ANNEX 83

EBC
Energy in Building and Communities Programme

International Energy Agency

Deliverable 3 – Governance Principles and Impact Assessment for Positive Energy Districts

Positive Energy Districts (Annex 83)

Energy in Buildings and Communities Technology Collaboration Programme

June 2026

Technology Collaboration Programme by iea

ANNEX 83

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Authors

Rosaria Volpe, University of Catania, Italy (rosaria.volpe@unict.it)
Adriano Bisello, EURAC Research, Italy (adriano.bisello@eurac.edu)
Andreas Tuerk, Joanneum Research, Austria (andreas.tuerk@joanneum.at)
Rose Mankaa, Institute of Sustainability in Civil Engineering, RWTH Aachen University, Germany (rose.mankaa@inab.rwth-aachen.de)
Francesco Guarino, University of Palermo, Italy (francesco.guarino@unipa.it)
Francesco Reda, Technical Research Center of Finland, Finland (Francesco.Reda@vtt.fi)

Contributing Authors

We wish to acknowledge the contribution of all Subtask C Members.

Participating countries in the EBC TCP: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Additional copies of this report may be obtained from: EBC Executive Committee Support Services Unit (ESSU), c/o INIVE vzw – International Network for Information on Ventilation and Energy Performance, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium).

www.iea-ebc.org
essu@iea-ebc.org

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)

Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: Low Carbon, High Comfort Integrated Lighting (EBC Annex 90 / SHC Task 70)
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities
Annex 98: Flexibilization and Optimization of Heat Pump Systems in Existing Buildings through Secondary-Side Digitalization
Annex 99: Air Cleaning for Sustainable and Resilient Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Summary

This report presents the main outcomes of Subtask C of the IEA EBC Annex 83 “Positive Energy Districts”. Subtask C focuses specifically on organising principles and impact assessment, offering a structured and interdisciplinary framework for evaluating PEDs across the economic, environmental, and social dimensions of sustainability. The report builds on an extensive literature review, methodological development, and case study analysis, primarily drawing from the European context where PED initiatives have been most actively tested and regulated.

PEDs are strongly tied to EU climate neutrality goals, the SET-Plan Action 3.2, and national strategies promoting high-efficiency buildings, renewable energy integration, and citizen participation in the energy transition. This broader context highlights the need for harmonised definitions, transparent governance, and robust assessment tools.

In detail, Chapter 1 introduces both Subtask C and the importance of PEDs.

The economic assessment (Chapter 2) provides an in-depth analysis of existing evaluation techniques, ranging from cost-benefit analysis (CBA) and Life Cycle Costing (LCC) to multi-criteria decision analysis and techno-economic modelling. It identifies the strengths and limitations of these methods when applied to district-scale energy systems. Critical economic indicators have been identified and include CAPEX, OPEX, payback period, net present value (NPV), internal rate of return (IRR), levelised cost of energy (LCOE), and business-oriented KPIs such as stakeholder engagement, market readiness, and job creation. Case studies from EU projects like EXCESS demonstrate how economic value can be generated through renewable integration, flexibility services, and new ownership models.

The environmental assessment (Chapter 3) expands beyond operational energy balance to include lifecycle impacts. It reviews methods such as Life Cycle Assessment (LCA), embodied carbon analysis, environmental KPIs, and district-level modelling tools. The chapter highlights common barriers such as data scarcity, limited tools for district-scale LCA, and inconsistent boundary definitions. A methodological framework is proposed for evaluating carbon emissions, renewable penetration, resource use, and retrofit scenarios, illustrated through a case study from the University of Palermo that quantifies environmental impacts of district renovation strategies.

The social assessment (Chapter 4) addresses the human dimension of PEDs, analysing issues of social acceptance, equity, community engagement, and stakeholder roles. Using Social Life Cycle Assessment (S-LCA) and survey-based approaches, the report maps the impacts on residents, workers, prosumers, and vulnerable groups. The sin.ikia case study demonstrates how social sustainability indicators, such as affordability, comfort, participation, and perception of benefits, can be incorporated in PED planning.

Chapter 5 introduces a multiple-benefit toolbox, integrating economic, environmental, and social insights into a single decision-support framework. This holistic perspective supports policymakers, planners, and developers in evaluating trade-offs, maximising co-benefits, and aligning PED initiatives with urban sustainability strategies, SDGs, and climate targets.

Finally, Chapter 6 discusses the main outcomes of the Subtask C study and outlines possible future directions for the establishment of an integrated, replicable, and robust framework for assessing PEDs, enabling informed decision-making and supporting cities toward climate-neutral, sustainable, and inclusive urban energy systems.

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1. Introduction

Positive Energy Districts (PEDs) represent a cutting-edge approach in urban energy planning, aiming for districts that produce more energy than they consume on an annual basis with a net-zero emission balance (JPI Urban Europe, 2020). This concept has also gained attention as cities seek to become carbon-neutral with the call for research and development focused on energy efficiency, renewable integration and sustainable and resilient cities.
Within this framework, there was the need for common definitions and standardised methodologies for PEDs various implementation stages. It is in this context that the International Energy Agency (IEA), within the Energy in Buildings and Communities (EBC) technology collaboration programme launched in 2020 the Annex 83 "Positive Energy Districts", after the preparation phase in late 2019, with the main aim of establishing a network of researchers to advance PEDs. This report presents the results of one of its Subtasks, namely Subtask C "Organising Principles and Impact Assessment". These results, including the analyses, methodologies and case studies, are mainly derived from the European context, building upon the experience of EU-funded projects, regulatory frameworks, and policy initiatives that have shaped the development of PEDs. It contributes to the existing knowledge of PED developments, with a focus on sustainability impact assessments. The report includes the perspective of economic, environmental and social impact assessment starting from the state-of-the-art, following with the definition of suitable and applicable methodologies tailored to PEDs, and then presenting case studies of PEDs in action, discussing therefore challenges and lessons learned. To reflect on the role of PEDs in the broader energy transition context and to highlight how the different spheres of economic, environmental and social pillars interact, a synthesis toolbox is offered under the multi-benefit approach.

1.1 Background and contributions

1.1.1 The context

The PED concept did not emerge in isolation, rather it evolved from decades of research and development in the field of energy-efficient buildings and communities. By the 2010s, net Zero Energy Buildings (NZEBs), i.e., buildings that with low energy demand and using renewables for energy production, became a policy focus in the European Union, also in light of specific Directives, such as the Energy Performance of Buildings Directive (EPBD, 2024 recast). As NZEBs grew in adoption, researchers and policymakers began to study the scaling of the net-positive energy idea from individual buildings to neighbourhoods and city districts (Hedman et al., 2021). The foundations behind this scaling consist in the possibility for cities to integrate different energy sources, to include urban planning aspects, to evaluate social benefits at the community level, as well as to foster the overall emissions reduction and increase the economic return. In this context of rapid diffusion of the new term "Positive Energy District", the European Strategic Energy Technology (SET) Plan included the targeted action 3.2 for supporting the planning and deployment of 100 Positive Energy Districts in Europe (SET Plan, 2018).
With this growing interest, different initiatives and cities in Europe defined PEDs with varying criteria, either focusing on the mere net energy balance of emphasising low carbon emissions. Additionally, early PED pilots in Europe revealed the need to address barriers, such as the regulatory ones. In Europe, organisations like JPI Urban Europe and other networks have facilitated discussions among different stakeholders involved in the process: cities, industries,

local communities and researchers, to reach a common understanding of PED ambitions as part of holistic urban strategies (JPI Urban Europe, 2020). These efforts highlighted that PEDs must integrate economic, environmental and social dimensions, moving beyond the mere achievement of positive energy balance.

In this context, IEA EBC Annex 83 has been conceived as a five-year collaborative research effort bridging together experts of different disciplines and from many countries worldwide to address the open questions surrounding PEDs (Hedman et al., 2021). The answers to these questions under the lens of Subtask C "Organizing principles and impact assessment" are presented in this report. Subtask C of Annex 83 was dedicated to developing and applying methodologies to assess the impacts of PEDs across three pillars of sustainability: economic, environmental and social. The approach has been structured into three parallel analyses (and this structure is reflected in this report, as well) for each sustainability dimension. In addition, the development and implementation of PEDs are strongly influenced by national regulatory and strategic contexts, reflecting a multi-level governance structure that connects European policy frameworks with local planning and decision-making. National transposition of EU Directives, such as the Energy Performance in Buildings Directive, as well as national energy and climate plans (NECPs) or also regional urban strategies, play a crucial role in defining how PEDs are governed, financed, and monitored.

The analyses have been divided into four main parts, i.e. the sections regarding the (i) literature review, (ii) framework development, (iii) case study analysis and (iv) synthesis of lessons learnt. Ultimately, the insights from all the three economic, environmental and social dimensions have been integrated in the multi-benefit approach, delivering an interdisciplinary assessment toolkit for PEDs. In the following, these Sections are introduced and described.

1.1.2 Economic impact assessment

The economic impact assessment is presented in Chapter 2 and focuses on evaluating the financial and economic viability of PEDs and their business environment. Starting from a review of the literature and studies on topics such as cost-benefit analysis of district energy systems, financing models, key performance indicators (KPIs) used in projects, existing economic assessment methods relevant to PEDs, as well as case studies, it was possible to define economic and financial models. These include models for renewable-energy consumption, energy trading mechanisms within districts and various ownership tariffs to incentivise positive energy outcomes. Building on this knowledge, an economic framework analysis has been conducted to adapt and refine these methods for the PED context. Existing methodologies, ranging from classical investment metrics (such as payback period, net present value of district energy investments) to life cycle costing approaches were compared to see how they could be framed within the specificities of PEDs. However, it is important to underline that economic sustainability in PEDs does not depend solely on financial parameters. Technical feasibility, such as system reliability, interoperability, and energy performance, as well as social acceptance, user engagement, behavioural patterns (to mention a few) are integral elements that condition costs, risks, and the overall viability of PED business models and should therefore be taken into account within a broader framework. Organisational business models have also been examined with the main grounding idea of how they could enable PEDs and affect revenue streams and risk allocation. Part of this analysis was also dedicated to mapping key stakeholders in the economic domain, from property developers and utilities to residents and local governments and understanding economic barriers and drivers within each PED implementation to permit the definition of new business models. These models have been then validated within the analysis of existing case studies from the EXCESS "FleXible user-CEntric Energy poSitive houseS" project, funded under the European Union's Horizon 2020 research and innovation programme under grant agreement N°870157 and led by Joanneum Research (Austria) to permit the definition of economic guidelines and recommendations ensuring long-term economic sustainability.

1.1.3 Environmental impact assessment

Chapter 3 offers the main outcomes of the environmental impact assessment studies. While PEDs are designed to be net-positive in operational energy, the activities developed within Annex 83 focused on a life cycle perspective to also account for the embodied impacts of construction materials, the effects on local environment, and end-of-life considerations. Coherently with the above introduced approach, the first stage of study consisted in a comprehensive literature analysis, with a focus on environmental impact assessment, projects and indicators. Many early PED projects proposed basic metrics like annual CO_2 emissions avoided or renewable energy fraction, with same examples regarding air quality or biodiversity in the district (Chau et al., 2015). Methods including Life Cycle Assessment (LCA) frameworks for neighbourhoods, tools for calculating embodied energy and carbon in building stocks and environmental KPIs have been analysed and compared to propose a recommended approach for PEDs, based on a combination of operational performance metrics and LCS-based metrics. For the operational impact, KPIs such as annual net CO_2 emissions, energy self-sufficiency or renewable energy penetration have been maintained from the existing knowledge and adapted to PEDs. In addition, for lifecycle impact other KPIs have been included, such as the carbon footprint for construction. Barriers, such as the lack of data or tools to easily perform district-level LCA, and drivers, such as the role of certification schemes that can motivate a comprehensive environmental accounting, were also included in the study. The developed environmental assessment approach has been tested in a case study of the University of Palermo.

1.1.4 Social impact assessment

PEDs are not only technical or financial projects, but they are communities. Thus, the impact of human and social dimensions is a core pillar when studying PEDs. In Chapter 4, the main outcomes of the social impact assessment activities conducted within Subtask C are presented. As a preliminary stage, a literature review on known social impacts of sustainable energy districts has been conducted, such as the social acceptance of new technologies, community engagement in the planning process, impacts on energy affordability and equity, impact on social cohesion. Data have been gathered from existing surveys and studies in pioneering projects, along with literature databases and methodologies for social impact assessments relevant to PEDs. Afterwards, various stakeholders' categories have been identified and their role assessed: this refers to prosumers, consumers, workers, to mention some of these. For each, it has been studied what social outcomes would be relevant and related metrics. A social life cycle assessment was applied here too, maintaining the attention at social impacts during construction (e.g., jobs created), operation (e.g., changes in lifestyle), and so on. The developed social strategy has been tested in a case study of the "Friedrich-Inhauser-Straße", an urban district in Salzburg, Austria, studied within the sin.ikia project, an EU-funded project under the Horizon 2020 Research and Innovation programme.

1.1.5 The multiple-benefit approach toolbox

The final step of Subtask C activities is presented in Chapter 5 with a toolbox able to synthesise the economic, environmental, and social analyses into an integrated assessment framework. The presented multi-benefit approach considers the different sustainability dimensions presented and how they can mutually influence each other. The tool has been developed to help policy makers, city planners, and project developers when aiming to evaluate PEDs.

1.2 PEDs in the broader energy transition and climate goals

PEDs are key urban forms in the broader energy transition, as they translate high-level climate and energy targets into tangible on-the-ground action in cities and, as such, they support the achievement of UN Sustainable Development Goals (United Nations, 2015). Urban areas account for a dominant share of energy use and emissions, so interventions at the district scale can have significant impact. As an example, Europe’s aim for climate-neutral cities by 2030 will likely rely on PED concepts to push some districts into net-positive territory (European Union, 2021). The assessments conducted within Subtask C indicate that PEDs not only cut emissions, but also create co-benefit effects in terms of innovation, new lifestyle, sustainable urban living and environmental awareness. By tackling decarbonising at the district scale, PEDs permit to gain knowledge on technical standards, financing schemes, citizen engagement models to inform city-wide programs and also national policies on sustainable energy.

Authors

Rosaria Volpe, University of Catania, Italy, (rosaria.volpe@unict.it)
Adriano Bisello, Institute for Renewable Energy, Eurac Research, Italy
(adriano.bisello@eurac.edu)
Andreas Tuerk, Joanneum Research, LIFE – Institute for Climate, Energy Systems
and Society, Austria (andreas.tuerk@joanneum.at)

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2. Economic impact assessment of Positive Energy Districts

2.1 State-of-the-art of PED economic assessment

This Section deals with an extensive review of existing literature concerning the sustainable development and economic evaluation of advanced urban districts. The objective is to derive transferable insights applicable to the Positive Energy District (PED) framework, offering a foundation for future investigative paths. The focus lies in examining how economic resilience is integrated within the built environment, particularly when innovative technologies and low-emission systems are involved. These economic evaluation strategies, when used proactively, can support the prioritisation of design choices, enhance cost-efficiency, and increase the overall value of interventions. Additionally, structured frameworks for assessing impacts are instrumental in shaping adaptive strategies and providing direction for decision-makers and stakeholders striving for enduring sustainability. Within this context, the review aims to:

- Explore existing research directions, identifying evaluation techniques, categories of impacts, performance indicators, and spatial definitions relevant to urban districts;
- Highlight theoretical and methodological shortcomings while proposing new lines of inquiry to support the long-term sustainability of PEDs.

2.1.1 Materials and Methods

An in-depth bibliometric analysis was carried out using various search queries across the SCOPUS and SCIENCEDIRECT platforms, focusing on themes related to economic evaluation and assessment, as outlined in Table 2.1. The study spans the full range of available literature, covering publications from 1975 through 2024. The review is structured around three core thematic areas: a broad, overarching category; a second domain emphasising spatial dimensions such as urban, district, and neighbourhood scales; and a third area centered on specific methodologies used for economic appraisal.

Table 1: Query strings in Scopus and Science Direct databases.

	Query	N° Doc. Science Direct	N° Doc. Scopus	N° unique items
Field 1	(ALL (economic AND evaluation) OR ALL (economic AND valuation) OR ALL (economic AND assessment) AND ALL (energy)) AND PUBYEAR > 1974 AND PUBYEAR < 2024	316,728	838,148	90,543
	(TITLE-ABS-KEY (economic AND evaluation) OR TITLE-ABS-KEY (economic AND valuation) OR TITLE-ABS-KEY (economic AND assessment) AND TITLE-ABS-KEY (energy)) AND PUBYEAR > 1974 AND PUBYEAR < 2024	2,398	50,610	7,520
Field 2	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND (Urban))	74	215	198

	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND (District))	41	211	184
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND (Neighbourhood))	14	14	14
Field 3	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Life cycle Assessment (LCA)")	22	8	20
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Sensitivity Analysis)")	27	49	40
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Cost Benefit Analysis"))	22	29	28
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Environmental Impact Assessment"))	11	14	12
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Monte Carlo Method"))	5	2	7
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Discounted Cash Flow"))	6	4	5
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Life Cycle Cost" OR "LCC"))	19	13	13
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Multicriteria" OR "MCDA" OR "MCA" OR "Multi-Criteria" OR "Multiple Criteria Decision Analysis"))	22	12	11
	TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Social Return on Investment" OR "SROI"))	1	1	1

TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Preference Evaluation" OR "Econometrics"))	11	2	3
TITLE-ABS-KEY (("economic evaluation" OR "economic valuation" OR "economic assessment") AND ("energy") AND ("Urban" OR " District" OR "Neighbourhood") AND ("Quantitative Analysis"))	19	4	2

In the first thematic area, the broad search across "all fields" yielded a total of 85,043 records. When the scope was narrowed to include only occurrences in titles, abstracts, and keywords, the number dropped to 7,633 entries. Within the "all fields" dataset, a significant concentration of publications (approximately 91%) was published between 2008 and 2021. Similarly, in the more restrictive query, the highest publication output occurred over the past 15 years, accounting for 6,040 entries, which represents 31% of the total.

In the second domain, focused on spatial scales, the terms "urban" and "district" appear in 215 publications, whereas the term "neighbourhood" is considerably less frequent, appearing in only 14 records.

As for the third analytical dimension concerning economic evaluation techniques, Cost-Benefit Analysis (CBA) emerges as the most frequently adopted methodology, identified in 49 documents. This approach is often complemented by Sensitivity Analysis, which appears in 29 publications.

2.1.2 Review discussion

A wide array of methods has been applied in the literature to assess the economic viability of energy-related interventions within the built environment. These methods are increasingly relevant to support the planning, design, and implementation phases of Positive Energy Districts (PEDs). Through an in-depth examination of selected studies, recurring economic methodologies (or those incorporating economic parameters) were identified, helping frame a systematic approach to support decision-making in sustainable urban development.

Among the most widely adopted economic approaches is Cost-Benefit Analysis (CBA), which enables the comparison of societal gains and expenditures linked to various energy technologies and systems (Mansouri Kouhestani et al. 2019; Delwati et al. 2019; Pirouti et al. 2013, Chester et al. 2013). This method is particularly suited for evaluating the comparative advantages of different energy carriers (Mena-Carrasco et al., 2012, Macias and Islas 2010). It helps decision-makers justify resource allocation by demonstrating how specific interventions can lead to net social benefits.

Life Cycle Costing (LCC) offers another perspective by evaluating the total economic impact of a technology or infrastructure over its operational lifespan, from initial investment through maintenance and decommissioning (Bisello et al., 2020). This long-term vision makes it useful for infrastructure planning and system upgrades.

Life Cycle Assessment (LCA), although originally developed to quantify environmental impacts, is frequently combined with economic parameters to support sustainability-oriented strategies. Examples include energy-from-waste systems (Zia et al., 2020) and solar heating systems with thermal storage (Dahash et al, 2021; Eriksson and Kjellström, 2010).

A more technical and performance-oriented method is Techno-Economic or Thermo-Economic Assessment, which focuses on estimating the unit cost of energy produced or saved through specific technological solutions (Zia et al., 2020). These assessments are essential in comparing alternatives from both energy and economic standpoints.

Multi-Criteria Analysis (MCA) provides a broader evaluation structure that integrates environmental, economic, and social parameters. It is designed to allow the simultaneous treatment of heterogeneous indicators in terms of type (qualitative or quantitative) and referring to domains that are also very distant from each other, such as CO_2 emissions, land costs, energy pricing, and public well-being (Angelakoglou et al., 2019). In some cases, MCA is combined with spatial analysis through the use of tools such as GIS to enhance planning accuracy (Mansouri Kouhestani et al., 2019).

Regarding the scale of application and analysed systems, the CBA approach is most frequently applied to urban or district-level studies, particularly when evaluating heating systems or district energy networks. At the building level, however, its use is less common and more often associated with nature-based solutions (e.g., green roofs or facades). Some district-scale studies also leverage GIS tools to refine building inventories and optimise renewable integration [37-39].

In terms of technological systems, the studies include:

- Heating and District Heating (DH) Systems: these are critical in colder climates, as observed in regions like Canada, Denmark, and the Netherlands (Delwati et al., 2019, Mena-Carrasco et al., 2012; Chen et al., 2021; Zuberi et al., 2021). Different configurations and renewable energy couplings (e.g., with geothermal or solar energy) are explored to minimise carbon footprints (Pirouti et al., 2013; Dahash et al., 2021).
- Distributed Generation and Multi-Energy Systems (DMES): strategies involving decentralised energy production, especially for thermal energy, are gaining attention in efforts to decarbonise building stocks (Dahash et al., 2021; Zuberi et al., 2021).
- Electricity Generation: interventions focusing on solar (Mansouri Kouhestani et al., 2019; Bandara et al., 2020; Calise et al. 2016) and wind (Macias and Islas, 2010; Mostafaeipour et al., 2020) energy sources aim to reduce the environmental impact of the electricity demand in buildings.
- Waste-to-Energy (WTE): addressing urban waste streams through energy recovery mechanisms is another avenue for impact reduction, provided proper management systems are in place (Zia et al., 2020; Leme et al., 2014).
- Nature-Based Solutions: urban greening interventions such as vegetated roofs and façades help improve outdoor air quality and thermal regulation, enhancing sustainability at the micro-scale (Teotonio et al., 2018).

In several studies, the economic assessment also considers GHG emission reductions, particularly CO_2, as a key output metric. However, few studies explicitly integrate emissions as a quantifiable economic benefit in the evaluation (Delwati et al., 2019; Chester et al., 2013; Leme et al., 2014).

It is worth mentioning that the literature reveals a growing interest in integrating financial metrics and performance indicators into sustainability evaluations. While Net Zero Energy Buildings (NZEBs) and Plus Energy Districts (PEDs) are often referenced in the studies (Bottero et al., 2021; Isaac et al., 2020; Derkenvaeva et al., 2022), the methodologies adopted vary depending on building type, climate zone, and urban density. Cost-optimal or cost-efficient solutions are typically identified using dynamic investment models (Isaac et al., 2020; European Parliament, 2012; Becchio et al., 2018; Rehman et al., 2019), frequently complemented by lifecycle analysis and present value calculations.

Some works employ CBA to measure the benefits not only to private investors but also to society as a whole, for example through Social Return on Investment (SROI) frameworks (Becchio et al., 2018). These are particularly useful for evaluating long-term community benefits of energy interventions.

In certain cases, economic valuation is inferred through Hedonic Pricing Models, which assess how sustainable features (e.g., rooftop PV systems, energy performance ratings) affect real estate values (Mansouri Kouhestani et al., 2019; McCord et al., 2020; Dastrup et al., 2012). These models often include spatial dimensions to account for regional variability and spill-over effects (Mosannenzadeh et al., 2017). Alternatively, Stated Preference Techniques, such as Willingness To Pay (WTP) studies, assess consumer readiness to invest in sustainable upgrades or support local renewable energy initiatives (McCord et al., 2020; D'Alpaos and Bragolusi, 2018). Some studies also examine employment creation, calculating the number of jobs supported by green interventions (Janssen and Dan; 2012), including savings from avoided social costs like unemployment subsidies (Good et al., 2019).

Despite the widespread use of financial methods, not all studies apply discounted cash flow (DCF) or similar techniques. Only about 45% of reviewed papers consider the time value of money. When used, discount rates typically range between 3% and 7%, depending on the method. For instance, 52% of CBA studies use a discount rate, while the percentage drops to 37% for thermo-economic assessments. COI and WTP analyses, by contrast, rarely apply temporal discounting. In this respect, it should be borne in mind that European regulations, such as Regulation (EU) No. 244/2012, provide structured approaches to evaluating minimum energy performance standards, offering national reference buildings and guidelines on cost-optimality for both private and public stakeholders (European Parliament, 2012; Akande et al., 2019). These regulations also distinguish between financial and macroeconomic perspectives, the former including taxes and subsidies, the latter focusing on broader societal impacts such as carbon costs.

As a final observation, though many studies mention environmental advantages and energy savings, fewer incorporate these directly into economic calculations. There is a clear need for more integrative methodologies that capture both tangible and intangible benefits, especially when assessing district-scale interventions and also considering a multi-stakeholder perspective, able to frame the complexity and subjectivity of the value judgement. In addition, improved knowledge exchange among research efforts would enhance coherence and foster methodological innovation, as many studies show limited cross-referencing despite thematic similarities.

2.1.3 Key Performance Indicators

The majority of the reviewed studies incorporate conventional financial metrics typically used in investment analysis. These include indicators such as Net Present Value (NPV) (Isaac et al., 2020), Payback Time (Mansouri Kouhestani et al., 2019), and Internal Rate of Return (IRR) (Calise et al., 2016). Additional metrics also assess monetary outcomes such as net economic benefits for both end-users and society at large, alongside assessments of total lifecycle or global costs (Bisello et al., 2020).

Beyond purely financial criteria, several evaluations introduce energy-focused indicators. These span from the share of self-generated energy used on-site to specific cost metrics like the Levelised Cost of Electricity (LCOE) and Levelised Cost of Heat, as well as net cost reductions in energy expenditure (Dastrup et a., 2012). Some analyses consider extended timeframes, projecting costs and benefits over durations as long as 25 years (Zuberi et al., 2021).

Approaches grounded in broader economic perspectives tend to employ societal-level performance indicators. Examples include employment intensity (e.g., number of jobs generated per €1 million invested), job creation across multi-decade horizons, and aggregated social returns often calculated as the combined value of energy savings and externalities over a project's lifecycle, minus the associated capital outlay (Clark et al., 2008). Some investigations also evaluate outcomes related to fuel poverty reduction (Rehman et al, 2019) showing interest towards socio-economic issues and fragile stakeholders.

Economic indicators are frequently intertwined with technical and environmental key performance indicators (KPIs). These may relate to indoor thermal comfort, building energy certification, energy savings, demand for primary energy, or infrastructure resilience (e.g., deferred investments in grid capacity). In many cases, financial metrics also account for indirect economic advantages, such as awareness of the cost-saving potential of energy efficiency or the impact of public subsidies and grants on reducing initial investment burdens (Kamer et al, 2017).

The main KPIs encountered in the papers analysed have been included in Table 2.

Table 2: KPIs for the economic impact assessment from literature

ECONOMIC METHOD	KPI
TECHNO/TERM ECONOMY	- LCOE (Levelised Cost of Energy) - EEP (Electrical Power Produced)
	- Energy efficiency - Exergy efficiency - Energy loss rate (Ren) - Exergy loss rate (Rex)
	- Endogenous avoidable exergy destruction - Exogenous avoidable exergy destruction - Endogenous unavoidable exergy destruction - Exogenous unavoidable exergy destruction
	- LCOH (Levelised Cost of Heat) - HEP (Heat Power Produced)
	- Annual losses heating - Cost of heat distribution
	- NPV (Net Present Value) - CAPEX - OPEX - IRR (Internal Rate of Return) - PBP (PayBack Period)
	- CAPEX - OPEX - Energy consumption - Emissions (CO_2 and other pollutants)
	- NPV (Net Present Value) - Energy consumption - Emissions (CO_2 and other pollutants)

CBA (COST BENEFIT ANALYSIS)	- NPV (Net Present Value) - PBP (Payback Period)
	- NPV (Net Present Value) - Installation Cost - Energy consumption - PBP (Payback Period)
	- Cost of Revenue different performance system - CO_2 emissions
	- CAPEX - OPEX - Salvage value
	- NPV (Net Present Value) - CAPEX - OPEX - IRR (Internal Rate Return) - WTP (Willingness to Pay) - PBP (Payback Period)
	- CAPEX - OPEX - Energy consumption - Emissions (CO_2 and other pollutants) - IRR (Internal Rate of Return) - PBP (Payback Period)
COI (COST OF ILLNESS)	- Direct cost - Indirect cost
	- Direct cost - Indirect cost - Intangible cost (WTP | VOLLY)
	- CO_2 emissions - Population - Land Prize - LCE (Levelised Cost of Energy) - EEP (Electrical power produced)

MCA **(MULTI CRITERIA ANALYSIS)**	- Reduced generation costs - Reduced ancillary service cost - Reduced congestion cost - Reduced unemployment subsidy - Reduced hospitalisation cost - Reduced tax revenue - Reduced electricity and thermal cost to consumers - Reduced outages events (momentary, sustained) - Increased property value - Improved indoor comfort - Reduced disease events - Reduced CO2 emissions, and other pollutants - Improved health conditions - GIS and light and raging (LiDAR) to estimate the rooftop PV electricity - Cost and revenue regarding different PV
LCA **(LIFE CYCLE ASSESSMENT)**	- Power output energy produced - LCOE (Levelised Cost of Energy) - NPV (Net Present Value) - Bioenergy costs - Commodity Prices - Bioenergy production
LCCA **(LIFE CYCLE COST ASSESSMENT)**	- Initial and operating cost - CO_2 emissions - Present Worth Factor (PWF) depending on the inflation rate and interest rate

2.1.4 Discussion and research gaps

Most economic evaluations related to energy-efficient urban transformations rely heavily on techno-economic approaches, predominantly structured around Cost-Benefit Analysis (CBA). These assessments frequently focus on cost-efficiency and long-term investment perspectives, often extending beyond 25 years. However, end-of-life costs, including disposal, remain insufficiently addressed. Similarly, the integration of PEDs within broader energy market frameworks (accounting for dynamic interactions with national grids or market signals) is rarely included in current methodologies. Similarly, the economic valuation of ancillary energy services related to peak shavings or grid stability are not considered at urban-district level. While traditional models persist, more comprehensive evaluation frameworks are beginning to emerge. For

example, the European Commission's Economic Appraisal Vademecum 2021–2027 recommends using Multi-Criteria Analysis (MCA) for complex urban investment projects involving overlapping sectors such as renewable energy, mobility, and climate adaptation. This approach allows for simultaneous consideration of economic, environmental, and social impacts, facilitating integrated urban development planning. In parallel, for building energy efficiency projects, the Commission supports cost-effectiveness evaluations inclusive of externalities, such as emissions reduction, maintenance cost savings, and property value improvements. The literature also reveals persistent methodological weaknesses. A common shortcoming is the omission of appropriate discounting mechanisms for future costs and benefits, despite their importance for establishing comparability in financial projections. Sensitivity analyses, though recommended, are underutilised. Furthermore, intangible or non-market co-benefits (such as improved urban biodiversity or public health) are often excluded due to the complexity of assigning monetary value, despite their significance in delivering societal gains. Many assessments continue to overlook the economic implications of carbon emissions. Even when climate concerns are acknowledged, uncertainty about appropriate pricing models and the ethical dimensions of discounting future environmental impacts pose unresolved challenges. Instead of focusing solely on avoided costs, more nuanced approaches such as Willingness-To-Pay (WTP) could offer insights into stakeholder preferences and societal welfare gains. Additionally, financial incentives remain crucial to mobilise private investment in green infrastructure, particularly where profitability is marginal. Public policies, tax incentives, and innovative financing models are instrumental in improving economic viability. Emerging proposals advocate for value-mapping approaches that capture the complexity of energy sharing, smart control systems, and cross-sector synergies in PEDs. These models consider both upstream and downstream processes and can support the development of new market opportunities, particularly when paired with supportive digital and regulatory frameworks.
The literature review also identifies key areas for further investigation:

- Geospatial integration: GIS tools can enhance the accuracy of spatial data, visualise energy demand and supply potential, and facilitate data-driven planning for PEDs.
- Carbon pricing in buildings: there is a need to develop coherent methods for valuing CO_2 reductions at the urban scale, ensuring that social impacts are also accounted for.
- Urban waste valorisation: more attention should be paid to transforming waste into energy while minimising environmental damage and advancing circular economy principles.
- Expansion of renewable sources: beyond solar and wind, the energy potential of wastewater treatment and sludge-to-energy systems should be explored for decentralised applications.
- Green infrastructure: the integration of green roofs and similar solutions should be supported by site-specific data rather than generalised bibliographic assumptions, ensuring accurate valuation of local social and ecological benefits, as well as insights on thermal comfort.
- District heating systems: these systems require optimisation, particularly regarding network temperatures. Investments in low-temperature DH infrastructure must be balanced with achievable cost savings to improve overall economic performance. Similarly, cooling district systems should also be investigated with more detail.
- Mobility integration: transport-related emissions and costs are largely absent from current PED evaluations. Their inclusion would support a more complete model of urban sustainability and contribute to climate neutrality goals.

