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Exploring tools and indicators to support collaborative planning, design, implementation, operation, and evaluation of Positive Energy Districts

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Abstract. The study defines an integrated parametric workflow to support PED collaborative design and implementation. Through a preliminary detailed analysis, existing tools for urban building performance simulation and microclimatic analysis were identified, tested, and selected, aiming at maximising their interoperability potential and overall support to collaborative PED planning practices. Subsequently, it is illustrated how to conduct an ex-post simulation analysis of medium and long-term interventions, with specific projections of different scenarios considering climate change impacts on energy demand. The evaluation of the proposed climate-adaptive interventions takes place using tools for the optimization of systems and technical solutions at the basis of the energy surplus and decarbonization of districts and neighbourhoods. The aim of this research is twofold: i) shading light on the absence of data management, especially at the initial stages of the PED project, resulting in uncertainty and slow-down of the whole implementation process, as well as associated difficulties to trigger virtuous replicability processes towards inclusive urban energy transitions; and ii) promoting the adoption of tools and integrated climate adaptation and mitigation frameworks to support collaborative planning and evaluation of Positive Energy Districts.

1. Introduction

Implementing Positive Energy Districts (PEDs) in the urban environment has set to be one of the European strategies towards the energy transition and sustainable development to accelerate the decarbonization of urban areas and promote the potential for replication and scalability of sustainable settlements in different cities. Although a common definition is still under discussion, it is generally accepted that Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy [1].

The focus of PEDs is long-term climate mitigation through energy efficiency, clean energy production, and energy flexibility, and all the efforts have been so far fundamentally based on building energy efficiency, and renewable energy on site production. In the last few years, in order to guide practitioners and decision makers, several tools have consequently been developed to simulate energy performances in urban settings, and without sophisticated and time-consuming on-site measurement procedures, relevant useful metrics can nowadays be obtained by modelling the whole study site with the support of urban building energy modeling (UBEM) approaches.

A PED is certainly a critical step towards the overarching goal of climate neutral cities but must also be considered a holistic framework supporting resilient, thriving, and affordable urban districts where people wish to live.

Evidently, resilience erosion and the need to realise climate proof urban areas represent urgent concerns and require adaptation and mitigation integrated planning and design approaches.

Consequently, progressing Positive Energy Districts in a climate change scenario raises several intertwined challenges that cannot be addressed recurring only to long-term mitigation design strategies and solutions. In that direction, the lack of integrated and comprehensive planning and design supporting frameworks to characterize climate resilient PEDs and identify relative requirements, is still notable.

Aiming to contribute filling these gaps, the objective of this research is on the one hand, to shade light on current challenges characterising the early stages of the PED implementation in a climate change scenario, and on the other hand to promote the experimentation of tools and evaluation methodologies able to support collaborative efforts toward Positive Energy Districts.

2. Methodology

In order to define the state of the art about planning and design methods under development in PED projects and urban transformations at district scale, existing tools for urban building performance simulation and microclimatic analysis were identified, tested, and selected, aiming at maximising their interoperability potential and overall support to collaborative PED planning practices. Specific criteria have been identified to orientate the tool selection – i.e., their specific features and fields of application, interoperability (variables generated in one software environment, and used as input in the other), data reliability and measurability, user friendly interface, and occurrences in scientific literature – according to the classification introduced by Brozovsky and colleagues [2] about computational fluid dynamics (CFD) analysis and building performance simulation (BPS).

After a literature review and the identification of available case studies, an original workflow was defined, with the objective to guide the identification and testing of different climate adaptation strategies while supporting the collaborative implementation of resilient PEDs towards climate-proof energy transitions.

Firstly, through a preliminary detailed analysis of the context, a framework to reduce energy demand and improve accessibility as well as designing infrastructures at different scales of intervention was defined, evaluating microclimatic conditions, resources availability, and system resilience. Secondly, different future scenarios considering climate change impacts on energy demand, resilience, and flexibility of systems were identified through ex-post simulations of planned medium- and long-term interventions. Attention was equally paid to the evaluation of different alternatives supporting energy sharing and overall PED flexibility.

Through the conducted study, the integrated workflow was subsequently tested on an existing PED case study, taking the perspective of practitioners and decision makers willing to ensure sound, evidence-based decision making, and collaborative implementation processes.

Finally, in the conclusions, existing limits to the conducted research were identified, together with the potential scope for further investigations.

