectively. However, such a significant increase in EV charging demand in the *existing policies* and *sustainable development* scenarios is almost not translated to the total peak load due to the reductions mentioned above in building peak consumptions.

It can be noticed that the difference in total peak demand among scenarios accounts for only 7%, confirming that efficiency measures in heating and cooling in buildings offset the electrification growth due to the significant EV penetration. The peak load contributions by end-use

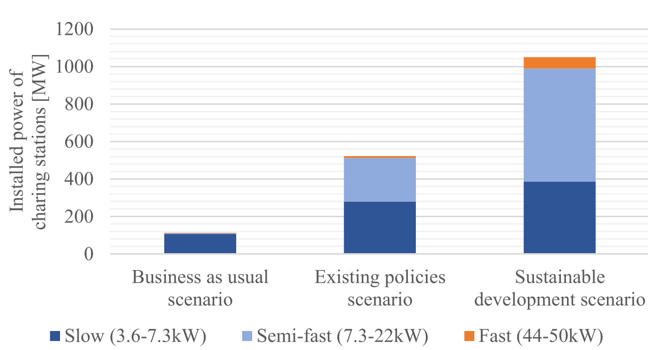


**Fig. 3.** Slow, Semi-fast and fast CS installed power (kW) for each scenario.

**Table 3**
Peak coincident demand [kW] at the district for EV charging per CS type and scenario.

| EVs peak power demand [kW] | | | | | | |
|---|---|---|---|---|---|---|
| scenario | Business as usual | | Existing policies | | Sustainable development | |
| | Day-time | Night-time | Day-time | Night-time | Day-time | Night-time |
| Slow | 8,157 | 6,651 | 13,145 | 24,522 | 13,677 | 27,381 |
| Semi-fast | 220 | 68 | 4,575 | 9,791 | 11,642 | 22,524 |
| Fast | 80 | 20 | 368 | 105 | 1,708 | 620 |
| Total | 8,457 | 6,739 | 18,088 | 34,487 | 27,027 | 50,525 |
| Simultaneity factor | 77% | 61% | 35% | 66% | 26% | 48% |

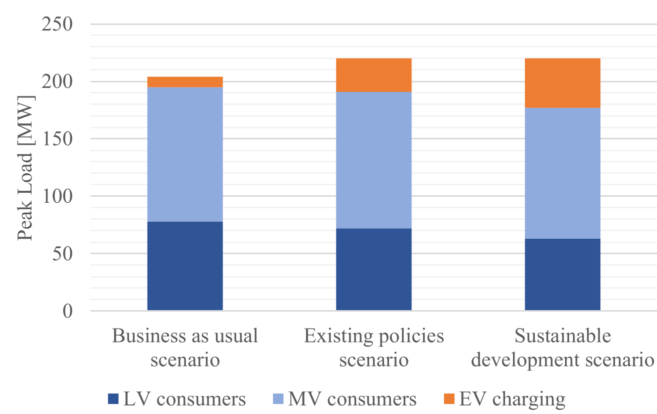


**Fig. 4.** Peak-load demand per consumer type and charging stations.

of electricity consumption are disaggregated for each scenario in Table 4. The additional peak electricity load from HPs does not increase the peak consumption from buildings. This is because their deployment is coupled with energy efficiency measures and optimized energy use through EMSs. In the existing policies scenario, the combination of collective HPs and energy efficiency allows for a reduction in the peak electricity load of residential buildings. In the *sustainable development* scenario, the DHC network, powered by geothermal HPs, supplies the heating and cooling demands of all buildings, achieving a reduction in the peak load of electricity.

