DIGITAL POSITIVE ENERGY DISTRICTS: A SCALABLE STRATEGY FOR URBAN HEAT AND POWER TRANSITION?

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Abstract

The "DigiPEQ" project (FFG No. 880562) explored the requirements and potentials of digital Positive Energy Districts (PEDs) in contributing to national and municipal decarbonization efforts and energy and climate goals. PEDs are identified as key in urban planning for energy sustainability, generating more energy than they consume through local renewables and digital technologies.

Insights into ten thematic modules were jointly developed with innovative practitioners of sustainable building and district development, user-oriented and sustainable cooperation and business models, Innovative digital technologies for integrated, user-oriented energy systems and the establishment of replicable planning and operational management processes of Positive Energy Districts.

Focusing on fundamentals, system boundaries, and framework conditions of digital, livable Positive Energy Districts, the project investigated dynamic **assessments** of energy and emission flows in PEDs, focusing on various system boundaries and conversion factors and how they can be quantitatively linked to municipal and national climate goals and scenarios.

Several key strategies for enabling **energy flexibility**, load shifting, grid services, sector coupling, and maintaining user comfort and acceptance, as well as aspects of load prediction and user behavior are investigated, highlighting the importance of adaptable control algorithms and the consideration of grid status in PEDs.

The project further addressed the **energy economic, legal, and technical environment**, emphasizing the need for regulatory frameworks to support PED development. Considerable legal and administrative barriers to PED implementation and near-term scalability were identified.

The project underscored the significance of **participative design** and information management in promoting sustainable behaviors in PEDs.It also explored the application of **new digital technologies** like ML, AI, and Web3 in PEDs.

Finally, the project highlighted the relevance of PED topics to **practitioners** and outlined strategies for knowledge and skill transfer in PED development, and a **criteria catalogue** is presented to steer and assess early PED development and planning processes in practice.

In conclusion, DigiPEQ demonstrates the promise of PEDs in urban energy transitions, offering insights for future district design and the role of digital technologies in this process.

Introduction

Positive Energy Districts (PEDs) are emerging as a pivotal solution in urban planning to achieve energy efficiency and sustainability. These districts generate more energy than they consume, utilizing local renewable sources and innovative digital technologies. The relevance of PEDs lies in their potential to reduce carbon emissions, enhance energy security, and promote sustainable urban development. The research in this area is focused on developing strategies for energy exchange, stakeholder engagement, implementation of energy concepts, and assessment methodologies to foster the realization of PEDs [1], [2]. They are neighborhoods or several connected buildings, often with diverse space uses, meeting

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the highest standards of energy efficiency. They cover their entire energy needs locally from renewable sources, enable flexible operation, and create the highest possible comfort and quality of life on-site through the involvement and participation of users [3], [4]. These districts provide high-quality usable spaces, promote the formation of energy communities, and play a crucial role in local and regional energy supply [5], [6], [7].

Objectives and Methodological Approach

The challenges and opportunities offered by PEDs, including energy flexibility, load shifting, grid services, and sector coupling, as well as aspects of user integration and their requirements for livable districts, were examined by developing and executing an "Innovation Course", developed and conducted for and with all relevant stakeholders and practitioners of an innovative and integrative planning process, i.e. developers, building and utility operators, architects, participation and communication specialists, building, mobility, building automation and energy engineers. Figure 1 shows the specific fields included and combined. This approach enabled the integration of practical insights with current scientific findings, discussing and combining them: Particularly, legal, and administrative conditions and barriers in implementation were successfully identified, and concrete proposals for their elimination were jointly formulated.

Figure 1 Digital Positive Energy Districts were investigated in ten topical Modules and

Results and Insights

The project demonstrates that PEDs, especially newly built have significant potential due to mixed-use and property-wide consideration of supply and demand curves. The vision of a connected energy system through infrastructural linking (heating/cooling/electricity network) and the establishment of organizational frameworks, such as local energy communities, offers a scalable, efficient way to achieve the energy and climate goals of 100% renewable electricity supply by 2030 and 100% total energy consumption by 2040 in an urban context. However, these challenges are more complex in retrofitting existing buildings. Key insights and topics are summarized in the following sections:

Positive Energy District Performance Assessment through Energy and Emission Balancing