3. Results

3.1 Integrated parametric Workflow

Given the dominant role of urban climate in energy planning at district scale, natural and imposed constraints [3] can be investigated through the integrated parametric workflow, collecting specific tools. Among them, ENVI-met V.5, Ladybug Tools 1.5.0, and City Energy Analyst are the simulation tools based on 3D models that have been selected for the present study.

Climate-adaptive design strategies have been defined and used to validate the workflow, by measuring the integrated benefits of technological devices, nature-based solutions, and green infrastructure [4] in an existing residential cluster, located in the outskirts of the city of Ludvika, in Sweden. The case study is a “Towards-PED” [5] residential settlement consisting of a group of 3 buildings covering a total area of about 8,100 m^2 and producing an annual cumulative energy value of 56,798 kWh with an integrated PV system servicing 150 inhabitants with a self-sufficiency rate of 20.4% [6]. The PED case study was selected ad-hoc, considering its relatively small size suitable for modelling, and after a dedicated technical visit conducted by the authors as members of the PED-EU-NET research network, in 2022.

The conducted research was designed to explore the contribution of climate-adaptive nature-based strategies and solutions to the microclimatic environment, and the overall social ecological performance of the neighbourhood. The impact on energy needs was first estimated, and feasible future scenarios were defined to ensure the balance among energy production, efficiency and flexibility as well as the achievement of decarbonization goals.

Understanding local climatic conditions plays a critical role, and detailed analyses of microclimate, solar radiation, and lighting must be conducted. After detailed energy demand analyses, the obtained results can feed the district energy system simulation. The outputs can finally be used to determine key performance indicators of PEDs (Figure 1).

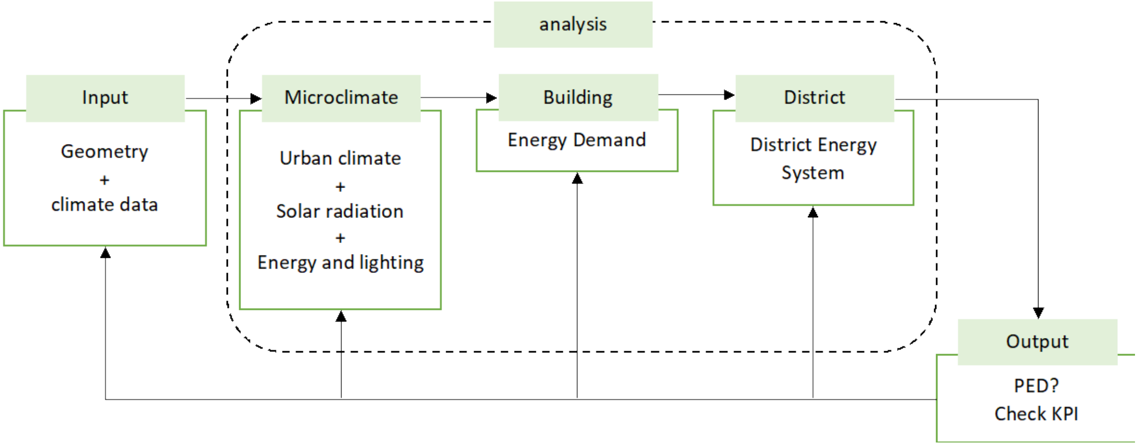

Figure 1. Integrated parametric workflow.

The developed framework integrates time-dependent methods for simulation of energy performance of buildings, modeling of conversion and storage technologies, assessment of local energy potential, optimization of two-level energy systems, and multi-criteria analysis. It is a useful tool to conduct both ex-ante analyses to identify and evaluate future scenarios to be implemented and ex-post simulations, assessing decarbonization performances of buildings and infrastructure at district scale.

3.2 Input data and analysis

3.2.1 Microclimate analysis. ENVI-met is a 3D prognostic microclimate model designed to simulate the surface–plant–air interactions in complex urban environments with a spatial resolution of 0.5–10 m and a temporal resolution of 10 s. The model physics is based on non-hydrostatic Navier–Stokes equations for wind flow computation, thermodynamics laws for calculation of temperature fields, and atmospheric physics for prognosis of atmospheric turbulence. ENVI-met allows to model and reproduce buildings in the urban environment, computing the surface material and simulating air flow, heat and moisture exchanges, and vegetation contribution to the urban microclimate. The typical simulation period is 24–48 hours with a time step of 1–5 seconds.

ENVI-met outputs can be used as input data for the simulations conducted to evaluate the energy performance of buildings carried out with Ladybug Tools weighting the building energy performance with microclimate data and providing reliable measurements through numerical models.