Finally, Table 5 presents the number of PV installations and the total installed PV capacity in the district, confirming the significant PV penetration under both the *existing policies* and the *sustainable development* scenarios. However, PV installations are excluded in the calculation of the peak coincident demand in the district. The peak coincident demand corresponds to the time of the day when the network is more

**Table 4**
Peak load disaggregation by end-use for each scenario.

| | Business as usual | Existing policies | Sustainable development |
|---|---|---|---|
| **Residential peak load [MW]** | 61.9 | 53.6 | 46.4 |
| **Tertiary peak load [MW]** | 96.4 | 96.4 | 77.1 |
| **Municipal peak load [MW]** | 28.7 | 28.7 | 21.7 |
| **HPs peak load [MW]** | 0.0 | 4.0 | 23.3 |
| **EV CSs peak load [MW]** | 8.5 | 29.2 | 42.7 |
| **Other uses peak load [MW]** | 8.5 | 8.5 | 8.5 |
| **Aggregate peak load [MW]** | 204.0 | 220.4 | 219.7 |

**Table 5**
PV distributed generation number of number of installations and total capacity in each scenario.

| Scenario | Business as usual | Existing policies | Sustainable development |
|---|---|---|---|
| Number of PV installations | 164 | 181 | 307 |
| PV installed capacity [kW] | 4068 | 10,500 | 31,000 |

stressed, accounting for 7/8 p.m. in Spain, when PV production during this time is very limited or null. In this case study, the installation of distributed energy storage systems and vehicle-to-grid is not considered and, thus, self-consumption from PV generation cannot have a significant contribution to reduce the evening peak demand.

### 4.4. Electricity distribution network

This section analyzes and compares the techno-economic results, and the graphical layouts of the DNs planned with the RNM model for each of the three studied scenarios. Fig. 5 illustrates the graphical layouts of the three DNs. As aforementioned, the three DNs supply have approximately the same peak load and share the same street configuration of the district. Therefore, from a graphical point of view, differences are small, despite the network supplying a significantly higher share of EV charging and PV installations under the *sustainable development* scenario.

Table 6 summarizes the main technical characteristics of the three designed DN. The extent of the LV and MV networks is defined by the total line length, which mainly depends on the geographical constraints of the area (i.e., street configuration) and the number of connection supply points. Both LV and MV network lengths are similar in the three scenarios.

Table 7 represents the number of LV consumer, MV consumer and EV CS supply points. The number of buses in the DN is determined by the amount of supply points, not by the total number of individual consumers and CSs. A single supply point could be an aggregation of several consumers or CSs at a single location. For instance, the relative increase from the *business as usual* scenario to the *sustainable development* scenario of the number of EV CS supply points with respect to the number of CSs is smaller as more CSs are located in the same parking area.

Additionally, energy losses are assessed to account for the efficiency of transporting electricity through the DN. Despite having a shorter MV network, the *business as usual* scenario has higher energy losses since its

**Table 6**
Technical characteristics obtained for the three designed networks.

| Scenario | | Business as usual | Existing policies | Sustainable development |
|---|---|---|---|---|
| **LV network** | **Length [km]** | 30.29 | 30.90 | 35.65 |
| | **Energy losses [kWh]** | 2867,267 | 2755,522 | 3259,364 |
| | **% Energy losses per annual energy demand** | 0.46% | 0.41% | 0.49% |
| **MV network** | **Length [km]** | 28.03 | 33.70 | 31.39 |
| | **Energy losses [kWh]** | 3599,651 | 3080,156 | 3106,953 |
| | **% Energy losses per annual energy demand** | 0.57% | 0.46% | 0.46% |
| **Distribution transformers** | **Total nominal power [kVA]** | 103,330 | 111,910 | 91,490 |
| | **Number** | 116 | 132 | 95 |
| | **Energy losses [kWh]** | 1830,464 | 1860,389 | 1536,918 |
| | **% Energy losses per annual energy demand** | 0.29% | 0.28% | 0.23% |

**Table 7**
Number of supply points per voltage level.

| Scenario | Business as usual | Existing policies | Sustainable development |
|---|---|---|---|
| **LV consumer supply points** | 449 | 446 | 454 |
| **MV consumer supply points** | 48 | 51 | 52 |
| **EV CS supply points** | 199 | 281 | 283 |