The project investigated how districts' energy and emission flows can be modeled and simulated to obtain dynamic assessments on the interplay of local renewable energy production and flexible district operation. Over the last years, several approaches have been put forward [4], [5], [6], [7], [8], [9], [10], [11], that can be classified by the key considerations illustrated in the following figure: System boundaries, weighting and conversion factors of energy flows in the assessment balance, and the target of the balance itself. As the name implies, the balance target of a Positive Energy District is generally accepted to be positive. This alone is however not sufficient to define a PED, as the scope of this positive balance varies greatly for different **functional, spatial and temporal system boundaries**: Functional system boundaries define which energy services are to be included in the balance and can range from covering HVAC operation, user plug loads, district street lights, individual motorized mobility, public transport, to embodied energy and emissions for construction, maintenance, and even food and holiday air travel of inhabitants. The inclusion of local renewable energy sources can change for different spatial boundaries: It is not uncommon to include “external” potentials such as large PV-roofs of neighboring industrial uses or contractually secured offsite wind power into so-called “virtual” system boundaries, leading to “virtual PEDs”[12]. Finally, although not universally accepted, the PED balance is typically assessed in terms of Primary Energy flowing over the system boundary, but different weighting factors are known to play a significant impact role in deciding the final result [11], [13], [14].

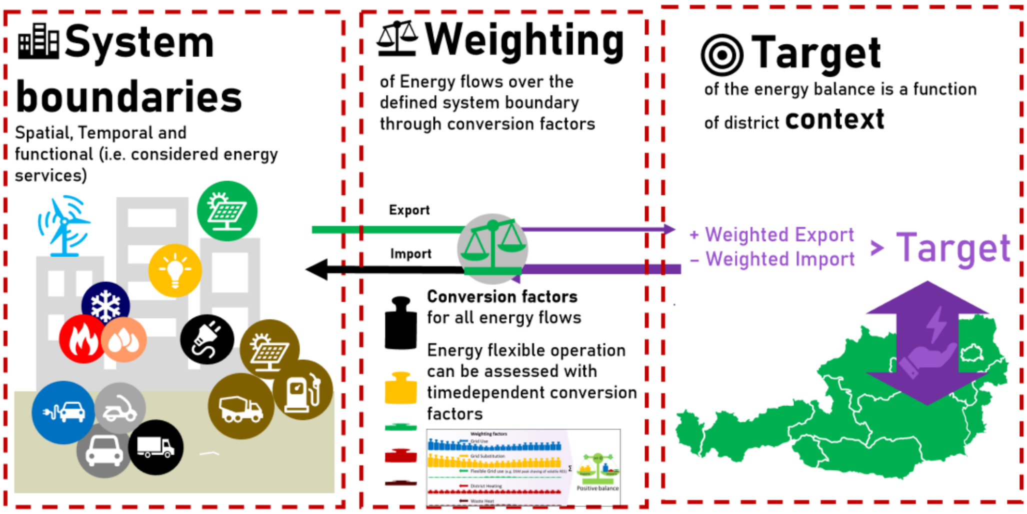


Figure 2 Three main consideration for quantitative Positive Energy District assessment [15]

In summary, the positive balance target of PEDs can not be considered a concrete standard, but rather a vehicle for instigating ambitious and holistic district development practices and communicating quantitative effects of sustainability measures. As such the approaches to PED assessment can be divided in one of the two: First, **process oriented approaches** acknowledge the diversity in context, challenges and ambitions between district development projects and thus favor flexibility in assessment scope and or targets [9], [16], [17], [18]. In Austria e.g., the **“klimaaktiv Siedlungen und Quartiere”** standard offers a step-by-step guide including certification for this process to interested district developers[5].

Normative approaches on the other hand aim to define PEDs through the use of quantitative targets for the district energy and emission balance [15], [19], [20]. This can be used to connect to municipal and national decarbonization goals, as it allows to bridge the gap between Top-Down goals and scenarios with Bottom-Up assessment models such as energy building performance certificates (EBPCs). In the case of DigiPEQ, the main approach investigated focuses on district balance targets linked to national and sectoral energy and emission scenarios [21]: The energy and emission balance model was examined as a quantitative evaluation system for positive energy districts and applied considering energy services for operation, everyday mobility, construction, and maintenance, and also the urban context [15]. The assessment is based on an annual balance of primary energy and emission import and export with monthly conversion factors and an hourly simulation resolution. Here, balance targets crucially depends on the context of the district’s density: Dense urban districts have a lower than zero balance target, whereas the balance targets for scattered settlements increases with one over the density, expressed as the floor area ratio. Analyzing green-field districts of different density in seven Austrian counties showed that all districts can achieve their density-specific balance target with high, but comparable ambition in terms of energy efficiency of thermal hulls and HVAC system, use of energy flexibility and high utilization of photovoltaics. In this approach, flexibility can also be assessed as part of the primary energy balance by assigning grid-supportive or flexible use of energy a discounted weighting in terms of its primary energy conversion factor. Similarly, seasonal mismatches are assessed by using hourly and/or monthly conversion factors for grid use and grid feed-in.

