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Holistic fuzzy logic methodology to assess positive energy district (PathPED)

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ABSTRACT

Climate change is a global emergency and cities need to be reinvented in view of minimising their footprint profiling. Under this scenario urban planners, engineers and all the professionals involved in the decision-making process need new tools able to provide holistic and flexible urban perspective. The PathPED methodology provides a holistic approach that, on the one hand, uses agent based fuzzy logic methodology to define urban transition scenarios, and on the other hand, provides an assessment of urban districts in terms of the commitments adopted under Paris agreement, that is: increase of renewable, energy efficiency and carbon neutrality. The transition scenarios are defined by five smart agents (buildings, vehicles, lighting, photovoltaics and geothermal) which develop Positive Energy District (PED) scenarios for 2020, 2030 and 2050. A transient simulation is used to assess the performance of the PED in terms of yearly and monthly energy balances, ESS performance and carbon footprint. Results show that a decisive inclusion of renewable energy sources (100%), complete transition to electromobility, and substantial improvements in the energy efficiency of buildings are required to comply with the highly ambitious European commitments under Paris agreement.

1. Introduction

According to UN—Habitat, cities are responsible for 78% of the world's energy consumption and 60% of the greenhouse gas emissions (GHG) (United Nations, 2020), with direct impacts in the environment and the development of societies. Some recent publications (C2ES, 2016; IEA, 2020; bp, 2018) estimate that buildings and mobility are responsible of about 46% of GHG worldwide. The willingness to mitigate climate change is promoting a rapid evolution of societies, that need to be transformed in multiple dimensions, comprising the electrification (Purohit et al., 2021) and digitalisation (Serrano, 2018; Petri et al., 2017) of energy loads, as well as switching to new means of mobility, like electric vehicles (EVs) (Castillo-Calzadilla et al., 2022).

The Paris agreement (Barston, 2019) is the first-ever universal, legally binding global climate change agreement, adopted at the Paris climate conference (COP21) in December 2015. It sets the basis to limit the global warming to 1.5 °C, which requires substantial reductions of greenhouse gas emissions from a peak in 2020 down to zero by the end of the century.

Under this agreement the EU and its Member States undertake certain commitments with respect to climate change to be progressively achieved in 2020, 2030 and 2050 (see Fig. 1). The European Union (EU) recently adopted a 55% net emissions reduction target by 2030 which paves the way for climate neutrality by 2050 (Europea, 2019). Indeed, energy modelling at European level has shown that 100% renewable energy system is technically possible (Connolly et al., 2016) by implementing smart systems that adopt additional flexibility by connecting the electricity, heating, cooling, etc. A recent study in Germany (Hansen et al., 2019) shows that measures related to energy savings and efficiency are crucial for achieving a 100% renewable energy system, and that the main challenges are within resource potentials. The European Economic Area (EEA) estimates that the EU's net emissions in 2020 were 34% lower than in 1990 but some reasonable transition pathways are still to be defined (Nik & Perera, 2020).

Abbreviations: ABM, agent-based model; CO_2, carbon dioxide; ESS, energy storage system; EV, electric vehicle; FL, fuzzy logic; GHG, greenhouse gas emissions; GD, green deal; DHW, domestic hot water; ICT, information and communications technology; JPI, joint programming initiatives; PED, positive energy district; PUB, public use building; PV, photovoltaic; RES, renewable energy sources; RUB, residential use building; SDG, sustainable development goal; SOC, state of charge.

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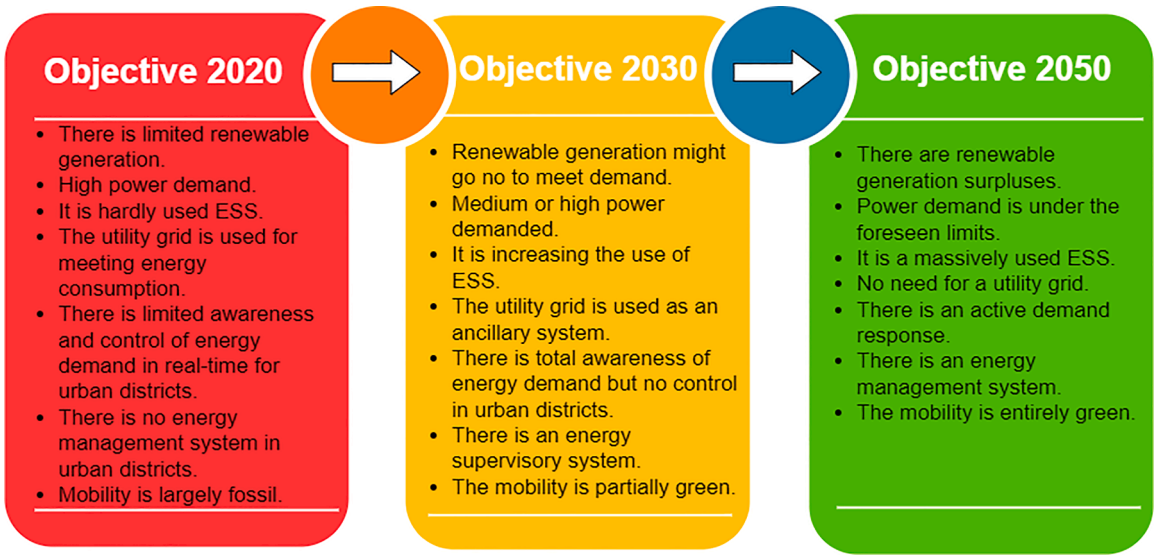

Fig. 1. European commitments under Paris agreement for 2020, 2030 and 2050.

That claims directly to European Cities to adopt important changes with respect to their overall landscape and configuration as well as to their energy management schemes (Kazan, 2019). The European Commission (EC) is decided to transform the current urban landscape and has announced an unprecedent action map under the so-called "European Green Deal" (GD) (European Commission, 2019).

The PathPED undertakes current EU position and analysis several transition pathways that help moving forward from a red 'objective 2020' to the yellow 'objective 2030' and finally to the green 'objective 2050'. Some authors have already reported that achieving a 100% renewable energy system in Europe is feasible for 2050 (Connolly et al., 2016; Thellufsen et al., 2020; Potrč et al., 2021).

By 2050 cities need to be neutral in terms of CO_2 emissions. But these long-term objectives require of to be transposed to clear and achievable action plans in the local contexts for each city. With diverse local contexts, some cities are expected to act as experimentation and innovation hubs (E. Commision, 2021) achieving earlier the neutrality, while others will learn from them and pursue similar strategies.

Some cities area already testing Positive Energy Districts (PEDs) concepts (Sareen et al., 2022) that will be later upscaled and replicated in the city boundaries and abroad. The PEDs are a new step in innovation with respect to Net Zero Energy Buildings (Nearly zero-energy buildings, 2022; Deng et al., 2014). Being an intermediate and actionable level between buildings and full cities, self-sustainable districts are identified as urban units with a key role for the energy transition (Howell et al., 2017). In some North European countries this is already a reality. For instance, the municipality of Aalborg has achieved the self-sufficiency by a combination of PV and wind power, and a 4th generation district heating that combines biomass and gas produced by gasification and biogas (Thellufsen et al., 2020).

In fact, national level reports and strategies in Denmark (Lund et al., 2021) showcase the capacity of Smart Energy System to achieve full energy balance and global neutrality (i.e. considering the sustainable use of biomass, electricity and gas exchanges with other countries). Also, at European level (Potrč et al., 2021), the gradual transition to a renewable energy system is possible with the optimisation of renewable energy supply networks. A multi-period mixed-integer linear programming (MILP) model has been proposed in this case to identify supply networks that represent a compromise between economic, environmental, and social aspects.

The scientific literature has evolved from analysing individual energy sub-sectors based on concepts such as 'smart grid', 'zero energy buildings' and 'power-to-heat' to holistic frameworks such as 'Smart Energy Systems' (Lund et al., 2017). In this sense, the joint analysis of thermal and electric carriers allows for the optimisation of energy storage systems (Lund et al., 2015) and avoids for oversizing of electrical infrastructure or smart grids (Lund, 2018).

In sum, urban districts should be analysed as an urban design unit where optimum settings to buildings, street-lighting, vehicles, etc. are provided. In accordance with Joint programming initiatives (JPI), a PED is an energy-efficient and energy-flexible urban area (or group of connected buildings) which produce net-zero greenhouse gas emissions and actively manage an annual surplus production of renewable energy (Derkenbaeva et al., 2021). To achieve this, they require integration of different systems, infrastructures and the interaction between buildings, the users and the regional energy and mobility systems while securing the energy supply and a good life for all in line with social, economic and environmental sustainability (Positive Energy Districts (PED), 2021).

PEDs consist of several buildings (new, retro-fitted or a combination of both) which actively manage their energy flows (Hedman et al., 2021). PEDs make optimal use of elements such as advanced materials, local RES and storage (Ala-Juusela et al., 2016), smart grids (Castillo-Calzadilla et al., 2022), demand-response, energy management (electricity, heating, and cooling), user interaction or involvement by the means of ICTs tools. When analysing PEDs, the self-sufficiency (Ala-Juusela et al., 2016; Cauševi et al., 2021) and the neutrality of the buildings implementing a local energy share scheme is crucial (Fichera et al., 2021).