Therefore, while economic evaluation methods are increasingly being applied to support sustainable urban transformation, there is a strong need to broaden their scope and improve methodological consistency. More comprehensive and site-specific approaches integrating energy, mobility, environment, and social dimensions are necessary to enable Positive Energy Districts to fulfill their transformative potential.

2.1.5 Conclusions

Addressing the urgent need for decarbonised urban energy systems requires the deployment of innovative, integrated solutions in buildings and infrastructure. However, this ambition often clashes with limited financial resources and an overwhelming variety of costly or competing technologies introduced by academic and market actors. To make informed choices, objective evidence is needed to prioritise actions, avoid short-sighted decisions, and assess what truly delivers value.

Economic assessment tools must therefore serve a dual role: first, as instruments for ex-ante appraisal, comparing costs, risks, and benefits across potential interventions; and second, as part of ex-post evaluation processes, measuring actual outcomes and efficiency. Despite the availability of many techniques, current literature shows a fragmented picture: while some methods focus on specific sectors such as large-scale energy or individual buildings they rarely account for the multidimensional impacts typical of complex urban ecosystems like PEDs. Often, sector-specific approaches fail to communicate the broader societal and environmental implications of proposed interventions, relying on partial or qualitative assessments.

As PEDs represent multi-system projects with far-reaching territorial and socio-economic effects, deeper research is needed to:

- Map interdependencies across building systems, energy networks, transport, and green infrastructure.
- Translate societal impacts into economic value using methods like Social Return on Investment (SROI).
- Position PEDs within broader energy markets, considering grid services and sector coupling (e.g., heating-electrification, e-mobility-storage).
- Evaluate peer-to-peer (P2P) energy sharing and community-based models in terms of equity and benefit distribution, considering the advantage of local energy sharing (e.g., Renewable Energy Communities).
- Understand PEDs as high-value urban assets aligned with ESG (environmental, social, governance) criteria and market transformation that requires a new energy infrastructure (e.g., district level PV, storage, geothermal filed, etc.).

Ultimately, PED evaluation should adopt a public value approach rooted in welfare economics to capture the full range of costs and benefits influencing community well-being. This includes environmental, health, cultural, and justice outcomes beyond financial returns (see the following multiple-benefits section in this publication). Integrating spatial analysis and GIS tools can further strengthen this perspective by embedding location-sensitive variables into the evaluation framework. Aligning PED outcomes with Sustainable Development Goals (SDGs) will help unify interdisciplinary efforts and build consensus on solutions that deliver inclusive, long-term value.

2.2 Methodological framework for economic impact assessment

2.2.1 Emerging regulatory framework conditions

The Clean Energy Package includes two types of energy communities as defined in the recasts of the Renewable Energy Directive, RED II, (Directive 2001/2018), and the recast of the Internal Electricity Market Directive (IEMD) (Directive 944/2019), the "Renewable Energy Communities" (RECs), defined in the REDII, and the "Citizen Energy Communities" (CECs), defined in the recast IEMD. It is important to note that the analysis presented in this Section focuses exclusively on the European Union regulatory framework. This can be explained by the fact that PEDs have been so far primarily developed and tested within the European policy context. These concepts allow citizens, public authorities and companies to collectively organise their participation in the energy system including energy generation, self-consumption, energy sharing and storage, and selling of energy (Tuerk et al., 2021).

Two major principles of both types of energy communities that open up new possibilities for Positive Energy Blocks and Positive Energy Districts (PEBs/PEDs) are the access of "non-professional" actors to the energy markets as well as the right to use the public grid for community-internal sharing. The latter increases the potential for interactions and optimisation between buildings. In addition, depending on the national frameworks, RECs and CECs may be entitled to operate electricity or heating grids, which may equally support the PED internal energy exchange. However, in the national transpositions of the energy community concepts, only electricity is often considered, using electricity grid typologies as boundaries for renewable energy communities.

PEBs and PEDs conceptually have more similarities to RECs than to CECs given their local character and a restriction to renewables in all current PEB and PED definitions. In addition, for RECs, supportive frameworks are emerging in several EU Member States, including, e.g., reduced grid tariffs for internal electricity sharing, improving the business case (Tuerk et al, 2021). CECs may, however, also be an interesting frame for PEDs. They are hardly restricted in their geographical expansion and could serve as an umbrella for several PEDs and other districts but also allow to include renewable energy generation units that are not in proximity to the district but are still part of a PED. CECs would not only allow for a broader exchange of electricity, but for a joint integration in the electricity market, e.g. for the collective marketing of flexibilities or surplus electricity. To this end, a CEC could itself act as an aggregator which may facilitate meeting the minimum capacity requirements that exist in many flexibility markets. However, also, the more limited energy sharing concept of the Clean Energy Package, collective self-consumption, could help optimise the use of renewables at the building level, or the level of clusters of buildings depending on the national legislation that defines the spatial scope for such activities. Collective self-consumption may be an alternative in case the organisational and legal requirements for an energy community may be seen as too challenging.

While there is literature on electricity sharing and placing PEDs in the context of energy communities as new organisational models there is less focus on the thermal side. On the thermal side, PEDs may take advantage of decarbonisation strategies of existing District Heating (DH) networks, now entering into the 5th generation, thanks to low temperature networks able to cover both the heating and cooling demands and integrating distributed energy resources (Buffa, 2019). Finally, in the PED discourse, the construction and the operation and management (O&M) costs of highly efficient buildings should be incorporated. Therefore, a more comprehensive approach to energy balance, and the techno-economic feasibility of PEDs is desirable.

2.2.2 Re-elaboration of the KPIs: economic and business indicators

This section provides an overview and re-elaboration of the KPIs available in the literature and related to economic sustainability within EU projects. This is followed by a detailed elaboration of the Global Cost indicator, as a central indicator for the Life Cycle Costing (LCC) of PEDs, PEBs and related technologies.

2.2.2.1 Overview on economic and business indicators

This section provides an overview on the analysis of socio-economic impacts within EU projects aimed at sustainability and energy innovation and discusses the challenges in quantifying the techno-economic feasibility of PEDs.
Key Performance Indicators (KPIs) on the topic are collected through a literature review and re-elaborated in order to: a) identify the emerging trends in the evaluation of the economic sustainability of PEDs; b) highlight possible conceptual gaps and barriers; and c) elaborate a set of relevant KPIs.
In this regard, a search was conducted considering the EU funded pilot projects on the topic of PEDs or on urban concepts which, while not aiming at a positive energy balance, present several analogies and connections with the PED concept.
In parallel, the outputs of EU initiatives focused on the development of such KPIs sets such as Smart Cities Information System (SCIS), CITYkeys, etc. have been included, as well as those deriving from the European standards.
Table 1 provides an overview of the economic KPIs developed in the revised EU projects outputs. It should be noted that the name of the KPI may vary slightly from project to project, while maintaining the same meaning. The Standard and/or Initiative are mentioned when relevant.

Table 3: Overview of the economic KPIs in the revised EU projects outputs.

No.	Key Performance Indicator (KPI)	Unit	Standard/Initiative	Project
1	Average Electricity Price for Companies and Consumers	[€/kWh]		POCITYF, triangulum
2	Grants for energy supply	[€/y]		REPLICATE, RUGGEDISED
3	Carbon Dioxide Reduction Cost Efficiency	[€/(tons CO_2 saved)/y]	CITYkeys	POCITYF, mySMARTlife, ATELIER, IRIS, STARDUST, PED-ID, City-zen
4	Energy Consumption Reduction Cost Variation	[€/MWh]		mySMARTlife, RUGGEDISED, RESPONSE
5	Gross Domestic Product (GDP) (value and change)	[€/cap], [€], [%]	CITYkeys, SDG	MAKING-CITY, REPLICATE, MAtchUP, REMO URBAN, triangulum
6	Total Investment	[€], [€/m^2], [€/kW]	SCIS	POCITYF, +CityxChange, REPLICATE, mySMARTlife, syn.ikia, ATELIER, IRIS, SMARTER TOGETHER, STARDUST, triangulum, RESPONSE, CITyFiED, PED-ID
7	Capital Cost (CapEx, Difference between Total Investment and Grants)	[€/m^2], [%]	ISO 37120:2018	syn.ikia, triangulum
8	Operational (OpEx)/Total Annual Costs (e.g. power, fuel, depreciation, interests, replacements and repairs, maintenance, inspection, insurance; value and/or reduction)	[€/y], [€/(m^2 y)]	SCIS	POCITYF, REPLICATE, syn.ikia, mySMARTlife, ATELIER, IRIS, SMARTER TOGETHER, triangulum, RUGGEDISED, RESPONSE, CITyFiED, PED-ID
9	Income-Cost Savings	[€]		mySMARTlife, IRIS, triangulum, RUGGEDISED
10	Return on Investment (ROI)	[%]	SCIS	SPARCS, POCITYF, +CityxChange, mySMARTlife, IRIS, RESPONSE, CITyFiED, City-zen
11	Net Present Value (NPV)	[€]	CITYkeys	mySMARTlife, syn.ikia, CITyFiED, PED-ID
12	Internal Rate of Return (IRR)	[%]	CITYkeys	mySMARTlife, syn.ikia, CITyFiED, PED-ID, City-zen

13	Payback Period	[y]	SCIS, CITYkeys	SPARCS, POCITYF, REPLICATE, mySMARTlife, syn.ikia, ATELIER, +CityxChange, IRIS, STARDUST, triangulum, RUGGEDISED, RESPONSE, CITyFiED, PED-ID
14	Economic Value Added (Difference between the yearly savings and the minimum required savings, equal to the Investment multiplied by the required rate of return)	[€/y]		syn.ikia, City-zen
15	nZEB Cost Comparison (Ratio between the total cost of the PED investment and its nZEB alternative, calculated for the lifetime period e.g. 60 years)	[%]		syn.ikia
16	Debt Service Coverage Ratio (DSCR)	[%]	ISO 37120:2018, SDG	SPARCS
17	Total Energy Carrier Cost	[€/y]		REPLICATE
18	Energy Bill Reduction	[€/y]		REPLICATE, SmartEnCity, SMARTER TOGETHER, triangulum, RUGGEDISED, CITyFiED, City-zen
19	Investment in Construction/Energy/Mobility/ICT	[€/m^2], [€/kW$_p$], [€]	SCIS	SMARTER TOGETHER, triangulum, RUGGEDISED, CITyFiED
20	Expenditures by the municipality (for the clean and smart energy transition)	[€], [€/cap], [%]	CITYkeys	SPARCS, POCITYF, REPLICATE, MAtchUP, SmartEnCity, REMO URBAN, mySMARTlife
21	Reduction in Energy Grid Investment (compared to the planned investment)	[€]		+CityxChange
22	Share of the Investment Covered by Funds/Grants (public or private)	[%]	SCIS	mySMARTlife, syn.ikia, IRIS, SMARTER TOGETHER, STARDUST, RUGGEDISED, CITyFiED
23	Expenditure in Local Economy	[%]		mySMARTlife
24	Local Job Creation	(no. of new jobs [-], [-/y], [%])	CITYkeys	POCITYF, +CityxChange, MAtchUP, mySMARTlife, REPLICATE, IRIS, SMARTER TOGETHER, triangulum, RUGGEDISED, CITyFiED, City-zen
25	Research Intensity (R&D expenditure as percentage of city's GDP)	[%]	CITYkeys, SDG	MAtchUP, REMO URBAN
26	No. of Blockchain Platforms	[-]		SPARCS
27	New Business Creation (No. of new Business ideas generated, new startups)	[-], [-/(100,000 hab y)]	CITYkeys, ISO 37120:2018	POCITYF, MAtchUP, REMO URBAN, SMARTER TOGETHER, RUGGEDISED
28	Participants in Urban Living Lab activities	[-]		SMARTER TOGETHER
29	No. of Innovation Living Labs	[-], [-/100,000 hab]	CITYkeys	+CityxChange, SMARTER TOGETHER
30	No. of New Projects generated and Volume of Funding	[-], [€]		SPARCS
31	User Interest in New Business Models	[Likert scale]		SPARCS
32	No. of Early-Stage Solutions Investigated	[-]		SPARCS
33	Model Developed and CBA for Blockchain	[-]		SPARCS
34	Total Distributed Energy Resources Capacity Traded	[%]		POCITYF, +CityxChange, RESPONSE

35	No. of New Patents	[-/y], [-/(100,000 hab y)]	ISO 37120:2018	SPARCS, MAtchUP, REMO URBAN, mySMARTlife, triangulum, RESPONSE
36	No. of Stakeholders in Co-creation	[-]		SPARCS
37	Stakeholder Satisfaction	[%]		SPARCS, GrowSmarter
38	No. of Relevant Stakeholders Engaged	[-], [Likert scale]	CITYkeys	SPARCS, mySMARTlife, SmartEnCity, IRIS
39	Ease of Use for Stakeholders	[Surveys-based Likert scale]		IRIS
40	Advantages for Stakeholders	[Surveys-based Likert scale]		IRIS
41	Market Orientation/Demand (Extent to which the project was planned on the basis of a Market analysis)	[Likert scale]	CITYkeys	SPARCS, STARDUST
42	Impact in Business Unit-IBU (Variables: no. of jobs, income, etc.)	[Likert scale]		mySMARTlife
43	New Forms of Financing (The extent to which the project has contributed to the development of new forms of financing)	[Likert Scale]		STARDUST
44	Energy flexibility Policies Legal Framework Compatibility (Level of suitability of the legal fram. for the integration of flexibility policies)	[Likert scale]		IRIS
45	Investment in New Public-Private Partnerships	[€/y]		triangulum
46	Replication Strategy (Multiple KPI; sub-KPIs: social compatibility, ease of use for stakeholders, trialability, technical compatibility, visibility of results, advantages for stakeholders)	[Surveys-based Likert Scale]		SPARCS, IRIS
47	Consumers Engagement in Local Energy Trading and DSM	[%]		ATELIER
48	Economic Incentives to promote sustainable actions (mobility, energy efficiency of districts)	[-], [€]		REMO URBAN, MAtchUP, REMO URBAN, SmartEnCity
49	No. of Contributions to European Standardisation Organisations	[-/y]		SPARCS
50	Total Housing Costs (rent, maintenance and energy cost) after building refurbishment (value and reduction)	[€/(household y)]		SMARTER TOGETHER, RUGGEDISED

From this study it results that, in the context of the sustainable design of innovative urban districts, greater attention is paid to the evaluation of the economic performance and sustainability of design solutions, while greater emphasis is needed on the development of tailor-made business models for PEDs and the definition of an overall strategic vision.
Due to the variability in measurement units, the comparability between the results of different projects and the benchmark between business processes and eco-energy innovation plans can be challenged.
As for the economic performance and sustainability of project solutions, almost all projects focus on the global evaluation of operational and capital costs (OpEx and CapEx) through Life Cycle Costing (LCC) analysis. The approaches are based on the development of discounted cash flows in constant and/or variable currency. Operational costs in the evaluation framework refer to capital-related annual costs (e.g. interests and repairs caused by the investment), requirement-related costs (e.g. power costs), and operation-related costs (e.g. costs of using the installation, i.e. maintenance) and other costs (e.g. insurance). These costs could vary for each year (Marijuán et al., 2018).
Capital-related costs encompass depreciation, interests, repairs and replacements of those assets or items purchased or implemented for improving the energy efficiency aspects of the system. Requirement-related costs include power costs, auxiliary power costs, fuel costs, and costs for operating resources and in some cases external costs. Operation-related costs include the costs of using the installation and costs of servicing and inspection. In this context, the KPIs from no. 6 to no. 12 are the most used, the most used KPI being the Payback Period.
At the building level, it may be relevant to reflect the building level cost using nZEB reference costs when performing the nZEB Cost Comparison, and if that is not available, the building common code costs in the respective demo sites in that country (Salom, 2021). The nZEB Cost Comparison is computed as the ratio between the total cost of the respective investment and its nZEB alternative. The calculation period should cover the expected lifetime of the PED and the reference, e.g. 60 years. As the PED concept is integrated into the energy system of the region where it is built, the more efficient and renewable the regional energy system is, the more efficient and renewable the building has to be, to be a PED.
The global cost calculation method is defined in a supplementing guideline to the EPBD, EU regulation 244/2012. The global cost calculation considers following basic cost categories: initial investment costs, running costs (operation and maintenance costs, energy costs) and disposal costs.
Furthermore, the EU guideline recommends to consider also the cost of Greenhouse Gas Emissions (GHG) in the global cost calculation at macroeconomic level but does not provide direct guidance on the calculation method. In addition, to reflect a truly market based approach in evaluating the cost efficiency of PEDs, grants and subsidies should be accounted for, rather than ignored (Salom, 2021).
In LCC applications, the end-of-life - deconstruction and disposal - phase is mostly neglected. Although considering that the quantification of disposal costs is not mandatory according to current legislation, it would be interesting to include it in the analysis. This could especially facilitate the full assessment of the economic impact of new technologies and the comparison of different technology packages. The quantification of the end-of-life economic impacts could be performed by means of estimates guided by primary data or exploiting advanced data science techniques, i.e. predictive algorithms, in the case of data availability.
The multifaceted and interconnected nature of sustainability requires a holistic and non-fragmented approach that allows, according to parallel and not successive steps, the assessment of economic impacts and social and environmental co-impacts. In this regard, new research trends aim at integrating LCC approaches with (Life Cycle Assessment) LCA and/or Social Life Cycle Assessment S-LCA, or with Multi Criteria Analysis (MCA) approaches based on KPIs. Within the EU projects investigated, the sustainability evaluation method is mainly based on the use of qualitative and quantitative indicators. Some projects evaluate the cost of GHG emissions at local level in order to benchmark the economic impact of decarbonisation approaches, by calculating the associated cost per ton of CO_2eq avoided (KPI no. 3, Table 3). On the other hand, further efforts could be direct to the definition of calculation methods suitable for the macroeconomic level.
Some experiences quantify some effects on the macroeconomic sphere induced by the project, such as the change in GDP and the change in the share of GDP for research (R&D

expenditure). Other projects also monitor the number of new patents and the number of new business ideas generated (KPIs no. 27, 35, Table 3) as indicators of the driving force behind innovation and research caused by project development and implementation.

Commonly analysed is the creation of new local jobs due to the project (KPI no. 24, Table 3), as an indicator of economic well-being and improvement of the social sustainability of the demo-site. Other socio-economic issues are considered, such as energy poverty (energy bills reduction), welfare and the unemployment rate of citizens.

In some cases, the increase in real estate cost due to building renovation is also included in the analysis. This could be a useful parameter for a more comprehensive assessment of economic sustainability (direct and indirect added value). Furthermore, it could be used in the development of risk assessment plans of the green gentrification phenomenon. This phenomenon, connected to the increase in the cost of rents (due to the project) and linked to the migration of poorer economic classes, could be stemmed in PEDs by planning coordinated economic and social intervention plans, in accordance with the principles of equity of the concept of sustainable development.

Another challenge is the quantification of economic benefits for the energy system (e.g. the grid), in order to include these opportunity costs in the economic analysis.

As for business models, few projects explore key aspects related to the development of specific business plans also through specific KPIs.

For the business ideas to be effective, a collaborative governance model is imperative to connect different stakeholders and align their interests and priorities for a general PED development and social-environmental-economic assessment. In such a model, a co-creation of the project proposal and the establishment of shared values and common vision among stakeholders could be achieved, aiming at finding the synergies and unlock the co-benefits of multiple stakeholders (Bertolami et al., 2024). On this line, KPI no. 36, Table 3, could be useful as it informs on the level of co-creation, even if specific surveys should be adapted to the site characteristics and stakeholders needs.

On the other hand, it would be useful by means of KPIs no. 31 and 38, Table 3, to evaluate the attractiveness of the project for stakeholders and the interest of users in the new business models. This information could be used to better calibrate the strategic vision of the project and evaluate ongoing variations to the business model. Other KPIs refer to the satisfaction and advantages for stakeholders.

As highlighted in the context of the projects SPARCS – "Sustainable energy positive and zero carbon communities", funded under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 864242, and STARDUST – "Holistic and integrated urban model for smart cities", funded the European Union's Horizon 2020 research and Innovation programme under grant agreement N°774094, there is a need for: a) a greater use of trade-off analyses between design alternatives in the early stage of the PED project; b) a greater Market Orientation, defined as the extent to which the project was planned on the basis of a Market analysis (related KPIs: no. 32, 41, Table 3).

As for the emerging regulatory frameworks, new financing schemes for PEDs should be envisaged. In the KPIs framework, KPI no. 43, Table 3, was defined to evaluate the extent to which the project contributes to the development of new forms of financing.

Finally, it should be noted that energy flexibility is an essential key point in the PED concept, as it can significantly contribute to the balancing of energy flows inside and outside the PED and facilitate the achievement of the PED target and economic sustainability goals. However, although there are several experiences at the single building level in the literature, new research efforts are needed to demonstrate solutions and models of flexibility at the district scale and in PEDs. Furthermore, from an organisational and business point of view, the definition of flexibility markets would require the development of new organisational models, engagement plans of users in local energy trading and Demand Side Management (DSM) platforms, as well as the suitability of the legal framework for the integration of flexibility policies, e.g. incentives for peak-shaving. As shown in Table 3, some KPIs could cover this issue, but an articulated and detailed plan is necessary in order to regulate policies and exploit the potential for flexibility.

2.2.2.2 Global cost indicator and cost-optimal approach

The new construction of PEDs and the refurbishment of existing districts from the PED perspective requires high initial investment costs, which are amortised to some extent over the entire lifetime of the buildings. In this regard, an important question that should be

addressed concerns the quantification of the amortisation extent and timeframe of different technology packages.
In this context, the evaluation of the life cycle cost of PEDs allows a more complete and comprehensive analysis of the economic viability of PEDs and could significantly favor the upscaling and replication of the PED concept.
The most common method for the assessment of life cycle-costs involves calculating the global cost as defined in the EU supplementing guideline 2012/C 115/01.
The approach focused on the quantification of the Global Cost in terms of Net Present Value (NPV), including all initial investment costs and the present value of operation and maintenance costs. Furthermore, the discounted value of the annual energy costs and revenues from renewable energy feed-in, for the whole calculation period, is considered within the Global Cost Indicator.
As outlined in Equation 1 below, the annual cash flows are discounted and summed up over the entire calculation period. Based on the recommendations for residential buildings discussed in the EU cost-optimal-framework guidelines, Global Costs could be assessed over a time period of 30 years.

$$C_G = C_I + \sum_{n=1}^{p} \frac{C_{OM}(n)}{(1+d)^n} + \sum_{n=1}^{p} \frac{C_E(n)}{(1+d)^n} \quad (1)$$

with

C_G	Global cost [€]
C_I	Investment cost [€]
C_{OM}	Annual operation and maintenance cost [€]
C_E	Annual energy cost and revenues [€]
d	Discount rate [-]
p	Calculation period [y]

Investment costs (without VAT) include all capital costs for the construction and implementation of renovation measures or energy efficiency measures. Investment costs are adjusted by the lifetime of the technology package in relation to the calculation period. This means that residual values are subtracted to the investment costs if the technology lifetime is higher than the calculation period. On the contrary, if the technology lifetime is lower than the calculation period, replacement cost is added to the initial investment costs. As illustrated in Equation 1, all future variables such as residual values and replacement costs are discounted and considered as present values by means of the discount rate.
On the other hand, operation and maintenance costs (COM) include the present values of all annual costs for operation and maintenance over the complete calculation period. Energy cost (CE) can be expressed according to Equation 2.

$$C_E = C_{ED} - R_{ES} - R_{DR} \quad (2)$$

with

C_{ED}	Cost for electricity purchase [€]
R_{ES}	Revenues for electricity supply [€]
R_{DR}	Revenues from Demand Response services [€]

The cost for electricity purchase (C_{ED}) is defined by the amount of electricity purchased from the grid and the purchasing price of electricity. The electricity price contains also VAT and grid related costs. Revenues from electricity supply (R_{ES}) are constituted by the amount of electricity supplied to the grid and the feed-in tariff. Potential revenues from Demand Response (DR) services are considered in the parameter R_{DR}.
Global costs are specified in the context of the cost-optimality methodology, according to the supplementing guidelines to the EPBD (EU 2012/C 115/01, 2012).

The cost-optimal approach could be used to benchmark minimum requirement for the energy performance of buildings and building elements. It encompasses a comparison of Global costs and Net Primary Energy Demand of different technology packages.
In general, it can be said that life cycle cost analyses such as the cost optimal methodology are important calculation approaches as they favor the additional benefits of PEBs. Life cycle costing is also highly relevant for contracting business models such as Energy Performance Contracts or Energy Supply Contracts. However, some costs are not considered in the calculation such as, for example, revenues from potential flexibility services to the DSO or cost savings through a non-intrusive renovation process where tenants don't have to move out during renovation. Furthermore, there are also several indirect benefits which cannot be easily quantified and therefore had to be omitted from the cost assessment.

2.2.3 Key stakeholders to mobilise

For a Positive Energy District (PED) several stakeholders such as cities and public bodies, industry and business, research and academia, citizens and civic society, private and professional stakeholders play a central role in the energy transition.
Satisfying outcomes of Positive Energy Buildings/Districts requires the involvement of a wide range of different stakeholders from the early phase of the project. Therefore, increasing the knowledge of PED, public communication, dissemination and public engagement among the public is crucial.
Citizens initiate and lead PEDs demonstrating an important bottom-up approach, where social identity, trust-building and power-relations play a fundamental role. End-users make decisions and act according to their motivations and social value orientation, and play a key role as this transition is primarily held for them. Along this line, citizens and civil society are also included as stakeholders, as tenants, citizens, landlords, media as well as citizen groups. Wider society plays an important role for PED/PEB. Residents, employees and other citizens should therefore be brought on board during the planning phase for inputs prior to communication of proposed plans.
When it comes to enforcing regulations and standards concerning PEDs, cities and public bodies such as supranational, national, local and regional authorities, national/local agencies and municipalities, play a key role. Furthermore, these authorities are associated with regulatory aspects in Europe, strategy-making and connected stakeholder engagement activities as well as innovation. Local authorities are more associated with enforcing regulations formulated at supranational, national or regional level.
Corporations with industry and businesses such as construction companies, real estate funds, utilities, electricity providers, electricity grid managers/owners are also essential to unlock the full potential of PED/PEC. A further deepening of cooperation between private firms and the public sector, as well as collaboration between different parties within municipalities is essential to boost performance of PEDs.
In this context the concept of "collaborative governance" arises, defined as the cooperation of wide range of sectors and field (industry, public administration, financial, economic and social) working together with research and academia (Hamdan et al., 2021).
The relevance of different stakeholders and actors involved depends on which stage of planning or operating the PED is currently at:

- Urban planning phase: citizens, citizen groups, non-governmental organisations (NGOs), authorities, municipalities, tenants, owners, Economic Chambers, Labour Chambers, construction companies, politicians, utilities urban planning department, architects and energy planners, engineers and designers of energy companies, developers, consultants, land owners, water companies, environmental protection agencies as well as building owners and users.
- Integrated build design process: citizen groups, NGOs, tenants, users, owners, planers, municipalities, Economic Chambers, Labour Chambers, construction companies, authorities, politicians, real estate funds, investors, society, utilities.
- Construction phase and its management: users, NGOs, citizen groups, tenants, real estate funds, planners, investors, utilities, owners, construction companies, authorities, politicians, Economic Chambers, municipalities.
- Operation phase: tenants, owners.
- Building operation process: construction company authorities, planners, municipalities, Economic Chambers, utilities, tenants, users, citizen groups, NGOs.

Local circumstances and practices also vary, depending on whether the related operations (e.g., energy, water) are private companies or municipally owned ones. In addition, land ownership has a great impact. Another factor influencing stakeholder composition is whether the project is a new construction or the refurbishment of an old building. In both cases, the involvement of appropriate moderators or mediators could facilitate the achievement of consensus solutions. Also, international collaboration with other cities through city networks or cooperation initiatives would add benefits.

At the national level it is important to define the general framework and minimum standards. As the general framework is set there, it is important that the government is active in this. In addition to legislating, the national and regional governments have the main financial resources to support the massive deployment of PEDs. Therefore, national-level financing and incentivisation schemes play a central role in encouraging energy efficient and positive energy buildings.