[5] See https://www.klimaaktiv.at/gemeinden/qualitaetssicherung/Siedlungen.html

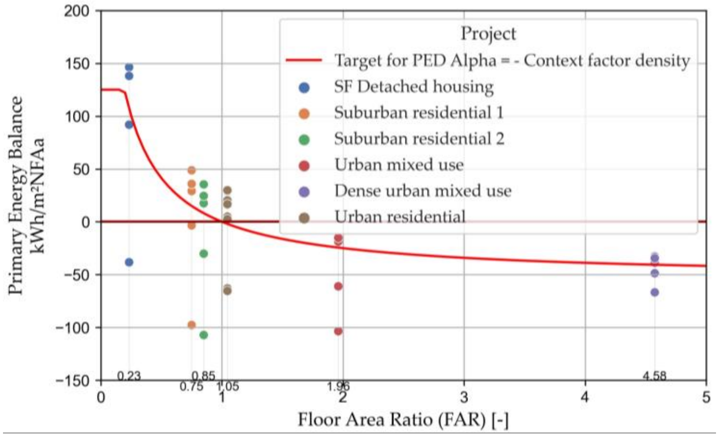


Figure 3 Austrian Target (red line) and modelled Primary Energy Balance for seven districts of different density (colored dots). Floor Area Ratio is defined as the gross floor area over the building plot area

Prediction of Loads and User Behavior

The project further investigated how districts' energy and emission flows can be modeled and simulated in practice to dynamically assess the interplay of local renewable energy production and flexible district operation and sector coupling: Whereas most of today's systems are designed and dimensioned on a balance and billing system only, where the matching of demand and supply is inherently done by the physics of the system only, cross sector coupling or integrated energy systems demands for more coordinated ways to exchange energy. A prerequisite of current installations is that demand is much greater than supply, so that no curtailment needs to be applied. Yet, PEDs can use renewable energies much more efficient if there are control algorithms applied that actively match supply and demand. Applying such control algorithms enables PEDs to serve as load even for largescale access power from wind parks or large PV power plants. Recent scientific work is investigating these issues to avoid curtailment in production, prevent, increase the number of renewable production volume, prevent supply shortfall and congestions. E.g., [22], [23] uses so called active community controllers for coordination and optimal usage of flexibility using electric and thermal storage capacities in buildings. Other projects such as [24], [25] use flexibilities from electric vehicles having the advantage that batteries in electric vehicles have a dual use reducing CO2 footprint and giving an important co-financing especially when used in car sharing operation. Another option is the storage of electricity via heat pumps in thermally activated building systems (TABS). With high thermal mass and insulation, these systems can block their heating and cooling operation to 6-12 hours with increased load in a timeframe of three to seven days without energy demand. Recent studies have concluded that user comfort is not negatively impacted for strictly positive temperature deltas of up to 3K (e.g. heating to 25°C instead of 22°C when a flexibility signal is present and withholding operation until the minimum setpoint of 22°C is reached again). Figure 4 illustrates these flexibility strategies in PEDs:

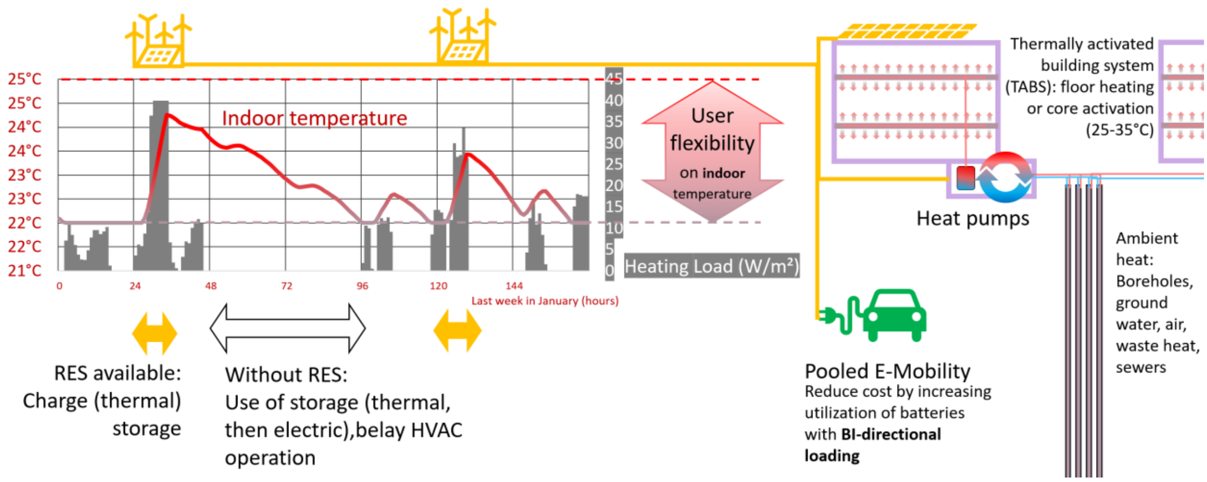


Figure 4 Example of flexible heating and cooling with Thermally Activated Building Systems and User flexibility of up to 3K increase in indoor air temperature during heating season

An important issue for such concepts is the prediction of load and consumption, which was a hot topic among the stakeholder community in the “innovation course”. Standard load profiles are the state-of-the-art to predict users’ load behavior. These profiles leverage the fact that with an increasing number of consumers spurious effects annihilate due to statistic effects. Figure 5 shows the effect of this standardization of load profiles depending on the number of users.

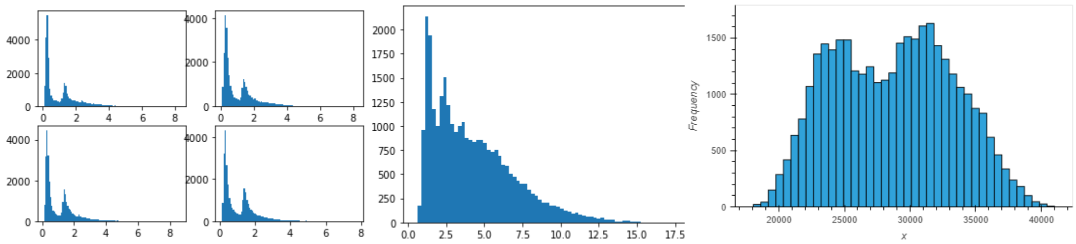
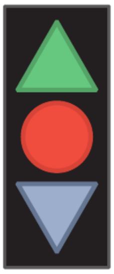


Figure 5: Load profiles for single households (left), aggregation of 4 households (middle), fully integrated standard load profile over all users (right) (figures based on data from [26])

On the base of practical installations, the participants of the innovation course investigated what is the effect of load profile assumptions on typical projects. Although this requires further research, the results show important effects. The participants investigated a residential home complex with 30 apartments and 1 shop by using the smart metering data from the housing units. They classified the housing units by the number of inhabitants and the life circumstances (e.g., working couple – no kids, family with one employed person, retired persons, etc.). Alternatively, [27] defined more individual personas including a more detailed background or [28] used machine learning to retrieve energy consumptions of individual production steps in a factory. In general, it is expected that due to uncertainties in the tenant structure (changes during the lifetime of a building need to be accounted for) a simple characterization will not provide large drawbacks and offer planning flexibility.

With a developed tool the participants have been able to create individual load profiles for differently used flats and aggregate them according to the building usage based only on the assumption of a yearly overall consumption. In particular for buildings with similar social background (e.g., only retired people) the outcomes deviated significantly from assumptions based on standard load profiles. This is an important fact to be considered in energy business models and resulted, e.g., in different ROI for the investment of roof-top PV installations. Outcomes are important for smaller installations such as renewable energy communities (REC) since local effects have a higher influence. Nevertheless, it might also be applicable to citizen energy communities (CEC) with a few but large consumers.