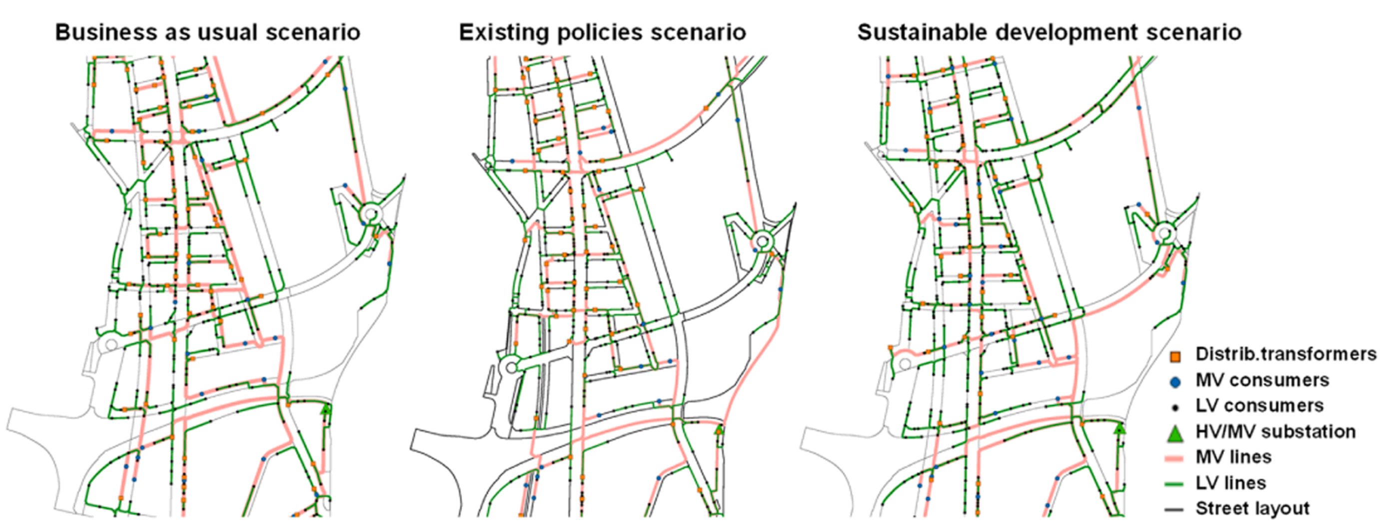


**Fig. 5.** Zoom of the graphical layout of the electricity distribution networks in, from left to right, the *business as usual*, *existing policies*, and *sustainable development* scenarios.

power lines are more loaded. The annual cost of energy losses is assessed in Table 8, which also summarizes the network costs for the three scenarios.

The two major factors determining the cost of the LV and MV networks are their lengths and the peak power of the supplied loads. Moreover, investments in distribution transformers mainly depend on the LV peak power that must be supplied in the district. Since all scenarios have a similar aggregate peak load (see Fig. 4), the resulting electricity grids' investments and operational costs in all scenarios are comparable. The DN for the *existing policies* scenario, with the longest MV network and the highest installed capacity of distribution transformers, requires the largest investment costs, which are just 10% higher than those in the *business as usual* scenario. Nevertheless, in the *existing policies* scenario, the installed power of CSs is increased fivefold (Fig. 3) and collective HP based systems are used in residential buildings for electrifying DWH, heating and cooling energy demands. Notably, the *sustainable development* scenario is the most economical scenario regarding DN costs, even though it has the largest share of EV CSs and PV installations. Thus, energy efficiency in buildings in the *sustainable development* scenario allows for maintaining a similar peak load and DN layout while increasing tenfold the total installed power of EV CSs as compared to the *business as usual* scenario. Table 8 illustrates that DN planning can benefit from a holistic approach that integrates multiple energy aspects by leveraging synergies between decarbonization actions (e.g., energy efficiency in buildings and EV adoption).