In this participatory governance model, it might be useful to include a PED certification protocol that could structure the dynamics of the construction process (Volpatti, 2024). It is worth highlighting that, currently, there is no officially recognised certification protocol for PEDs. Nevertheless, some existing methodological references could serve as the foundation. These include the JPI Urban Europe "Reference Framework for Positive Energy Districts and Neighbourhood (2020), the SET-Plan Action 3.2 Implementation Plan (2018). In addition, also the work of the IEA EBC Annex 83 also contributes to this objective. It would provide greater security for both investors and citizens a guarantee of the investment, timing and quality of the building transformation intervention. It would guarantee the perfect execution of the work by the companies in order to achieve the highest level of certification. District certification protocols are in place, but, so far, they have not guaranteed investors and citizens that the PED will be built and that it will respect all the steps for its success.

2.2.4 Barriers

This section addresses the main barriers in the implementation and diffusion of PEDs and discusses research gaps and conceptual and technical silos. In addition, the section provides useful insights and perspectives aimed, on the one hand, at a more comprehensive analysis of the economic feasibility of PEDs, and on the other hand at facilitating the achievement of the PED target through tailor-made business models.

2.2.4.1 Missing organisational models

Issues of missing organisational models can be divided up in issues during the developing and planning phase, the operating phase and the post-operating phase.

One issue of PED with missing organisational frameworks lies in the complexity of processes in the life cycle of the buildings: developments could fail in the planning, constructing or operational phase.

In Europe, the standard project delivery system is designed "bid build" (Kubba, 2017), which means that there is a clear cut between the design phase and the build phase, which is marked by the procurement of the construction companies ("bidding"). This results in a system where construction companies do not take part in the planning phase and the owner has to invest additional time for assigning construction contracts. Lack of communication and documentation as well as lack of knowledge about technologies and their costs discourages investors and citizens from participating. Therefore, it is vital to increase public awareness for the topic and interest conflicts: Positive Energy Buildings are currently not the focus of cities and cities have a lack of know-how on which technologies and which types of buildings are suitable. In some cases, innovative solutions, although technically feasible and reasonable under the energy balance perspective, such as Building-Integrated PV (BIPV) on building façade are not feasible due to limitations in local building regulation (Vermette et al., 2024).

When working with several departments in public administration, different interests of owners and stakeholders involved require fast and current knowledge transfer, especially in the field of legal questions or technical issues.

Limited knowledge of developing or operating a smart grid, and limited knowledge concerning the development of smart city districts hinder the fast expansion of PEDs, as additional external expertise is often required. Continuation of business-as-usual is too easy for city administrations and other organisations not forced by the market to evolve and adapt to new circumstances. For them the "status quo" means lower risks and no transaction costs, while change is a hard task to accomplish, only tackled when pushed by local politicians or personal interest (Borsboom-van Beurden et al., 2023). Furthermore, there is the risk of failure to achieve costs and energy goals as participants are not sufficiently aware of the manifold interactions of holistic planning contexts. The lack of political and legal framework might lead to higher follow-up costs if economically feasible and energetically reasonable solutions are inhibited by legal limitations.

As mentioned above, costs present the key limiting factor for the scope and ambitions of such projects. It is nearly impossible to make buildings across the city fully autonomous from energy networks by designing them to cover all their energy demand themselves. This would require massive PV arrays, installing geothermal technologies, energy storage, etc., which would not be economically sensible anymore.

Moreover, there are business model and financial challenges: How can the construction of passive or positive energy buildings be more reliable?

The involved actors lack an overarching common strategy, because each one seeks to fulfil a very specific agenda. It turns out to be difficult to understand the motivations of different stakeholder groups such as financial and other co-benefits.

2.2.4.2 Infrastructure and organisational limitations

One of the main challenges of planning a PED is to find a suitable location for energy infrastructure installations, especially in the case of autonomous PEDs.

On the other hand, when aiming for high energy-flexibility, dynamic and virtual PEDs may be of greater use for surrounding energy grids than autonomous ones. In this regard, synergies with the energy and energy flexibility needs of neighbouring districts should be investigated, as they could alleviate the infrastructure limitations and enhance the effect of Demand Response (DR) actions, facilitating the definition and effectiveness of flexibility market.

Further, some existing PED concepts do not include electric mobility and its energy demands and flexibility potential, which remains an important knowledge gap.

Already existing PED concepts fail to adapt to important aspects of modern urban areas such as:

- high population density;
- space scarcity and shape of buildings;
- limited availability of renewable energy sources.

Even if PED might work for small communities, issues with scaling up solutions of small pilot developments to become part of larger city developments occur.

The challenge of smart city innovation does not only affect technology, but also service transformation, integration and improvement. Having new or redeveloped districts fully relying on electricity (even for mobility) means having new dedicated infrastructure designed to answer local peaks and backup solutions, integrating storage and digital management systems in buildings or public spaces. During the planning and operation, there could be the immanent risk of losing stakeholders due to an occurring lack of engagement or interest. During the operation, legal and tax challenges could occur due to the mixed properties. In addition, energy sharing between different organisations, in commercial terms, is in some ways hindered by current regulations.

The upscaling and roll-out of the PED throughout the wider district and city poses further organisational and operational challenges. Furthermore, the motivation of the Distribution System Operator (DSO) to engage with and contribute as a partner in local PED projects can be a critical barrier.

Organisational barriers include challenges when it comes to collaboration with private investors. The private sector was often dissuaded from the involvement due to too many regulations. There is a central role of building-ownership, as on the one hand, life cycle costs are associated with long-term ownership. On the other hand, private real estate investors tend to have limited willingness to invest in long-term technologies.

Furthermore, there are additional issues concerning the post-operating period, such as the assessment of the technologies' after-lifetime emissions, not included in the PED metrics. This marks a significant knowledge gap that is essential to be considered to cover a full life cycle of PEDs.

2.2.4.3 Uncertainty of the costs for PEDs

Although PEDs require typically high investment costs, there is a wide range of design options and a significant variation of the costs. Furthermore, possible energy sources might also change, making evaluation and consideration of alternative energy sources necessary. Additionally, there is some stress concerning the timeframe, especially pressures to speed up construction activities, question marks concerning long-term effectiveness as well as user behaviour.

It should also be considered that PED standards could end up being seen as insufficient in the long-run as changing climates need to be accounted for, to assure that PEBs are able to perform as intended in the future. The NZEB metrics would require adaptations to changing climate influences, such as higher cooling demand.

2.2.4.4 Regulatory barriers

While the aim of PEDs is to provide flexibility to the energy system, flexibility markets are far from been fully developed in many EU countries. In some EU countries there are minimum capacity requirements, or the prequalification processes for decentralised renewables are very complex. Also, there is a high level of fragmentation between regulations in the electricity and heating sectors. In addition, with regard to the cooling sector, the regulatory landscape is less mature compared to the heating domain, especially for PEDs.

Another regulatory barrier is that building regulations may prevent the implementation of certain technologies. In addition, electricity sharing is limited or not yet available in several EU countries.

2.2.5 Organisational models

For the success of PEDs, it is of great importance to ensure commitment of the people through an open process and broad stakeholder engagement when developing city's or region's strategy. Further officials should raise the awareness of all stakeholders and educate them on all energy efficiency, flexibility and local RES integration. Municipalities can support building designers from the beginning through other means than mandating or encouraging PEDs in urban plans: provide practical guidance, initiate discussions, organise energy nights, bring stakeholders together, offer one-stop-shop models for project owners and construction firms launch awareness raising campaigns and disseminate knowledge. These models refer to a single, integrated contact point through which project owners can access technical, financial and administrative assistance for PED planning, implementation and operation.

Stakeholders should promote a common, interdisciplinary understanding of the complexity of PED planning processes for all stakeholders involved.

The design build approach includes reaction to bid build, performance-based design-build-model achieves higher quality at lower cost. In this regard, the introduction of a performance-based procurement approach as a common practice, not only for public tendering but also for private construction, could overcome some organisational barriers. This could be used to integrate the planning and construction phase in order to achieve the specific goal of a high-performance PED, by assigning this as target to the planning and construction company.

For the development of the project to be effective, more emphasis should be placed on the integration of planning and construction. Actors of planning and construction need to exchange information and roles should be known. Tasks and functions of stakeholders should be assigned. On the other hand, different target criteria and co-benefits on the perspective of stakeholders should be quantified, such as increased productivity, improve health, publicity value etc.

Within the construction process communication between individual participants is necessary, as the different systems are closely linked. There is also a necessity to keep comprehensive documentation of the interactions of individual systems as well as the functionality of the individual system

Three key aspects for developing a framework for PEDs that include stakeholders and citizens:

- Enabling a common energy and energy flexibility market to translate European energy market to a local scale;
- Integrating e-mobility as a service to combine mobility and energy systems;

- Creating connected communities, actors in the energy system and markets who can directly benefit from the results and act as market participants democratising energy systems.

Recommendations for new policy interventions, market (de)regulations and business models to deliver positive energy communities to ensure learning can be shared.
In this regard, an effective model should be based on open innovation frameworks, open data architectures, and access to large amounts of information and results, both for transfer of knowledge and experiences between cities and solutions providers within the project, and with external stakeholders.
Key points of local co-creation and collaboration are: networking; collaboration with partners, competitors, universities and users; corporate entrepreneurship by enhancing corporate venturing; proactive Intellectual Property Management by creating new markets for technology; Research and Development (R&D) for achieving competitive advantages in the market. Engagement with external stakeholders can tap into knowledge and innovation outside of the project, combining internal and external ideas: creating a balance between exploratory and exploitative innovation.
Several further concepts and ideas of organising stakeholders in PEB/PED have been put forward by Ahlers et. al.:

- Foundation of a company by stakeholders with the ambition to commercialise the expertise;
- Co-create and co-design smart city services towards energy transition with citizens via social networking, city apps, public consultations and participative workshops;
- Provide private-public and public-public dialogue platform such as Gameplay: all stakeholders in a certain destination are invited to plan together/collaborate.

PEDs should be developed using area-based approaches and social oriented policies. Area-based approaches mean allowing for different combinations of policies that would target specific groups in PED development considering their local (spatial) contexts. Social oriented policies mean targeting (especially) vulnerable groups through providing alternatives or supportive conditions that would allow affordability and inclusion.
In order to face challenges described above such as high population density, space scarcity, and limited availability of renewable energy, the development of dynamic and virtual PEDs should be prioritised over autonomous ones. Dynamic and virtual PEDs allow flexibility through interacting with neighbouring PEDs and VPPs. As observed in the practical examples, this can lead to successful implementation and sustainability of PEDs.
The concepts of PEBs and PEDs are in principle synergetic with the energy community concept as PEBs/PEDs relate to technical characteristics and optimisations while energy communities provide a legal and regulatory framework for the organisation and governance of a community, at the same time providing new regulatory space for specific activities and market integration. Renewable Energy Communities (RECs) address all types of renewable energy and have a local character. They could provide a suitable framework for PEBs and PEDs by defining their geographic scope, the eligibility of members and their governance, as well as the general purpose of the community. Focusing on an increased share of renewable energy in the system or collectively self-consumed within the community, RECs are supposed to receive public support. Citizen Energy Communities (CECs) on the other hand can operate over a larger area, limited only by national borders or even involving international cooperation

2.2.6 Financial models

There are several financing models being discussed, some of which are already used for PV or renovation, but with limited technological coverage. These include:

2.2.6.1 PEDs as future Energy Performance Contract (EPC) models

In this model, also maintenance costs should be considered, one option is to develop performance-based contracts to include also the maintenance of the complicated system (e.g. appointing a general contractor for a wide energy-facility management that goes beyond the boundaries of the buildings, perhaps even including the neighbourhood e-mobility system).

2.2.6.2 Property Assessment Clean Energy (PACE)

This alternative is being piloted in Europe and has been successfully implemented in the US. The benefit of these loans is that they are not linked to home or building owners but rather to the building itself, which enables transfer of ownership including the financial repayment obligations. This particular model has been structured around bonds provided by municipalities, such as Los Angeles, Miami and New York, with repayments made through property taxation over a period of 15-20 years. The adoption of PACE is currently at hold in Europe due to regulatory issues.

2.2.6.3 On-bill financing (OBF)

OBF schemes aim to lower the initial investment cost burden of energy renovations and address split incentives issues. OBF allows utilities (or other parties) to act as a cushion to the impact of initial investment costs for home or building owners, either via an on-bill loan or on-bill tariff structure.

2.2.6.4 Revolving funds

These funds capture some of the savings linked with energy efficiency measures and re-invest these into further projects. The Estonian Kredex Credit and Export Guarantee Fund has had considerable impact and could be considered for further replication.

2.2.6.5 Energy Efficiency Funds

Several international funds exist, often bringing together public and private investment, to mobilise energy renovations. Key players include the European Energy Efficiency Fund (EEEF), the SUSI Energy Efficiency Fund and the Renewable Resources and Energy Efficiency (R2E2) Fund.

2.2.6.6 Targeted public PED financing

Currently individual PED technologies (e.g. PV and storage, envelope insulation, Heat pumps) and services (e-mobility, EVs charging stations, etc.) receive specific funding. There is no funding for systemic PED solutions, apart from EU R&D projects, that only cover a minor part of the investments and are mainly deputed to knowledge creation and testing of advanced solutions not yet on the market. Financing and incentive schemes at the national level (or even city level) promoting PEBs should also include social issues improving social equality. The requirement to show the life cycle effects should be made mandatory in the planning phase or in connection of the building permit, not just related to costs, but also to environmental aspects.

2.2.6.7 CO_2 pricing

Introducing a CO_2 or an environmental tax (that possibly includes lifecycle emissions) could help in the roll-out of PEBs (also social issues improve social equality), while enabling circularity. There is the risk of overinvestments into technology onsite, in particular oversizing electrical storage systems that need cooling in summer, and have in some cases limited environmental benefits (Pucker et al, 2021). There is a lack of existing examples of cost-benefit analyses of PEBs (including life cycle cost and emissions).

In the following more details about Energy Performance contracting are provided. EPC are an alternative financing mechanism, where the initial investment costs are completely financed by future energy cost savings. Initial financing is typically organised by the ESCO (either own funds or third-party financing), which is the main advantage of EPC to building owners. As PEDs reduce the energy demand and costs to a minimum and generate new revenue streams from RES feed-in, EPCs can be a very promising financing model for PEDs. For a profitable EPC, the payback period of the investment must be within the typical contracting period of EPCs (max 20-30 years). Therefore, cost effectiveness of applied technologies as well as the deployment of new innovative revenue streams (e.g. demand response services, P2P trading, etc.) are crucial for the profitability and widespread market uptake of EPCs for PEDs. The basic idea of the EPC business model is that the ESCO will be remunerated based on the energy savings generated through the contract. The basic EPC business model is described in Figure 1. It shows that the baseline energy consumptions reduced through the implemented measures. The energy savings are used to pay back the investment costs. After the contract duration, the customer receives all savings.

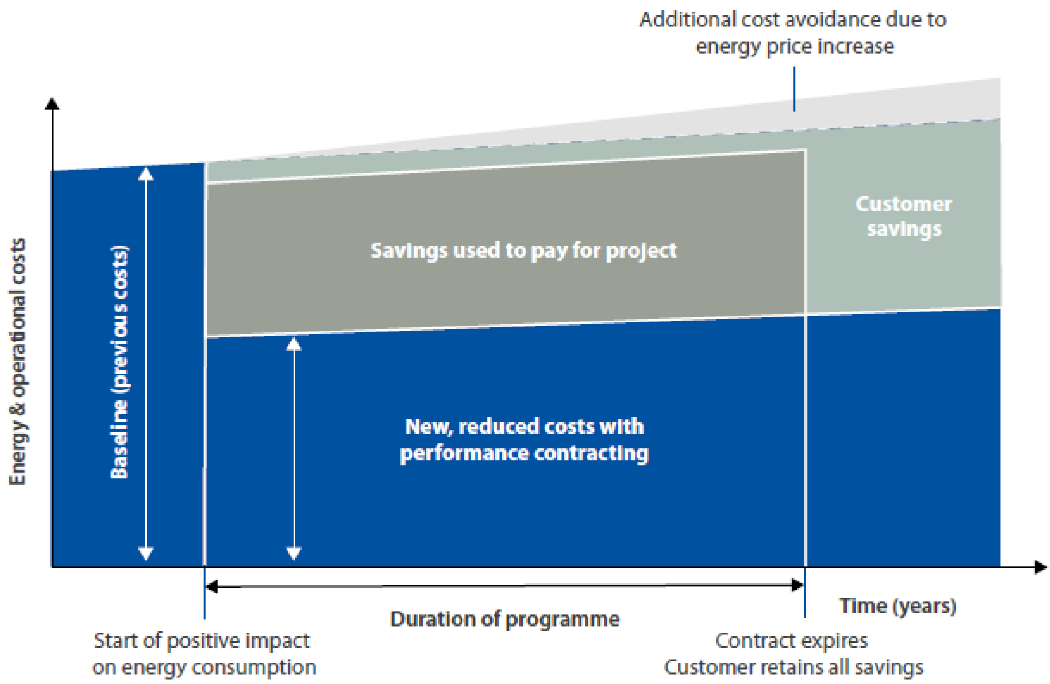

Figure 1: Basic concept of EPC

The following paragraph describes some specific characteristics of the basic EPC business model. EPCs focus on buildings with energy systems that are outdated and inefficient and a deep renovation of the building is needed. The EPC project is usually designed and planned by the building owner or a facilitator in combination with contracted architects. The installation and operation of equipment and technical facilities is done by the ESCO.
The technical improvements of the building can include deep renovation of building structures (e.g. building envelope, roof, basement, interior, facilities like elevators, etc.) as well as the replacement or new construction of in-house energy supply and consumption systems (e.g. energy efficient heating, ventilation, air conditioning, lighting, etc.). Often it also includes the utilisation of renewable energies and the installation of heat pumps. The ownership of all equipment and facilities installed is usually transferred to the building owner at the date of acceptance as defined in the contract. The contract usually also includes services such as energy accounting and management as well as the measurement of actual energy consumption and the verification of the energy savings achieved. Other services can be grant applications and approval procedures. Furthermore, operation services such as optimisation of operation and maintenance of installed facilities and the auditing and certification procedures, can be additional services that are defined in the EPC contract (Csaszar et al. 2015). EPC contracts usually define the specification of the building (size, type of use, operation mode, etc.). EPCs can be categorised in shared-savings models and guaranteed-savings models. The following subsections will outline the basic components of those two models and the differences between the models.

2.2.6.8 Shared savings model

In the EPC shared savings model, the ESCO is undertaking the investment, as well as the project planning and implementation as shown in Figure 2. The energy savings are shared between the ESCO and the customer. The investment is paid back by the part of the energy savings that are obtained from the ESCO. In the shared savings model, the ESCO has the technical risk of achieving the agreed savings and the credit risk as the ESCO is responsible for investment. This means that in the shared savings model, the only financial commitment the client will have to bear is to pay back the investments made by the ESCO through the savings achieved, at a pre-determined rate or proportion and over a certain period of time (Pätäri et al. 2014). The performance risk (i.e. the uncertainty of future energy consumption) can therefore be regarded as being shared between contractor and client (Bertoldi et al. 2006, Winther et al. 2017).

Figure 2: Shared savings model (IEA 2018)

Guaranteed savings model
In the EPC guaranteed savings model, the ESCO guarantees a certain amount of savings to the customer. The ESCO only takes the technical risk of achieving the agreed savings. The customer obtains a bank loan or uses its own equity to pay contractually determined fees to the ESCO and the bank. Therefore, the customer has the credit risk in the guaranteed savings model. In other words, the customer is required to provide the necessary financial resources and therefore the contractor assumes the entire performance risk (Bertoldi et al. 2006, Winther et al. 2017, Pätäri et al. 2014). Figure 3 graphically shows the concept of the guaranteed savings model (IEA 2018).

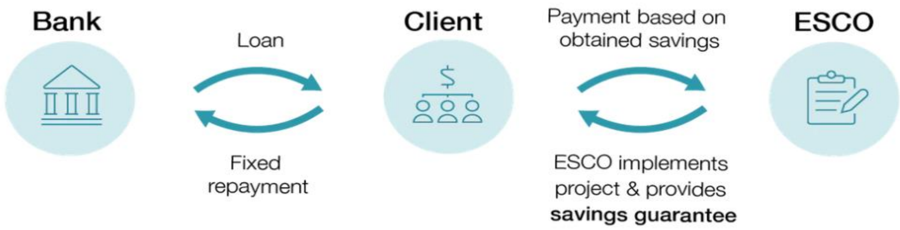

Figure 3: Guaranteed savings model (IEA 2018)

2.2.7 Conclusions

This chapter has shown several approaches to assess costs of PED technologies and technology packages, possible business and financing models as well as stakeholders involved, as commented in Section 2.2.3. So far as this report shows cost assessments still have their weaknesses as not all cost can be quantified, Life cycle costing as illustrated in this report is hardly applied, CO_2 pricing in the building sector not yet operational. Financing models that are used in the building sector are not yet applied for more innovative technologies, due to risk averse decision making. Next to regulatory barriers, such as a limitation of energy sharing and only emerging concepts for energy communities and decentralised flexibility, the roles and interest of related stakeholders is unclear and diverse, thus synergetic organisation model are still to be developed or streamlined. For example, energy utilities typically prioritise system reliability and cost recovery, whereas building owners are mostly interested in lowering energy bills or increasing the value of their property, and, to add another element to this analysis, municipalities focus on meeting climate targets or reducing energy poverty. A possible way to circumvent this is to tying the concept of PED more strongly to the achievement of climate-neutral urban goals by envisioning specific financing programs that would stimulate the interest of real estate developers and market operators even in areas where the market does not yet seem ready to reap the benefits of energy sharing and energy sustainability.

2.3 Case study application and insights

This chapter shows some applications of the economic framework methodologies and is mainly informed by the project EXCESS EU Horizon.

2.3.1 Applying the cost-optimality approach

Figure 4 depicts, as an example, a graphical representation of the main results deriving from an application of the **cost-optimality approach** applied to different energy technology packages in the EXCESS project. Specifically, Figure 4 elaborates some data obtained for one of the pilot-cases (Spanish demo-site). Different technology packages (different degrees of renovation, heat pumps, PV and PVT) are compared in terms of global costs and Net Primary Energy Demand in order to define cost-optimal solution for the achievement of the PEB target (Mayer et. at., 2023). This has a different impact if compared to PED, where a group of buildings are considered. However, this analysis is offered to give initial insights into the concepts of energy positivity at the urban level.

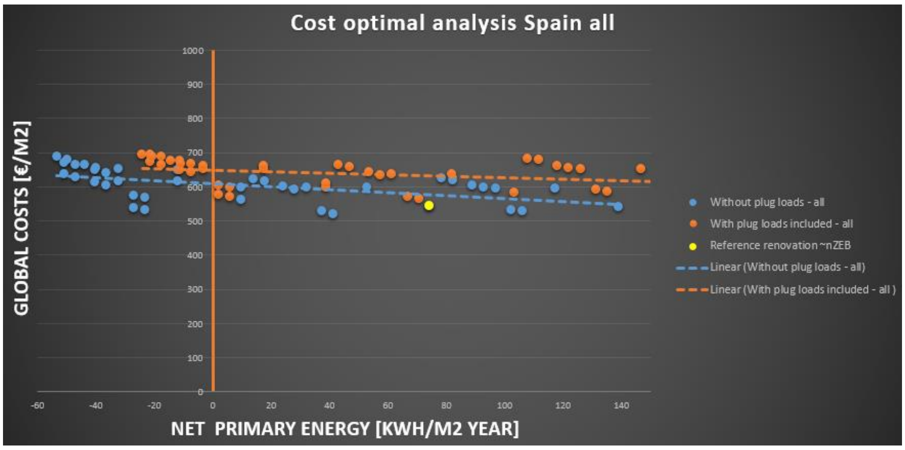

Figure 4: Graphical representation of the main results deriving from an application of the cost-optimality approach applied to different energy technology packages for the achievement of the PEB target. Example for the EXCESS Spanish pilot case (Mayer et. at., 2023).

The figure above shows that a PEB can be reached with only minor increase of global costs. This is caused by the high solar radiation in Spain, and the limited number of apartments in the 3-storey building.

Another case study is the Finnish case study of EXCESS, a Positive Energy Building constituted by 8 floors and located at Kalasatama district, in the city of Helsinki. The city centre is typically equipped with a District Heating (DH) network and buildings are a mixture of residential and commercial buildings. The pilot building has 51 apartments and a total heated area of around 4000 m^2. The energy system in place for the Kalasatama PEB is a hybrid geothermal energy system. It combines semi-deep geothermal energy wells with collectors in ~ 600-meter-deep boreholes, a 67kW multisource heat pump, building integrated PV panels (87 kWp) and solar thermal PVT (79 kWp) that will produce electricity and heat for the building and recharge the bedrock. The heat pump needs to be compatible with multiple primary sources (ground and solar sources) and multiple operating modes (active heating and cooling). To increase temperature levels to a suitable level for space heating and domestic hot water, the hybrid energy system utilises heat from the PVT panels, ventilation and ground source heat with heat pumps. The building structure, heating, ventilation and air conditioning is designed as energy efficient as possible. To optimise the overall energy system performance, an integrated smart control system enables demand response and two direction electricity trade. Figure 5 illustrates the net primary energy demand and global cost of all technology packages with and without plug loads. For the Finnish pilot case, plug loads of only 12.7 kWh/(m^2 y) are assumed. It can be seen that there are no technology packages with a net primary energy demand below 0. This means that there are no technology packages which could lead to a PEB solution. One central reason is the shape of the building. The building has 8 floors but only a small built surface area and therefore reduced possibilities for renewable energy generation with PV or PVT facilities. Another reason is the rather cold climate that leads to a relatively high energy demand for space heating compared to other geographical areas in the European Union.

Figure 5 also shows the difference between a standard renovation according to the nZEB standard (in yellow) and an energy renovation scenario according to the PEB standard. It can be seen that global costs increase with a reduction of net primary energy demand (from nZEB to PEB). In the Finnish case a PEB level can be achieves only with a significant increase of global costs, as the building is high and has many apartments, solar irradiation in Finland is low, while the heat demand high is (Mayer et al. 2023).

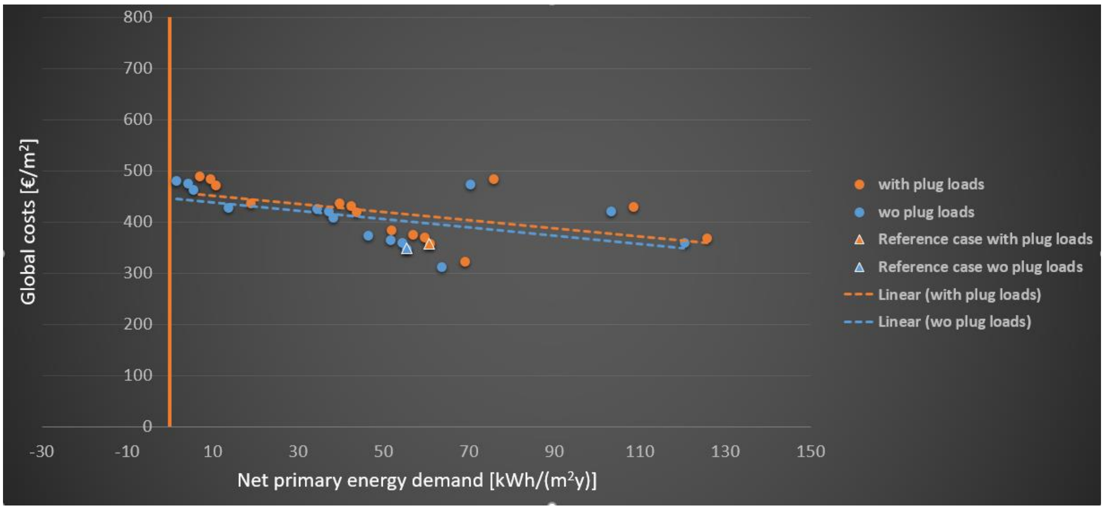

Figure 5: Cost optimal analysis Finland – all technology packages

Comparing the two cases shows that global costs for reaching a PEB not only depend on the technologies, but also the building shape, the type of users and the climate zone.

2.3.2 Flexibility revenues of PEBs: A case study

The Austrian EXCESS case study is located in the "Tagger-Werk", a former industrial area in the south of Graz, the second-largest city in Austria. The EXCESS demo case, a former feed production silo, is part of a 19-building-strong complex with about 31.000 m² gross floor area, shown in Figure 6. Upon completion, the EXCESS positive energy silo will become an office building.

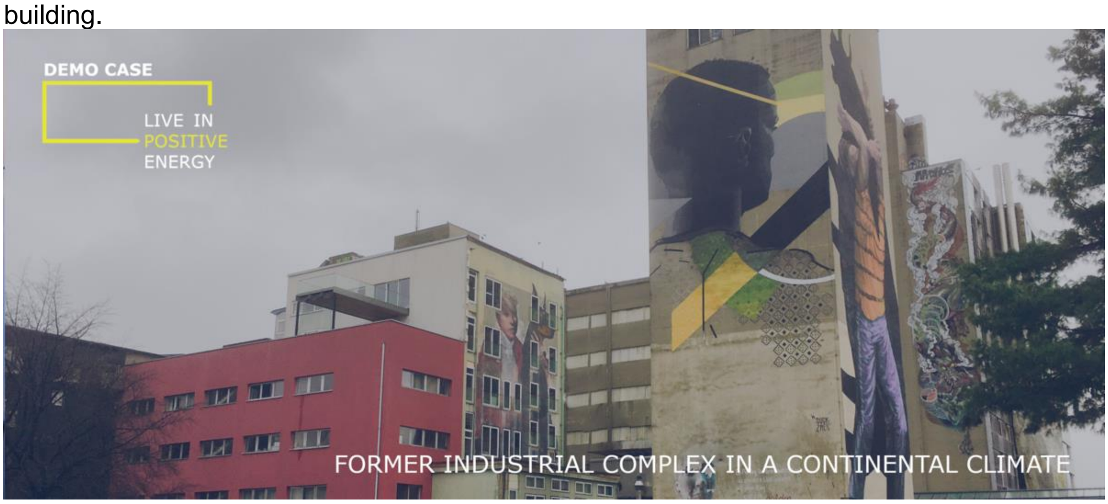

Figure 6: Case-study Austria – PEB as a former industrial building

A positive energy house standard will be achieved by activating the existing thermal mass of the building structure via pre-fabricated multifunctional facade elements including integrated PVs to supply the heat, cold and electricity demand of the building. The building will be heated with a groundwater heat pump. A battery will be installed to increase the self-consumption rate. The flexibility revenue simulation in this report considers one technology set-up with a battery and one without showing the impact of energy storage. The building's electricity consumption (flexible and non-flexible loads) and the expected PV generation profile were simulated with the building simulation software TRNSYS. Figure 7 shows the building's energy demand and generation for one year without any optimisation. It can be seen that there is high PV generation compared to electricity demand which is a typical characteristic of a PEB as the yearly energy balance of PEBs must be positive. The Figure also shows that there is a high flexible energy demand in winter as well as in summer which comes from heating and cooling with a controllable groundwater heat pump (Mayer et al.,2024).