Energy models generally follow two approaches: either a top-down or a bottom-up approach (Ringkjøb et al., 2018). Often top-down models follow the economic approach, considering macroeconomic relationships and long-term perspectives (Mai et al., 2013). Bottom-up models are generally based on detailed technological descriptions of the energy system. The purpose of bottom-up modelling is to obtain insight into their technological performance for optimal decision making at the design (Bagheri et al., 2018; Pastore et al., 2022), operations (Mohammadi et al., 2022; Mohanty et al., 2022) and control level (Mohammadi et al., 2022). Thus, the technological characteristics of the system components are modelled endogenously (i.e., are dependant on other variables or parameters in the model). Some standard software packages as EnergyPlan (Lund et al., 2021) are very popular and generally combined with ad hoc applications for specific purposes. Although some authors (Hansen et al., 2019) have stressed the importance of linking bottom-up with top-down modelling proposals, to the

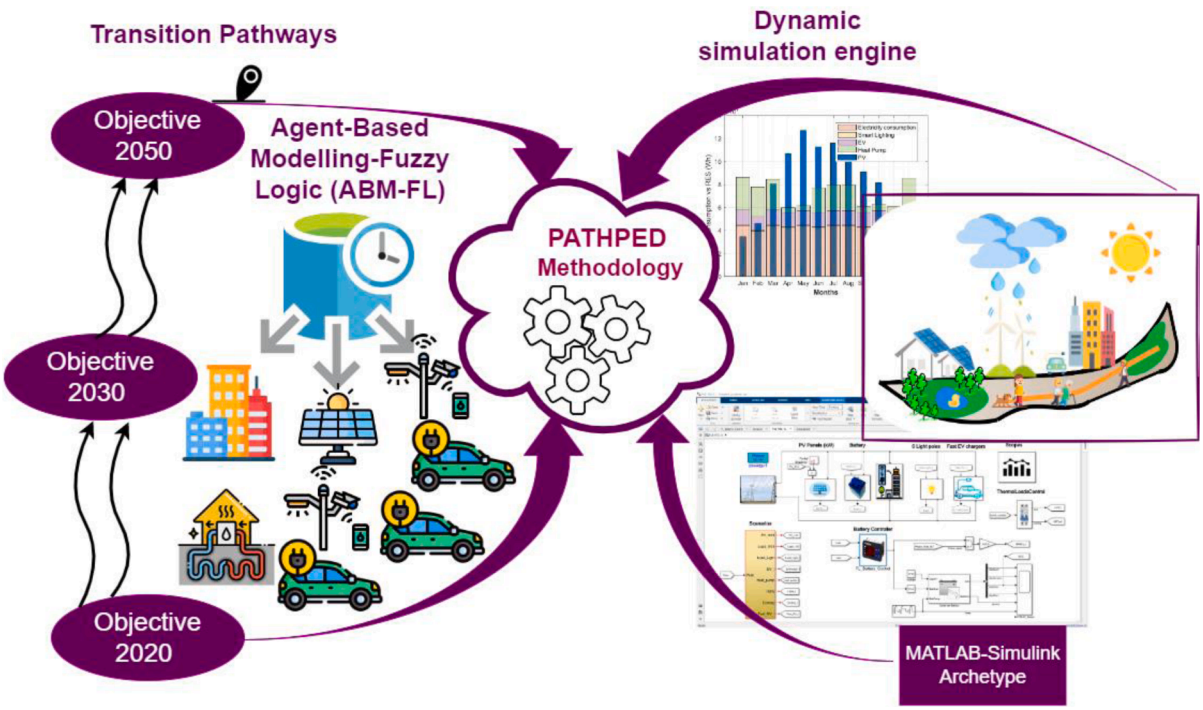

Fig. 2. Holistic methodology (PathPED) to assess urban districts in terms of energy balances and carbon footprint.

authors' knowledge, there is no clear proposals in this sense.

Agent-based modelling (ABM) is a specific case of engineering based (bottom-up) models. For example, ABM has been used for decision-making processes (Chappin et al., 2017) or for energy demand estimation (Hansen et al., 2019). ABM has been used to simulate human behaviour in smart homes (Kamara-Esteban et al., 2016), the effect of energy trading in a local network (Lovati et al., 2020) or specific applications of microgrids (Lovati et al., 2021) where for example, various price schemes (Mohandes et al., 2019) are considered for the adoption of PV infrastructure. In general, ABM are used to assess decision making processes and their impact on complex issues: investments in residential sector (Sachs et al., 2019), configuration of energy grids (Fichera et al., Jul. 2020), or optimal operation for energy storage (Lagorse et al., 2009). In some cases, the agents work on common objectives and therefore provide answers helped by artificial intelligent engines (Lagorse et al., 2009). However, we have not found references where agents (and agent-based modelling) were used to represent the smart elements that jointly define an urban district.

Indeed, energy assessments are particularly complex in cities (Hoekstra et al., 2017) since the main energy sectors there (buildings and vehicles) correspond to diffuse systems, and therefore, the cooperation of multiple agents is required. It is in this context where Agent Based Modelling (ABM) becomes a powerful tool for the holistic simulation of dynamic environments where multiple factors (agents) evolve following an independent but also coherent behaviour (Wilson and Wu, 2017). With respect to energy modelling, agents (buildings, vehicles, renewable energy sources, smart grid, etc.) will draw transition pathways (Howell et al., 2017) that may derive in more (or less) promising scenarios according to Paris agreement goals and national or regional strategies.

The PathPED methodology combines a top-down and bottom-up perspective. On the one hand, it includes an Agent Based Modelling (ABM) that allows evolving along transition pathways gaining long-term perspective of energy management systems. On the other hand, a dynamic simulation tool facilitates the hourly assessment of energy infrastructure and self-sufficiency analysis of the district. On the top of that, we define agents as smart things (representing buildings, lights, or vehicles) able to decide on a fuzzy logic scheme about their characteristics and requirements in view achieving positive energy balance and carbon neutrality.

This article proposes a holistic methodology (called PathPED) that uses fuzzy logic for the definition of urban transition pathways and dynamic modelling for the assessment of Positive Energy District. PathPED provides a decision support system for the delivery feasible PEDs at city level in the frame of the European Green Deal framework and objectives for 2030 and 2050.

The overall energy performance assessment is performed with a dynamic simulation engine, allowing for the quantitative assessment of energy loads, management of energy storage systems and self-sustainability of the district. It provides decision-makers with a smart and dynamic modelling framework capable of building and simulating scenarios that perfectly represent an urban district. PathPED attempts to build a more quantifiable roadmap (steps or strategies) to drive through small districts towards PEDs.

This paper analyses a set of three scenarios in line with the European objectives for 2020, 2030 and 2050. This paper presents both an ABM-FL based tool for building non-biased scenarios and a simulation environment able to assess the feasibility of those scenarios that draw district conditions in terms of positivity.

The manuscript is organised as follows: Section 1 presents the motivation of this research work; Section 2 presents the methodology aspects implemented for designing an agent-based simulation engine that uses fuzzy logic (ABM-FL) and a dynamic simulation tool for Positive Energy Districts; Section 3 details both the results of the PathPED methodology when following the light transition pathway; and finally, Section 4 draws out the conclusions and future work.

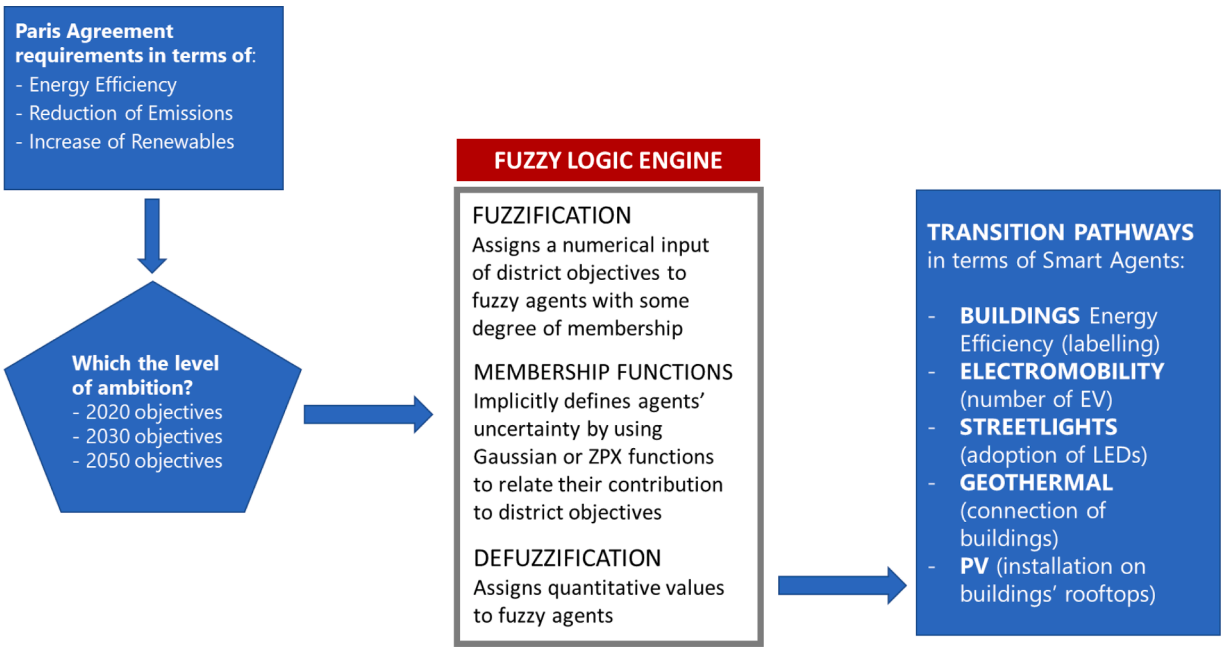

Fig. 3. Evolution of agents according to fuzzy logic scheme that defines transition pathways for the cities of the future.