### 4.5. Scenario comparison

Table 9 summarizes the main results of each scenario. The comparison shows that electrifying building and transport energy demand in the analyzed district leads to significant $CO_2$ emission reductions without significantly higher DN investments. However, much higher DN costs would have resulted from a short-sighted planning approach that only considered the increasing deployment of EV CSs and HPs. Note that despite a much higher installed capacity of EV CSs in the innovative *sustainable development* scenario, the peak load is comparable to the other scenarios. This result can be explained by higher building energy efficiency and smart charging in the *sustainable development* scenario. This finding highlights the importance of integrating multiple energy models when planning energy infrastructure for new urban areas to take advantage of synergies between different technologies.

**Table 8**
Economic results obtained for the three designed networks.

| Scenario | | Business as usual | Existing policies | Sustainable development |
|---|---|---|---|---|
| LV network | Investment Cost [€] | 1815,555 | 1806,458 | 2093,832 |
| | Annual Operation & Maintenance cost [€/year] | 18,838 | 18,743 | 21,726 |
| | Energy Losses Cost [€/year] | 153,141 | 147,172 | 174,083 |
| MV network | Investment Cost [€] | 4235,850 | 4813,421 | 4648,593 |
| | Annual Operation & Maintenance cost [€/year] | 62,429 | 70,536 | 69,315 |
| | Energy Losses Cost [€/year] | 192,257 | 164,511 | 165,942 |
| Distrib. transf. | Investment Cost [€] | 9843,554 | 10,830,078 | 8481,064 |
| | Annual Operation & Maintenance cost [€/year] | 225,232 | 247,803 | 194,057 |
| | Energy Losses Cost [€/year] | 135,693 | 140,546 | 115,339 |
| Total Costs | Investment cost [€] | 15,894,959 | 17,449,957 | 15,223,489 |
| | O&M [€/year] | 306,499 | 337,082 | 285,098 |
| | Losses [€/year] | 481,091 | 452,229 | 455,364 |

## 5. Discussion

Although this case study provides insightful conclusions on the synergies that arise from combining multiple energy models for planning the energy infrastructure of new urban districts, it has potential limitations. First, the proposed approach plans the energy infrastructure from a techno-economic perspective without considering the governance of the urban district. Each of the different energy aspects entails decisions that affect different stakeholders, and it is not assessed in this case study how the preferences of these stakeholders could be aligned to achieve a technically and economically efficient solution. Second, emerging technologies that allow to further reduce the peak load of the district, such as distributed energy storage and vehicle-to-grid, have not been modelled. Besides, other mechanisms to leverage the flexibility of DERs in the urban districts, such as local flexibility markets, could also be considered in addition to smart charging and controllable domestic loads' response to tariffs.

However, the main conclusions drawn in the preceding chapter illustrate the advantages that models that follow an integral approach can provide over conventional ones that analyze separately the impacts of different energy aspects. The main benefit of combining multiple energy models is that the synergies and interactions between them can be leveraged to improve cost efficiency. Moreover, the proposed approach is based on a modular framework that facilitates its extension to incorporate the missing aspects discussed above, such as governance or energy storage. Furthermore, the case study analyzes the planning of energy infrastructure in a new district, but the proposed approach could be adapted to study the electrification of existing urban and rural areas.

## 6. Conclusions

This paper presents a novel approach to designing and assessing energy infrastructure that integrates energy management in buildings, EV charging deployment, and DN planning for innovative and decarbonized real-scale urban districts. The proposed approach is used to assess the impact on the design of DN infrastructure of high energy-efficient buildings and high electrification levels, shifting towards an interconnected energy system where most of the energy demand in thermal uses and transportation is supplied with electricity. The synergies and implications that arise from this combination of decarbonization technologies have been studied in a real large-scale case study for a new district in Madrid, Spain. The main finding of this case study is that a highly electrified scenario, which combines energy-efficient buildings with high adoption of HPs and EVs, can reduce $CO_2$ emissions without requiring additional investments in electricity distribution systems.