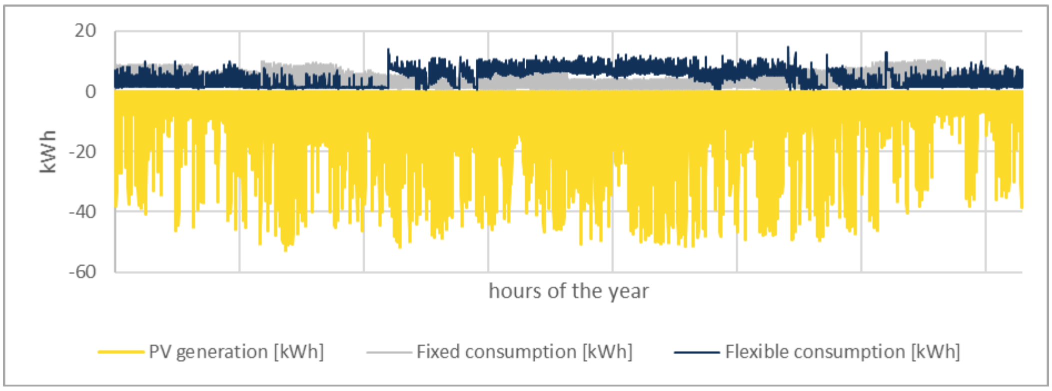

Figure 7: Electricity demand and PV generation of demo case Austria

Table 4 shows the main assumptions and parameters for the simulation. The flexible electricity tariffs are based on the EPEX spot market electricity prices from the year 2023 and typical values for service fee and grid fee. Fixed electricity tariff and electricity feed-in tariff were defined based on the market price level of 2023. The maximum shift of the heat pump was assumed to be 12 hours (Mayer et al.,2024).

Table 4: Assumptions and calculation parameters Austria

Data	Values / assumptions
Flexible electricity tariff (incl. grid fee)	EPEX spot 2023 + 0.015 € service fee + grid fee (0.09 €/kWh) + 20% VAT
Fixed electricity tariff (incl. grid fee)	0.25 € (incl. grid fee and VAT)
Revenues for surplus feed-in	0.08 €/kWh
Max shift of flexible load (heat pump)	12 hours
Battery	60 kWh /60 kW Charging eff: 0.95; Discharging eff: 0.95 Charging max in low price hours: 60% Charge < 0.14 €/kWh; Discharge >0.18 €/kWh

Table 4 shows the building's input data (demand and supply) and the results of the optimisation model for all simulated use cases. It can be seen that the building shows an almost positive yearly energy balance as the total yearly onsite PV generation is similar to the total yearly energy demand of the building. The reference case without optimisation leads to overall yearly electricity costs of 7,488 €/year with a fixed electricity tariff and 7,884 €/year with a flexible electricity tariff (without optimisation). (Mayer et al. 2024)
The optimisation of the PV self-consumption rate without a battery through the shift of the heat pump reduces electricity costs by around 32% to 5,063 €/year. The reason is that the electricity feed-in tariff is lower than the electricity purchasing price. With a battery, the self-consumption rate could be further increased and as a result electricity costs are reduced to 2,993 €/year. However, it has to be mentioned that the investment costs of the battery were not considered in our analysis. To calculate the profitability of the battery, energy cost savings

must be compared with investment costs and yearly depreciation of the battery (Mayer et al.,2024). UC2 assumes a flexible electricity tariff and optimises for the overall lowest costs based on current PV production and DAM prices. The data shows that in almost all hours of the year, it is more profitable to optimise the self-consumption of the PV compared to an optimisation according to Day-Ahead Market (DAM) prices. Only in those times where the electricity DAM price including grid fees is lower than the electricity feed-in tariff, it would make sense to prefer grid consumption to self-consumption. Therefore, the model optimises first for self-consumption and in a second step according to the DAM prices. Load shifting according to DAM prices is more relevant in winter, when not enough PV is available. The results of UC2 show that overall electricity costs could be reduced by around 32% through optimisation with DAM prices. The usage of a battery storage could further decrease electricity costs, similar to UC1. Typically DAM price optimisation is more relevant for buildings without PV. The more PV is installed, the less important DAM optimisation is as PV self-consumption is typically more profitable. This is also reflected in the results of UC2. Figure 8 graphically shows the simulation results of the Austrian case study.

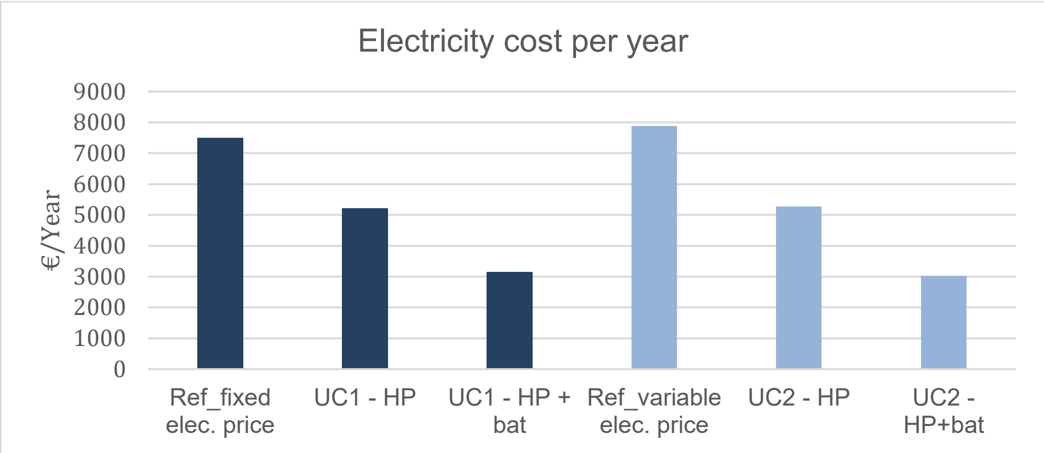

Figure 8: Simulation results – Electricity (Mayer et al.,2024).

As EXCESS showed in comparing the pilots, flexibility revenues depend on a variety of factors, next to the assumptions on revenues and technologies also on the type of building in particular the buildings thermal mass. While older buildings often have a higher thermal mass due to thicker walls, they may be less suited to implement new technologies.

2.3.3 Key insights of the case studies

As the cases above show economic KPIs depend on a variety of factors that will also determine the replicability of the PEB and PED concepts. Next to economic assumption of cost and revenues the economics of PEB technologies are highly influenced by the climate zone in which they are implemented. For example, different applications of PVT panels are more suitable for southern, central, or northern European regions, depending on local temperature ranges and solar irradiation levels. Also building types, ages, and users determine PEB achievement and related costs. Low-storey buildings with a big roof size for PV or PVT installation, could achieve PEB-level much easier than multi-storey buildings with limited roof size.

While the development of technology costs can be forecasted, revenues from monetising flexibilities are harder to quantify, as flexibility markets for small and decentralised assets are only emerging.

Authors

Andreas Tuerk, Joanneum Research, Austria (andreas.tuerk@joanneum.at)
Clemens Mayer Joanneum Research, Austria (Clemens.Mayer@joanneum.at)

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3. Environmental impact assessment of Positive Energy Districts

3.1 State-of-the-art of PED environmental assessment

Positive Energy Districts are a promising pathway to enhance the sustainability of cities by ensuring that districts generate more energy than they consume through efficient design, renewable energy integration and community engagement.

Traditional energy assessments often focus on operational efficiency while neglecting broader environmental impacts, such as embodied emissions, land use and urban metabolism. However, as also recommended in the literature, a comprehensive evaluation of both direct and indirect environmental consequences across the entire lifecycle of a district is necessary to implement a proper conducted environmental impact assessment. The literature review here conducted is based on the work of (Volpe et al., 2025), developed within the activities of the Annex 83, and examines the extent to which environmental impact assessment methodologies are currently integrated into PED planning and monitoring, while also discussing the existing gaps and proposing pathways for a standardised methodology that accounts for the unique features of PEDs.

3.1.1 Review methodology and theoretical framework

The literature review here presented used the Scopus database to identify and classify relevant academic publications. In particular, three successive query strings were used to capture the existing research on zero-energy districts, sustainability, and environmental evaluation. These query strings are: 1) (zero AND energy AND districts); 2) (zero AND energy AND neighbourhood); and 3) (“Positive energy district" OR "Zero energy district" OR "solar districts" OR "smart district") AND ("Environmental" OR "sustainability"). The final refined query yielded 144 documents, with a significant increase in relevant publications observed after 2016, suggesting a growing academic interest in the field (Burnham, 2006). In addition to this search, a keyword co-occurrence analysis was performed to map emerging research trends. Central themes included “zero energy buildings”, “energy efficiency”, and “sustainable development”, with notable cluster forming around the words “life cycle assessment”, “LCA”, “urban sustainability”. However, it has been noted that the term “Positive Energy District” remained relatively underrepresented in keyword networks, reflecting its status as an emerging but underdeveloped research domain (Volpe et al., 2025). The theoretical analysis also highlighted a diversification in terms of the main methods adopted to conduct an environmental impact assessment. On one side, some literature prefers to apply operational-phase methods, which evaluates districts based on real-time energy use, emissions, and system performances. On the other side, lifecycle-oriented approaches are also implemented, i.e. including all stages from design to construction and decommissioning. This dual perspective is critical, as having a narrow focus only on operational metrics can overlook long-term impacts, such as those associated with construction materials or demolition waste (Guarino et al., 2020).

In addition to LCA, other methodologies, such as Multi-Criteria Decision-Analysis (MCDA) and urban sustainability certification schemes were also examined. These contribute valuable tools for stakeholder engagement and scenario evaluation but often lack the depth required for rigorous environmental impact quantification (Becchio et al., 2018). A way to benefit from these approaches is to have them in combination with other strategies, tools and frameworks to support evidence-based decision-making and foster replicability across projects and urban contexts. MCDA, however, is also implemented to evaluate alternatives based on a range of environmental, economic and social indicators, or to find trade-offs between competing objectives (Bottero et al., 2015).

Regarding the environmental impact assessment of PEDs, it can be observed that diverse methodologies have been developed in the literature. The most prevalent is the LCA, which evaluates the environmental impacts across the entire lifespan of a PED, from raw material extraction to demolition (ISO 14044, 2006). LCA is particularly relevant for PEDs because it accounts for embodied energy and emissions, which are often neglected in operational analyses. Several studies have then extended the LCA to include multiple urban components, such as mobility, energy infrastructure and public spaces (Lausselet, et al., 2020). However, due to the high level of rigor, the implementation of LCA at the district level is challenged by data availability, system boundary complexity as well as the difficulties in properly selecting the functional units (e.g., per square meter, per inhabitant).

To complement LCA, simulation models are often introduced in the literature. These can range from EnergyPlus to CFD tools to predict energy demands, thermal comfort or also urban microclimates under various scenarios. In addition, these models can be effectively used in the early design stages of PEDs. However, although highly detailed, these tools are based on initial assumptions that are highly dependent on specific case studies, thus posing some difficulties in their predictive validity and general replicability without a certain degree of adjustment (Crawley et al., 2000).

Approaches can also be divided into bottom-up, i.e. from the individual simulations, and top-down, i.e. from aggregated data, methods for PED modelling. Hybrid approaches combining Geographic Information Systems (GIS) with simulations are also available as they offer a powerful tool for spatially explicit analyses (Mastrucci et al., 2020).

Another relevant layer involves sustainability certification schemes such as LEED for neighbourhood development, BREEAM communities, and DGNB for districts. These frameworks promote best practices and offer benchmarks, though their applicability to PEDs remains limited due to a predominant focus on environmental aspects without a fully coverage of systemic urban dynamics (Sharifi et al., 2021).

Despite their strengths, these methodologies often operate in silos. Therefore, there is the need for a synergistic framework integrating all these tools, methods and schemes into a cohesive process tailored to PEDs.

3.1.2 Key Performance Indicators for PEDs

To monitor the effectiveness of PEDs in achieving sustainability goals, the use of Key Performance Indicators (KPIs) is fundamental. The literature identifies nine macro-areas for KPI application:

- Climate change, with indicators that include greenhouse gas emissions, urban air quality, and temperature regulation (Walker et al., 2018);
- Renewable energy production, for tracking the proportion of energy demands met through renewables and assessing the density and integration of these sources within the district (Volpe et al., 2022)
- Final energy consumption, disaggregated by sector (i.e. including residential, industrial, commercial profiles) for determining energy efficiency at different scales;
- Energy intensity, a metric that relates energy usage to economic activity, typically expressed in energy per GDP unit (Lauseelet et al., 2020);
- Energy autonomy, with KPIs assessing the level of local generation and self-consumption, a defining characteristic of PEDs (Fichera et al. 2020);
- Transport-related emissions, derived from mobility patterns and modal shares, these indicators extend sustainability assessments beyond buildings (Nematchoua et al., 2018);
- Municipal waste and recycling, quantified by recovery and recycling rates and reflecting circular economy efforts;
- Health impacts, with KPIs including toxicity measures and exposure indicators, especially relevant in dense urban areas (Guarino et al., 2020);
- Land and water use, covering biodiversity, soil exploitation, and water scarcity (Xia et al., 2021).

These KPIs are not standalone metrics. They are deeply interrelated and are often used as input for decision support systems. In addition, it is also important to align PED KPIs with the UN Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) (Cellura et al., 2022).

Finally, also international standards, such as ISO 37120 and ISO 37123, which provide guidance for the development and benchmarking of urban indicators should be considered in the analysis and for KPIs definition.

3.1.3 Comparative results, limitations and conclusions

In the paper of (Volpe et al., 2025), published as a result of the investigation of this Section, 22 PED-related case studies applying LCA techniques have been compared. The comparison has been framed using multiple functional units, including total district emissions, emissions per inhabitant, per square meter of the districts, and per square meter of heated floor area. This is essential for understanding how boundaries and assumptions influence environmental outcomes.

The Global Warming Potential (GWP) among the reviewed districts varies widely, from 105 tons CO_2eq/year to over 5400 tons CO_2eq/year. Likewise, the Gross Energy Requirement (GER) spans a range of 5 to 560 terajoule/year. Such variability underscores the importance of clearly defining analytical boundaries, especially when comparing geographically, climatically, or functionally diverse urban areas (Riera Perez et al., 2013).

From the comparison, moreover, buildings emerged as the main contributors to GHG emissions, followed by transportation systems. Infrastructure such as open spaces and energy systems showed less impact. However, despite having a moderate impact, it is important to not overlook these components, in particular considering that PEDs may evolve to include integrated systems such as district heating, storage in a shared configuration, as well as electric mobility infrastructure (Lotteau et al., 2015).

A major insight from the comparative review is the disparity in methodology across studies. As it emerged, the inconsistency in system boundaries, emission factors, and functional units of the different papers of the literature makes it difficult to generalise any results or derive standardised benchmarks. For example, some studies adopt static grid emission factors, while other model time-varying dynamics of renewable integration (Hachem-Vermette et al., 2019).

To address these inconsistencies, the results of this literature review converge to a standardised roadmap for PED environmental assessments. This includes:

- Clear definition of the functional units based on the objective of the study;
- Transparent reporting of system boundaries and included lifecycle stages;
- Harmonisation of impact categories (GWP, acidification, ozone depletion, etc.);
- Adoption of dynamic LCA and scenario modelling to account for temporal evolution and technology shifts.

Of course, having a standardised roadmap does not imply rigidity. On the contrary, flexible methodological templates are able to ensure contextual adaptation while ensuring minimum comparability standards across projects.

PED evaluation has to embrace an interdisciplinary integration of environmental science, urban planning, energy system engineering and social innovation. Any framework for the impact assessment should not only account for carbon neutrality, but also address cross-sectoral impacts, reinforcing the broader role of PEDs in fostering sustainable and resilient cities.

Authors

Rosaria Volpe, University of Catania, Italy, (rosaria.volpe@unict.it)
Adriano Bisello, Institute for Renewable Energy, Eurac Research, Italy (adriano.bisello@eurac.edu)
Andreas Tuerk, Joanneum Research, LIFE – Institute for Climate, Energy Systems and Socie-ty, Austria (andreas.tuerk@joanneum.at)
Francesco Guarino, University of Palermo, Italy, (francesco.guarino@unipa.it)
Emanuela Giancola, CIEMAT, Department of Energy, Spain
Maria Nuria Sanchez, CIEMAT, Department of Energy, Spain
Giovanni Tumminia, CNR, Consiglio Nazionale delle Ricerche, Italy
Elisa Marrasso, University of Sannio, Italy (marrasso@unisannio.it)
Giovanna Pallotta, University of Sannio, Italy (giopallotta@unisannio.it)
Emanuele Cutore, University of Catania, Italy
Maurizio Cellura, University of Palermo, Italy (maurizio.cellura@unipa.it)
Alberto Fichera, University of Catania, Italy (alberto.fichera@unict.it)
Sonia Longo, University of Palermo, Italy (sonia.longo@unipa.it)
Carlo Roselli, University of Sannio, Italy (croselli@unisannio.it)
Maurizio Sasso, University of Sannio, Italy (sasso@unisannio.it)
Xiaojin Zhang, Institute of Construction and Infrastructure Management, ETH, Switzerland
Ilaria Marotta, National Research Council of Italy - CNR (ilaria.marotta@cnr.it)
Alberto Brunetti, University of Palermo, Italy (alberto.brunetti@unipa.it)
Roberta Rincione, University of Palermo, Italy (roberta.rincione@unipa.it)
Francesco Reda, Teknologian Tutkimuskeskus VTT, Finland

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3.2 Methodological framework for environmental impact assessment

3.2.1 Research question motivating the study

The primary aim of this research is to establish a framework for conducting the Environmental Impact Assessment of Positive Energy Districts (EIA-PED). Typically, an EIA involves evaluating the environmental performance of a system, aligning with the system's function and environmental objectives (Janseens et al., 2017). A framework refers to a set of structured guidelines aimed at achieving a specific objective. Thus, in the context of this study, the presented EIA-PED framework is designed to offer a systematic approach for estimating the potential environmental impacts and benefits associated with PEDs, and contributing to support any action focusing on the effective mitigation of the environmental consequences associated with human activities and urban areas. This framework should guide all stages of PED development, encompassing design, implementation, operation and management. For instance, during the design phase, it should provide insights into relative contributions of various urban systems across all life cycle stages to a diverse range of environmental impacts. It should also facilitate comparisons between design alternatives, identify areas of concern and trade-offs, and address the potential influence of user behaviours on environmental impacts. During the implementation stage, the framework should aid in monitoring environmental performance and provide valuable insights for managing energy flows within and across the PED boundaries, ensuring effective mitigation of environmental impacts. Lastly, the framework can serve as a benchmark for evaluating the environmental performance of a PED, allowing comparisons with other districts. This offers insights for replication and assists stakeholders in applying adequate metrics for environmental impact assessment.

Under these premises, the EIA-PED framework proposed in this study encompasses practical guidelines for stakeholders engaged in decision-making processes or addressing environmental impact of PEDs. These guidelines enable cross-comparisons with other cases and provide a shared foundation for interpretation and ex-post evaluation of the results.

The process of defining a framework aimed at achieving a specific goal does not necessarily need to adhere to existing approaches, methodologies or methods. Instead, it can be crafted in a direction perceived as reliable and effective for the investigation. The proposed EIA-PEDs framework, here outlined, is structured as a series of steps organised into: (i) the research question driving the study, (ii) the chosen methodological approach and modelling considerations; (iii) the tools and strategies for data collection; (iv) benchmarking and comparisons for the purpose of communication and replication, as depicted in Figure 9.

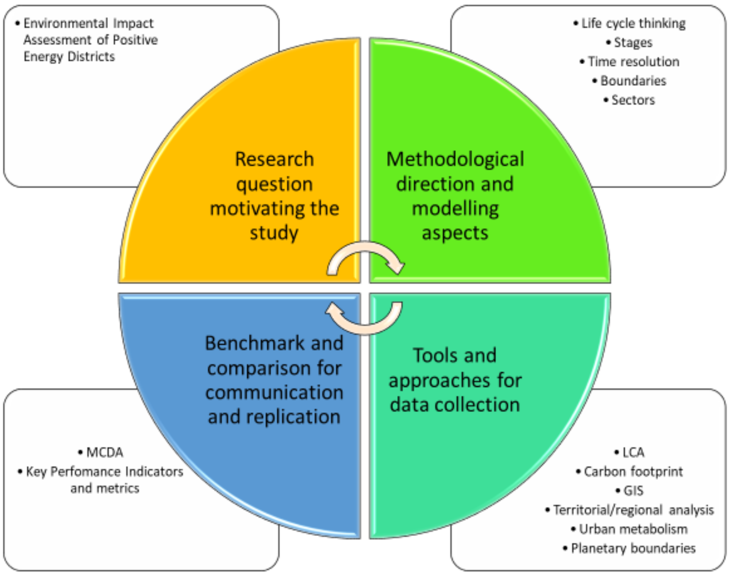

Figure 9: Overview of the EIA-PEDs framework

The central research question guiding this framework pertains to targeting the environmental impact assessment (EIA) of PEDs. With the primary objective of the framework established, the subsequent critical step involves selecting the methodology around which the framework will be structured. In this study, the Life Cycle Thinking perspective has been adopted due to its proven effectiveness in estimating the environmental impacts of processes, products, services or systems. The subsequent phase entails evaluating tools and approaches, a stage of particular significance that informs and drives the analysis within the framework. Given the data-intensive nature of EIA-PEDs, which also vary across different typologies of PEDs, diverse reliable methods are available for data collection. Subsequently, the impact assessment can be conducted using purpose-built indicators, strategically crafted to enable cross-comparisons, replication, and effective communication among stakeholders. The final link in the chain involves connecting metrics and objectives to interpret the results.
The depiction in Figure 9 highlights that the EIA-PEDs framework encompasses multiple distinct steps. These steps can be interconnected to complement each other or selected alternatively, contingent on the unique characteristics of the conducted environmental impact assessment.

3.2.2 Methodological and modelling aspects

The EIA-PEDs framework is established within the life cycle thinking methodology. To effectively conduct an EIA, various aspects should be considered. These aspects encompass geographical boundaries, time horizon, time resolution, and sectors, all of which are elaborated upon in the subsequent sections.
Geographical boundaries for PEDs can be selected from various options based on their definitions, significantly influencing the energy flow balance considered in environmental impact assessments.

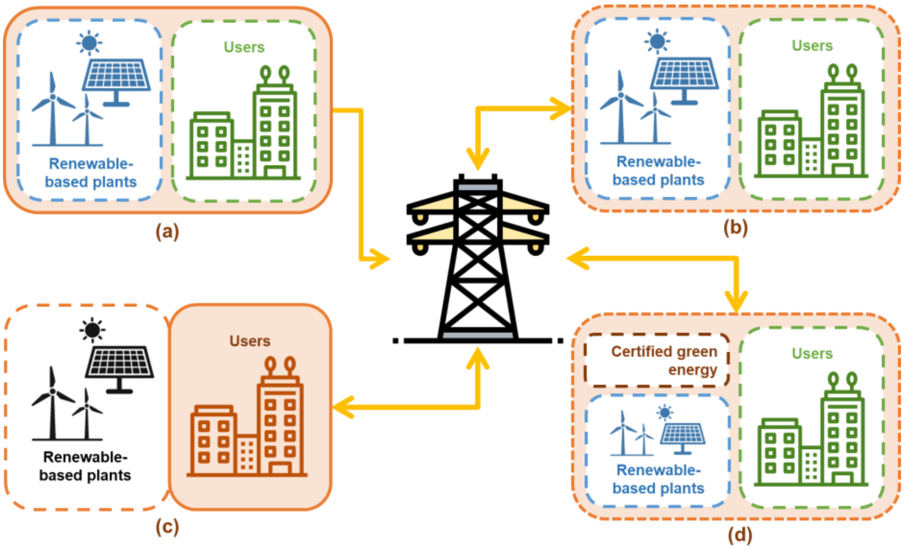

Figure 10: Layout of (a) autonomous, (b) dynamic, (c) virtual and (d) candidate PED.

Figure 10 illustrates four types of PEDs outlined in the literature: autonomous, dynamic, virtual and candidate (Salome et al., 2021). Autonomous, dynamic, and virtual PEDs all exhibit a net positive annual energy balance. The autonomous PED features clearly define geographical boundaries and is fully energy self-sufficient by utilising renewable-based plants located within its boundaries. While energy imports are not allowed, any energy surplus can be exported to other PEDs or to external grids. Conversely, the dynamic PED can interact bi-directionally with other PEDs, external power grids and district heating/cooling networks. It retains well-defined geographical boundaries, unlike the virtual PED, which allows the installation of renewable-based plants and energy storage systems outside of its boundaries. Lastly, the candidate PED lacks a net positive annual energy balance within its geographical boundaries, compensating for energy deficits through the import of certified green energy. The dynamic PED configuration is often recommended as it emphasised both renewable energy production and energy efficiency within geographical boundaries. It offers more flexibility in the design, implementation, and operational, making it economically advantageous. In contrast, implementing autonomous configurations can be challenging due to space limitations, high energy demand, or budget constraints (Laitinen et al., 2021). While autonomous configurations might be considered a reliable option for islands, with difficult access to centralised power grids, the JPI Urban Europe (JPI, 2020) stresses that energy autonomy should not be the sole aim it compromises cost efficiency, affordability and system flexibility. The virtual PED might be the most suitable configuration for dense urban districts, characterised by limited space for installing renewable production plants and realising the dedicated distribution infrastructure. But this concept requires careful evaluation to avoid "green washing" or potential accounting tricks. The key evaluation criteria of whether an urban district can be considered as a virtual PED lies in the additionality of renewable energy production. For example, buying enough renewable electricity certificates to meet and surpass the electricity demand of the district is not sufficient to claim that an urban district is a virtual PED; indeed, the investment made to acquire renewable energy has to be associated with additional installed renewable production systems. On the contrary, virtual PEDs may account on procurement schemes such as power purchase agreements or direct ownership of new installed renewable production facilities, even if outside of its geographical boundary. Furthermore, the choice of PED configuration also depends on whether the district is new or existing. For new districts, all three concepts - autonomous, dynamic, virtual – can apply depending on context. For existing districts, virtual PED is the minimum requirement.

In existing PED projects, environmental impact assessments are commonly conducted on an annual basis (Bastos et al., 2023). The approach involves assessing the annual environmental impacts of specific elements (such as buildings, vehicles, etc.), multiplying them by their lifespan, and subsequently calculating the total impacts or greenhouse gas emissions savings over the PED's lifetime. This annual assessment reflects the current PED performance but may overlook future system transitions, such as the gradual decarbonisation of the energy systems. Although it may appear less significant, this consideration becomes crucial due to factors like the finite lifespan of a certain renewable energy systems, for instance, solar photovoltaics with a lifespan of around 35 years. This lifespan is often shorter than that of buildings and other facilities, necessitating renovations or replacement during the PED's existence. If the energy systems accessible to PEDs, even outside their boundaries, achieve complete decarbonisation when replacements occur in the future, the obligatory installation of renewable energy production facilities within the PED's boundary could become unnecessary. This, in turn, affects material production required for future building and facility renovations. Therefore, it is advisable that the time horizon selected for the EIA-PEDs spans multiple decades to account for potential future changes. Regarding time resolution for assessments, as on-site renewable energy production and storage are integral to PED configurations, adopting a relatively short time resolution is crucial. This allows the integration of key time-dependent factors like weather, electricity tariffs, and the electricity supply mix. In this context, hourly resolution is recommended as the minimum requirement for accurate evaluation.

Sectors encompassed within the EIA-PEDs framework primarily include buildings, on-site renewable production and storage systems, energy and water networks (including sensors and management systems), urban transportation (mobility) and open space. Buildings and their components have often been the central focus of environmental sustainability research due to their significant contributions to energy requirements and environmental impacts in urban areas. While buildings and energy systems are immediately integrated into most analyses, water, open space and mobility are frequently considered within specific contexts and objectives. Urban mobility, both private and public, significantly contributes to environmental impacts. It exhibits substantial non-renewable energy demands, fossil fuel dependence, greenhouse gas emissions, and traffic-related air pollution with associated public health effects. However, integrating mobility into the EIA-PEDs framework poses challenges and entails subjective choices. First, the selection of the system boundary for modelling mobility requirements and impacts can be complex. Clarity is required on whether the assessment solely includes operational impacts or also encompasses embodied impacts like those linked to vehicle manufacturing, even though they are not directly influenced by district-scale decisions or features. Another point of discussion revolves around the consideration of the requirements and impacts, such as whether the mobility of PED residents or vehicles traveling to/from the PED, like commuters, should be factored into the EIA. It's worth noting that when the energy consumption of the mobility sector is included,

achieving a positive energy balance becomes more challenging or even impossible for certain districts.
The inclusion of open space depends on the addressed performance indicators. For instance, if evaluating urban heat islands effects, green infrastructure within open spaces is generally integrated. However, in cases where the EIA-PEDs framework concentrates on energy requirements and GHG emissions, open space is often excluded from the model due to its assumed low relative contribution to the outcomes.

3.2.3 Tools, approaches and data collection

- **Operational stage carbon footprint**

One approach to account for GHG emissions (such as CO_2 and/or CO_2eq) associated with energy supply and demand in PEDs operational stage is to adapt the Baseline Emission Inventory (BEI) framework, originally introduced by the Covenant of Mayors for Climate & Energy. The BEI's purpose is to quantify GHG emissions in a baseline year, providing a reference value for subsequent years as part of the implementation of the Sustainable Energy and Climate Action Plan developed by local authorities. This approach enables the assessment of the plan's effectiveness in reducing emissions and allows for adjustments as needed. The following sections detail methods useful for compiling emission inventories at the PED level, beginning with data collection and the selection of emission factors (EFs), and then delving into the quantification of energy requirements and related emissions.

- **Activity-based data collection**

The BEI primarily focuses on supporting local authorities when dealing with the energy sector. To enhance data disaggregation and inventory precision, the energy sector can be further divided into subcategories:
- residential buildings, which includes all CO_2 (or CO_2eq) emissions resulting from operational energy usage in households;
- tertiary buildings, equipment, and facilities. This subcategory encompasses CO_2 (or CO_2eq) emissions from energy usage in commercial and public buildings (such as schools, hospitals, etc.) and facilities within the authority's jurisdiction. Facilities not meant for energy provision (e.g., wastewater treatment plants) fall within this category. Otherwise, they are categorised as energy production plants;
- public lighting;
- road transportation (within the authority's jurisdiction);
- urban rail transportation (within the authority's jurisdiction).