2. Methodology

The PathPED methodology (Fig. 2) provides a holistic methodology that, on the one hand, uses agent based fuzzy logic methodology to define urban transition scenarios, and on the other hand, provides an assessment of urban districts in terms of the commitments adopted under Paris agreement, that is: renewable energy increase, energy efficiency and carbon neutrality (or greenhouse gas reduction). This methodology is able to settle down high level EU commitments in the form of a district configuration and assess it back using a dynamic simulation model that provides main European requirements as well as other important measures related to overall energy performance, dependence of storage systems, or energy independence from the utility grid. Fig. 2 provides a general overview about the different elements of the expert knowledge system and how they interrelate.

The PathPED methodology has been co-designed by multiple agents interested in investigating how an urban district can contribute with global objectives. The collaborative approach undertakes quadruple helix methodology involving entities from governments, academia, industry and citizenship (Martín et al., 2021). Other interesting approaches use ad-hoc GIS based systems (for example) to interactively define energy retrofitting scenarios (Torabi Moghadam and Lombardi, 2019).

2.1. Smart agent-based model

Agent-based models are computational models (MacAl and North, 2010; Bonabeau, 2002) that describe the simultaneous operations and interactions (Wooldridge, 2009). These modelling technique attempts to re-create and predict the appearance of complex phenomena looking for explanatory insight into the collective behaviour of agents obeying simple rules. In ABM, a system is modelled as a collection of autonomous decision-making entities called agents. These entities are placed into an *environment* and are able to *autonomously react* to changes in the environment. This definition in turn implies the agents' capability of sensing the environment and actuating in order to interact and change it (Liao, 2005). In PathPED, the *agents* are the buildings, streetlights, EVs, and RES located into an urban district in Bilbao, the *environment*. They are able to autonomously react to the increasing requirements of Paris agreement and are able to transform the district in a subsequent set of scenarios that would progressively create a Positive Energy District (or not), depending on the decisions made by the agents following a fuzzy logic approach.

We identify districts as main urban unit that could be easily extended covering entire areas in the city or could be replicated in other neighbourhoods or cities. The agents are the main elements of those districts: buildings, with a variety of consumption profiles and by different efficiency rates; streetlights and traffic lights with various technologies; thermal or electrical RES with varied technologies, etc.

The agents are able to interact and to adopt different features according to a fuzzy logic engine that provides feasible combination of elements (energy efficiency of buildings, percentage of electric vehicles, etc.). Fig. 3 shows how the agents react to the fuzzy logic scheme: First, they adhere the requirements required by each of the objectives defined for 2030 or 2050; then, these general objectives are translated into specific features of district elements following a fuzzification - defuzzification scheme; and finally, specific characteristics of the urban district are provided in terms of usage of renewable energy, efficiency of buildings, etc. In this manner, the agents evolve following strategic pathways that facilitate the transition towards the cities of the future. Current this methodology is focused in achieving the commitments in the Paris agreement, but this same engine could also accommodate other local or regional objectives.

As result, the agent-based modelling follows a fuzzy logic approach that provides specific characteristics of an urban district such as the energy efficiency that urban stock should attain; the percentage of EVs within the area; or the adoption of renewable energies. These parameters are indeed the input for the dynamic simulation of the district (next section).

2.2. PED simulation archetype

This dynamic simulation considers the PED as an urban unit. Indeed, we adopt JPI terminology in a general sense, but the positivity of the district is to be assessed by the dynamic simulation engine. In this sense, a district is considered to be a PED when annual energy balances result positive.

We propose a PED archetype that has been inspired on the characteristics of the PED (North area) to be deployed in Zorrotzaurre (Bilbao) under the ATELIER project.

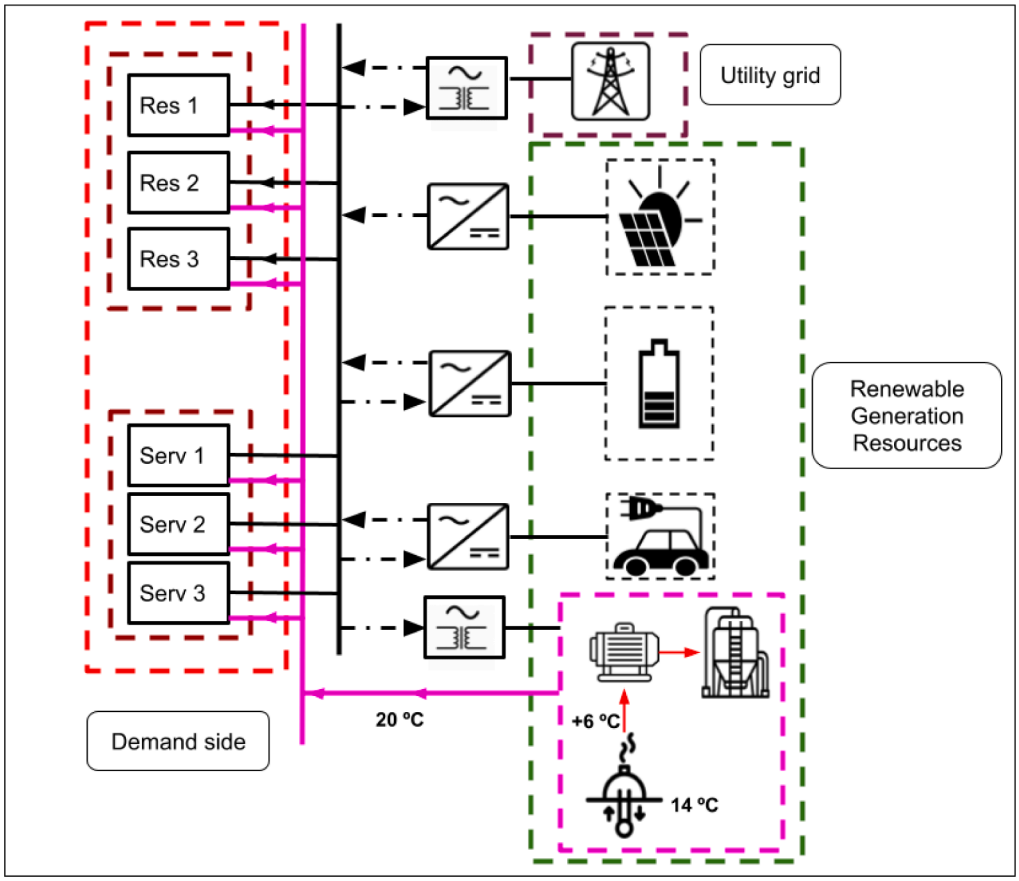

Fig. 4. PED archetype inspired on the PED of Zorrozaurre (Bilbao).

Table 1
Characteristics and energy requirements of the buildings of the PED.

Block	Condition	Use	Floor area (m^2)	Thermal net energy need (kWh/year)		
				Heating	Cooling	DHW
1	New	housing	3391	181	90	72
2	Retrofitted	PUB	3540	367	255	39
3	Retrofitted	PUB	5793	226	158	24
4	Retrofitted	PUB	3749	209	146	22
5	New	housing	4161	240	120	48
6	New	housing	2353	218	109	43
		Total	22,987	1444	880	250

The simulation analysis allows forecasting the effects and impacts of this deployment and makes possible to experiment about possible future scenarios according to European demands. The data used for this purpose has a twofold origin:

- The Bilbao data-commons allows understanding the dynamic plot of Zorrotzaurre and the conditions under which the transition pathways will take place (Martín et al., 2022). Bilbao data-commons have been designed by multiple agents, and for example, a citizen science activity was implemented where participants provided data about building stock including details about: construction year, accessibility, isolation, energy performance (by means or energy labels), etc. This information was confronted with the cadastral open data portal.[2]
- Strategic plans of the City Council of Bilbao. At this respect, the figures used for example vehicle fleet of the PED are not exact but realistic estimations that represent an innovative district under construction.