The proposed integrated 3D-model-based workflow uses Rhinoceros 7 (Robert McNeel & Associates, 2020) to characterize urban buildings and infrastructure, managing climate data into Dragonfly Urban Weather Generator (UWG) to define local climate scenarios and evaluate microclimatic conditions with ENVI-met. Output data allow to perform building energy analyses with

Ladybug and Honeybee aiming at measuring the integrated benefits deriving from climate-adaptive strategies on energy consumption reduction. Once the district demand has been defined, City Energy Analyst provides practitioners with the possibility to conduct energy system optimization analyses to evaluate how energy sharing could significantly improve PED's self-sufficiency, and how aggregating the building demand and supply in an optimal configuration could effectively support energy flexibility.

3.2.2 Energy performance. Ladybug Tools is an open-source Grasshopper plug-in (Roudsari, M. and Mackey, C., 2013) to define a parametric environment where designers can investigate the relationships between urban microclimate and building energy performance. Running inside Grasshopper, the tool is able to collect in a single platform different types of analysis and simulations, from climate data management to couple CFD and BPS analyses [7][8], depending on the different dedicated component adopted: Ladybug performs detailed climate data and solar radiation analyses in order to measure the microclimate and outdoor comfort conditions according to urban geometry; Honeybee is able to run and visualize daylight simulations using Radiance and energy models using OpenStudio and EnergyPlus; Butterfly can conduct advanced computational fluid dynamic (CFD) simulations using OpenFOAM and Dragonfly, a component able to conduct energy simulations at district-scale, evaluating the urban heat island effects on the energy consumption in buildings with the Urban Weather Generator tool.

Ladybug Tools outputs consist in defining the building energy demand as a result of the integration of climate-adaptive and mitigation strategies.

3.2.3 District energy system. City Energy Analyst (CEA) is an open-source computational framework developed by Jimeno Fonseca (2013) for analyses and energy system optimization at district scale. The tool enables the analysis of energy, carbon, and financial benefits of multiple urban design scenarios in conjunction with optimal schemes of distributed generation. CEA is a GIS-based tool with a user interface able to facilitate the spatiotemporal analysis of energy demand and potential infrastructure solutions. CEA combines knowledge of urban planning and energy systems engineering into an integrated simulation platform, providing designers and practitioners with the possibility to study the effects, trade-offs, and synergies of urban design options and of energy infrastructures [9].

3.3 Scenarios and iterations

Energy demand reduction was set as the input for City Energy Analyst to compare two different energy sharing scenarios to optimize the DH system and the energy flows, reducing the annual CO_2 emissions and overall system maintenance cost: 1) connecting the 3 residential buildings as a cluster; and 2) connecting the residential cluster with the closest commercial building. The second scenario recorded a lower value of annual emissions of district-scale system, i.e., 32.75 tCO_{2eq}/year, compared to 33.57 tCO_{2eq}/year of the first scenario. Furthermore, CAPEX and OPEX values were calculated to estimate the amount of yearly actualized financial expenditures in relation to the two alternatives: the first scenario would require CAPEX equal to 341 kUSD/year, compared to an estimated value of 344 kUSD/year for the second alternative. The OPEX were estimated at 331 kUSD/year, and 346 kUSD/year, for scenario one and two, respectively.

Microclimatic analyses carried out with ENVI-met on the existing scenario highlighted some critical issues regarding the cold natural ventilation and the heavy rainwater run-off volumes, during the wintertime. In addition, Ladybug and Honeybee solar analysis demonstrated how the rising summer thermal loads on building façades increase the cooling demand, with a cumulative value of 170.31 kWh/m^2 for the West façades and 167.46 kWh/m^2 for the East façades, while the South façades showed an incident solar radiation value of 249.25 kWh/m^2.

Nature-based solutions and green infrastructure were introduced in the renovated scenario according to the potential integrated benefits and ecosystem services to be provided by tree planting and improved water drainage of the soil.

According to the conducted simulations, the proposed solutions would reduce the cold winter ventilation up to 36%, while the lower summer solar radiation would provide higher outdoor and indoor comfort levels, and a consequent energy demand reduction for cooling up to 9%. Through permeable pavements, the run-volumes would be reduced up to 57%, from 0.14 l/m^2/day to 0.06 l/m^2/day, with a peak discharge reduction of 57%, from 0.49 m^3/day to 0.21 m^3/day, benefitting accessibility and liveability of open spaces. Furthermore, the newly proposed tree species would improve the air quality, increasing the pollutant sequestration capacity up to 15% for the CO_2, 9% for the ozone, 8% for the nitrogen dioxide, and up to 30% for the PM_{10} particles.