While the energy sector holds relevance for PEDs, the emission inventory here discussed energy demands linked to road and urban rail transportation. As a rule, for district-level analyses, it is pertinent to work with relevant data, excluding national average values that may not align with the district's specific characteristics. The methodology adopted for gathering the required data must be consistent, accurate and based on reliable sources. The data about final energy consumptions can be acquired from energy suppliers and grid operators or simulated through energy systems' modelling software with high temporal accuracy.

- **Emission factors' choice**

Obtaining the final emissions estimate requires the selection of appropriate emission factors (EFs) in line with the recommendations from internationally recognised organisations, such as the Intergovernmental Panel on Climate Change (IPCC, 2022). Broadly, EFs fall into two main categories: activity-based and life cycle-based. Activity-based EFs rely on the carbon content of fuel and quantify the direct emissions from combustion plants used for electric, thermal or cooling energy supply. Life cycle-based EFs encompass emissions throughout an energy carrier's entire life cycle, including those from its supply chain. The choice between activity-based and life cycle-based depends on their distinct goals. The activity-based approach aligns with IPCC principles, making it suitable for national GHG inventories under the UNFCCC and Kyoto Protocol (UNFCC, 1997). It also fits within the European regulatory framework for climate and energy. Conversely, the life cycle-based approach is well-suited for evaluating trade-offs across various environmental impact analyses and complies with European Directives 2009/125/EC and 2010/30/EU.

• **Emission inventory development**

As shown in Figure 9, a generic district is characterised by electric, thermal and cooling energy demands, pertaining to residential and/or tertiary buildings as well as facilities within the districts. The thermal (TP), cooling (CP) and electric (EP) energy production plants can be located within or outside of the district, but in the latter case, only when activated by renewable energy sources (RESs). Hereinafter, the notations PED, NL (standing for non-local) and US are utilised throughout this work to differentiate between plants (TP, CPs or EPs) within the PED boundaries, those outside the boundaries and user-owned facilities, respectively.

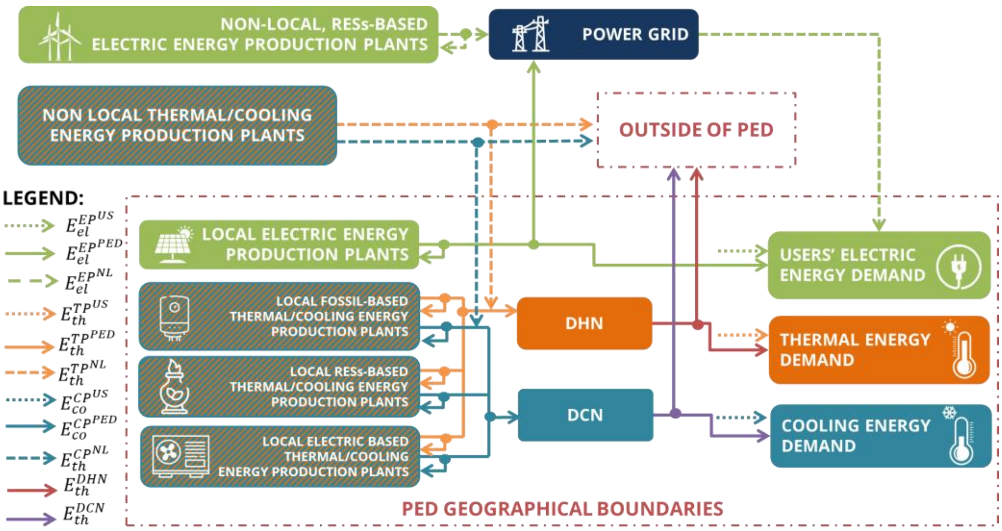

Figure 11: Schematic overview on energy flows in PEDs

The explanation of the energy flows of Figure 11 is presented in Appendix 1.

3.2.4 Tools and approaches for data collection

The Life Cycle (LC) stages are outlined in EN15804, which include the material product phase (A1-A3), construction phase (A4-A5), use phase (B1-B7), and end-of-life disposal and treatment (C1-C4) (as depicted in Figure 12). An additional section, D, accounts for benefits and loads beyond the system boundary. The incorporation of a life cycle perspective is crucial within the framework to offer a comprehensive and holistic EIA. This approach helps prevent potential burden shifting across stages while guiding the design, implementation, and management of PEDs. In certain cases, concentrating on specific LC stages can yield insightful yet partial environmental performance data for a PED (e.g., focusing on operational-phase carbon footprint accounting often centers on energy consumption during the use phase, B6), thus requiring fewer data and modelling resources. Ensuring transparency regarding the included LC stages is essential, along with maintaining consistency in the terminology and definition of these stages (clarifying what is encompassed and assumed).

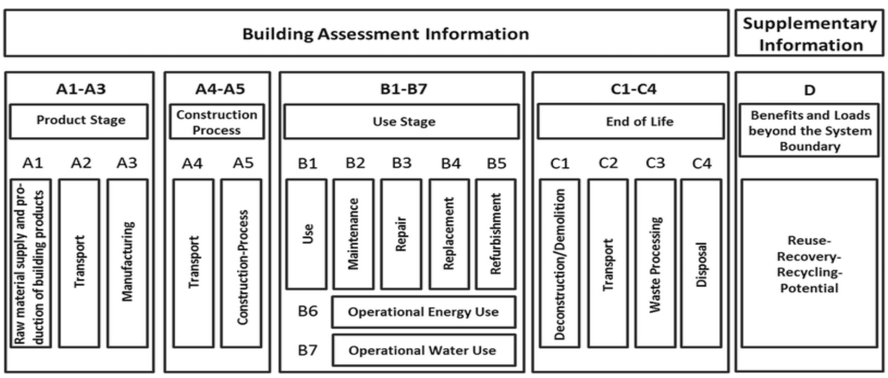

Figure 12: Life cycle stages of a building defined in EN15804

Life Cycle Assessment (LCA) is an internationally standardised methodology USED to estimate potential environmental impacts associated with a product, system or service, from cradle-to-grave, i.e., from raw material extraction, to manufacture, transport, use and end-of-life (Guinée, 2001). LCA provides a holistic, systematic, and detailed calculation of potential environmental impacts, including both upstream and downstream processes and a wide range of environmental factors. This approach helps prevent unforeseen and undesirable consequences and trade-offs. LCA can provide a holistic approach in the assessment of urban areas by quantifying resources and environmental impacts beyond geographical boundaries and considering a comprehensive life cycle perspective, all while maintaining consistent and comparable metrics. LCA entails four essential stages: goal and scoping, inventory analysis, impact assessment, and interpretation. Scoping defines study purpose, system boundaries, and functional units, while inventory analysis quantifies inputs and outputs across the product's life cycle.

When performing LCA for a PED, several choices for functional units are available. The functional units applied can be categorised into three groups:

- environmental impact per unit area, with variations in the type of area used, such as living floor area, heated floor area (or gross floor area, including unheated areas);
- environmental impact per capita;
- environmental impacts for the whole district.

(Lausselet et al. 2019) indicated that the choice of functional unit can significantly influence the results and conclusions of the assessment. It is recommended to use environmental impacts for the entire district as the primary functional unit, and environmental impacts per capita as the complementary functional unit for reference. The study highlights that using environmental impacts per unit floor area could be misleading, as it fails to account for compact design with less built area. Conversely, in a compactly designed district, the smaller area may yield relatively high environmental impacts per unit of built area. Another limitation of using functional units per area is that it overlooks the specific use of the area, potentially leading to unfair comparisons among districts with different usage compositions (e.g., residential vs. business/industrial district).

The extensive effort required for data collection and issues related to data availability often pose obstacles to the widespread application of Life Cycle Assessment (LCA) at the district level. The data necessary for conducting an LCA for a district varies based on the sectors encompassed within the system boundary. Typically, it includes data concerning building envelopes, onsite energy generation technologies (such as solar photovoltaics, electricity and heat storage devices like batteries and thermal energy storage units), networks, and sometimes the mobility sector (including vehicles, their operation, and public transport) as well as open spaces (like street lights). For building LCA and onsite energy technologies, especially solar photovoltaics, national databases and sometimes supplier-specific Environmental Product Declaration (EPD) reports are available. These EPD reports include specific Life Cycle Impact Assessment (LCIA) results comprising 13 environmental impact categories reported over 12 stages, as defined in EN 15804:2012+A2:2019.

While the application of LCA to urban areas and systems has been on the rise, there is still room for enhancing its implementation in evaluating the environmental performance of Positive Energy Districts (PEDs). There's a need for well-structured life cycle-based frameworks that include appropriate data and metrics, designed specifically to support the design, development, and implementation of PEDs. These frameworks should focus on capitalising on the opportunities they offer, such as reducing operational energy requirements and increasing the share of renewable energy sources. Additionally, these frameworks should address the distinct challenges and risks posed by PEDs, including the potential burdens and risks associated with additional electricity generation infrastructure and Information and Communication Technology (ICT) solutions, like critical raw material requirements.

3.2.5 Benchmark and comparison for replication and communication

Positive Energy Districts (PEDs) represent multi-dimensional, thus complex, systems since they comprise different energy vectors, materials and management practices, e.g. circular economy, waste management, etc. These elements contribute, in a holistic manner and with different weight to the reaching of PED's final targets. The high level of complexity can be managed if different performances are defined and systematically evaluated. A proved effective methodology to assess one or more specific performances of a system or process,

i.e. PEDs, calls for the definition of tailored-made Key Performance Indicators (KPIs). Going into more detail, a KPI is a measurable value, or metric, that provides a “high level” (or synthetic) information about a specific performance status of a system. In order to be effective each defined KPI must be easily measurable and relevant. Giving the performance or aspect to be investigated the related KPI can be expressed in quantitative terms, i.e. numeric values, or qualitative terms, e.g. yes or no [Asih et al., 2020). Furthermore, a KPI can have different levels of aggregation both in time in terms of time resolution (hourly, monthly, annual, etc.) and of space (system boundaries, extension of sub-systems, energy vector, sectors, building- or district level). Regarding the time dimension each KPIs could be measure in different time horizon. In the case of PEDs different levels of aggregation in time and space could vary accordingly to the type of PED, i.e. autonomous, dynamic or virtual (as explained in Section 2.2.2) and external input preferences of relevant stakeholders. Furthermore, the choice of the aggregation level strongly depends on the availability of original input data and the desired accuracy of the analysis, considering that computational effort (simulation and optimisation) increases with the decrease of the aggregation level. It is worth noting that only KPIs with equal dimensions can be aggregated together, for example different total CO_2 emission per energy vector can be summed to give the total CO_2 emission of the PED. It is important to avoid redundancy (importance of knowing the relationship between KPIs, i.e. some indicators can be written as function of other defined indicators thus not adding new insights during the analysis. Thus, is important to know correlation between KPIs in order to advise a cause-effect relationship to better understand the investigated process. Finally, KPIs values can be as follows: planned or target value (short term), planned or target value (long-term), actual value, variance (planned/actual).
The application of KPI can be used during different phase to accomplish different objectives:

- During the design phase of a PED to give a specific direction, e.g. it can be used to build the objective function of an optimisation model.
- During the monitoring phase the evolution of PED to devise deviation from the desired state and act accordingly.
- Ccommunicate to relevant stakeholders the actual state (as-is) of the PED with a future perspective of the desired state (to-be).
- To define minimum (or maximum) threshold value that determines whether or not final goals have been reached.
- Compare different PED through a benchmarking analysis.
- Drive changes for continuous improvement.

In order to be effective each KPI should be clearly and unambiguously defined, in the sense that it is well understood what process, sub-system or event is attached to that specific KPI and so can affect its value (Hey, 2017). Should the KPIs varying during the monitoring phase, each of the listed potential causes should be carefully analysed to find the correlation and drive actions. Clear relationships are defined based on geographical boundaries, sub-system, energy vectors, etc. Regarding the environmental performance of a PED a full suite of indicators should be defined to cover key aspects.
Sustainability is a multi-dimensional concept thus not easily captured by a single indicator. Under the triple-bottom line framework the three main dimensions for sustainability are environmental (or ecological), economic and social. For each one of them different indicators can be defined as mono-dimensional KPIs. The environment is the core of the sustainability dimension and represents the ability to safeguard the reproducibility of natural resources and preserve fundamental functions of the environment over time; hence it encompasses the fundamental role of natural resources and their use, and the reduction of non-renewable resources and material degradation of nature and natural processes. In order to realise the new sustainability perspective, first it is necessary to define the environmental goals to achieve according to the SDGs.
Diverse assessment methods exist for evaluating the environmental impacts of PEDs, which produce different Key Performance Indicators (KPIs). The following figures have visualised a review of existing environmental evaluation frameworks based on 23 smart city and community and PED projects funded by H2020 since 2015 as well as 2 well-known smart city evaluation and reporting schemes: Smart City Info System (SCIS) and CITYkeys.

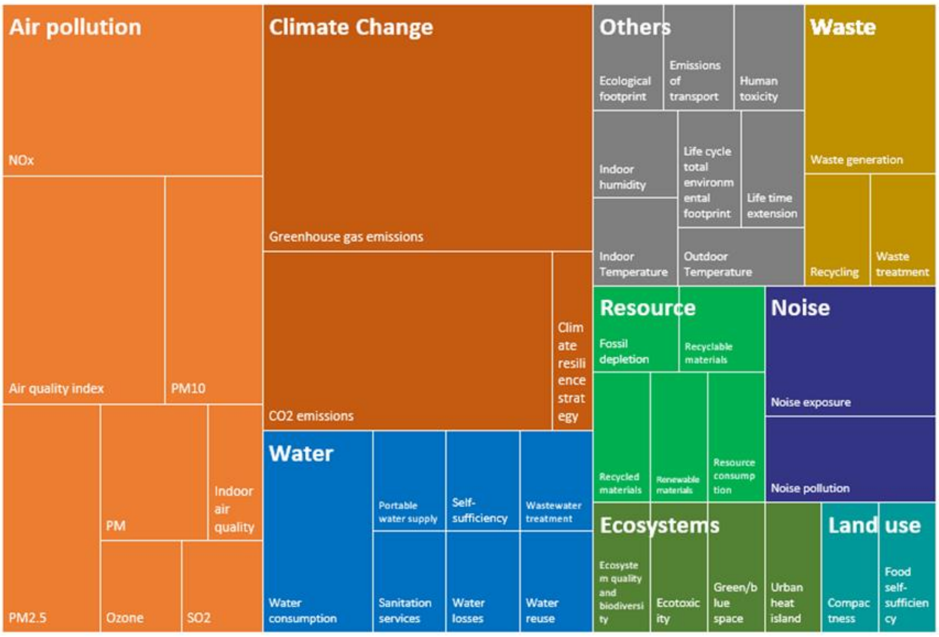

Figure 13: Area of Environmental Assessment for Positive Energy Districts, based on review of Smart City and Community (SCC) projects funded by H2020 from 2015 to 2024

Figure 13 shows the coverage (e.g., air pollution, climate change, etc.) and variations of KPIs applied in the reviewed projects and reporting schemes. The larger the area is, the more variations of indicator within each coverage or sub-coverage (e.g. NOx, GHG emissions, CO_2 emissions, etc.) there are. It is shown that the coverage of air pollution and climate change have a lot of variations for their KPI definitions. For example, within climate change, the KPIs focusing on GHG emissions have large variations as it could correspond to different sectors (e.g. GHG emissions from energy consumption of buildings only, or for mobility sector only), or it could correspond to different time horizons (e.g. for one year or for the entire lifespan of the PED). Climate change is also dominated by either the quantification of greenhouse gas emissions or CO_2 emissions. Although the former covers more gases, these two terminologies are used inter-exchangeability and are not always clearly differentiated. The KPI variation within air pollution is comparably large and is dominated by either the concentration of individual air pollutants or the quantification of air quality index. On the other hand, most of the KPIs are for performance onsite and lack of life cycle perspective.

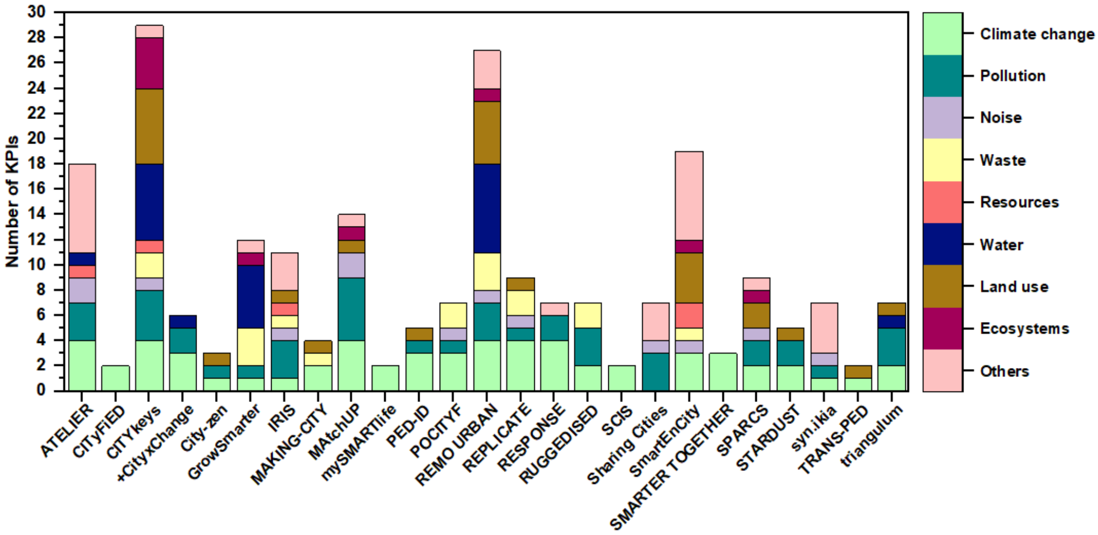

Figure 14: Number of Environmental Key Performance Indicators (KPIs) by EU H2020 Projects and their coverage areas

Figure 14 shows the number of environmental KPIs covered by each EU project or reporting scheme. It shows that the number of KPIs per project or reporting scheme ranges from 1 to 29. Every project has covered climate change, which is followed by the next most common assessment area: air pollution. Other areas which are also of importance, such as resources, water, noise, land use, etc. are less common to be evaluated. Some projects have relatively wide coverage (i.e. covers at least 5 areas), including CITYkeys, RemoUrban, SmarTenCIty and ATELIER, and only very limited projects have KPIs that integrate multiple assessment areas (categorised under "Others"), such as life cycle total environmental footprint, which covered 16 environmental impact categories including climate change, acid rain, human and eco-toxicity, particulate matter, water consumption, land use and resources. Such KPI can potentially facilitate decision-making and policy formations through a reduced amount of performance indicators. Table 5 summarises the main environmental KPIs defined in the context of the EU H2020 project outputs and shows the frequency of use within the projects. As visible in the detailed list of indicators, there is a large variability in the KPI units, which could undermine the comparability between studies. Overall, the most used indicator to evaluate the environmental performance of urban areas and the environmental impact of design strategies is the Greenhouse (CO2eq) Gas Emissions/GHG emissions. LCA indicators are used in a few projects, including SmartEnCity, ATELIER, CITyFiED and PED-ID. As for the LCA KPIs, only one of these utilises a multicriterial LCA approach based on several indicators, in order to avoid shifting impacts from one category to another, while the others are focused on the Global Warming Potential KPI. On the other hand, sustainable urban design should also be oriented towards a broader perspective based on strategic plans for circular production and consumption, through the optimisation of energy and resources flows and circularity. In this regard, the most frequently used KPI refers to the Recycling Rate of Solid Waste, followed by the Use of Waste Heat. Other KPs are only covered by one or a few projects, highlighting the need for a more comprehensive assessment framework. The category related to the preservation of the natural environment, species and land use has a low coverage even if it contains useful indicators for sustainable urbanisation both from an environmental point of view (protection of ecosystems and contrast of unsustainable use of the land, local food production, heat islands) and social point of view (e.g. aimed at creating a mixed-use and stimulating environment, which promotes the happiness of citizens). Furthermore, the assessment of the environmental and socio-economic performance of electric mobility and the quantification of the environmental impact is at the center of considerable interest as it constitutes one of the most developed actions in the framework of EU H2020 projects, together to the energy retrofitting of buildings and the integration of local RES. In this context, some KPIs are related to the mobility electrification and clean transport solutions. Among them, some refer to the performance of green mobility (e.g. use by citizens, reduction of emissions, etc.) and others refer to the planning of the necessary infrastructures and the optimal design. As for the quantification of the environmental impact on the district's life cycle, also in this case it is mainly based on the calculation of the operational CO2eq emissions avoided (expressed in [%] or [tons or kg CO2eq/100 km traveled by EVs], as shown in the Table).

Table 5: Summary of the main environmental KPIs defined in the context of the EU H2020 project outputs reported in Figure 10 and frequency of use within the projects

<table>
<tr><th>KPI</th><th>Unit</th><th>Frequency of use</th></tr>
<tr><td>Climate change and pollution</td><td></td><td></td></tr>
<tr><td>Greenhouse (CO_2eq) Gas Emissions (value and/or reduction) total and per sector</td><td>[tons or kg CO_2eq/(m^2 y)], [tons or kg CO_2eq/(m^2 mth)], [tons or kg CO_2eq/(kWh y)], [tons or kg CO_2eq/(MWh y)], [%], [tons or kg CO_2eq/100 km traveled by EVs], [tons or kg CO_2eq/y], [tons CO_2eq/(cap y)]</td><td>||||||||||||||||||||||||||||||||||||||||||
									</td></tr>
<tr><td>Reduced Carbon Emission per building</td><td>[tons CO_2eq/y]</td><td>||||||||||||||||||||||||||||||</td></tr>
<tr><td>Citizen Empowerment to Climate Conscious Actions</td><td>[Likert scale]</td><td>||||||||||||||||||||</td></tr>
</table>

<table>
<tr><td>Urban Heat Island (Max difference in air temperature within the city compared to the countryside during the summer months)</td><td>[°C UHImax]</td><td>||||||||||||||||||||</td></tr>
<tr><td>Climate Resilience Strategy</td><td>[Likert scale]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||</td></tr>
<tr><td>Air Pollution NO_x/tHC/$PM_{e-2.5}$/PM_{10}/[..] (total value and/or reduction)</td><td>[ppm/y], [%], [μg/m^3], [g/cap]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||||||||||||||||||||||||||
||||</td></tr>
<tr><td>Air Quality Index</td><td>[-], [tons NO_x/y], [tons SO_2/y], [0-100] scale: 0-25 very low, >100 very high</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||||||||||||||||||||||||||
||||||</td></tr>
<tr><td>Noise Pollution (Noise Level or Population affected by noise>55 dB at night time)</td><td>[dB], [%]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||||||||||||||||||||||||||
|||||||||||||||</td></tr>
<tr><td>Illuminance/Daylight Factor (inside and outside the buildings)</td><td>[Lux], [%]</td><td>||||||||||||||||||||||||||||||</td></tr>
<tr><td>Carbon Footprint Reduced in Mobility</td><td>[%], [teq CO_2eq/y]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||</td></tr>
<tr><td>Low-Carbon Measures Incentives for final users</td><td>[€/cap]</td><td>||||||||||||||||||||||||||||||</td></tr>
<tr><td>LCA</td><td></td><td></td></tr>
<tr><td>Global Warming Potential (GWP)</td><td>[tons CO_2eq/(cap y)], [tons CO_2eq/y]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||</td></tr>
<tr><td>Life Cycle Primary Energy Demand</td><td>[MJ/(m^2 y)]</td><td>||||||||||||||||||||||||||||||</td></tr>
<tr><td>Ecotoxicity</td><td>[CTU_e]</td><td>||||||||||</td></tr>
<tr><td>Human Toxicity</td><td>[CTU_h]</td><td>||||||||||</td></tr>
<tr><td>Fossil Depletion</td><td>[MJ]</td><td>||||||||||</td></tr>
<tr><td>Life cycle total environmental footprint</td><td>[Points]</td><td>||||||||||</td></tr>
<tr><td>Ecological Footprint</td><td>[gha]</td><td>||||||||||||||||||||</td></tr>
<tr><td>Waste and resources</td><td></td><td></td></tr>
<tr><td>Increased Efficiency of Resources Consumption (Reduction in material consumption)</td><td>[%]</td><td>||||||||||</td></tr>
<tr><td>Domestic material consumption</td><td>[tons/(cap y)]</td><td>||||||||||</td></tr>
<tr><td>Urban Solid Waste</td><td>[tons/cap y], [tons/(cap mth)]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||</td></tr>
<tr><td>Recycling Rate of Solid Waste</td><td>[%]</td><td>||||||||||||||||||||||||||||||||||||||||||
||||||||||||||||||||||||||||</td></tr>
<tr><td>Sewage Systems Management</td><td>[%]</td><td>||||||||||</td></tr>
<tr><td>Waste Recycling Awereness</td><td>[Surveys-based Likert scale]</td><td>||||||||||</td></tr>
<tr><td>Symbiotic Waste Heat Legal Framework Compatibility (Level of suitability of the legal framework for the integration of symbiotic waste heat solutions)</td><td>[Likert scale]</td><td>||||||||||</td></tr>
<tr><td>Heat Recovery Ratio (Percentage ratio of thermal energy recovered through a waste heat recovery system)</td><td>[%], [MWh]</td><td>||||||||||||||||||||||||||||||</td></tr>
</table>

Use of Waste Heat-Recovery	[MWh/y], [%]
Investment in Smart Waste Management System	[€]
Payback Period of Smart Waste Management	[y]
Water	
Wastewater Receiving Treatment	[%]
Households with Smart Water Meters	[%]
Households with Drainage System Management	[%], [Likert scale]
Grey and rainwater use (Percentage of houses equipped to reuse grey and rainwater)	[%]
Population with Potable Water Supply Service	[%]
Water Consumption	[l/(cap day)], [l/(cap y)]
City Water Monitoring	[%]
Hot Water Circulation Loss Factor	[kWh/y]
Water Circulation Losses	[kWh/(m^2 y)]
Temperature of the delivered DHW	[°C]
Water Exploitation Index (abstraction as % of long-term freshwater resources in the basin)	[%/y of m^3]
Sanitation Services	[%]
Environmental compatibility	
Environmental Awareness	[Likert scale]
No. of organisations with new sustainable approaches	[-]
Buildings with Green Certificates	[%]
Land use and ecosystems	
Inhabitants in High-Density Areas	[%]
Urban Compactness	[m]
Local food production	[% of tons]
Population Density	(no. of hab per km^2 [-])
Green Areas	[ha/100,000 hab], [m^2/cap], [%]
Pedestrian Area	[km^2/100,000 hab]
Budget on Green Space Management	[€]
Mixed-Used Development	[m^2/cap]
Occupied Dwellings	[%]
Brownfield use (Share of brownfield area that has been redeveloped)	[% of km^2]

<table>
<tr><td>Share of blue spaces</td><td>[%]</td><td>||||||||||</td></tr>
<tr><td>Native species (Change in native species no.)</td><td>[%]</td><td>||||||||||</td></tr>
<tr><td>High Quality Public Space</td><td>[Surveys-based Likert scale], (no. of social media comments on new space [-])</td><td>||||||||||||||||||||</td></tr>
<tr><td>Public outdoor recreation space</td><td>[m^2/cap]</td><td>||||||||||</td></tr>
</table>

3.2.6 Discussion and conclusions

A comprehensive framework for conducting the Environmental Impact Assessment of Positive Energy Districts (PED) across all stages of lifecycle has been established, structured into research question, methodology and modelling, Data collection and benchmarking.

The development of the EIA-PEDs framework operates under the methodological umbrella of Lifecycle Thinking considering key factors: Geographical boundaries, time horizon, time resolution, and sectors. The choice between different types of PED configurations, such as autonomous, dynamic, and virtual, significantly impacts energy flows and sustainability goals. Dynamic analysis over multiple decades with short time resolution is recommended for accurate environmental assessment and accounting for factors like weather, tariffs, and supply mix. Sectors like buildings and energy systems are central to the framework, while water, mobility and open spaces present challenges arising from varying boundary definitions and complexities. Balancing these factors is essential for fostering sustainable, adaptable, and efficient urban districts in the face of evolving energy and environmental landscapes.

The tools and approaches for evaluating carbon footprints in the operational stage of PEDs hold substantial implications for emissions assessment and reduction strategies. Utilising a structured approach like the Baseline Emission Inventory (BEI) aids in accounting for GHG emissions due to energy supply and demand in PEDs, enabling the measurement of effectiveness in sustainability plans. Activity-based data collection, focused on the energy sector, is crucial for precise emissions assessment. Subcategories like residential buildings, tertiary buildings, and public lighting help in precise emissions disaggregation. However, transportation-related emissions may need to be excluded or considered through localised data collection to better reflect district peculiarities. The choice of emission factors (EFs), whether activity-based or life cycle-based, depends on specific goals, compliance with international standards, and alignment with regional regulations.

The integration of Life Cycle Assessment (LCA), Urban Metabolism (UM), and Geographic Information Systems (GIS) provides valuable insights and tools for comprehensive environmental impact assessment of PEDs. LCA offers a holistic evaluation across stages, while UM considers socio-economic and environmental processes. The selection of functional units is crucial in LCA, while the data availability remains a challenge. However, standardised databases and supplier-specific Environmental Product Declarations (EPDs) aid the LCA process. Combining UM with Material Flow Analysis (MFA) and LCA enhances understanding of material flows' environmental implications and integrates different urban components within a systemic framework. GIS complements LCA by introducing spatial considerations, enabling site-specific analyses and addressing issues like traffic-related air pollution. This interdisciplinary approach empowers decision-makers to assess, plan, and manage PEDs' environmental performance effectively.

Regionalised analysis focused on specific regions allows a more accurate quantification of impacts highly dependent on local conditions. This approach is particularly relevant for PEDs, where impacts can vary greatly based on the geographical context. Challenges such as data quality, compatibility, and the need to consider social, economic, and sustainability dimensions in addition to environmental aspects remain, but the integration of regionalised LCA and GIS enhances the visualisation and comprehension of impact results, holding great potential for driving multidisciplinary sustainability across sectors.

The concept of planetary boundaries (PBs) offers a framework to understand humanity's safe operating space within environmental limits. The transgression of PBs, highlights the need for a holistic approach to address interconnected environmental processes. Integrating

PBs with Life Cycle Assessment (LCA) allows for a comprehensive evaluation of the environmental impact of Positive Energy Districts (PEDs), considering both current outcomes and future projections.

The multitude of assessment methods and Key Performance Indicators (KPIs) for PEDs calls for standardisation and a comprehensive framework. Prospective analysis and IAM scenarios enhance long-term environmental assessment and the identification of transformation strategies. Integrating prospective aspects into LCA allows for the consideration of evolving socio-economic and technological contexts, ensuring accuracy and reproducibility of results. However, challenges such as semantic inconsistencies, data quality, and accurate interpretation of information need to be addressed for successful integration. The integration of PBs, prospective analysis, and LCA offers a robust foundation for assessing and replicating PEDs sustainably, guiding decisions and contributing to a resilient built environment aligned with global sustainability goals.

