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Development of an early design tool for the sustainability assessment of positive energy districts: methodology, implementation and case-studies

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Abstract. The concept of Positive Energy District is one of the research ideas that embody the ambitions of decarbonization, renovation (both literal and in a wider perspective) and inclusivity for the urban environment portrayed in the EU activities. In this framework, the paper presents a modeling and simulation tool which allows for an early-design depth to be applied in the field of Positive Energy Districts renovation design and integrated performance assessment. The work aims at creating a tool for stakeholders and designers that would allow them to: a) Calculate carbon impacts along the life cycle for different technical systems and materials used for retrofitting; b) Compute use stage carbon emissions, including import-export of electricity;
c) Computations of PED carbon emission balances, along the expected useful life of the district computing both embodied and the use stage carbon emissions. The tool has been created as a spreadsheet including typical profiles of energy use per building archetype, with the inclusion of available and free Life Cycle Assessment data within the life cycle carbon assessment and aims at jointly developing use stage and life cycle considerations. It was tested on a district case studies in the EU.

1. Introduction

The environmental impacts of the urban areas are estimated to be about 70% of the global share in 2020 [1], in this framework in recent years efforts are being concentrated in the development of positive energy districts (PED) [2]. According to the SETPLAN EU, PEDs are districts with annual net zero energy import and net zero CO_2 emission working towards an annual local surplus production of renewable energy [3] which have found structural roles in several European initiatives like EU Green Deal, Fit for 55 and RePower EU.

Working on a district scale can be an effective approach to achieving sustainability goals because it allows for a more focused and targeted approach, which can be easier to implement and monitor. This needs a long-term commitment to develop policies, programs and infrastructures that support the environmental, social and economic sustainability of the city. Also, it is worth mentioning that working on a district scale can create lighthouse areas which can compensate the impossibility to renovate the i.e. historical heritage districts.

Modelling Positive Energy Districts (PEDs) presents several challenges due to the complexity of the systems involved such as the integrated nature of PEDs as integrated system of systems, limited monitored data availability and the related uncertainty.

Achieving the right amount of energy data for modeling PEDs can be a challenging task in the early stages of the design when detailed data are not yet available. For the development and implementation of Positive Energy Districts (PEDs) it is thus important to develop modelling and decision support tools, especially in the early stages of the design. Modelling tools can be used to design and optimize the energy systems of a district, to evaluate the performance of PEDs under different operating conditions and scenarios and to assess the impacts of policy decisions on the development and operation of PEDs. The available design tools for PED usually are either based on geo-referenced data (e.g. City energy analyst and Urban Modeling Interface), are integrated with other tools (e.g. Insight, and Sefaira) or require a large amount of districts data or performance related data and information (e.g. Intelligent Community Design and COFFEE). The study presents “PED TREE" (*Positive Energy District Tool for Resource and Environmental Evaluation*), an early design tool providing the possibility for practitioners to obtain an initial assessment of the performances of a district with limited data requirements, while also providing additional information such as the estimation of the carbon footprint of the district.

2. Methods

The tool proposed allows to investigate the performances of existing districts using customizable building archetypes, plan renovation actions at the district level and calculate potential embodied impacts along the stages of the life cycle. The tool includes detailed archetypes building energy simulation outputs performed in energy plus environment which are combined and assembled into the modelling of a district. The tool integrates energy data from the HOTMAPS project [4] and in terms of geometric information from the ENTRANZE project (single family house, apartment block, office and school) [5] and ASHRAE 90.1 (multifamily houses, trade, health, hotels and restaurants and other non-residential) [6].

An example of the archetypes introduced in the tool is reported in Figure 1.

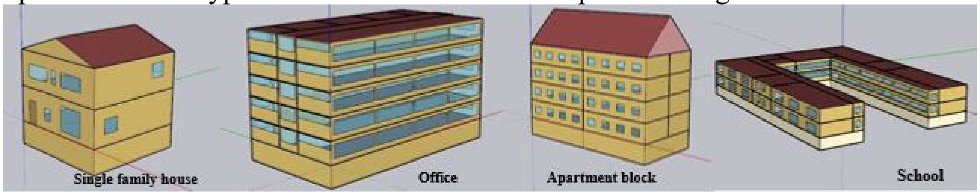

Fig.1. Sample archetypes modeled in the tool

Non-steady state through the Energy Plus modeling and simulation engine is performed and the tool is directly fed yearly dynamic simulation results for each of the archetypes, existing and renovated, for several construction ages (quality and thermal building performances decreases with aging) and nations in the EU.