Following smart agents are considered as main elements in the Zorrotzaurre PED (Fig. 4):

- 6 Buildings, comprising 3 residential (RUB) and 3 of public (PUB) buildings, such as offices, schools etc. The details of these buildings are presented in Table 1. Depending on the usage, different hourly consumption patterns are adopted (Red Eléctrica de España (REE), 2021). Energy use in buildings for space heating and Domestic Hot Water production can be switched between Natural Gas, Geothermal Heat and Direct Electricity use.
- Vehicles: we assume that the PED includes 100 private vehicles and that they can use petrol-based fuels or electricity depending on the scenario. The curve of charge of Volkswagen ID3 is taken for EVs, as it is considered to be an average European EV.
- Streetlights: the PED includes 20 that use traditional lamps or LEDs depending on the scenario.
- Geothermal Energy: A network of five interconnected rings delivers stable source temperature levels in the range of 13–14 °C along the year.
- PV monocrystalline technology as RES for electricity generation: PV arrays can cover up to 3000 m^2 surface area where roofs are orientated to the South with 30° degrees inclination.
- Ancillary systems: a centralised Energy Storage System (ESS) based on li-ion batteries that maximises local management of renewable production in the PED.

[2] https://appsec.ebizkaia.eus/O4GC000C/vistas/visor.xhtml.

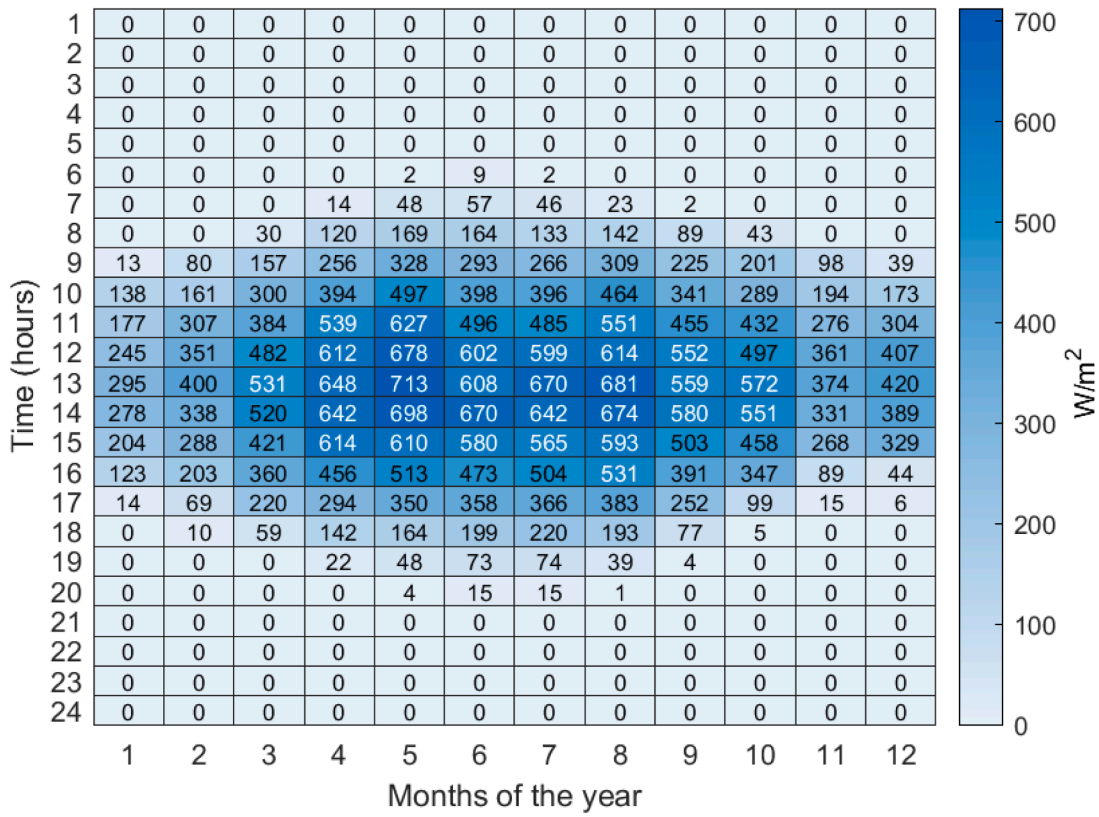

Fig. 5. Daily average irradiance in Bilbao expressed in W/m2.

- Electric grid: A smart microgrid assures the self-management of energy assets as well as the connection with the utility grid. Each element in the PED configuration is connected to a bus distribution (Castillo-Calzadilla et al., 2022).

The PED archetype has been implemented in MATLAB & Simulink, version 2021a.

The energy interchanges are calculated by the law of Kirchhoff currents since this matches entirely with PED definition. The energy

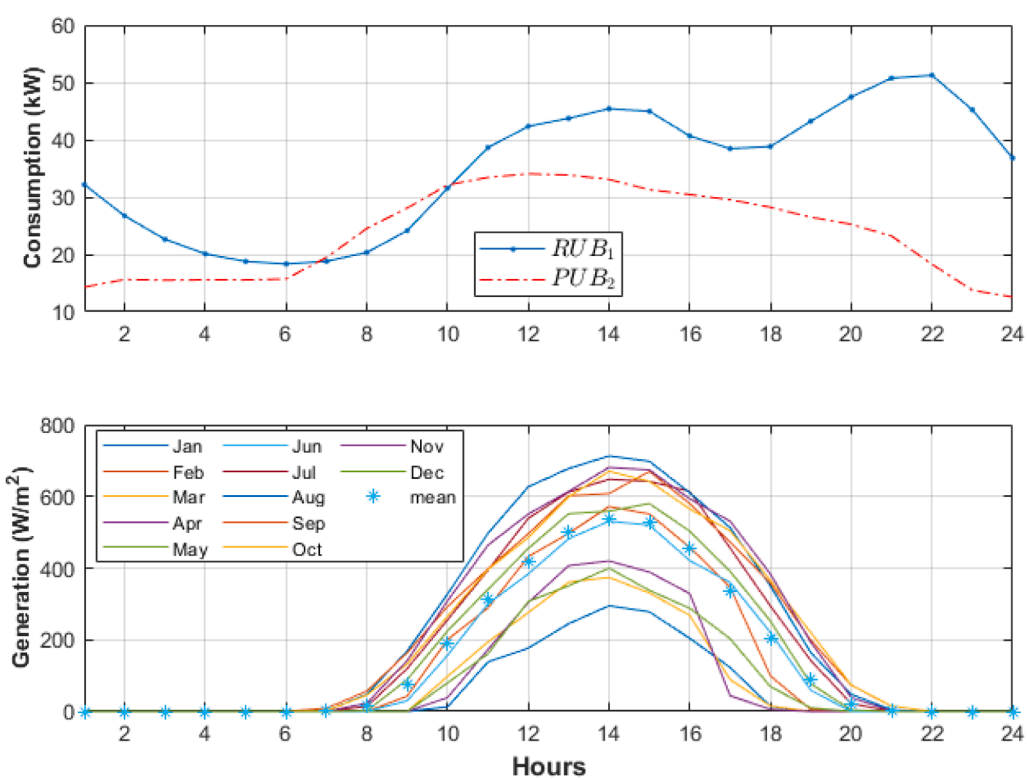

Fig. 6. Buildings consumption and irradiation potential in the PED.

Table 2
Smart agents in the PED.

Agents	Variations
Energy efficiency of buildings	Classifications A to F (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2009)
Usage of LED lighting	Percentage
Transition to EV	Percentage
Connection to geothermal system	Number of buildings
Installation of PV panels in the roof	Number of buildings

consumption of each element (buildings, lights, EVs) is calculated by Ohm's law using 230 V as nominal voltage. The utility-grid is represented by a 3-phase grid of 230 V and 50 Hz. The idea is to make the district self-sufficient as much as possible by implementing an ESS that is part of the microgrid and supports the PED allowing the storage of energy surpluses. The utility grid works as a virtual energy buffer system that provides energy to the PED when it is not able to meet the demands. The EVs increase the flexibility of the PED, since they can be used as dynamic energy storage systems.

3. Results

In this section of the manuscript are gathered all the results of the simulation and exploration of scenarios conducted in this research study.

3.1. Analysis of the potential of positive energy district (PED) in Bilbao

The PED is (by definition) a set of interconnected buildings and district infrastructure that ensures smart and integrated energy management scheme. However, the PED performance is also connected with the natural resources for energy generation (for example, solar irradiance) or with the requirements of certain infrastructures (properties of the soil can determine the feasibility of geothermal). Additionally, there are other urban and social conditions that determine the characteristics of a PED: the type of buildings (blocks or family houses), the space to set up the elements to manage a micro-grid or energy storage system, the disposition of electric hubs for EVs, etc.

This section performs the analysis of the potential of a PED in Bilbao, considering the energy profiles for a district of around 23,000 m^2 that comprises a new neighbourhood with high presence of cultural and knowledge-based industry.

Fig. 5 shows the potential of the PED archetype for the generation of energy from solar energy. The time window that goes from 11 h to 16 h and from month 4th to 8th (May to August) correspond with the highest energy potential. The irradiation potential in the North of Spain is similar to other areas in central Europe, so these results could be easily extrapolated to most European cities.