In conclusion, this EIA-PEDs framework encompasses practical guidelines that can be used to benchmark PED's environmental performance against other districts, guiding replication efforts contributing to informed decision-making and effective management of PEDs.

Authors

Rosaria Volpe, University of Catania, (rosaria.volpe@unict.it)
Xiaojing Zhang, Institute of Construction and Infrastructure Management, ETH, Switzerland
Joana Bastos, Joint Research Center,
Ilaria Marotta, National Research Council of Italy - CNR (ilaria.marotta@cnr.it)
Emanuela Giancola, CIEMAT, Department of Energy, Spain (emanuela.giancola@ciemat.es)
Maria Nuria Sanchez, CIEMAT, Department of Energy, Spain
Elisa Marrasso, University of Sannio, (marrasso@unisannio.it)
Giovanna Pallotta, University of Sannio, (giopallotta@unisannio.it)
Francesco Guarino, University of Palermo, (francesco.guarino@unipa.it)
Sonia Longo, University of Palermo, (sonia.longo@unipa.it)
Maurizio Cellura, University of Palermo, (maurizio.cellura@unipa.it)
Alberto Fichera, University of Catania, (alberto.fichera@unict.it)
Maurizio Sasso, University of Sannio, (sasso@unisannio.it)
Toni Castillo-Calzadilla, University of La Laguna, Tenerife, Spain
Vainu Terttu, VTT Research center, Finland

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3.3 Case study application and insights

This study investigates the environmental and energy implications of retrofitting a representative university district in Southern Italy within the Positive Energy District (PED) framework not only implementing its definition but fully integrating the environmental analysis. Through calibrated energy models and comprehensive data analysis spanning 2017–2023, multiple renovation scenarios were explored—ranging from insulation upgrades to full HVAC system replacement and rooftop photovoltaic integration. In addition to this, a complete Life Cycle Assessment (LCA) was conducted for each intervention, examining nine environmental indicators beyond just carbon emissions. The implementation of this real case study shows how the methodology implemented in this study is important to evaluate the environmental impact of a district, in a repeatable way, and as a lesson learned. Learning from case-studies. from an environmental perspective
Has as primary goal, to create a reference dataset for PEDs and to refine and develop environmental assessment methodologies through real case studies. Results show that while full renovation, with photovoltaics supplying up to 80% of district demand, can reduce the Global Warming Potential by up to 34% and Cumulative Energy Demand by 63%, certain categories such as eutrophication and ozone layer depletion experience significant increases. This highlights the importance of integrating embodied impact analysis in energy planning. This methodology shed light on how much coupling energy performance and environmental impacts, scenario-based grant the opportunity to replicate and to assess a district's positivity with a more holistic approach, underscoring the need for flexible PED definitions more adaptive to urban constraints. Finally, a SWOT analysis performed on the study case, validates the methodology's replicability while emphasising challenges such as data accessibility and interpretation. This research contributes practical insights for scalable PED implementations in Mediterranean climates.

3.3.1 The context

The building sector is responsible of almost the 40% of the global energy use and process emissions (Apostolopoulous et al., 2023; Domenech and Bahn-Walkowiak, 2019), however despite the relative weight on the total, decarbonising single buildings, districts and cities still is a research topic complex to investigate the reason as it encompasses the technical part (analysis of the building stock), the interpretation of the results (design of the different scenarios and environmental impacts) and the implementation of the results (Healey and van der Leer, 2024). To a greater extent, it can be understood as if implementing a holistic and synergistical approach to planning new urban areas. In addition, the hiatus of robust and replicable standardised frameworks, functions as an attrition factor to policy-makers when it comes to Positive Energy Districts (PEDs) (JPI, 2020). The methodologies to assess the energy efficiency of city districts find their validation in the application to real cases enhancing the replicability and reliability of them, creating a database with real case studies. There are many examples of research or joint programme, like the 100 Positive Energy Neighbourhoods by 2025 promoted by the Urban Europe Joint Programming Initiative (JPI) (European Commission, 2021; Tian et al., 2022). Certainly, this initiative contributed to increase the level of attention of the public dialog, but not only. In fact, contemporarily to this new sentiment, the evaluation of new cases implementing typical input output methodologies quantifying the impacts on the environment and humans seems mandatory to have a clear view of what decarbonising projects could entail. In fact, reducing the primary energy consumptions and the related emissions after a retrofit implementation, is too often the sole impact category environment-related to be analysed in decarbonisation projects (Luu et al., 2025). In fact, if on the one hand, "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" (Sessa et al., 2024), on the other hand achieving this positivity, might reveal unexpected negative impacts when a thorough environmental analysis is performed. Therefore, if the integration of different systems and infrastructures might solve the challenge of decarbonising urban districts, at the same time, it could impact in a negative way on the social, economic and the environmental pillars of sustainability (JPI, 2020), not entailing only the quantitative approach of the energy balance, but considering other less tangible (and often underestimated) aspects, like quality of life or biodiversity resilience. If assessing the definition of Positive Energy

Districts (PEDs) itself, as detailed in the (Global Covenant of Mayors; 2023), is the first and most researched step to evaluate (Bruck et al., 2022), creating the need for additional cooperation and knowledge sharing to disseminate and validate those methodologies is the second most challenging research topic (Gondeck et al., 2024).

Above all, the need to embed the environmental perspective needs still overarching recognition and standardisation. In fact, considering all the activities which exist on the territory, implying a higher degree of interconnectivity, is sufficed only by a holistic approach (Guarino et al., 2023). The importance of real case studies in this direction, contributes to validate previous studies, testing the replicability of the methodology, despite the environmental implication is mentioned in the very end of many studies.

One of the most critical issues encountered in the evaluation and design of a PED is the data collection phase and the possibility to have access to substantial monitored data. On the one hand, the approach to modelling has been researched exploiting even front-end technologies like digital twins or digitalisation (Koirala et al., 2024) to simulate energy demands and consumption. On the other hand, the evaluation of the environmental impacts is certainly a function of many other variables, like the geographical boundaries definition, the time horizon resolution, the industrial sectors within the district boundaries, the destination of use of the building stock and other assumptions.

In this regard, the recently enacted Directive 2024/1275 of the European Parliament and of the Council on the Energy Performance of Buildings (EPBD), adopted on 24 April 2024, introduces a series of increasingly stringent and binding requirements aimed at accelerating the decarbonisation of the building sector (The EPBD Decrypted: A Treasure Chest of Opportunities to Accelerate Building Decarbonisation, 2024). These provisions call for comprehensive interventions across both existing building stocks (Art. 8) - with particular emphasis on the non-residential built environment (Art. 9) - and in the enhancement of renewable energy integration, notably the optimisation and exploitation of solar energy generation potential (Art. 10).

Closely aligned with these objectives is the introduction of the Building Renovation Passport (Art. 12), a pivotal tool designed to catalyse the large-scale renovation of existing buildings. This instrument is grounded in the improvement of technical building systems and the systematic replacement of obsolete technologies (Art. 13). Interestingly, the Directive mandates the development and deployment of adequate financial mechanisms, support measures, and policy instruments to overcome existing market barriers, thereby enabling the substantial investments required. This is integral to Member States' national renovation plans aimed at transitioning the entire building stock towards zero-emission standards by 2050 (Art. 17).

All such measures are to be implemented with full consideration of the Global Warming Potential (GWP) across the entire life cycle of new constructions (Art. 7 and Annex III) (Olasolo et al., 2023), as well as within the context of retrofit and renovation processes for existing buildings. Its recent implementation paves the way to calculate the actual environmental impacts of a district confronting its baseline and the retrofitted version and, besides the amount of carbon dioxide and other Greenhouse Gases, reports on the other impact categories. Obtaining the estimated emissions (processing the energy items of the inventory), selecting the right entry (geographic and sector specific – often missing of recent data or completely null), and the functional unit (i.e., a square meter of a residential building has not the same energy intensity as that of a commercial activity) allocating the impacts, constitute some of the challenging but necessary steps to attribute to a standard energy balance equation, an environmentally-aware approach.

Aligned with the "activity C2: Environmental assessment C2.3 Learning from case-studies" this study aims at developing a replicable study based on environmental informed decision, towards supporting decision-makers to justify and planning in accordance to a baseline scenario and potential PED ones. It investigates the energy performance and the relative environmental impacts of a set of buildings located on the University of Palermo campus. The initial analysis is based on energy modelling developed using in situ measured real data and the creation of representative building archetypes. The objective is to establish a simplified yet robust benchmarking methodology, intended to serve as an easily replicable environmental assessment framework alongside existing approaches discussed previously.

The energy balance evaluation integrated with a broader set of Key Performance Indicators (KPIs), following the Environmental Footprint (EF) methodology serves as a transferable framework to support environmentally informed decision-making by key stakeholders. This approach leverages enriched metadata - such as geo-referenced information - to facilitate interactions with the surrounding territory, enabling the contextualisation of environmental impacts related to building retrofitting strategies.

3.3.2 Methods and data modelling

The methodology implements the environmental framework activities within the case-study from the University of Palermo campus. Some buildings inside the university boundaries "Viale delle Scienze" were selected as representative of a district and a rigorous structure was realised to profile a standardised methodology.
Figure 9 showcases the workflow of the study, where the dashed lines define the main blocks of the process. The next paragraphs will follow the outline presented in Figure 9.

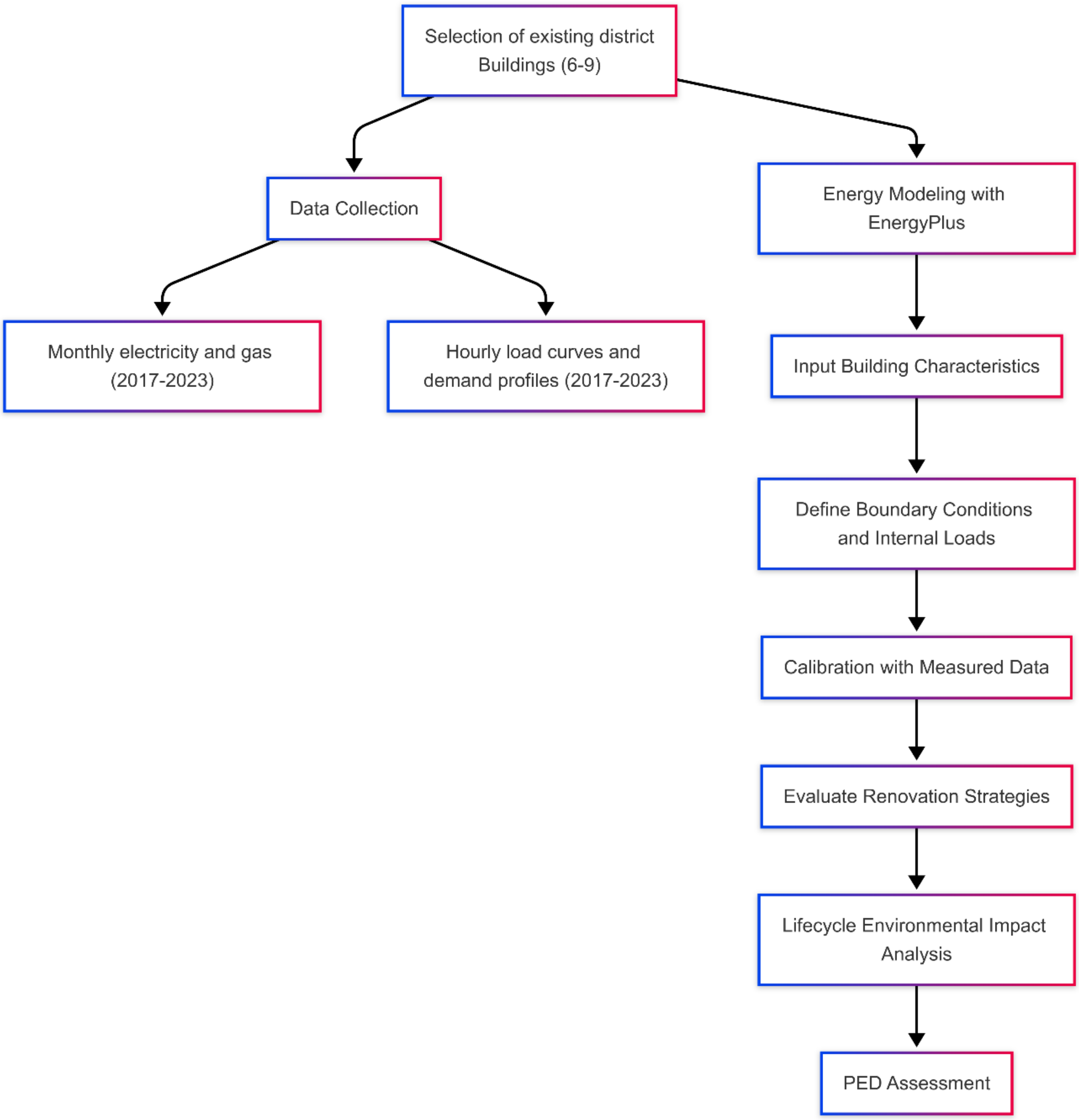


Figure 15: Representation of the workflow used for this study

The selected buildings were chosen based on their operational relevance inside the campus for their constructive similarities and for their proximity (Figures 2 and 3).
The buildings are insisting on a vast natural area, encompassing an archaeological park and a naturally depressed area, habitat of various birds, small rodents and plants, called "Fossa della Garofala". Together with the park outside the campus, there are multiple recreational areas within it.

Figure 16: Aerial view of the buildings selected for the study belonging to the engineering department of the University of Palermo

More in detail, the methodology considered the following activities:

- Selection of the building belonging to the Engineering Department (individually as "Building 6," "Building 7," "Building 8," and "Building 9," as illustrated in Figure 17, modelled and simulated under dynamic conditions using in EnergyPlus environment;
- Data harvesting of monthly electricity consumption and gas heating data (from 2017 to 2023), hourly electric load curves and energy demand profiles (from 2019 to 2023). To be analysed and mapped;
- Definition of each building's opaque and transparent envelope, occupancy rates, lighting systems, and electrical equipment incorporated into the simulation models. These inputs were further refined by adjusting boundary conditions, defining representative energy profiles, occupancy patterns, internal loads, and other relevant building features;
- Model calibration: conducted to ensure that the simulated energy performance closely matched the real-world conditions observed in the existing buildings;
- Definition of scenarios based on renewable energy generation solutions, evaluated based on the calibrated models;
- Characterisation of the environmental impacts related to the selected renovation approaches following a lifecycle thinking approach;
- Technical feasibility of achieving a positive energy balance within this specific context, to address targeted PED requirements.

After this, the elaboration of a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis was made to understand how this analysis poses regarding the challenges encountered and the potential replicability.

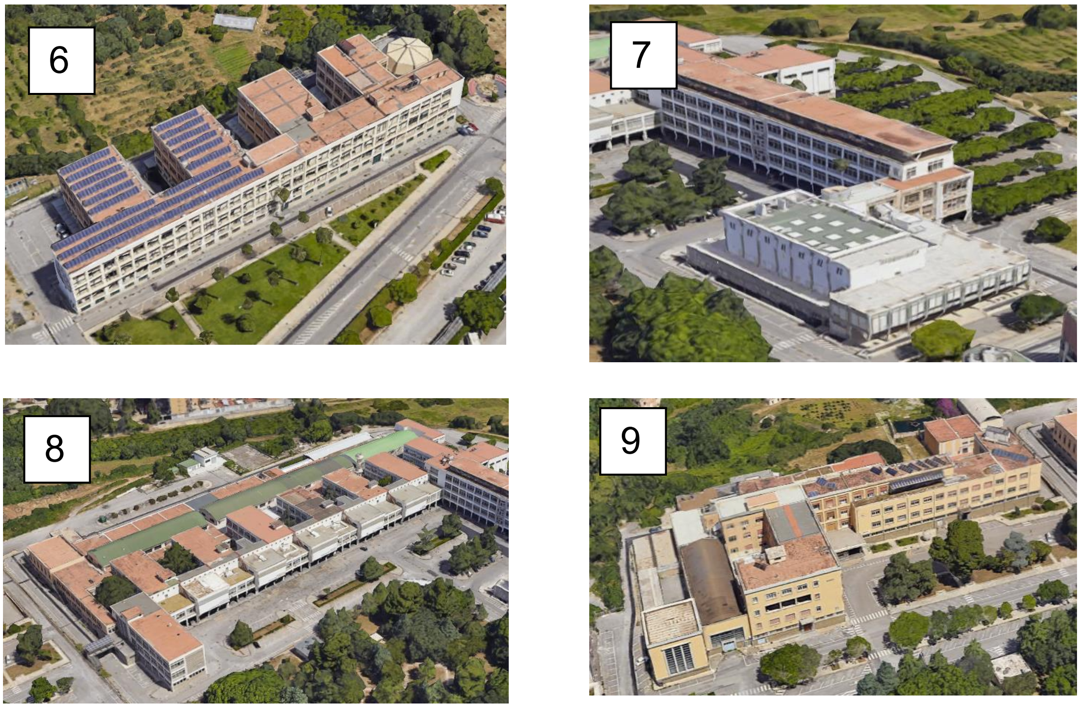


Figure 17: Buildings selected in the campus of the University of Palermo. The tags indicate the numbers of buildings.

The main block objects of the study, present in the aerial view in Figure 16, are detailed in Figure 17 with the numbered labels.
To characterise the building stock made of four buildings, historical data were acquired along with some technical inspection of the sites to check the plate information about the central gas heating systems and other specifications of the buildings as visible in Table 6. The time data series acquired covered the period between 2017 and 2023 considering both thermal and electricity data. The modelling, performed over Euclid-NREL Energy Plus Plugin was complemented using the Design tool SketchUp.

Table 6: Buildings' characteristics

	Envelope specifics	Total thickness [m]	(U-Value) [W/ (m^2 K)]
Exterior walls (ext. → int.)	- Tuff stone (high-density, porous sandstone with good thermal/acoustic performance) - Exterior cement plastering - Interior plaster + cladding paint	0.36	1.4
Ground floors (ext. → int.)	- Grit tile top-finish - Cement screed - Sandstone/rock pebbles	0.27	2.4
Interior pavements	- Concrete and masonry slabs - Plastered - Grit tile top-finish	0.34	2.1
Interior ceilings	- Concrete and masonry slabs - Plastered - Finished with cladding paint	0.34	2.1
Flat roof / Exterior top-level	- Concrete and masonry slabs - Plastered - Tiled floor finish	0.36	2.0
Features of glazing and framings		**Structure of the layers [mm]**	
Exterior windows	Glazing: double pane, clear glass, air-filled. Frame and dividers: aluminum frame without thermal break	12-10-12	

The building models - shown in Figure 18 - were subdivided into approximately 100 distinct thermal zones, each representing a unique area with specific thermal behaviour and usage characteristics. These zones were carefully identified and categorised into offices, laboratories, classrooms, restrooms, stairwells, elevators, unconditioned spaces, and other specialised areas. For each zone type, key operational parameters were defined, including occupancy rates, internal gains, energy loads, and activity levels. These variables were calibrated and adjusted based on observed and expected user behaviour, as well as the typical usage patterns of lighting systems, electric equipment, and other appliances.

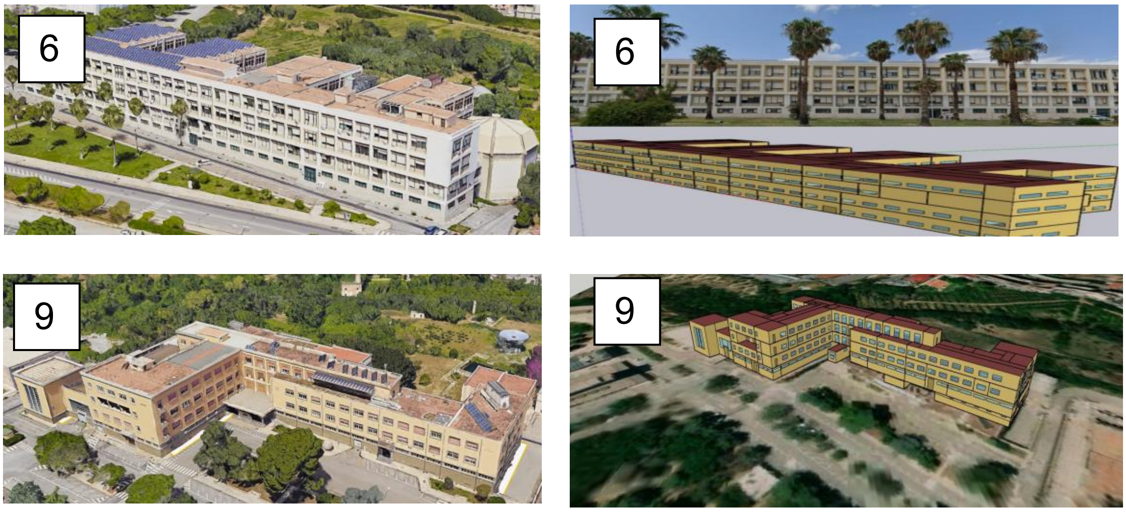


Figure 18: Representation of building 6 and building 9 and related archetype models

3.3.3 PED renovation strategies

A range of renovation scenarios was developed to explore the most promising retrofit solutions for the district under study. These scenarios were carefully designed to reflect both conventional improvements and advanced upgrades, including the integration of renewable energy systems.

Each scenario was evaluated for its impact on energy efficiency, thermal comfort, and environmental performance, with interventions targeting various building components from the envelope and glazing systems to lighting, HVAC, and rooftop solar integration. They are briefly described in the following paragraph.

Scenario 1: rockwool insulation for envelope enhancement

- Application of external rockwool insulation (180 mm thick), including anchoring substructure;
- Resulting U-values (Walls / Roof):
  - *Building 6*: 0.175 / 0.182 W/(m²·K);
  - *Building 7*: 0.172 / 0.188 W/(m²·K);
  - *Buildings 8 and 9*: 0.172 / 0.183 W/(m²·K).

Scenario 2: cork-based thermal insulation

- External cork insulation system (195 mm total thickness);
- Resulting U-values (Walls / Roof):
  - *Building 6*: 0.175 / 0.182 W/(m²·K);
  - *Buildings 7, 8 & 9*: 0.172 / 0.183 W/(m²·K).

Scenario 3: high-performance window replacement

- Installation of new low-emissivity (low-e) selective double-glazed windows with air gaps and thermal break aluminum frames:
  - *Building 6*: Glazing structure 3-13-3 mm; U-value: 1.216 W/(m²·K); SHGC: 0.315;
  - *Buildings 7, 8 and 9*: Glazing structure 4-12-4 mm; U-value: 1.227 W/(m²·K); SHGC: 0.314.

Scenario 4: LED re-lamping

- Replacement of all conventional lighting with high-efficiency LED systems.

Scenario 5: Thermostat Optimisation

- Implementation of optimised thermostat setpoints:
  - 20°C for heating;
  - 26°C for cooling;

  resulting in more efficient HVAC system operation.

Scenario 6: HVAC System Replacement

- Transition to high-efficiency, fully electric HVAC systems across all buildings.

Detailed comparisons of performance and efficiency against the baseline are available in Table 7, highlighting the improvements achieved with Scenario 6.

Scenario 7: renewable integration - photovoltaic systems.

Roof PV was planned as described in Table 8 with the overall estimation for 908 kWp for photovoltaics.

Scenario 8: PED full renovation – implementation and combination of the most effective energy renovation actions previously assessed.

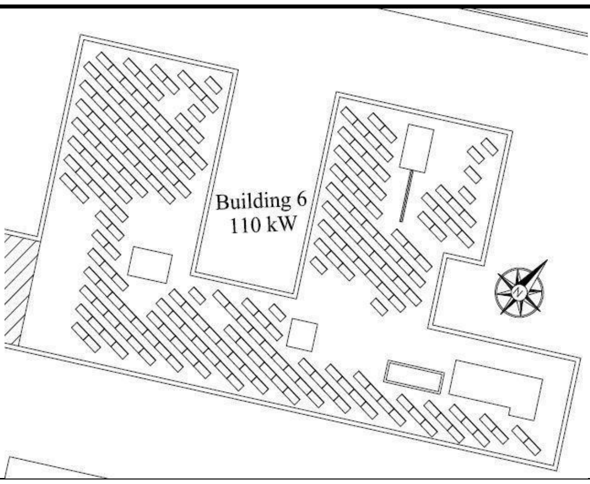
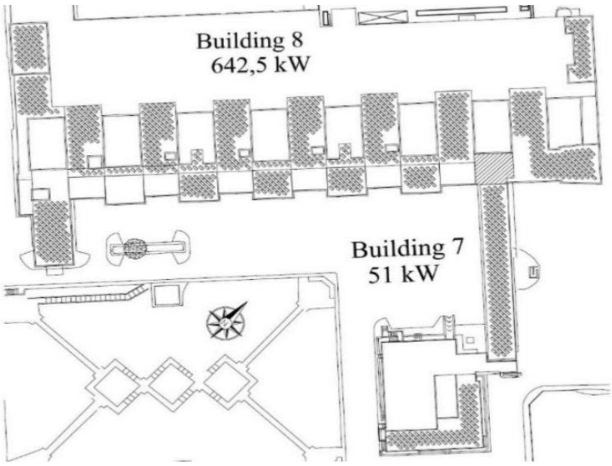
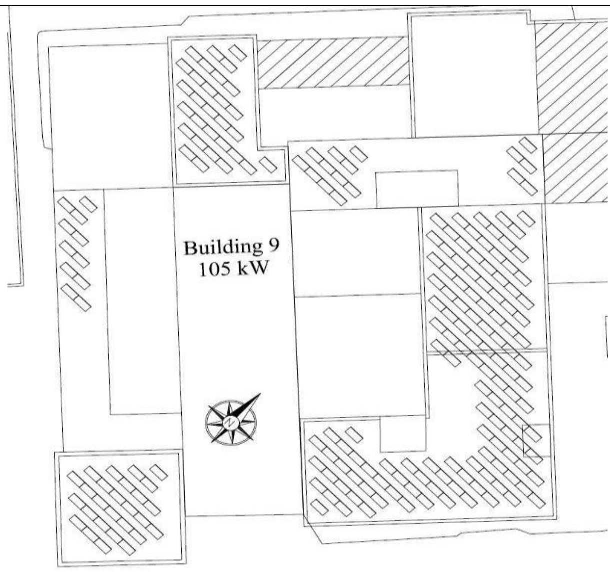
Table 7: Comparison between baseline energy performances and scenario 6 renovation performances

	BASELINE SCENARIO					SCENARIO 6		
	Heating System	**η**	**COP**	**Cooling System**	**EER**	**HVAC System**	**COP**	**EER**
Building 6	-Natural gas boilers with fan coils and radiators as terminal units	0.90	-	Autonomous split units	2.85	Reversible hydronic heat pumps	3.34	3.34
Building 7	-Natural gas boilers with fan coils as terminal units	0.82	-	Hydronic chillers with fan coils as terminal units	5.05	Reversible hydronic heat pumps	3.28	3.26
	-Autonomous split units	-	2.95	Autonomous split units	2.85	Unchanged		
Building 8	-Natural gas boilers with radiators as terminal units	0.97	-	Autonomous split units	2.85	Reversible hydronic heat pumps	3.24	3.22
	-Rooftop system powered by reversible heat pumps	-	2.85	Rooftop system powered by reversible heat pumps	2.75			
Building 9	-Natural gas boilers with radiators as terminal units	0.91	-	Autonomous split units	2.85	Reversible hydronic heat pumps	3.28	3.26
						Variable Refrigerant Flow System	4.50	3.62

In the PED scenario the following solutions are implemented:

- Envelope insulation from Scenario 2 (Cork Insulation);
- Window replacement from Scenario 3;
- Lighting system upgrade from Scenario 4;
- Thermostat optimisation from Scenario 5;
- Full electrification from Scenario 6;
- Photovoltaic integration on rooftops for renewable energy production from Scenario 7.

Table 8: Showcase of the installations of PV fields on the rooftops of the buildings

<table>
<tr><th></th><th>PROPOSED LAYOUTS PER BUILDINGS OF THE PV FIELDS</th><th>Installed PV peak power [kW$_P$]</th></tr>
<tr><td>BUILDING 6</td><td>
</td><td>110</td></tr>
<tr><td>BUILDING 7</td><td rowspan="2">
</td><td>51</td></tr>
<tr><td>BUILDING 8</td><td>642</td></tr>
<tr><td>BUILDING 9</td><td>
</td><td>105</td></tr>
</table>

3.3.4 Life Cycle Assessment

In parallel with energy modelling and simulation, all proposed renovation scenarios underwent a Life Cycle Assessment to evaluate their environmental impact.
To ensure a consistent and credible assessment, the environmental footprint developed by the European Commission of each renovation measure was calculated from a life cycle perspective. These included emissions linked to material production, transportation, installation, and in some cases, end-of-life treatment. The evaluation was grounded on a 30-year average useful life for HVAC systems, solar thermal panels and building renovation materials with emission factors sourced from the Ecoinvent 3.6 database.
The environmental dataset compiled for this study accounted for the entire supply chain, covering raw material extraction, manufacturing processes, and logistics. Where applicable, it also included emissions from waste management and production by-products.
This environmental evaluation was carried out in accordance with ISO 14040:2006 and ISO 14044:2021 standards, ensuring methodological transparency and compliance with internationally recognised LCA frameworks.
More into details 9 impact categories are considered after the environmental footprint methodology:

1- global warming potential;
2- acidification;
3- eutrophication;
4- photochemical oxidation;
5- abiotic depletion elements;
6- abiotic depletion fossil fuels;
7- water scarcity;
8- ozone layer depletion;
9- Cumulative energy demand.

The scenarios defined were analysed from the energy balance perspective to evaluate in which of them the dimension of energy positivity would be achieved. Leveraging on equation (1) performed on a yearly basis, the energy balance B was formulated as the difference between G_j, the annual energy generated by rooftop integrated photovoltaic panels, with *j* ranging from 1 to 8.760 and C_j, the annual energy consumed within the district (with *j* ranging from 1 to 8.760); it implies that a B>0 value characterises the district as a positive.

$$B = \sum_{j=1}^{n} G_j - \sum_{j=1}^{n} C_j \sum_{j=1}^{n} G_j - \sum_{j=1}^{n} C_j \quad (1)$$

Not to be solely constrained to the energy balance, but to evaluate the environmental perspective, equation (2) was introduced as actualised and annualised emissions balance *B'* related to the retrofit intervention, as difference between the baseline use stage embodied emissions for all the 9 impact categories (from j to n=9) EbI_j, and the PED scenario impacts (including embodied impacts correlated with the renovation actions and the residual use stage impacts) as $ErI_{j,k,}$ where the k ranges from 1 to m that is the total number of the impact categories and equal to 9.