The main operational steps the tool adopts are the following:

1) District modelling. In this stage the users chooses the number of buildings belonging to specific archetypes based on country, building type and construction period. Each archetype is associated with a useful energy demand (UED) valued per m^2 of conditioned floor and represents the net energy required to cover energy needs like space heating and cooling. In addition, users can freely choose the existing renewables power and the roof/public areas to assign as PV area for district renovation.
2) District performance assessment. In this stage the tool will generate the energy profiles for generation and consumption and will compute PED balances. The tool calculates also the primary energy balance according to equations 1, which depends from primary energy factors from ISO 52000 [7].

$$B = E_E \cdot PEFnr_E - ((I_E \cdot PEFnr_E) + (I_M \cdot PEF_M)) \tag{1}$$

Where: B refers to the balance results of the district;
E_E refers to the electricity exported to the grid;

$PEFnr_E$ refers to the primary energy factors for electricity;
I_E refers to the electricity imported from the grid;
I_M refers to the methane consumption;
PEF_M refers to the primary energy conversion factors of methane.

The dynamic nature of the data employed allows for instantaneous energy balances to be computed as well as hourly import-export flows to-from the district.

3) District renovation. In this stage the impacts of the renovated consumption related to the retrofit of all buildings in the districts are calculated. Expected results for the renovated district are computed and are analyzed by comparison also with the existing district. A direct connection is performed with national renovation legislation limits (e.g. the renovation will include an insulation layer on the exterior of the envelope to reach the required transmittance values). The primary energy and electricity balances follow the same logic as in the previous step. If the balance of equations 1 is positive, the district achieves the PED target.
4) Environmental impacts. In this stage the tool evaluates the environmental impacts of the district with a Life Cycle thinking inspired calculation. Data from ecoinvent [8] are computed to calculate the Cumulative energy demand and the Global Warming Potential for the operational stage including energy uses (electricity and methane consumption) and the production stages. Only the renovation process is included at this stage, meaning that the environmental impacts for the production of the materials used during the renovation are computed but the environmental impacts caused by the materials constituting the original envelope are not. For the production phase of the renovated district the tool calculates the insulation thickness used for roof and external wall and window area within national legislative limits. The tool computes the quantity of materials necessary according to the geometry of the archetype and provide the corresponding embodied impacts. In addition, the tool assesses the impact resulting from installation of photovoltaics.

Environmental impacts are analyzed using the ecoinvent database and the methods chosen are the IPCC 2021 and Cumulative energy demand.

The tool is applied to a section of the University of Palermo (UNIPA) campus, located in Palermo (Italy) for a total number of 10 buildings, covering an area of 43.200 m^2, the campus uses boilers centralized systems for heating, in operation since from December 1 until March 31 for a maximum of 8 hours a day. In addition, the buildings use local split systems that compensate for lost production from the centralized system. For cooling the campus uses a mix of split and central heat pump system while for domestic hot water uses a mix of electric water heaters and centralized systems. The aim of the analysis is to check the feasibility of the achievement of the target of PED for the existing district within the campus. Renovation is planned with regards to the external insulation, substitution of windows and installation of photovoltaics.

3. Results

The existing UNIPA campus, according to the in-situ monitoring performed for the year 2022, is characterized by the following energy uses (Tab.1).

Table 1. UNIPA campus consumptions

	Electricity [kWh]	Methane [m^3]
Annual consumption	4.37E+06	1.53E+05

The district generation was performed by adopting and scaling the school archetype, characterized by education and office uses. The existing district in UNIPA is composed of un-insulated buildings built between the 1960 and 1970 and thus have comparable features with the archetype school, considered as built in the same time frame in Italy. Calibration data shows that the district model has consumptions which are only moderately lower for both methane and electricity, probably due to the presence of energy intensive laboratories, but an overall deviation of 10% is considered acceptable for the purposes of the tool and of the paper. Table 2 depicts a comparison between the annual consumption of existing district and the consumption of the modeled one in the tool.