Fig. 6 represents the hourly profile of buildings in terms of consumption of residential (RUB) and public (PUB) buildings, as well as PV energy production assuming that the roofs of the buildings are completely used for RES generation (3000 m^2 available). The consumption profiles of RESs and PUBs are well differentiated, the figure represents the accumulated consumption of the three RUB and the three

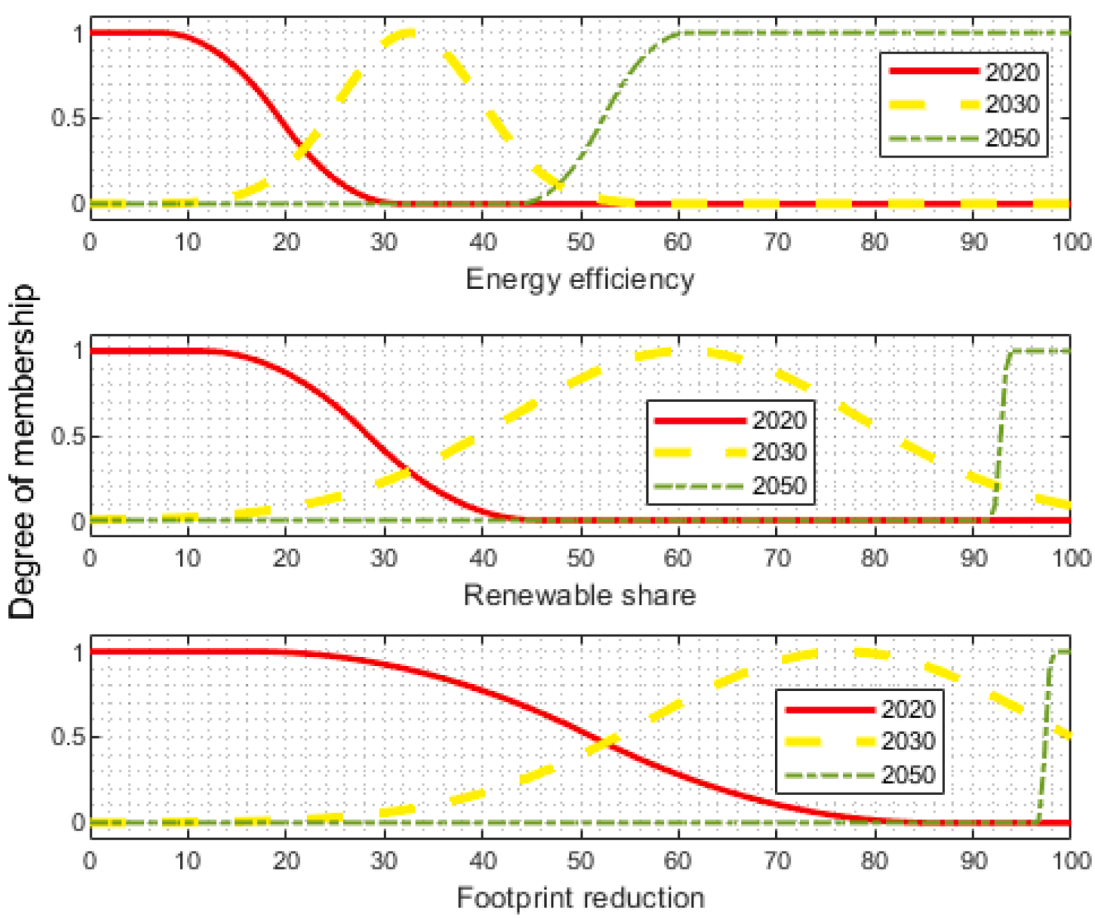

Fig. 7. Degree of Membership rules that govern the fate of smart agents along the transition pathways in terms of main objectives of Paris agreement: energy efficiency, increase of RES and footprint reduction.

Table 3
FAM rules associated to fuzzy logic in PathPED methodology.

	BUILDINGS LABELLING	EVs	LIGHTING	GEOTHERMAL in buildings	PV in buildings
RES ADOPTION		✓		✓	✓
ENERGY EFFICIENCY	✓	✓	✓		
FOOTPRINT REDUCTION	✓	✓	✓	✓	✓

PUBs in our PED archetype. Notice that we are considering buildings of 10 floors, 6 blocks for floor, 60 apartments per tower (building) and in total we are assuming 360 dwellings for the district.

In agreement to REE consumption profiles (Red Eléctrica de España (REE), 2021), residential buildings (RUB) have two peaks periods at 14 h and 22 h, while public used buildings (PUB) present a flatter consumption profile with a maximum around 12 h. There seems to be a match between the buildings' electric load and PV electricity generation, which indicates a good chance to meet energy demands.

3.2. Transition pathways defined by agent-based modelling

The fuzzy logic engine provides PED scenarios that meet 2020 (current), 2030 and 2050 objectives (see Fig. 2) by a smart combination of agents as defined in Table 2.

The agents (Fig. 3) are continuously evolving and taking decisions thanks to a fuzzy logic scheme (see Annex 2) that defines a multidimensional area as result of a set of membership functions that describe the (fuzzy) logic approach. The evolution of the PED allows a fuzzy combination of strategies that in sum will attain European objectives for 2020 (current scenario), 2030 and 2050. Fig. 7 shows the membership rules that allow agents to evolve in terms of reduction of emissions, increase of the share of RES, and improvement of energy efficiency (measured as percentage of improvement) following the European objectives for 2020, 2030 and 2050 (Fig. 1).

The PED is therefore composed by smart agents that according to PathPED methodology can dynamically evolve. Thanks to fuzzy logic engine, the smart agents follow several rules generating a dynamic multi-agent scenario that evolves drawing different (compatible) long-term strategies (Lee, 1990a, 1990b). These rules are generated building the fuzzy associated memory (FAM) rule-table for the five smart agents with objectives in terms of energy efficiency, adoption of RES and footprint reduction (see Fig. 7). The agents ruled for this PathPED methodology are presented in Table 3. Additionally, Annex 2 gathers the 42 rules that compose the PathPED methodology.

Table 4 presents three feasible scenarios for the PED that fulfil respectively 2020, 2030 and 2050 objectives as result of the ABM fuzzy logic approach. These are three of the multiple solutions (combinations of energy labelling in buildings, lighting technology or adoption of RES) that could achieve the objectives. Indeed, the smart agents have a great impact in terms of energy efficiency, share of renewables and footprint reduction.

With increasing ambitions towards 2030 and 2050, there is a need to increase the number of EVs, adopt LEDs lighting systems, and improve the energy efficiency of buildings.

With respect to energy efficiency, buildings should progressively transition from label F in 2020 to A in 2050. As a reference, the greatest share of the building stock in Spain (built in between 1960s and 1980s) shall be labelled between D and G (representing G the poorest performance). A labelling features a well-orientated, designed and insulated building with efficient installations.

Fig. 8 shows the values adopted by smart agents and their impact in terms of energy efficiency and carbon footprint. When the whole fleet of cars in the PED are EVs, we achieve 100% of energy efficiency and 100% of footprint reduction. It shall be noticed that, for 50% energy efficiency can be attained by very different values of EVs in the PED since several smart agents can compensate this contribution. The same effect occurs with when analysing the effect of adopting LEDs for street-lights, for 100% reduction of footprint and 100% of energy efficiency, the 20 lamps of the PED need to be LED, however, if considering a halfway situation with 10 LEDs installed, we would be moving in a wide spectrum of values with regard to improvement of energy efficiency (40%-100%) and footprint reduction (0%-50%). With respect to energy efficiency in buildings, building stock with labels below C (D, F, G) poorly contribute with the improvement of PED efficiency or the reduction of overall footprint.

In terms of smart agent contribution to adoption of RES and footprint reduction, the connection of buildings to geothermal and the installation of PV panels are the main variables. Fig. 9 shows the effect of PV (% of rooftop surface covered panels) and geothermal energy (number of buildings connected to geothermal rings) with this regard.

100% of RES adoption can be achieved with 50% of rooftop surface covered by PV panels and 3 buildings connected to geothermal system. In these scenarios, high efficiency is considered and therefore a

Table 4
Results of agent-based modelling where fuzzy logic determines the evolution of main agents (or elements) in a PED to fulfil European objectives for 2020 (current scenario), 2030 and 2050.

Objective	PED characteristics presulting from the ABM-FL
2020 20% reduction in greenhouse gas emissions 20% of energy from RES 20% increase in terms of energy efficiency	**Buildings**: both (residential & public used) with the efficiency label of "F" **Vehicles**: 19 EVs and 81 fossil powered vehicles (41 diesel and 40 gasoline) **Lighting**: 19 conventional and 1 LED. **PV production**: 35% of rooftop area **Thermal energy**: 2 buildings connected to geothermal, 4 buildings use natural gas
2030 55% reduction of greenhouse gas emissions (GHE) 32% of energy from RES 32.5% increase in terms of energy efficiency	**Buildings**: both (residential & public used) with the efficiency label of "B" **Vehicles**: 58 EVs and 42 fossil powered vehicles (gasoline) **Lighting**: 7 conventional and 13 LEDs **PV production**: 40% of rooftop area **Thermal energy**: 4 building connected to geothermal, 2 buildings use natural gas
2050 100% reduction of GHE (zero emissions) 100% energy from RES	**Buildings**: both (residential & public used) with the efficiency label of "A" **Vehicles**: 97 EVs and 3 fossil powered vehicles (gasoline) **Lighting**: 4 conventional and 16 LEDs **PV production**: 100% of rooftop area **Thermal energy:** All buildings connected to geothermal