In PED additionally the status of the grid has to be considered in automation and optimization algorithms, since the amount of exchangeable energy is limited by grid capacity. It was identified that mechanisms are required to achieve the goal of a positive energy balance of the district. Although technical and organizational rules (e.g. grid codes) are in place to stabilize frequency and voltage forward-looking and anticipatory signalization is required to use volatile renewable energy sources, especially, in urban PED with limited space for production including spatial conflicts with recreation and ecosystem services. Within the “innovation course” a traffic light system (see Figure 6) was presented to allow planning and optimization in the 5 minutes range relieving reserve energy provisioning and giving consumers and prosumers a tool to act in a grid friendly way.



red	green	blue	Interpretation	Response
0	0	0	no light ⇒ no signal received	act as usual
1	0	0	grid access is diconnected	island mode if possible
1	0	1	energy supply is scarce	insert more & use less now if feasible
0	0	1	energy is "expensive"	insert more & use less if convenient
0	1	1	ambivalent situation	act as usual
0	1	0	energy is "cheap"	insert less & use more if useful
1	1	0	green curtailment is enforced	insert less & use more now if feasible
1	1	1	ambiguous signal ⇒ ignore it	act as usual

Figure 6: Multi-Level Traffic Light Signals Integrating Energy Market and Grid Needs [29]

Energy Economic, Legal, and Technical Environment

From an energy economic perspective, the contributions of Positive Energy District primarily is to balance load and consumption imbalances in general and to grid services in particular were examined. One objective was to actively motivate users to grid-friendly operating modes, thereby providing energy flexibility resources.

Potential economic welfare gains of PEDs are found to be significant, both in terms of monetary dimension as well as with regards to positive environmental and societal effects [30].

The regulatory framework plays a decisive role in the development and implementation of positive energy districts. With regards to potential hindering blocks for rapid implementation, several legal frameworks require particular attention. Especially the rights of and for consumers play a vital role.

This entails rules specific for Austria, such as the heating cost accounting law, which entails a very strong legal position in favor of tenants and homeowners. Furthermore, legal frameworks will most likely be modified once positive energy districts attain increased significance.

Thus, in summary, though PEDs offer a promising solution for the sustainable energy supply of residential and commercial areas, specific problems require solving before they reach further practical significance. The regulatory characteristics of the Austrian energy system which entail specificalities such as feed-in tariffs and laws abiding the integration into the electricity grid, are decisive for the viability and scalability of positive energy districts. Close cooperation between politicians, energy suppliers and the regulatory authority (Energie Control Austria) will be required to drive forward their development and implementation and thereby support a sustainable energy transition.

Information Management and Use of Participative Design Approaches

One significant objective driving these contributions is facilitating user empowerment to cultivate sustainable awareness. Incorporating gamification approaches and providing attractive information are critical strategies for achieving this objective. As applied in sustainable development, gamification involves integrating game elements into non-game contexts to enhance engagement and encourage positive behaviors. This approach has shown promise in various domains, including education, health, and environmental conservation.

Research indicates that gamification can effectively engage users and motivate sustainable behaviors. For instance, a study by [31] highlights the positive impact of gamification on user engagement, emphasizing its potential to enhance motivation and participation. By integrating game-like elements, such as challenges, rewards, and competitions, into information management systems, users are more likely to participate in sustainability initiatives and adopt environmentally friendly practices actively.

Participative design approaches further amplify the impact of information management in plus-energy districts. These approaches involve actively involving end-users in the design process, ensuring their perspectives, needs, and preferences are considered. Research by [32] emphasizes the importance of co-design in creating solutions that resonate with users, fostering a sense of ownership and commitment. In the context of plus-energy districts, participative design enhances the relevance of information and promotes a sense of community and collective responsibility. For embedding the participative design even further, the concept of personas has been used in the creation process of the information management. Personas are fictional characters that shall represent different future user types within the target audience, hereby especially in regards to ecological behavior, environmental awareness and their sustainable or not-so sustainable attitudes. With the help of personas, significantly more life situations have been able to be covered in the design to avoid bias and blindness to everyday situations of future inhabitants.

In conclusion to this point, the convergence of information management and participative design approaches holds immense potential for promoting community-friendly climate behavior in PEDs. By incorporating gamification strategies, the use of personas and ensuring the accessibility of information, stakeholders can enhance user engagement and foster sustainable awareness for plenty of target groups. Additionally, the integration of participative design approaches empowers residents, democratizes decision-making processes, and aligns information management strategies with the community's specific needs and avoids bias that could lead to exclusion.