Table 2. Comparison between simulation and monitored data of UNIPA campus

	Monitored	Simulated	Deviations
Methane [m^3]	1.53E+05	1.38E+05	-10%
Electricity [kWh]	4.37E+06	3.97E+06	-9%

Further validation of the tool modelling efforts with Finnish case studies from the RESPONSE project is currently ongoing, in Table 3 a preliminary comparison of the energy consumptions between the simulated residential buildings and the case study.

Table 3. Comparison between simulation and monitored data of residential buildings (Turku, Finland)

	Monitored	Simulated	Deviations
Electricity [kWh /y]	1.04E+06	9.52E+05	-8%

The UNIPA campus renovation includes the increase of local power generation through the installation of 7600 m^2 of photovoltaics (amounting to about 20% of available roof space) and the decrease in consumption by coating the roofs and exterior walls and replacing windows. Table 4 shows the results of the energy balances calculated according to equation 1 for the UNIPA campus. The PED target is not fully achieved and further efforts will need to be investigated for the design of the renovated district. Figure 2 shows the effects of retrofit on consumption and generation within the district considering typical week in winter (a) and in summer (b) on UNIPA campus.

Table 4. District energy balance

Renovation electricity generation [kWh/y]	Renovation electricity consumption [kWh/y]	District electricity balance [kWh/y]	Renovation methane consumption [m^3/y]	Electricity exported (primary) [kWh/y]	Electricity imported (primary) [kWh/y]	Primary energy balance [kWh/y]
1.09E+06	2.18E+06	-1.09E+06	1.01E+05	1.01E+06	-4.50E+06	-3.49E+06

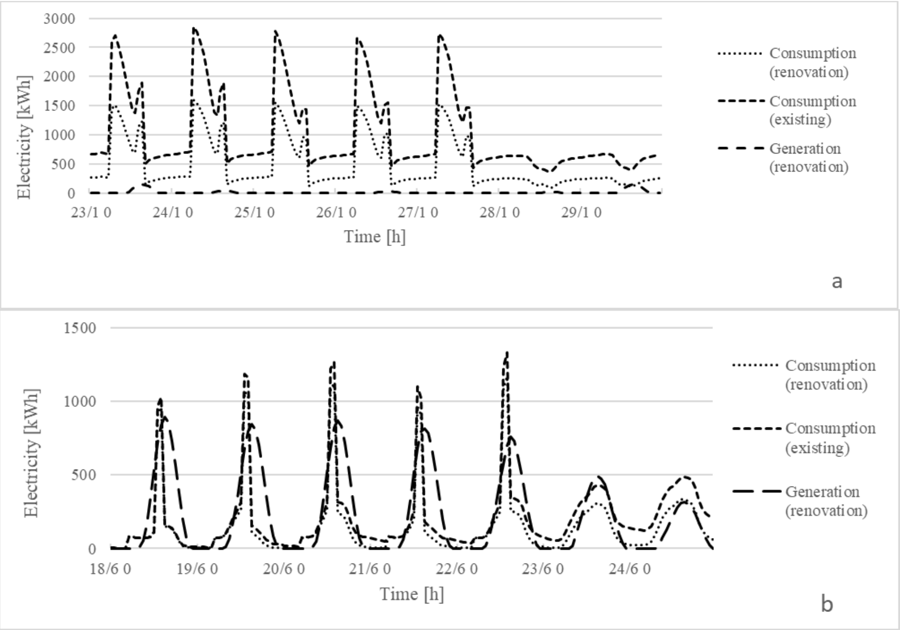

Fig. 2. Hourly comparison of electricity generated and consumed in the district for winter (a) and early summer (b)

The renovated district includes: glazed surfaces with U= 1 W/m^2 K and the exterior walls with U=0.23 W/m^2 K while the roof with U value =0.19 W/m^2 K.

The difference in consumption between pre- and after renovation can be assessed through Figure 3.