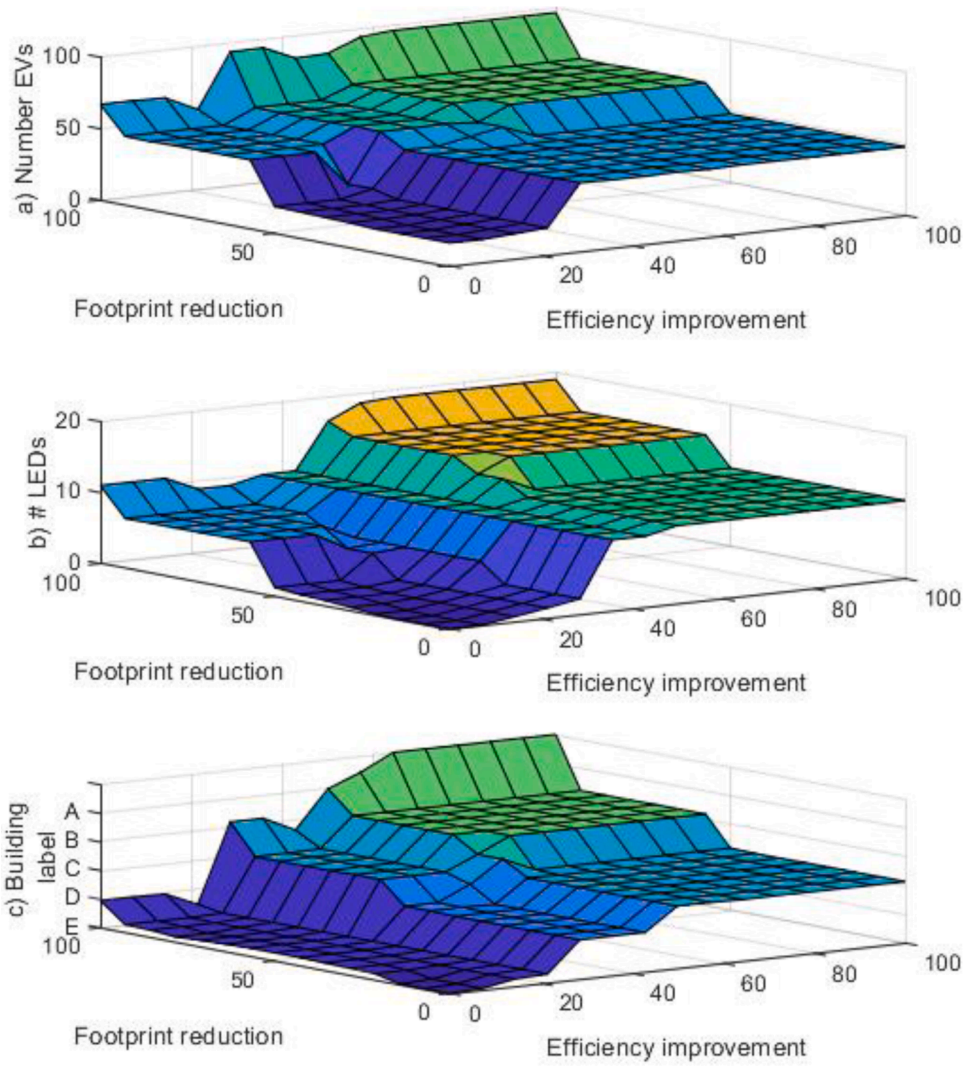

Fig. 8. Surface map for the agents that represent energy consumption and therefore having direct impacts in energy efficiency and carbon footprint.

relatively small RES production is required. In terms of footprint reduction, 100% reduction is only attained when all the buildings in the district connect with geothermal systems and install PVs. It is also remarkable, that a high reduction of footprint is achieved (around 90%) when only 50% of buildings installing PVs and connect to geothermal systems, which again is explained by a highly efficient PED.

3.3. Assessment of PED performance in terms of energy generation and consumption

This section analysis the self-sufficiency of the PED in terms of energy for the three scenarios. Achieving a positive balance would be a very important characteristic in view of ensuring access to affordable, reliable and sustainable energy for all (SDG7). The challenge is then to ensure that renewable energies, helped by storage systems, cover the local energy demand.

Fig. 10 shows the monthly distribution of PV generation and the behaviour of different energy demands: direct electricity consumption, streetlight consumption which depends on the technology used, electromobility demand that becomes higher as the number of EVs increase, and heat pumps that show very different requirements in winter and summer and vary with the energy efficiency performance of the buildings. It shall be noticed that electric loads associated to heat pumps are linked to the heat production through low temperature (13–14 °C) geothermal rings that remains constant along the year. Service-level temperatures are achieved by means of two heat pumps with a COP of 4.7. Numerical values showing monthly variability along the three scenarios are available in Annex 1.

When comparing the PED energy balance along the 2020–2030–2050 path, it is clearly seen that, while RES only cover direct electricity demands in May for 2020, by 2030 PV meets or exceeds loads such as smart lighting and part of electromobility during the summer months. In 2050, all energy demands are covered by PV generation during most of the year (April to October) not only due to the increase of solar energy generation but also because the PED is more efficient.

The monthly energy balances are shown in Fig. 11, from 2020 to 2030, net energy imports are reduced from 671 MWh to 472 MWh, due

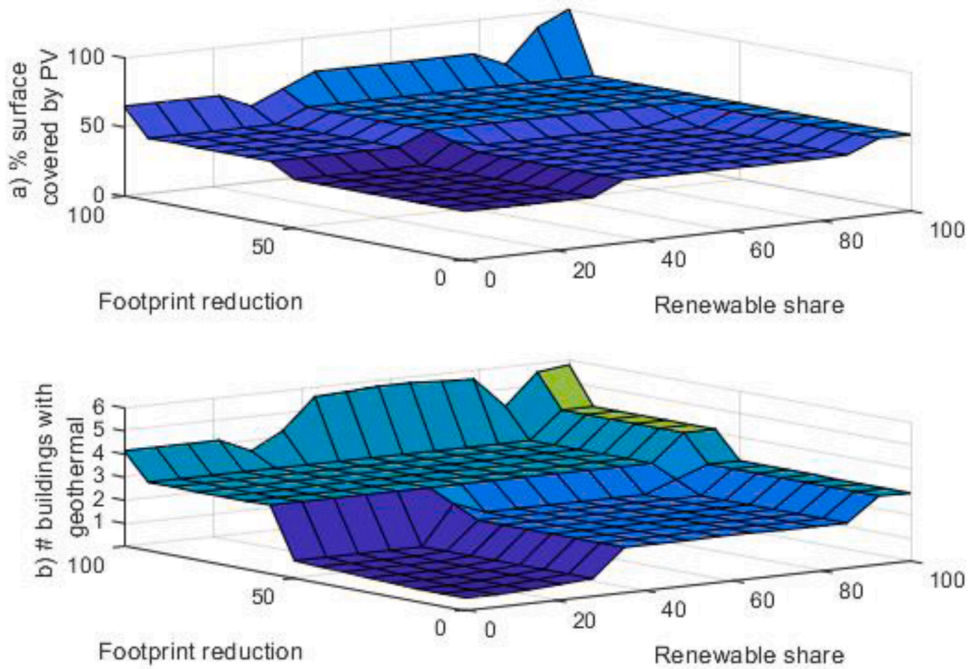

Fig. 9. Surface map of agents that represent renewable energy generation and therefore having a direct impact on footprint reduction and share of RES.