The case study results show that HPs could efficiently decarbonize building thermal energy demand. Collective systems per building based on HPs significantly reduce both $CO_2$ emissions and the LCOHC for residential buildings compared to conventional gas-based thermal solutions. In the case of tertiary buildings, the proposed DHC network with geothermal HP loops reduces NRPE consumption by 66%. However, the high investment required by the DHC network increases the LCOHC and might require public support. Additionally, the combination of collective HP systems or DHC networks, energy efficiency measures and EMSs reduce the electricity peak load of buildings.

The three DNs designed to supply the required electricity demand in each scenario are considerably similar regarding their network components, costs, and layouts. These similarities are due to comparable peak load demands. The stability of the district peak demand across the three scenarios can be explained by more energy-efficient buildings allowing for higher penetration of EVs. The *sustainable development* scenario, the most energy-efficient scenario with the highest electrification, results in

**Table 9**
Results summary by scenario.

| | Business as usual | | Existing policies | | Sustainable development |
|---|---|---|---|---|---|
| | Residential | Tertiary | Residential | Tertiary | Residential & Tertiary (*) |
| **NRPE consumption ratio [%]** | 90 | 120 | 50 | 120 | 50 |
| **$CO_2$ emissions [kg/m$^2$]** | 5.1 | 9.6 | 2.2 | 9.6 | 2.76 |
| **LCOHC [€/MWh-th]** | 142.4 | 26.5 | 41.1 | 26.5 | 106.5 |
| **PV installed capacity [MW]** | | 4 | | 11 | 31 |
| **EV CSs installed capacity [MW]** | | 11 | | 52 | 105 |
| **EV peak load [MW]** | | 9 | | 29 | 43 |
| **HP peak load [MW]** | | 0 | | 4 | 23 |
| **Aggregate peak load [MW]** | | 204 | | 220 | 220 |
| **DN investment cost [€]** | | 15,894,959 | | 17,449,957 | 15,223,489 |
| **DN O&M cost [€/year]** | | 306,499 | | 337,082 | 285,098 |
| **Energy losses cost [€/year]** | | 481,091 | | 452,229 | 452,229 |

(*) Residential and tertiary buildings are coupled by DHC network in the sustainable development scenario.

the lowest DN cost despite having a considerably higher number of installed EV CSs to be supplied. Therefore, the case study illustrates the potential benefits of more energy-efficient buildings for integrating EV charging, avoiding further network investments in scenarios with high electrification levels. This result highlights the importance of using integrated planning approaches that consider multiple energy aspects, such as the one proposed in this paper, when planning real-scale urban districts.

Future studies should investigate integrating other grid technologies, such as energy storage, active demand, smart transformers, or vehicle-to-grid capabilities in EV CSs, and how they would impact the costs of the designed distribution networks in multi-energy systems. Lastly, the planning of multi-energy networks focused on planning coupled district heating and electricity distribution networks in urban areas should be further investigated.

## Author Statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, this manuscript is not submitted to other journals, and all authors have agreed to this submission.

## CRediT authorship contribution statement

**Rafael Cossent:** Writing – review & editing, Conceptualization. **Tomas Gomez:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Carlos Mateo:** Writing – review & editing, Supervision, Conceptualization. **José Ignacio Linares:** Writing – review & editing, Conceptualization. **Miguel Martínez:** Writing – original draft, Visualization. **Luca De Rosa:** Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Francisco Martín-Martínez:** Writing – review & editing, Software, Methodology. **Álvaro Sánchez-Miralles:** Writing – review & editing, Supervision. **Fernando Postigo:** Writing – review & editing, Software, Methodology.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tomas Gomez reports financial support was provided by IDOM Consulting, Engineering and Architecture S.A.U. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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