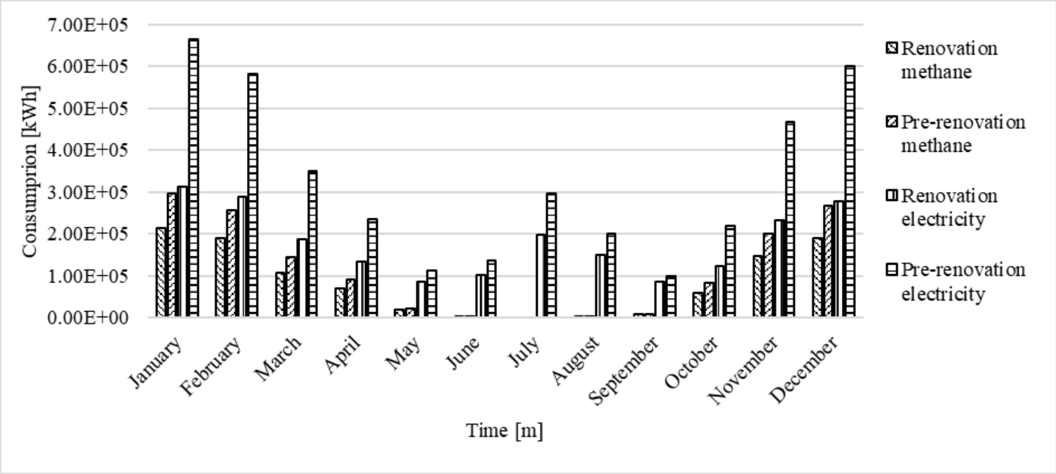

Fig. 3 Monthly comparison energy uses in the UNIPA campus

Figure 3 shows how using insulation and replacing windows reduces electricity and methane consumption especially in winter. The retrofit reduces by 40 kWh/m^2 the electricity uses and by about 1 m^3/m^2 of methane uses. Despite the reduction in consumption the presence of energy-intensive facilities (laboratories) would require larger photovoltaic system to offset electricity consumption. Comparisons of the pre-renovation CO$_2$ and cumulative energy demand emissions and renovation scenario emissions during the use phase and production phase are reported in Table 5.

Table 5. Comparison between environmental impacts of existing district and renovation scenario

		Existing district		**Renovation Scenario**	
		[KgCO$_{2eq}$]	[MJ]	[KgCO$_{2eq}$]	[MJ]
Use Phase	Electricity import	1.45E+06	3.19E+07	5.69E+05	1.25E+07
	Methane consumption	7.43E+04	6.38E+06	5.45E+04	4.68E+06
Production phase	Insulation	-	-	1.44E+04	2.61E+05
	Windows	-	-	6.34E+05	1.12E+07
	Photovoltaic system	-	-	3.03E+06	4.75E+07

The results show that if only the use phase is analysed, the district retrofit resulted in a reduction of impacts related to electricity import by about 60% and a reduction of impacts related to methane consumption by about 25% for both impact categories. Comparisons for the renovation scenario and existing district of the emissions during all the phase considered one year of use phase are reported in Table 6. Results show that in the case proposed the environmental and energy footprint of the districts improve significantly in the renovation scenario.

Table 6. Comparison between life cycle impacts of pre-renovation and renovation scenario

	Existing district	**Renovation Scenario**
[KgCO$_{2eq}$]	1.52E+06	7.89E+05
[MJ]	3.83E+07	1.99E+07

Conclusions

The paper proposed a simplified tool for the assessment of the feasibility of the achievement of the PED level of an existing district towards its renovation. The tool contributes to the state of the art with the possibility of generating districts models based on detailed Energy plus archetypes simulations while complementing it with further data, such as carbon footprint analyses.

The tool clearly identifies the possibility for the analysed district to potentially reach the PED target through the combination of different retrofit strategies and especially by the installation of a photovoltaic system that can compensate for on-site energy uses. The life cycle calculations included allow for the analysis of the impacts resulting from these strategies and provides a calculation of the hidden impacts to investigate if the environmental costs of the renovation outweigh the benefits/improve the environmental performances of the district. LCA analysis shows that by comparing the life-cycle impacts with the existing district, the interventions made in the renovation scenario allow for a reduction in environmental impacts in both impact categories considered.

Future research should therefore focus attention on the need to create appropriate databases that contain all the information needed to represent the European building stock and to extend the environmental analysis of PEDs to all stages of the life cycle, avoiding shifting impacts.

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