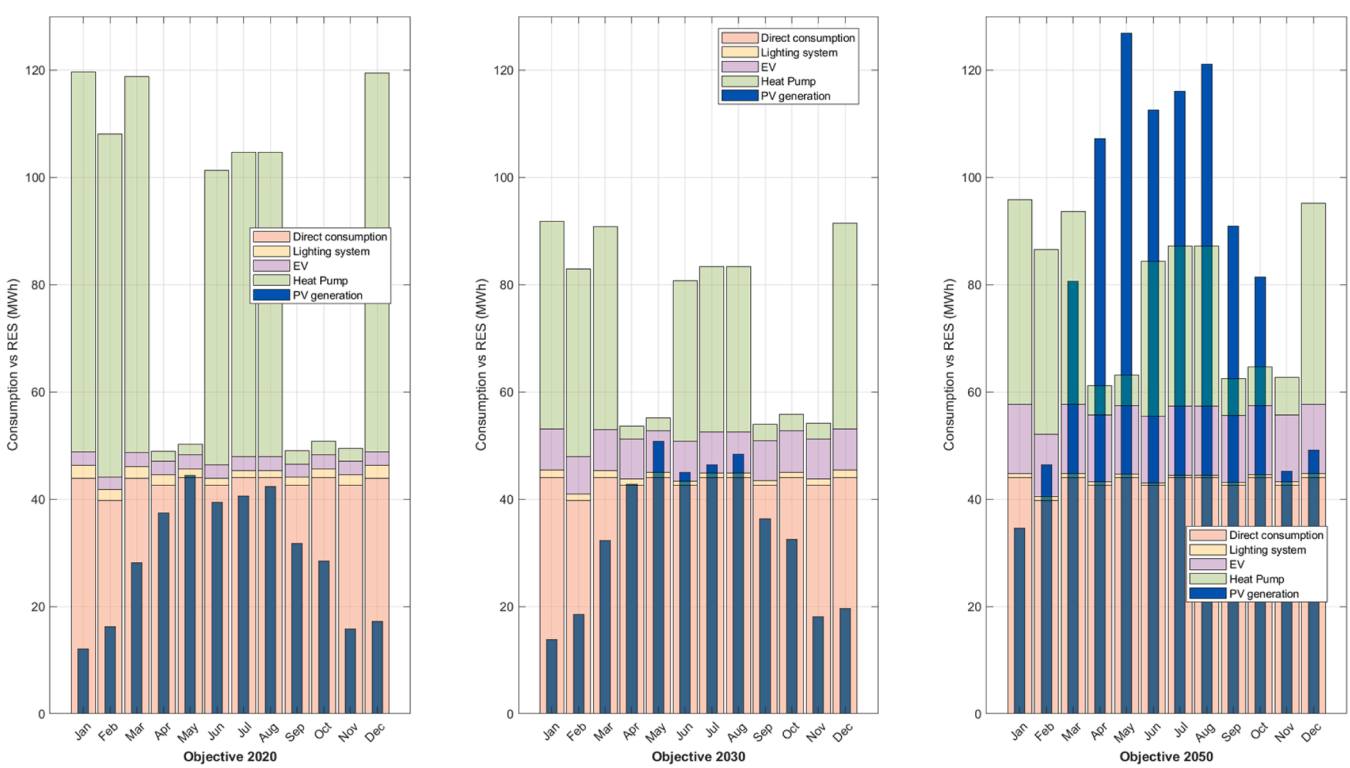

Fig. 10. Monthly energy balances considering renewable generation and different energy demands in the PED scenarios that represent European objectives for 2020, 2030 and 2050.

to lower consumption (from 1025 to 877 MWh). Moreover, self-sufficiency is improved, as it is improved from 2 building and 9 EVs in 2020 to 4 and 58 EVs in 2030. By 2050, a positive net energy balance of 68 MWh, six buildings are connected to geothermal rings and both the lighting and the EVs (97 out of 100) are supported by local PV panels.

The energy demand in buildings varies along the energy transition pathway, that is, in the long-term perspective of the PED. The energy used by heat pumps is reduced from 455 MWh in 2020 to 255 MWh in 2030 and remains almost stable for 2050. It is also noteworthy that the energy use in winter is reduced from 284 MWh in 2020 down to 161 MWh in 2030.

The demand of EVs, increases with the popularisation of this technology from 30 MWh in 2020 up to 90 MWh in 2030 and 151 MWh in 2050. This substantial increase of electricity demand is partially be

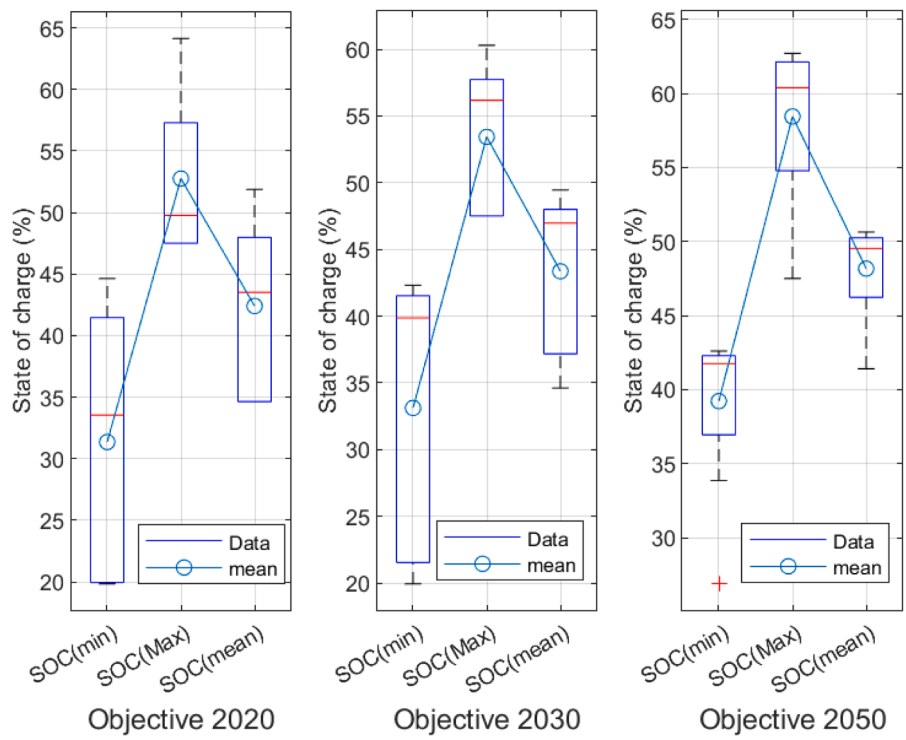

Fig. 11. ESS PED behaviour: minimum, mean and maximum values of average daily profiles of SOCs for the 12 months of the year in scenario 2020, 2030 and 2050.

compensated with the consumption of streetlights that is reduced from 21 MWh to 8 MWh and the aforementioned reduction in energy use in buildings.

The ESS has been designed to ensure the local utilization of RES while keeping in mind that State of Charge (SOC) should never be below 20% or above 98.5% to guarantee its performance (Castillo-Calzadilla et al., 2018). Fig. 11 represents monthly minimum, mean and maximum values of average daily profiles of SOCs for the three considered scenarios.

It is clearly seen that minimum values are larger for 2020 (20%-45%) and for 2030 (20%-43%) scenarios than for 2050 (34%-43%). This is considered to be related to the monthly energy balances of the PED in the winter months in 2020 and 2030, which makes the ESS to work under lower (or more extreme) conditions. For the 2050 scenario, positive energy balances are achieved for most of the days along the year, and therefore works smoother with lower variations of minimum, average and maximum values. All in all, the ESS seems to be a well-sized design system since the SOC is always higher that 20% which guarantees the local energy system to work in a safe bandgap.

Fig. 12 shows the evolution of emissions avoided (tons of CO_{2eq}) when comparing the three scenarios of PED. In 2020 627 tons of CO_{2eq} are saved, mostly due to use of geothermal energy (77%) and the integration of PV (13%). In 2030, total emissions avoided are increased to 627 tons of CO_{2eq}, with an increased relevance of electromobility (35%). In 2050 569 tons of CO_{2eq} are saved, which are quite homogeneously distributed across geothermal, PV and EV system, with a slightly larger share (39%) of EVs.

In sum, Fig. 12 draws two important conclusions: The use of renewable energies is providing huge opportunity for decarbonisation (1) and, buildings are requiring less energy in the long term, so that other loads such as EVs become more important (2).

Table 6 presents a summary of the results in terms of annual energy balances and footprint assessment against its BAU counterpart (see Table 5 for reference footprint).

In the long-term perspective, the PV generation is increasing in time while the Geothermal system is providing exactly what is being required. At some point, the increasing number of buildings connected to geothermal system is compensated with better performance of

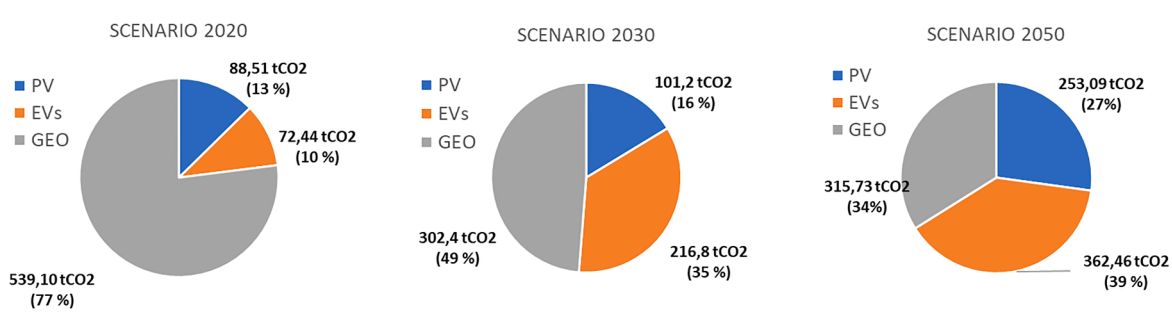

Fig. 12. Total emission saved in terms of tonCO2eq for 2020 scenario, 2030 scenario and 2050 scenario.

Table 5
Footprint of BAU energy supplies to the district.

Energy Supply	Footprint (kgCO2eq/kWh)
Natural Gas	0.252
Electricity from the Spanish grid	0.25
Petroleum-based fuels for mobility	2.64

Table 6
PED assessment in terms of energy balances and overall footprint for 2020, 2030 and 2050 scenarios.

	RES (MWh/y)		CON. (MWh/y)	PED Footprint Savings ($tCO_{2eq/y}$)			PED Footprint
	GEO	PV	(Elect)	GEO	PV	EVs	tCO_{2eq}
2020	2139	354	1025	267	89	72	890
2030	1200	405	877	302	101	216	264
2050	1252	1012	944	315	253	362	0

buildings (transition from F labels in 2020 to B labels in 2030). In fact, the rise in heat supply required in the transition from 4 to 6 connected buildings is compensated by the increased efficiency of adopting A labelled buildings instead of B.