A value of $B'B'$*<0* implies that from an environmental perspective connected to the j^{th} indicator, the renovation towards PED has a positive connotation.

$$B' = \sum_{j=1}^{n} EbI_j - \sum_{\substack{j=1 \\ k=1}}^{n,m} ErI_{j,k} \; B' = \sum_{j=1}^{n} EbI_j - \sum_{\substack{j=1 \\ k=1}}^{n,m} ErI_{j,k} \quad (2)$$

In the light of the above remarks, the PED "extended target" can be reached if the final calculated balance is negative (i.e. if $B'B'$<0).

3.3.5 Results

Hereby, the outcome of this study will be shown with the validation process which consists of analysis of the existent and the related calibration which in batch will lead to the validation of the model.

The analysis of the building's consumption benefitted from the real values of data consumption, namely, electricity and natural gas over the period 2017-2023.
Accounting for all fluctuations - due to the varying number of occupants and to seasonal variation - the buildings met their heating demand on average (considering the gas-powered heating system).
The comparison between the energy demand for electricity and for heating for the baseline scenario and all the buildings together, in Figure 19, shows how the heating (blue bars) is recorded mostly in the winter months (December, January, February, March), while the electricity demand (green bars) can be observed throughout all the months of the year.

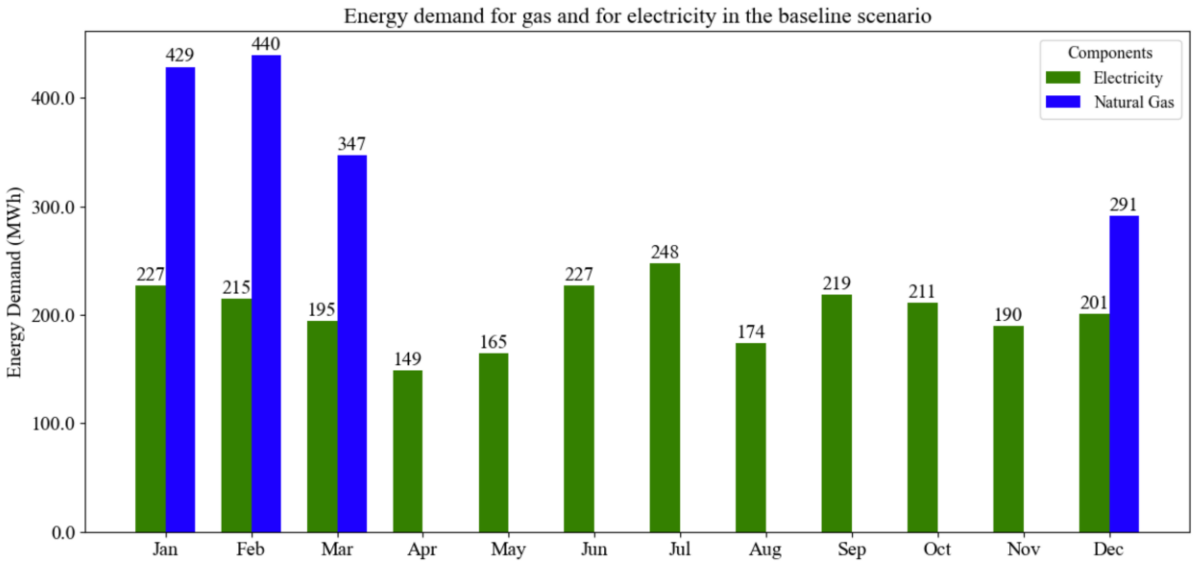


Figure 19: Comparison for the demands of energy for electricity and natural gas, in the baseline scenario

A progressive calibration process granted the validation of the models, always keeping the maximum deviation within the ±10% between the monthly data calculated from the models and those ones derived from the bills.
In Table 9 there are the deviations between the real consumption from the bills and the simulated model, all below the value of ±10%.

Table 9: Deviation on the energy demand for electricity for measures and simulations

Electricity demand [kWh]				
	Building 6	Building 7	Building 8	Building 9
	Deviation Baseline/Simulation	Deviation Baseline/Simulation	Deviation Baseline/Simulation	Deviation Baseline/Simulation
Months				
January	7.92%	-0.69%	-5.29%	-3.02%
February	7.39%	-9.11%	-7.08%	5.81%
March	-3.59%	8.25%	5.06%	6.16%
April	-6.15%	4.37%	-9.53%	-0.86%
May	0.02%	6.64%	2.22%	2.79%
June	-7.26%	0.98%	-6.47%	9.56%
July	-6.94%	-9.64%	-0.68%	-9.94%
August	-8.00%	-9.38%	2.17%	1.45%
September	5.76%	-7.54%	0.32%	-2.24%
October	3.99%	-8.25%	-3.32%	-0.73%
November	7.67%	-2.22%	4.03%	7.74%
December	2.10%	-2.51%	-7.51%	4.00%
Avg. deviation	0.06%	-2.49%	-2.23%	1.61%

The hourly energy demand for electricity, considered the cooling, and the lighting and, in the case of building 7 the thermal zones served by heating pumps, were considered too.
Similarly, Table 10 shows the deviation between the bills and the simulated energy demand for heating, where only building number 9 stands out for a value close to the lower band of -10%.

Table 10: Deviation baseline/scenarios on energy demand for heating for measured and simulated models

Heating demand [kWh]				
	Building 6	Building 7	Building 8	Building 9
	Deviation Baseline/Simulation	Deviation Baseline/Simulation	Deviation Baseline/Simulation	Deviation Baseline/Simulatio n
Months				
January	-1.17%	1.46%	0.31%	-9.65%
February	4.88%	4.81%	0.66%	-9.84%
March	2.98%	1.08%	0.51%	-7.83%
December	1.15%	-6.10%	0.49%	-6.77%
Avg. deviation	1.46%	0.31%	0.49	-8.52%

The minimum deviation value (in absolute terms, it is associated to the data connected to the natural gas energy demand for the building 8 (i.e. with an average deviation of 0.49%), while the maximum one occurs for the energy demand from methane associated to Building 9 (with an average value of 8.52%).
Consequently, all the other mean deviation values here assessed lie (as above shown) within the range defined by these two values.
Figure 20 and Figure 21 display instead the calibration results for the entire district, also highlighting how, from an overall perspective, the monthly discrepancies here registered - compared to the ones derived from the individual buildings' validation assessment - are reduced.

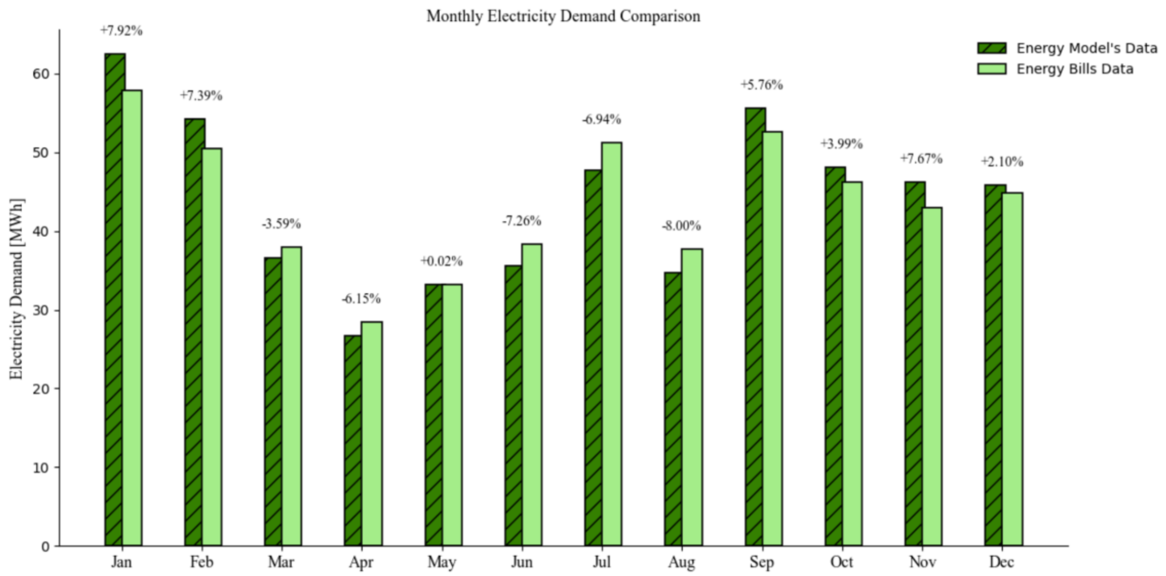


Figure 20: Results of the calibration for electricity energy demand with deviation

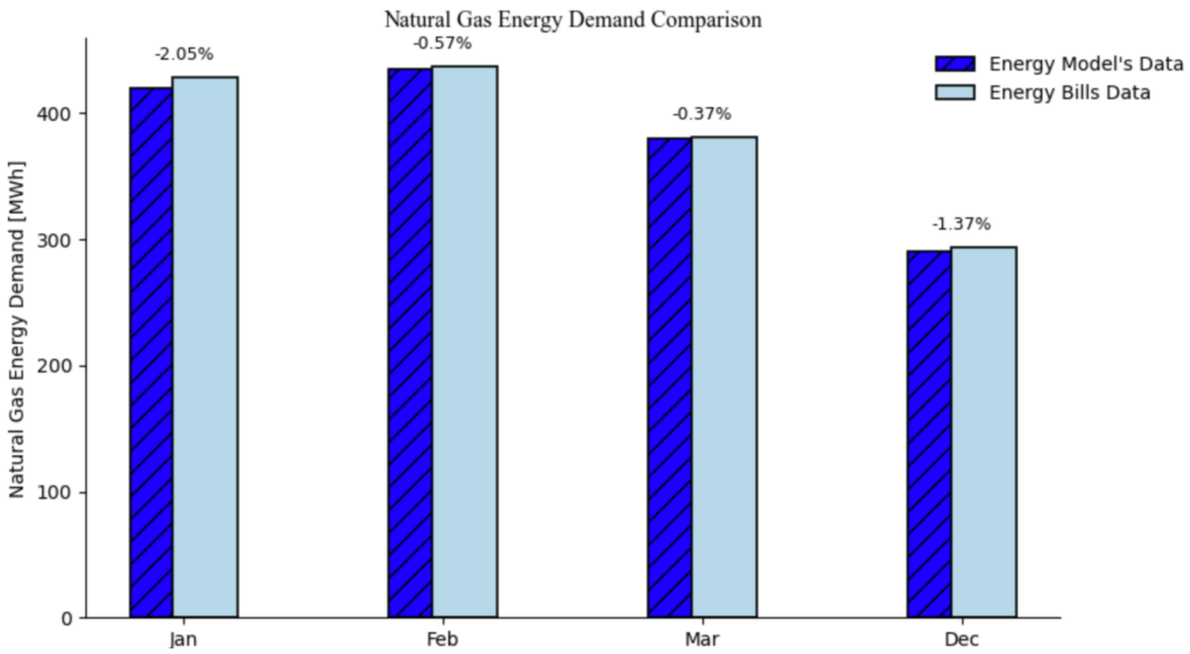


Figure 21: Results of the calibration for natural gas energy demand with deviation

3.3.6 District's renovation scenarios analysis

The different scenarios are analysed singularly and compared to the baseline energy demand for electricity and for (heating) natural gas.
This comparison gives the opportunity to reason on the real effect of the individual intervention on the baseline.

Table 11: Electricity demand per scenario, compared to the baseline demand for electricity. At the bottom of the table, the deviation with the baseline. The negative sign represents a lower energy demand.

Electricity demand [kWh]								
MONTH	**Baseline**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 8**
January	225,337.73	225,126.93	225,126.34	225,371.27	142,982.84	225,026.96	340,026.92	221,005.73
February	211,396.88	211,165.98	211,164.72	211,448.06	135,717.68	211,096.58	330,738.42	227,119.43
March	203,090.09	202,956.08	202,954.58	203,128.51	132,672.38	202,930.73	297,402.15	198,617.25
April	142,424.79	142,424.79	142,424.79	146,331.43	95,611.92	142,424.79	142,496.91	96,090.08
May	169,389.78	168,741.86	168,703.35	171,403.61	117,838.23	160,571.86	169,742.87	107,517.20
June	223,156.05	212,932.31	212,763.45	215,228.04	156,971.11	193,793.36	221,285.45	114,917.12
July	234,400.77	217,668.64	217,326.48	224,929.11	171,096.97	203,535.95	231,178.73	127,791.46
August	169,465.92	165,978.69	165,936.24	166,787.81	113,796.74	161,216.74	169,472.92	102,417.54
September	218,035.42	215,238.84	215,734.86	212,787.69	149,067.27	192,636.07	215,836.77	123,121.93
October	206,567.92	206,567.92	206,567.92	203,496.30	131,271.40	206,567.92	206,626.23	132,720.26
November	198,402.67	198,402.67	198,402.67	195,494.17	126,942.73	198,402.67	198,459.51	128,317.50
December	196,491.70	196,302.02	196,300.74	192,837.16	123,564.33	196,307.94	274,953.93	173,673.27
Total	2,398,159.71	2,363,506.71	2,363,406.13	2,369,243.16	1,597,533.59	2,294,511.56	2,798,220.81	1,753,308.77
Deviation		**-1.44%**	**-1.45%**	**-1.21%**	**-33.39%**	**-4.32%**	**16.68%**	**-26.89%**

As can be observed from Table 11, scenario 1 and scenario 2 exhibit modest reductions in demand (–1.44% and –1.45% respectively), while scenario 3 shows a similarly minor reduction (–1.21%). Scenario 4 stands out with a substantial decrease in electricity consumption (–33.39% compared to the baseline).
A moderate reduction (–4.32%) is shown by scenario 5, outperforming the previous ones, but still lower compared to the gains achieved in scenario 4.
Conversely, scenario 6 records an increase in electricity demand (+16.68% relative to the baseline), implying the transfer of loads from gas-based systems to the newly designed ones.
Finally, the PED scenario with full renovation, shows a strong reduction of –26.89%, indicating a substantial shift towards energy autonomy, although maintaining a significant absolute demand level.

Table 12: Gas use per scenario, compared to the baseline demand for heating. At the bottom of the table, the deviation with the baseline

				Heating demand [kWh]				
MONTH	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	PED
January	420,033.47	356,788.69	356,086.24	424,169.88	449,124.37	298,340.04	0	0
February	437,123.44	385,680.00	384,602.61	444,048.24	465,324.12	334,963.01	0	0
March	345,773.72	297,985.93	296,259.33	356,762.34	372,834.70	234,958.14	0	0
April	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0
December	287,179.24	236,953.47	235,794.07	289,489.48	311,481.32	192,374.11	0	0
Total	1,490,109.87	1,277,408.10	1,272,742.26	1,514,469.93	1,598,764.52	1,060,635.30	0	0
Deviation		**-14.27%**	**-14.59%**	**1.63%**	**7.29%**	**-28.82%**	**-100.00%**	**-100.00%**

Analogous and complementary trends can be traced in Table 12, with a significant reduction (– 28.82%) in heating energy use, indicating the implementation of efficient measures such as improved envelope performance, upgraded heating systems, or control strategies. Finally, the last two scenario, 6 and Full Renovation, eliminate the heating demand (–100%), with full electrification align with ambitious decarbonisation goals, such as zero-heating energy buildings.
To have a reference for all the scenarios with a synoptic overview, all the energy use metrics are reported in Chat 8, where it is possible to see the PED scenario and the baseline one for electricity.

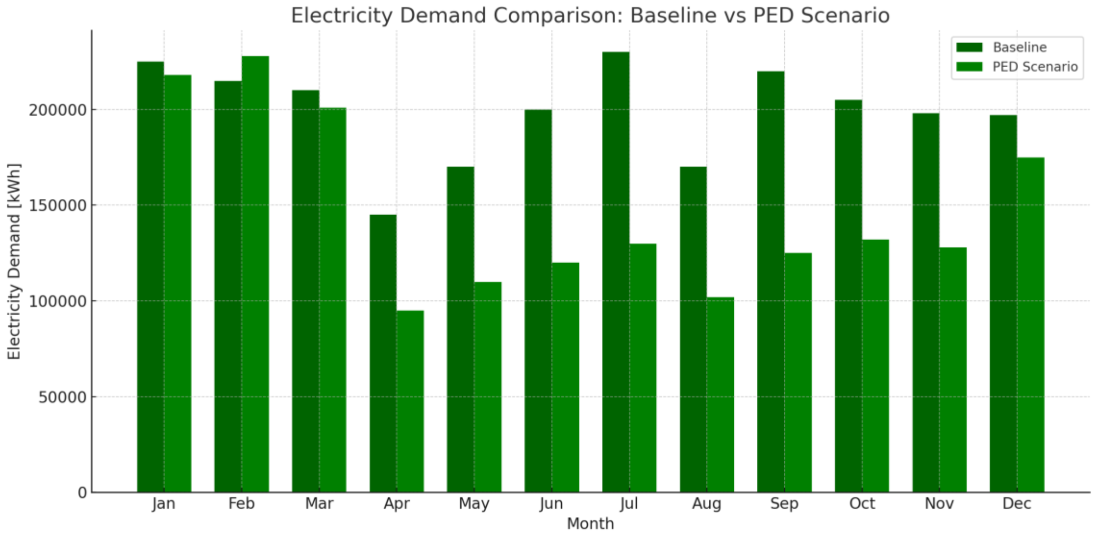
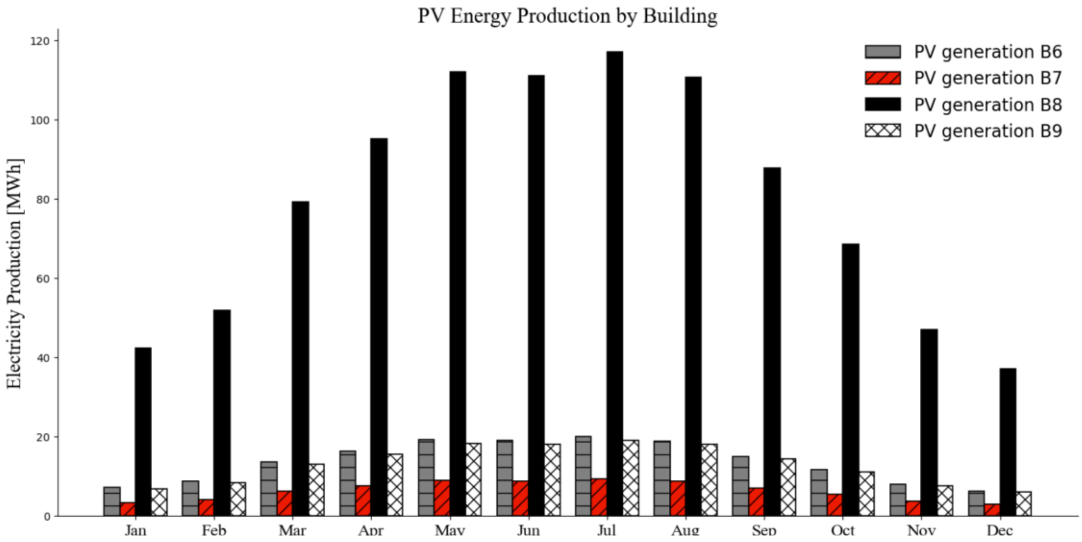


Figure 22: Representation Energy demand comparison for electricity between baseline and scenario PED (full-renovation).

The outcomes of the simulated electricity demand for the PED scenario (full-renovation), include an important reduction equal to a – 48.50% for the months of June and significant reduction of the energy demand during winter months, especially in November and December, thanks to the fully electrification of the heating and cooling system. Additionally, in the months from April to September photovoltaic production exceeds the district energy demand of the baseline scenario.



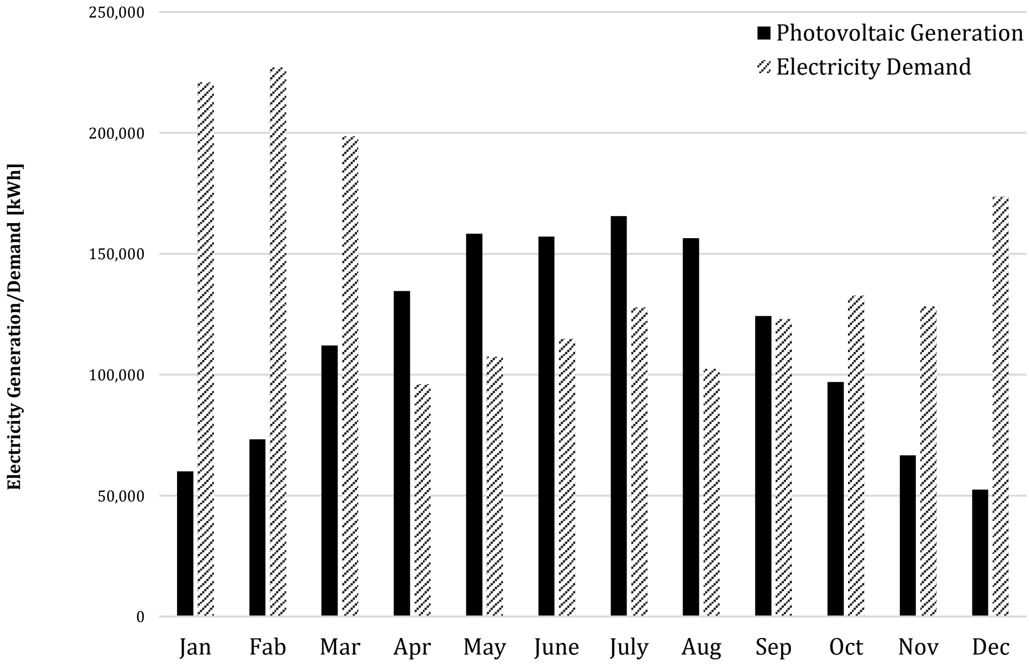


Figure 23: Representation Energy production from PV per building (up), and the photovoltaic generation versus the electricity demand for the entire district

3.3.7 Life Cycle Assessment and Environmental Study

The environmental impacts were evaluated following the Life Cycle Assessment methodology. Therefore, the categories of impact were reported in Figure 24 and Figure 26, comparing the two scenarios of interest: the baseline and the fully renovated scenario since now on named "PED".

In the PED scenario, there is a clear reduction in Global Warming Potential, mainly due to the de-creased reliance on natural gas and improved energy systems, even if electricity imports still contribute significantly. However, acidification and eutrophication impact slightly increase, primarily due to the material and energy demands of thermal plant renovation and insulation

installations. Notably, photochemical oxidation sees a mild reduction yet retrofitting processes like windows and cork insulation remain visible contributors.
This suggests that while PED strategies are effective in reducing carbon emissions, trade-offs exist in other environmental categories.
For example, Eutrophication potential registers an increase of 52~53% in the PED scenario.
This increase is likely associated with up-stream processes and material manufacturing impacts, introduced by the renovation interventions.
The Global Warming Potential is significantly reduced, showing an almost 50% decrease compared to the Baseline Scenario.
This improvement is largely attributed to enhanced thermal performance, complete electrification, and the integration of renewable energy sources, while, for Acidification and photochemical Oxidation, the results indicate mixed trends: a slight increase in acidification and a modest reduction in photochemical oxidation, due probably to the reduced use of resources in the use phase (Table 13).

Table 13: Main takeaways of the LCA for the PED scenario.

Impact Category	Main Contributors in PED Scenario	Observations
Global Warming Potential (GWP)	Electricity Import, Natural Gas, Cork Insulation, Windows Replacement.	GWP is significantly reduced in the PED scenario; insulation and efficient systems help.
Acidification	Electricity Import, Thermal Plants Renovation, Windows & Cork Insulation.	Slight increase in total impact, mainly due to thermal plant renovation emissions.
Eutrophication	Electricity Import, Thermal Plants Renovation, Windows Replacement.	Increased impact compared to baseline, driven by retrofit-related activities.
Photochemical Oxidation	Electricity Import, Cork & Windows Replacement, Thermal Plants Renovation.	Reduction overall, but visible contributions from renovation processes.

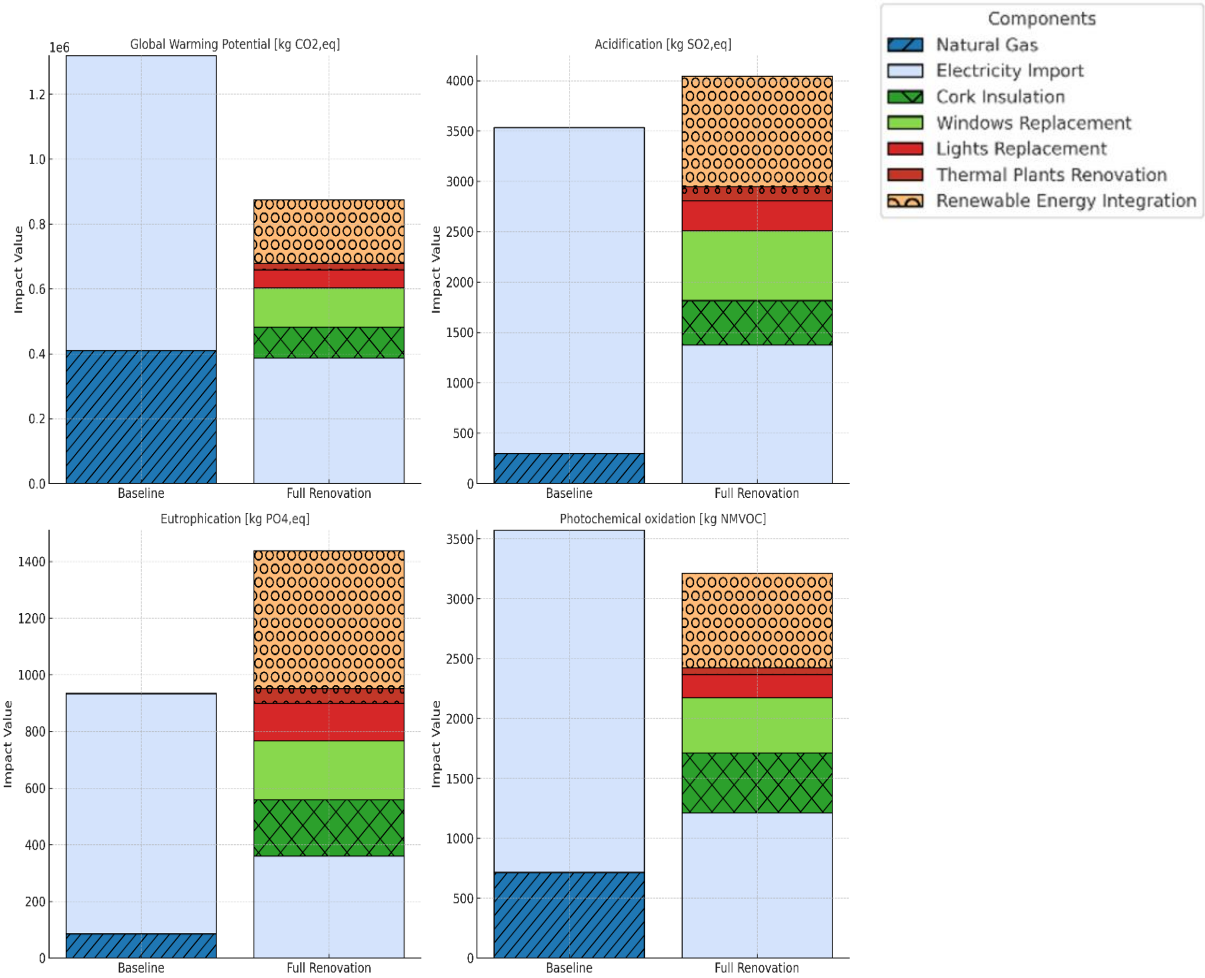


Figure 24: Representation: Single score baseline vs. PED scenario for categories Global Warming Potential, acidification, eutrophication and photochemical oxidation.

As evident from Figure 24 and Figure 25, the single score plots for the different components show that higher impacts on photochemical oxidation, abiotic depletion (elements and fossil fuels), water scarcity and ozone layer depletion are to attribute at the cork insulation material and the thermal plant renovation.
Furthermore, in the cases of acidification, eutrophication, abiotic depletion (and elements) and ozone layer depletion, the fully renovated scenario presents higher values of cumulated impacts.

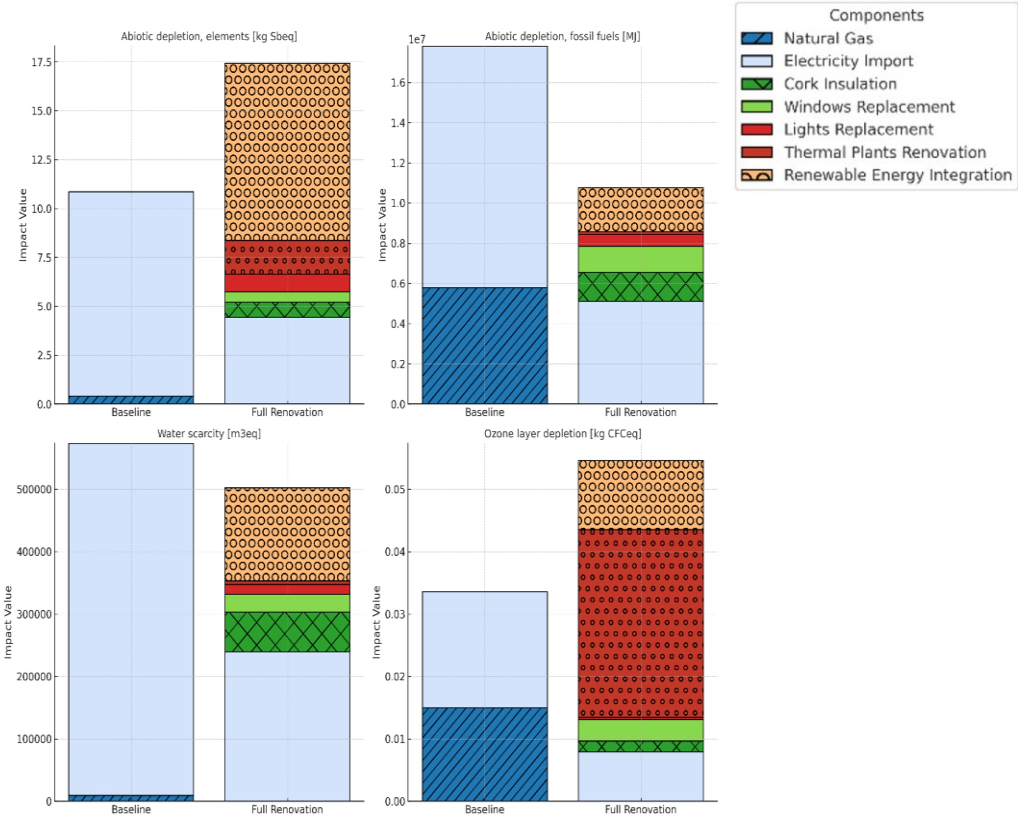


Figure 25: Representation Single score baseline vs. Full Renovation scenario for the impact categories Abiotic Depletion (elements and fossil fuels), water Scarcity and ozone layer depletion.