Consideration and Application Possibilities of New Digital Technologies

The contemporary landscape of digital technologies has undergone a transformative evolution, with an escalating adoption of cutting-edge innovations over the last decade. The emergent Web3 technologies such as Blockchain, Ethereum and other protocols, Machine Learning (ML) for data processing, and Artificial Intelligence (AI)-based generators for image and text generation, are of particular significance. In this era of technological proliferation, the discourse on the consideration and application possibilities of these new digital technologies becomes paramount, especially in the context of PEDs, where the intersection of sustainability and technological advancement holds the promise of revolutionary developments.

ML algorithms, with their capacity to analyze vast datasets and discern intricate patterns, contribute significantly to optimizing user experiences by personalizing content recommendations and enhancing predictive functionalities [33] the context of PEDs, ML applications extend to energy management systems, enabling adaptive and intelligent control mechanisms that enhance energy efficiency. Within the project, applications were investigated that can manage the information flow from data acquisition at sensor level via preprocessing to maintaining consistent data storages. After a basic introduction, various company data was analyzed and directions given on how to gather, collect, clean and store the data setup necessary to work with ML. Yet, without opening the confidential company data to the public, following conclusions have been drawn:

- There is nothing, a script cannot do (with the prerequisite, access rights and connectivity to data points is given)
- Regular testing and plausibility checks on automated structures need to be done.

Certain problem types can be handled with toolchains such as Great Expectations under Apache-2.0 License, however they give mostly little freedom for adaption to be embedded into existing company toolchains [34]. In the context of Web3, also the tokenization (the virtual representation of a predefined unit, for example, a kWh) of energy assets through blockchain, coupled with using digital tokens as rewards, offers a tailored and effective incentive mechanism for motivating energy-saving behaviors in the unique context of plus-energy districts. By aligning with behavioral economic principles and emphasizing positive reinforcement, this design approach encourages personas and future residents to actively contribute to their PEDs surplus energy generation and overall sustainability goals.

Finally, there is to say, that the use of multiple new digital technologies might lead to exclusion of certain, most typically older, user-groups. With participatory design as explained in the previous paragraph, the complexity of understanding and representing such mechanisms shall be minimized in order to achieve the desired results. Needless to say, the most sophisticated technology is of no use, if there are no users willing or able to use it.

Perceived relevance of PED topics by practitioners

When bringing innovative concepts such as PEDs to the ground, the barriers and challenges perceived by practitioners and stakeholders of concrete district developments should be considered. The following figure summarizes the feedback of participating practitioners, that are all already involved in implementing PEDs as part of their day-to-day activities, in terms of most interesting, most novel (new) topics, and which topics they could take-away the most: The results showcase the importance of cross-cutting activities and breaking up existing silos and highlight certain key topics such as green financing, energy flexibility modelling, ecological and advanced district scale energy modelling, but also possible applications of AI and the importance of site visits and learning from real-world examples.

Table 1 Practitioners feedback when being asked what topics were most "new", most "interesting" and had the highest "take-away" for their practical work. Grades rank from 1 (highest) to 5 (lowest)

Rank	Ten best "New" Modules	Grade	Ten most "Interesting" Modules	Grade	Ten greatest "Take-Aways"	Grade
1	Green Financing	1,0	Übung "Raus aus Gas - Rein in PEQ"	1,0	"Raus aus Gas - Rein in PEQ"	1,0
2	"Raus aus Gas - Rein in PEQ"	1,3	Übung anhand Smart Block Geblergasse	1,0	Übung anhand Smart Block Geblergasse	1,2
3	Advanced Machine Learning	1,4	Flexibilität	1,1	Workshop Vernetzung u Reflexion	1,4
4	Exkursion Smart Block Geblergasse	1,5	Green Financing	1,1	Ökologische Bewertungsmethoden	1,4
5	Gruppenarbeit Usability	1,6	Impulsvorträge und Diskussion	1,1	(Tages)Lichtversorgung	1,4
6	Simulation mit IDA Districts/ICE	1,6	Gruppenarbeit Usability	1,2	Exkursion Co-living Seeparq	1,4
7	Vereinfachte Verfahren in der Quartiersimulation	1,6	Ökologische Bewertungsmethoden	1,2	Impulsvorträge und Diskussion	1,4
8	Smart Block Geblergasse	1,7	Energiemärkte im Umbruch	1,2	Energiemärkte im Umbruch	1,4
9	Inbetriebnahme-management	1,7	(Tages)Lichtversorgung	1,3	Verkehrsentstehung	1,4
10	Model Predictive Control	1,7	Erschließung von Flexibilitäten in aktiven Energiegemeinschaften	1,3	Exkursion Smart Block Geblergasse	1,5

The importance of cross-collaboration is also showcased in these projects designed to transfer new knowledge and skills on PED development into the field by a joint effort from practitioners and researchers. It highlights the concrete gaps and opportunities for the improvement of planning infrastructure, methods and result:.