4. Conclusion

The complexity of the urban environment facing climate change points to the need to closely investigate microclimatic conditions and the energy potential of buildings, infrastructures, and open spaces, through integrated approaches prioritising human centred transformations, ensuring both thermal comfort and the achievement of the PED targets, i.e., an energy surplus and net zero carbon emissions.

Evaluating thermo-hygrometric comfort requires measuring physical parameters at local scale – i.e., air temperature, humidity, natural ventilation, precipitation, etc. – assessing the occupants' perception together with visual and acoustic comfort, defined as that "particular state of mind that expresses satisfaction with the surrounding environment" (EN ISO 7730:2006).

Once the thermo-hygrometric comfort has been set as one of the main objectives, the level of energy consumption becomes the critical factor, since physical parameters are closely linked to people's wellbeing, as well as liveability and robustness of the urban space.

Exploring the local energy potential, and the microclimate contribution to the energy demand, is a key priority when planning PEDs, aiming at guiding urban transformations towards carbon neutrality and the achievement of energy security targets. Evidence-based design approaches can support decision-makers and planners in optimising solutions considering the district energy demand, the potential positive impact on the environment, and the effectiveness of climate-adaptive design strategies.

Coupling building performance simulation and CFD analyses in an integrated workflow can inform planners and decision-makers for energy master planning at district and urban scale. Although energy demand reduction has been set as the main priority, it requires a collaborative early-stage design to provide both climate-adaptive solutions and climate change mitigation effects in the urban environment. Multi-layered analysis conducted in Grasshopper allow data exchange, using outputs of specific tools as inputs to others, in a step-by-step PED evaluation process.

Since selected tools are based on simplifications and user interpretations an error gap is acceptable, in principle, with the aim of reducing time-consuming calculations and data measuring. On the positive side, the integration of GIS- and BIM-based tools favours the interoperability and reliability of information needed to define future scenarios at district scale. Consequently, it can be concluded that future works would benefit from the defined integrated parametric workflow, possibly supporting replication and rapid uptake of collaborative energy planning and implementation practices.

References

[1] SET-Plan Temporary Working Group 2018 *SET-Plan ACTION n 3.2 Implementation Plan: Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts*.

[2] Brozovsky J Radivojevic J and Simonsen A 2022 Assessing the impact of urban microclimate on building energy demand by coupling CFD and building performance simulation *Journal of Building Engineering*, 55, 104681, https://doi.org/10.1016/j.jobe.2022.104681

[3] Haase M and Lohse R 2019 IOP Conf. Ser.: Earth Environ. Sci. 352012019

[4] Andreucci M B Cupelloni L and Tucci F 2021 Simulations beyond the building, identifying climate adaptation scale jumping potentials to district and city level. Research by design for the city of Monterotondo (Italy) *Proceedings of Building Simulation 2021: 17th Conference of IBPSA*. BS 2021 Bruges, Belgium September 1-3, 2021. https://doi.org/10.26868/25222708.2021.30490

[5] Zhang X Penaka S R Giriraj S Sánchez M N Civiero P and Vandevyvere H 2021 Characterizing Positive Energy District (PED) through a Preliminary Review of 60 Existing Projects in Europe *Buildings*, 11(318). https://doi.org/10.3390/buildings11080318

[6] Huang P et al. 2019 Transforming a residential building cluster into electricity prosumers in Sweden: Optimal design of a coupled PV-heat pump-thermal storage-electric vehicle system *Applied Energy*, 255, 113864. https://doi.org/10.1016/j.apenergy.2019.113864

[7] Allegrini J and Carmeliet, J 2017 Coupled CFD and building energy simulations for studying the impacts of building height topology and buoyancy on local urban microclimates *Urban Climate*, 21, pp 278–305. https://doi.org/10. 1016/j.uclim.2017.07.005

[8] Natanian J Maiullari D Yezioro A and Auer T 2019 Synergetic urban microclimate and energy simulation parametric workflow. *Journal of Physics: Conference Series*, 1343(1). https://doi.org/10.1088/1742-6596/1343/1/012006

[9] Fonseca J A 2016 *Energy efficiency strategies in urban communities*. Eidgenössische (Zürich: Technische Hochschule Zürich).