In sum, a positive energy balance is achieved by 2050.

The opportunity of footprint saving is increasing along the district pathway, especially linked to the implementation of PVs and EVs. With a steady increase in the share of renewables increase and the energy efficiency improves from 34% in 2020 to 46% in 2030 and fully renewable in 2050.

Table A1
Objectives for scenarios 2020, 2030 and 2050.

	MWh/month (Objective 2020)				
	PV	Direct	Lighting	EVs	Heat Pump
Jan	12,11	43,94	2,34	2,57	150,78
Feb	16,23	39,69	2,11	2,33	136,19
Mar	28,20	43,94	2,18	2,57	149,23
Apr	37,50	42,57	1,96	2,49	4,10
May	44,41	43,99	1,71	2,57	4,23
Jun	39,36	42,54	1,36	2,49	117,02
Jul	40,58	43,96	1,40	2,57	120,92
Aug	42,32	43,96	1,40	2,57	120,93
Sep	31,81	42,57	1,51	2,49	5,17
Oct	28,48	43,99	1,71	2,57	5,35
Nov	15,84	42,57	1,96	2,49	5,17
Dec	17,19	43,94	2,34	2,57	150,34
TOTAL	354,03	517,65	21,97	30,31	969,44
	MWh/month (Objective 2030)				
Jan	13,86	43,97	1,42	7,70	66,45
Feb	18,57	39,71	1,29	6,96	60,02
Mar	32,26	43,97	1,33	7,70	64,90
Apr	42,86	42,57	1,20	7,46	4,10
May	50,75	43,99	1,05	7,71	4,23
Jun	45,01	42,56	0,83	7,45	51,31
Jul	46,41	43,98	0,86	7,70	53,02
Aug	48,39	43,98	0,86	7,70	53,02
Sep	36,35	42,57	0,92	7,46	5,17
Oct	32,54	43,99	1,05	7,71	5,35
Nov	18,10	42,57	1,20	7,46	5,17
Dec	19,66	43,97	1,42	7,70	66,01
TOTAL	404,75	517,80	13,41	90,71	438,76
	MWh/month (Objective 2050)				
Jan	34,65	43,98	0,84	12,88	28,52
Feb	46,44	39,73	0,76	11,63	25,76
Mar	80,69	43,99	0,79	12,88	26,96
Apr	107,18	42,58	0,71	12,47	4,10
May	126,93	44,00	0,62	12,88	4,23
Jun	112,60	42,57	0,49	12,47	21,56
Jul	116,09	43,99	0,50	12,88	22,28
Aug	121,06	43,99	0,50	12,88	22,28
Sep	90,91	42,57	0,54	12,47	5,17
Oct	81,39	43,99	0,62	12,88	5,35
Nov	45,25	42,57	0,71	12,46	5,17
Dec	49,17	43,98	0,84	12,88	28,07
TOTAL	1012,37	517,94	7,91	151,66	199,45

4. Conclusions

PathPED methodology defines Positive Energy District (PED) as main functional unit for urban design and treats its main elements (buildings, streetlights, vehicles, PV, etc.) as agents able to evolve and decide their future according to a fuzzy logic engine. These agents draw transition pathways that define the long-term fate of districts as they fulfil European commitments defined for 2020, 2030 and 2050. The PathPED methodology also includes a dynamic simulation tool able to assess the PED scenarios, in terms of district self-sufficiency (or even positivity), ESS requirements and the progressive reduction of carbon emissions. In this manner, by comparing the PED scenarios drawn for featuring 2020, 2030 and 2050 scenarios the following transition pathway is observed:

- Transition of buildings to higher energy performance (up to B or A label levels), which results in relevant energy savings pushing forward the self-sufficiency of the district.
- Transition to renewable heating and cooling systems through geothermal energy Jointly with the rise in the energy performance of buildings, this allows for a substantial footprint reduction.
- The adoption of RES together with the improvement of energy efficiency provides an impressive reduction of carbon footprint for the PED down to full sufficiency by 2050.
- Evolution of the vehicle fleet up to (almost) fully EVs in 2050. This supposes a 5-fold increase in terms of electricity requirements (from 30 MWh in 2020 to 151 MWh in 2050) but lowers the PED footprint leading to savings in the range of 362 $tCO_{2eq/y}$ in 2050.

These results show that the PathPED methodology is a suitable tool to provide very valuable quantitative assessment of future urban scenarios, which should support urban planners, investors, and governments in the decision-making process.

Future work in PathPED would make automatic the connection between the fuzzy engine and the dynamic simulator and therefore would facilitate the continuous temporal mode of transition pathways and their overall assessment in terms of PED performance.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be available on Zenodo

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Annex 1

See Table A1

Annex 2.

Equations describing the partial degree of membership that regulates the fuzzy logic approach

'1. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Current_22) then (NewLabelling is F) (1) '
'2. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Pledge_30) then (NewLabelling is F) (1) '
'3. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Paris_50) then (NewLabelling is E) (1)
'4. If (Efficiency_rise is Mid_EFF30) and (Footprint_reduction is Current_22) then (NewLabelling is D) (1) '
'5. If (Efficiency_rise is Mid_EFF30) and (Footprint_reduction is Pledge_30) then (NewLabelling is C) (1) '
'6. If (Efficiency_rise is Mid_EFF30) and (Footprint_reduction is Paris_50) then (NewLabelling is B) (1)
'7. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Current_22) then (NewLabelling is C) (1) '
'8. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Pledge_30) then (NewLabelling is B) (1) '
'9. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Paris_50) then (NewLabelling is A) (1) '
'10. If (Renewable_share is Low_RES22) and (Footprint_reduction is Current_22) then (PV_m2 is VLRES) (1)
'11. If (Renewable_share is Mid_RES30) and (Footprint_reduction is Current_22) then (PV_m2 is LRES) (1)
'12. If (Renewable_share is High_RES50) and (Footprint_reduction is Current_22) then (PV_m2 is MIDRES) (1) '
'13. If (Renewable_share is Low_RES22) and (Footprint_reduction is Pledge_30) then (PV_m2 is LRES) (1)
'14. If (Renewable_share is Mid_RES30) and (Footprint_reduction is Pledge_30) then (PV_m2 is MIDRES) (1)
'15. If (Renewable_share is High_RES50) and (Footprint_reduction is Pledge_30) then (PV_m2 is MIDRES) (1) '
'16. If (Renewable_share is Low_RES22) and (Footprint_reduction is Paris_50) then (PV_m2 is HRES) (1)
'17. If (Renewable_share is Mid_RES30) and (Footprint_reduction is Paris_50) then (PV_m2 is VHRES) (1)
'18. If (Renewable_share is High_RES50) and (Footprint_reduction is Paris_50) then (PV_m2 is TOTRES) (1)
'19. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Current_22) then (Number_EVs is VF) (1) '
'20. If (Efficiency_rise is Mid_EFF30) and (Footprint_reduction is Current_22) then (Number_EVs is FEW) (1) '
'21. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Current_22) then (Number_EVs is FEW) (1)'
'22. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Pledge_30) then (Number_EVs is FEW) (1) '
'23. If (Efficiency_rise is Mid_EFF30) and (Footprint_reduction is Pledge_30) then (Number_EVs is MID) (1) '
'24. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Pledge_30) then (Number_EVs is MANY) (1)'
'25. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Paris_50) then (Number_EVs is MANY) (1) '
'26. If (Efficiency_rise is Mid_EFF30) and (Footprint_reduction is Paris_50) then (Number_EVs is VH) (1)
'27. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Paris_50) then (Number_EVs is VH) (1) '
'28. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Current_22) then (LEDs is VF) (1)
'29. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Pledge_30) then (LEDs is FEW) (1)
'30. If (Efficiency_rise is Low_EFF22) and (Footprint_reduction is Paris_50) then (LEDs is MID) (1)
'31. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Current_22) then (LEDs is MID) (1)
'32. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Pledge_30) then (LEDs is MANY) (1)
'33. If (Efficiency_rise is High_EFF50) and (Footprint_reduction is Paris_50) then (LEDs is VH) (1)
'34. If (Renewable_share is Low_RES22) and (Footprint_reduction is Current_22) then (Geothermal is Vfew) (1)'
'35. If (Renewable_share is Mid_RES30) and (Footprint_reduction is Current_22) then (Geothermal is Few) (1) '
'36. If (Renewable_share is High_RES50) and (Footprint_reduction is Current_22) then (Geothermal is Mid) (1)'
'37. If (Renewable_share is Low_RES22) and (Footprint_reduction is Pledge_30) then (Geothermal is Mid) (1) '
'38. If (Renewable_share is Mid_RES30) and (Footprint_reduction is Pledge_30) then (Geothermal is Mid) (1) '
'39. If (Renewable_share is High_RES50) and (Footprint_reduction is Pledge_30) then (Geothermal is Many) (1)'
'40. If (Renewable_share is Low_RES22) and (Footprint_reduction is Paris_50) then (Geothermal is Many) (1) '
'41. If (Renewable_share is Mid_RES30) and (Footprint_reduction is Paris_50) then (Geothermal is All) (1) '
'42. If (Renewable_share is High_RES50) and (Footprint_reduction is Paris_50) then (Geothermal is All) (1) '

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