Table 2 Knowledge and Skill Transfer projects for practitioners of PED development

Transfer project	Description
Supergrätzel	Designing a combination of energy communities and 'Supergrätzel' utilizing existing networks with a focus on social aspects (energy poverty).
Anonymous Measured Profiles	Analysis of electricity consumption data from different households in a multi-family house as a basis for Plus-Energy planning.
Energy Flow in Small Communities	Access to energy production and consumption data to create an energy flow diagram with a focus on heat consumption.
Planning Data Pool	Collecting and recording electricity and heat consumption data to develop characteristic values for the planning and monitoring of Plus-Energy districts.
From PED to AD (autonomous district)	Creating a roadmap for the development (or extension) of a simulation tool for Positive-Energy districts focusing on the degree of energy autonomy.

Data Quality Monitoring	Checking data sets before they are used for further processing.
OBENAUF - District with a Cherry on Top	Optimization of roof areas at the district level using an existing densification project (on the top, Währingerstraße) - measures and feasibility.
Onboarding Tool EEG	Development of a user journey for the digital founding of a Renewable Energy Community for implementation on the team4.energy platform.
Integral Planning Freudenau	Construction kit for a development concept for a future renovation district (Freudenau).

In a "PEQathon" format, the complex topic was finally successfully tested in an interdisciplinary planning workshop using concrete urban development areas in Vienna as examples. The results were adopted by the City of Vienna: The PED consideration and the resulting balance goals for energy supply and emissions in operation, mobility, and the establishment of a climate-neutral district are now incorporated into the development and implementation plan of the "WieNeu+" and "RausAusGas" district "Am Tabor".

The PEQathon results were assessed by a jury using the following point-based catalogue, that tries to encapsulate and weigh the most important aspects of PED development at an early planning stage:

Table 3 "PEQathon" PED early planning process assessment catalogue

Task	Criterion	Weight
Task A: District and Neighborhood	Achievement of quantitative PED Targets (Primary Energy Balance)	10
	Design of the Development Process	5
	Climate Resilience, Avoidance of Heat Islands, Rainwater Management	5
	Energy Flexibility and Storage	5
	Suitability for Integration of Digital Components	5
	Sector Coupling and Grid Services	5
	Fair Effort Sharing for the Transformation of the Entire District	5
	Integration of Stakeholders and Users	10
Task B: Micro-Districts	Proof of PED Targets	20
	Greening Concept	10
	Economic Efficiency over the Life Cycle	5
	Probability of Implementation	5
Task C	Improvement of Tender Documents	10

Final Considerations and Outlook

The added value of the PED consideration lies in the context-specific, but holistic assessment of building operation, everyday mobility, and embodied energy at the district level, thus bridging the gap between individual building code and assessments to overarching climate and energy goals of municipalities and cities. This also includes important questions of "Effort Sharing" and how the burdens and responsibilities of the transition can be distributed.

The collaborative exploration in ten thematic modules revealed that digital, livable PEDs can significantly contribute to national and municipal energy goals. Key insights include the importance of user-oriented and sustainable models, innovative digital technologies, and the need for replicable planning and operational processes in PEDs. The project underscored the challenges and opportunities in new constructions and retrofitting existing buildings, highlighting the complexities of energy flexibility, load shifting, and grid integration. The research also revealed the critical role of participative design and information management in fostering sustainable behaviors within PED communities. The exploration of new digital technologies such as ML, AI, and Web3, offered insights into future possibilities in energy management and user engagement. The project's findings are crucial for stakeholders, practitioners, and policymakers, providing a roadmap for implementing PEDs effectively.

In conclusion, DigiPEQ underlines the transformative potential of PEDs in achieving sustainable urban development, enhancing energy efficiency, and advancing towards climate neutrality.

It should also be noted that the term “**Positive Energy District**” is frequent cause for confusion and debate as to what exactly it refers to. It should be replaced by the more comprehensible term “**Climate Neutral District**” in future research.

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