Furthermore, it is evident how the cumulative energy demand from the fully renovated district compared to the baseline, shows the extent of the reduction in imported electricity achieved in the PED (full renovation) scenario (Figure 26).

Figure 27 shows the impact categories for the different scenarios, normalised on the baseline impact categories values. Values below 1 identify that the PED energy efficiency scenario could be achieved but having some major impacts. In fact, for abiotic depletion of elements and ozone layer depletion, a marked spike can be observed, likely due to the materials and technologies involved in deep renovation (such as insulation, electronic systems and refrigerants). Overall, while the PED model supports decarbonisation goals, it highlights the need for careful material selection and circular strategies to minimise burden-shifting across environmental categories. The PED full-renovated scenario in green, despite impacting less for come categories like global warming potential, photochemical, abiotic depletion (fossil fuels), water scarcity and for the cumulative energy, for the others like ozone layer depletion, abiotic depletion (elements), eutrophication and acidification, shows marked spikes, needing a careful attention when evaluating the environmental issues connected with renovation choices of the positive energy district in exam. As evident, the area filled-in with gray colour represents the contours of the baseline values for the selected 9 indicators. It is evident that for cumulative energy demand and global warming the PED scenario is always below certain value, making it less impactful.

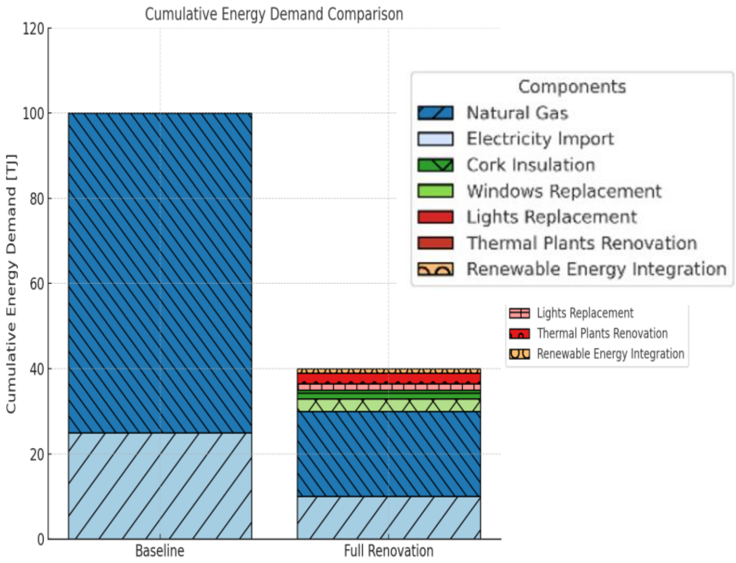


Figure 26: Cumulative energy demand comparison between the full renovation scenario and the baseline scenario.

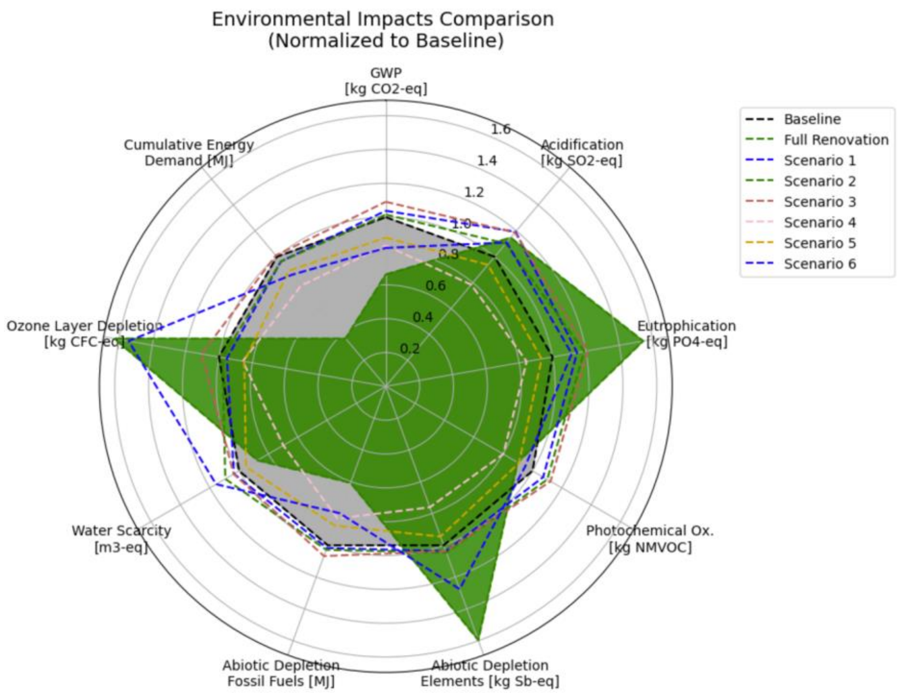


Figure 27: Impacts categories for all scenarios normalised on the baseline impacts categories, including the full Renovation (PED) one.

3.3.8 Positive Energy District balance and respective targets' achievement road to PED assessment

From an environmental performance perspective, detailed assessment of each renovation strategy - evaluated on an annualised basis and disaggregated by individual impact category (Figure 28) - reveals critical trends. Electricity import consistently emerges as a dominant contributor across all nine environmental impact categories analysed. In contrast, as previously discussed, thermal plant renovation exhibits a marked influence specifically on ozone layer depletion, indicating a localised but significant environmental burden.

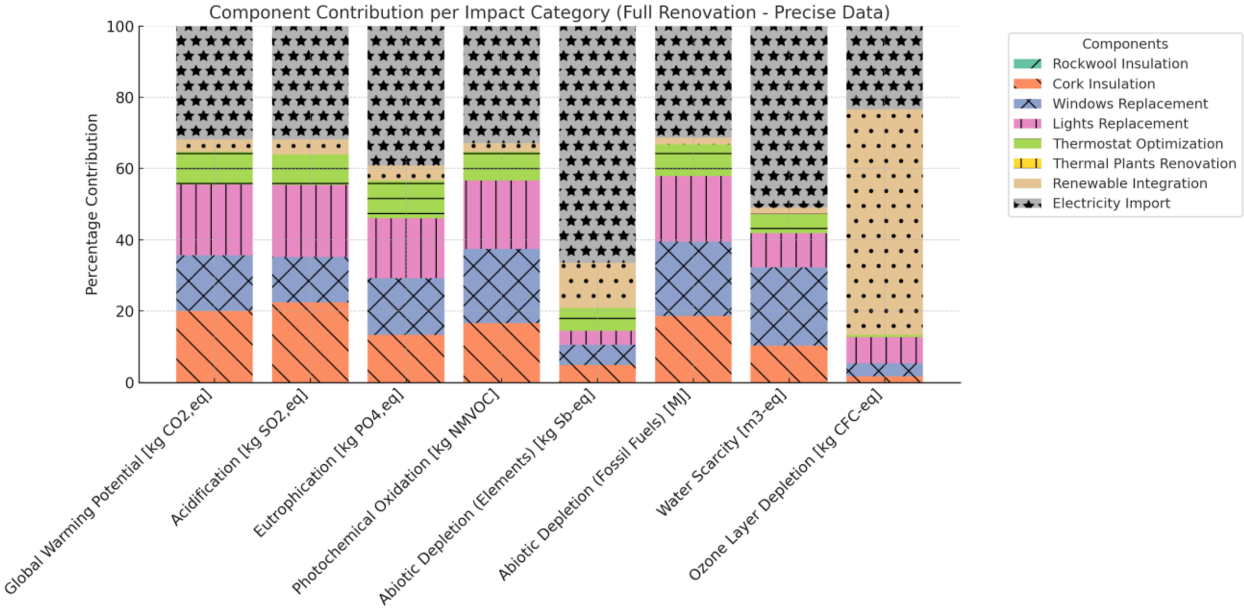


Figure 28: Dominance analysis of the different component contribution per impact.

As shown in Figure 28, electricity import emerges as the dominant contributor across several categories, most notably in GWP, Photochemical Oxidation, Abiotic Depletion (Fossil Fuels), and Water Scarcity, highlighting the persisting dependence on non-renewable electricity during the operational phase despite energy efficiency efforts. This underscores the importance of aligning PED retrofits with decarbonised energy grids to fully realise climate neutrality objectives. In contrast, materials such as Cork Insulation and Windows Replacement significantly impact GWP, Eutrophication, and Photo-chemical Oxidation, emphasising the embodied environmental costs of envelope upgrades, even when sourced from biogenic or recyclable materials.

Additionally, Renewable Integration, while crucial for reducing operational emissions, shows a non-negligible contribution to Abiotic Depletion (Elements) and Water Scarcity, likely attributable to mineral-intensive technologies such as photovoltaics and associated electronics. Similarly, Lights Replacement and Thermostat Optimisation, though less intensive overall, contribute visibly to categories like Abiotic Depletion (Fossil Fuels), reflecting upstream manufacturing impacts.

These results highlight the multi-dimensional nature of environmental trade-offs in deep renovation strategies. While the PED approach achieves substantial reductions in energy demand and carbon intensity, as previously shown in the deviation and spider web plot (Figure 27), the material intensiveness of the retrofit introduces burdens in resource-related categories. Thus, the case study reinforces the necessity of integrating life cycle thinking into renovation planning, advocating for low-impact material choices, supply chain transparency, and an eventual transition to fully renewable and circular energy systems to avoid problem-shifting across environmental domains.

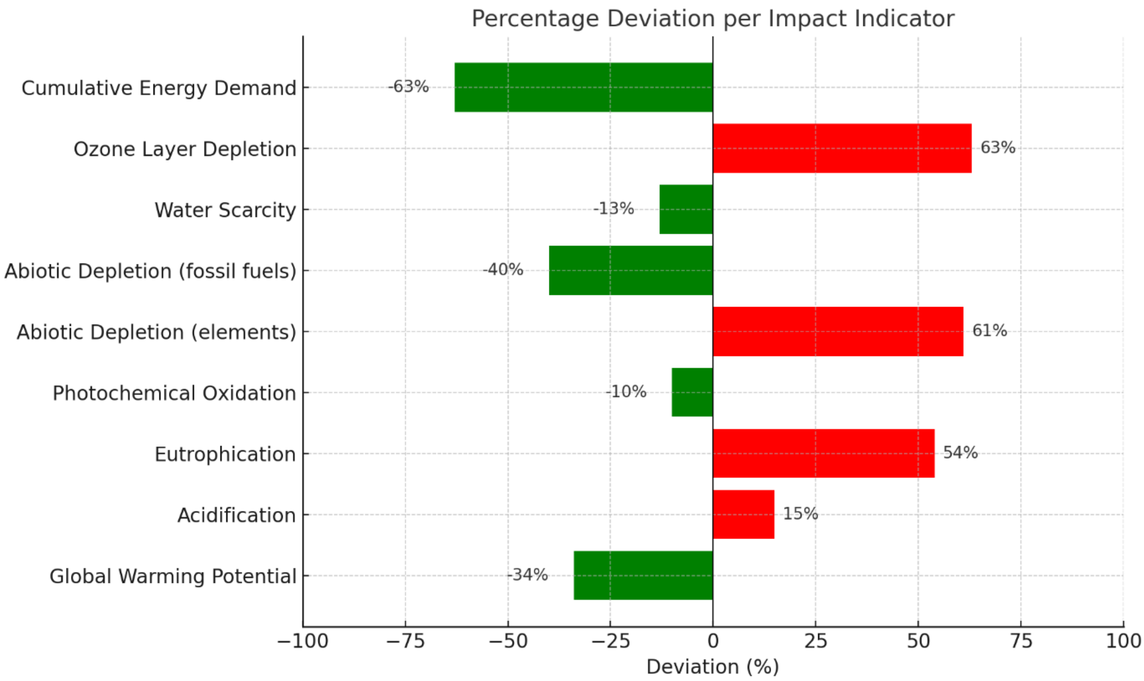


Figure 29: PED scenario with the analysis of the annualised environmental indicators percentage variation compared to the baseline (0%).

The trade-offs associated with the Full Renovation (PED) scenario are well showcased when compared to the baseline ("0%", in Figure 29). Most notably, the cumulative energy demand exhibits a substantial 63% reduction, indicating the scenario's effectiveness in decreasing total energy consumption through efficiency measures and renewable integration. Similarly, global warming potential is reduced by 34%, highlighting a meaningful decline in greenhouse gas emissions, alongside moderate reductions in water scarcity, fossil fuel depletion, and photochemical oxidation. These improvements globally underscore the PED scenario's contribution to climate mitigation and resource conservation. However, these gains come at a clear environmental cost. The most concerning impact is a 63% increase in ozone layer depletion (remarkably high in Figure 28), suggesting the use of materials or processes that involve ozone-depleting substances - potentially linked to insulation foams, refrigerants, or manufacturing inputs. Additionally, abiotic depletion of elements rises by 61%, revealing a higher demand for non-renewable mineral resources, likely due to the embodied impacts of advanced building materials and technologies. Eutrophication and acidification also increase, though to a lesser extent, indicating additional nutrient and acidic emissions possibly associated with construction activities or material production. In sum, while the PED scenario achieves significant progress toward energy and climate goals, it also introduces environmental burdens in terms of resource extraction and atmospheric emissions, emphasising the need for more circular and low-impact material strategies in future retrofit planning.

3.3.9 Discussion

The findings obtained for the selected case study focusing on the combined evaluation of PED targets and the environmental Life Cycle Assessment for these four non-residential buildings representative of a district in a southern Mediterranean university campus, are at the kernel of this lesson learned and are the results of the implementation of the environmental framework. This approach, studying in detail the material selected and used for the renovation showed particularly functional, delivering the following takeaway messages:

- Global Warming Potential and Cumulative Energy demand vary from -34% to -63% as in Figure 29, reinforcing the need for a careful evaluation and contextualised selection of the indicators to interpret;

- Renovation shows not to entail certain environmental prices when selecting high energy efficient material, like the cork, impacting significantly on the water-related compartment (Figure 28). This remarks the need of a thorough scrutiny of the material to renovate the building and their synergistical environmental impacts;
- The interplay with building energy performance analysis and Life Cycle Assessment to capture the full environmental trade-offs of Positive Energy District (PED) scenarios grants a better environmental-informed decision when decision makers have access to these studies in the planning and feasibility phase of the retrofit of entire neighbourhoods;
- The implementation of energy solutions (e.g., installing PV fields on public land) may generate socio-environmental conflicts, such as changes in land use that affect community spaces. These indirect consequences highlight the need for assessment tools that can integrate social dimensions into environmental and energy evaluations;
- Environmental trade-offs go beyond the technical dimension, involving socio-ecological dynamics that standard tools may fail to capture (as in the life cycle thinking approach) urging to define robust and standardised methodology to follow and compare, creating “libraries” as benchmarks.

The environmental framework applied in the case of the campus of the University of Palermo, gives the opportunity to deliver a high-end Strengths Weaknesses Opportunities Threats (SWOT) analysis. The Strengths Weaknesses Opportunities Threats (SWOT) analysis provides a comprehensive evaluation of the environmental approach.
Among the strengths, the method stands out for its replicability, owing to its linear and modular structure, and for the use of monitored data, which enhances credibility and site-specific relevance. Scenario-based flexibility enables the selective variation of input parameters, and adherence to the EPD (Environmental Product Declaration) framework ensures familiarity and acceptance in professional and academic domains. Additionally, reliance on validated commercial software contributes to standardisation and partial resolution of third-party verification challenges.
However, several weaknesses constrain the robustness and scalability of the approach. The main is the high demand for monitored data, which can hinder implementation when such data are scarce or costly to collect. Software/tools costs also pose barriers, especially for institutions without access to advanced commercial platforms. Further complications arise from the subjectivity in interpreting impact results, variability in emission factor selection, and the overall time-consuming nature of data collection and item selection.
Despite these limitations, the methodology presents several promising opportunities. It facilitates environmentally-informed decision-making and supports a holistic, interdisciplinary approach that fosters systemic thinking. This approach also enables feasibility studies on environmental impact during early project planning stages, helping to mitigate risks associated with outdated or environmentally harmful solutions.
On the other hand, threats mainly revolve around data inventory reliability and accessibility. The aggregation of real data and discrepancies in commercial databases can compromise consistency and reproducibility. Updates and changes in database entries may lead to incompatibilities across studies, weakening comparability and third-party validation. Finally, software-specific limitations, such as inconsistencies in selecting equivalent materials or emission factors, introduce methodological uncertainty that must be addressed through rigorous cross-referencing and transparent documentation.
In conclusion, the SWOT analysis reveals that while modular and replicable scenario-based environmental assessments enhance methodological robustness, persistent issues like limited data availability, reliance on commercial software, possible expertise assumptions and biases, the need of commercial soft-ware (or at least database) and time-consuming analysis processes pose significant barriers. A holistic evaluation would balance technical accuracy with stakeholders’ engagement, encompassing their needs and social acceptance indicators.

3.3.10 Conclusions

This study has examined the feasibility of retrofitting a representative university district in southern Italy with the ambition of aligning it with the Positive Energy District framework within a one-year operational timeframe as a lesson learned to work as benchmark for further study cases replicating the same methodology. The implementation of the life cycle assessment approach enriched the energy performance analysis, with a structured scenario-based

comparative study. Implementing a set of targeted energy retrofit strategies—including thermal envelope enhancements (both opaque and transparent), lighting system upgrades, and integration of efficient electrical equipment— produced a substantial reduction in operational energy demand, despite not being capable of offsetting (solely with extensive use of installed PV fields), the reliance on the power distribution grid.
Results show that a rigid application of a mere PED mathematical balance may neglect significant environmental aspects which may worsen even significantly in the effort of achieving a positive energy balance.
In detail, results demonstrate that while scenarios like thermal insulation and lighting upgrades contribute positively to operational efficiency, they may also introduce substantial embodied burdens. Likewise, PED scenario (full renovation), showed, despite being energy efficient, high values of ozone depletion indicator.
The environmental trade-offs emphasised too the critical importance of material selection and eco-design. For instance, the cork insulation scenario achieved notable reductions in GWP and Cumulative Energy Demand (CED), but scenarios involving intensive HVAC replacement exhibited negative deviations in ozone depletion metrics.
Ultimately, this research advocates considering PEDs not as a static objective, but as an evolving system requiring multidimensional optimisation. The district should be viewed as a dynamic energy-environmental ecosystem rather than a set of discrete buildings, considering the surroundings and the possible impact on the biome. Therefore, future approaches must account for energy flows, environmental burdens, and socio-urban interactions simultaneously, considering the possible analysis of how different scenarios might actually have an impact on the ecosystem of the urban areas to plan possible mitigating actions.

Authors

Emilio Sessa, University of Palermo, Italy, emilio.sessa@unipa.it
Alberto Brunetti, University of Palermo, Italy, alberto.brunetti@unipa.it
Lorenza Di Pilla, University of Palermo, Italy, lorenza.dipilla@unipa.it
Lorenzo Ilardi, University of Palermo, Italy, lorenzo.ilardi@unipa.it
Roberta Rincione, University of Palermo, Italy, roberta.rincione@unipa.it
Sonia Longo, University of Palermo, Italy, sonia.longo@unipa.it
Maurizio Cellura, University of Palermo, Centre For Sustainability and Energy Transition (UNIPA), Italy, maurizio.cellura@unipa.it
Francesco Guarino, University of Palermo, Italy, francesco.guarino@unipa.it

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4. Social impact assessment of Positive Energy Districts

4.1 State-of-the-art of PED social assessment

4.1.1 Methodologies

Sustainability is recognised as a crucial aim in pursuing the development that leads society to environmental balance and social justice. Elkington's "Triple Bottom Line"(TBL) strategy (1997) is widely recognised as a key source for the three-pillar concept of sustainability, encompassing economic viability, social responsibility, and environmental impact. Despite being constantly overlooked, the social dimension of sustainability is vital to address and secure human well-being. Moreover, policies focusing on stakeholder collaboration and on the social aspects of a district, have been found to be instrumental in developing successful PED case studies (Derkenbaeva et al., 2022). Nevertheless, specific methods for assessing social sustainability for PEDs are lacking in research.

Several benefits can be drawn from a PED, such as enhanced social cohesion, improved energy literacy, the development of social networks, the promotion of global partnerships, and reduced energy poverty (Gjorgievski et al., 2021). In addition, urban energy systems directly affect the well-being and happiness of urban inhabitants. While it generates energy within the city, it improves energy efficiency and achieves carbon neutrality, relying on citizen involvement (Kammen and Sunter, 2016). Consequently, social inclusiveness and participation of various stakeholders are important success factors in establishing citizens-centric carbon-free energy solutions. However, in the context of energy communities, a quantitative framework for evaluating the social impacts and benefits is missing.

Thus, a literature review to map the existence of initiatives to assess the social sustainability of PEDs and PED-related projects was conducted in order to deepen the understanding. The platforms Web of Science, Scopus and Research Gate were consulted using the string that contained the keywords combination: “Positive Energy Districts” or “Positive Energy Neighbourhoods”, followed by the keywords “social” or “social aspect” or “social sustainability” or “social impact” and “Open Access” to narrow the scope. The defined time frame was from 2016, as this literature review is state-of-the-art, until 2021 when the search was conducted. Therefore, existing studies addressing main themes related to the concept and definition of PED are also presented here. The literature review entailed creating a harmonised set of KPIs and social impact categories, and identifying relevant stakeholders, in order to support future social assessments of PEDs. Based on the review of the literature and the 24 PEDs from the JPI UE PED Booklet (Gollner et al. 2020), the social impacts identified and defined are presented in the following sections. Several positive or negative social impacts in general ultimately aiming at the well-being of people are presented in Table 14.

Table 14: Social impacts of PED

Impact category	Change through PEDs	Nature: Positive/Negative	Source
Community policing/security	improved	positive	(Shnapp et al. 2020)
Crime rates	reduced	positive	(Shnapp et al. 2020)
Common community purpose/a sense of community	building among Inhabitants	positive	(Shnapp et al. 2020; Hearn and Castaño-Rosa 2021)
household incomes	increased	positive	(Shnapp et al. 2020)
local circular economy (in tourist areas)	boosted	positive	(Shnapp et al. 2020; Hearn and Castaño-Rosa 2021)
labour productivity	increased	positive	(Gouveia et al. 2021)
Employment opportunities	increased	positive	(Shnapp et al. 2020)
opportunities for entrepreneurship	increased	positive, as a social benefit	(Uspenskaia et al. 2021)
modern urban services	accessible	positive	(Uspenskaia et al. 2021)
well-organised recreational area	accessible	positive, as a social benefit	(Uspenskaia et al. 2021)
Inhabitants' life quality /living condition	improved	positive	(Shnapp et.al 2020, Gouveia et al. 2021, Haarstand and Wathne 2019, Bisello 2020, Uspenskaia et al. 2021)
The mental health of residents	enhanced	positive	(Hedman et al. 2021; Gouveia et al. 2021)
Social acceptance	increased	positive	(Hedman et al. 2021)
Social inclusiveness	increased	positive	(Hedman et al. 2021)
Indoor comfort	improved	positive	(Hedman et al. 2021)
The well-being of inhabitants/ vulnerable families	improved	positive	(Hedman et al. 2021; Hearn and Castaño-Rosa 2021)
Social cohesion	increased	positive	(Hedman et al. 2021)
Energy poverty	Expected mitigation	both, depending on the district's situation	(Haarstand and Wathne 2019; Hearn et al. 2021; Gouveia et al. 2021; Hedman et al. 2021)
awareness	raising	positive	(Haarstand and Wathne 2019)
citizen engagement, supporting engagement	increased	positive	(Giourka et al. 2020, Haarstand and Wathne 2019)

Gentrification (for those vulnerable groups)	may be exacerbated	negative	(Hedman et al. 2021, Gouveia et al. 2021; Yazar et al. 2020)
consensus among stakeholders	difficult to achieve	negative	(Shnapp et.al 2020, Hearn and Castaño-Rosa 2021)
energy illiteracy, lack of awareness	barriers in PEDs	negative	(Hearn and Castaño-Rosa 2021)
passive participation of citizens	increased	negative	(Nguyen and Batel 2021)
lack of trust	Increased between stakeholder	hindering development	(Hearn and Castaño-Rosa, 2021)

Among the 24 PED projects, a total of 15 projects summarised their respective social impacts and expectations, with no adverse impacts included. Apart from the positive impacts of the two already running projects, the remaining 13 projects express high expectations for PED deployment. In addition to the ultimate impact of improving people's standard of living and well-being, almost half of the projects considered the impact of accessibility, including access to local services, amenities, mobility, and local infrastructure. Job creation through PED has also been demonstrated in the operation stage.

The importance of the social dimension and respective measuring indicators for cities and communities have been recognised internationally through standards and initiatives such as the UN Sustainable Development Goals, ISO 37120 - Sustainable Cities and Communities -Indicators for City Services and Quality of Life, and the United Nations Economic Commission for Europe (UNECE). The SDGs set the international agenda to make cities and human settlements inclusive, safe, resilient, and sustainable and define indicators to, among others, ensure access to adequate, safe, and affordable housing and basic services and upgrade slums, provide access to safe, affordable, accessible and sustainable transport systems for all, enhance inclusive and sustainable urbanisation and capacity for participatory, integrated and sustainable human settlement planning and management. The UNECE endorsed a set of indicators under the dimension of Society and Culture to address Education, Health, Culture, Safety, Housing, and Social inclusion categories.

The authors also address social innovation structures related to citizen-led energy transitions (Walker et al., 2010), and how government responds to them (Warbroek and Hoppe 2017). It is of course worth stating that informed and engaged 'Positive Energy Citizens', as PED residents, can significantly impact the energy performance targets, by managing to articulate demand while maintaining the Indoor Environmental Quality IEQ goals within the energy production profiles at the district level. They contribute to shaping the district's energy performance to a positive energy balance within a specific timeframe and might be able to react and adapt their energy needs towards PED energy limits. This implies significant attention to household and social practices under varied and specific cultural, climatic, and boundary conditions.

The conventional approach tends to set up a dominant ideal energy consumer, a characterised 'persona' who is intended to develop functional and rational decisions about her energy uses in the function of the building typology. Academic studies (Stephenson et al., 2010) refer to the disruption of this concept of the ideal consumer. Energy demand also implies significant agency by households and energy communities. This is limited and is subject to broader societal expectations that are constantly changing and inevitably ramping up; over the past few decades alone, expectations of cleanliness, comfort, and convenience have changed rapidly, and individual households and single communities, however, committed, cannot remain unaffected by these wider societal trends. Social scientific energy research may support accommodating users' diversity in the Social Impact Assessment processes of PEDs communities. The adoption of frameworks and methodologies such as the Energy Cultures Framework (Stephenson et al., 2010) or Time Geography research (Ellegård, 2018) could be useful and bring new ways of understanding the social implications of PEDs and how to integrate those into a comprehensive Impact Assessment of Key Performance Indicators (KPI) Framework for PED.

Methodologies for sustainable city indexes and green building schemes have been developed incorporating defined social performance indicators. Based on KPIs in the social and human dimensions under the KPIs framework reviewed in the previous section, 56 KPIs were collected, from the JPI PED projects and KPIs from other reviewed literature. An analysis and mapping of the social issues and common KPIs resulted in a harmonised list of KPIs as presented in Table 2 of the appendix. These KPIs were identified through stakeholder needs and the specific scope of urban interventions and are compared through relevant evaluation frameworks and monitoring databases (Angelakoglou et al. 2020).

The level of integration of indicators varies greatly from one methodology to another (Akande et al., 2019) e.g., A set of KPIs expressed in monetary units, for smart cities based on the Gross Social Feel-Good Index, (Bosch et al. 2017) which includes 13 Society and Culture KPIs as part of a framework that intends to assess and rank cities based on how smart and sustainable they are. The "people" dimension is one of the 5 dimensions embedded in this framework developed under the EC CityKeys project (Angelakoglou et al., 2020).

From the perspective of social sciences, there is also a broad spectrum of indicators and indices relating to environmental aspects and their direct or indirect impact on human well-being. However, no studies addressing specific social science indicators related to PEDs were found. Here, social science aspects are considered for PEDs building upon the relationship between the environment and all it may contain and its effects on human life as a whole.

Moser (2005) states that Environmental Psychology analyses people's perceptions, attitudes, and behaviours concerning the social and physical context on four levels: 1) Microenvironment (private spaces); 2) Proximity Environments (working place, parks, neighbourhood, etc.); 3) Public and collective environments (cities, villages, etc.); 4) Global environment comprising the totality of the world and everything it contains. Also, Environmental Psychology pertains to a broad spectrum of sciences including Environmental Engineering, Urban Planning, and Human Ecology, among others.

Among the different characteristics an environment encompasses is the quality of being restorative providing well-being and health to people surrounding it. Restorative environments are those that allow a respite in someone's attention resulting in mental fatigue reduction (Alves, 2017). A particular place is restorative when a person gains psychological distance from the demands of daily life and engages instead with something pleasant and interesting (Collado et al., 2017). Several places in an urban city can be considered as restorative, such as large recreation areas, pocket parks, a garden, a room with plants, or even looking out the window to a street with trees bouncing jointly with the wind. Therefore, restorative environments can play a crucial role in promoting quality of life, well-being, and health in a citizen-friendly urban space.

The concept of affordances relates to the quality or stimulus that an object transmits to an organism (Lewin, 1975; Gibson, 1986). From the first definition of affordances, many studies have been developed exploring how humans experience the landscape and the relevance of this to people's attitudes, behaviours, and ultimately to well-being. A key element of landscape perception is how people make sense of the environment and what it offers, and in turn, processes that form the basis of environmental perception, aesthetic landscape, and appreciation are dealt with by theories of landscape perception and preference (Thompson, 2018).

Also, in the Environmental Psychology approach, spatial structure arises as an environmental physical aspect in which the space with all it contains is organised promoting or hindering human appropriation, interaction, and development (Campos-de-Carvalho, 2008). In the same direction, spatial policies are an important measure when tackling mobility and energy consumption reduction issues by deepening understanding of citizens' needs and mobility to better place spatial coordinates such as homes, locality of work, and other facilities (Meurs & Haaijer, 2001).

4.1.2 Results analysis

Frameworks and methodologies to assess the social performance of cities, communities, and similar human settlements have been designed according to the different scopes in which these sets of indicators are used and serve to further analyse the overall impact of specific urban design principles. Each method or approach has its advantages and disadvantages and can be based on qualitative and/or quantitative assessments. Social Impact Assessment (SIA) includes the processes of analysing, monitoring, and managing intended and unintended social consequences -both positive and negative planned interventions, as well as any social change processes caused by them, ex-ante and ex-post (IAIA, 2013).

Regarding the assessment of social impacts, further measures should be envisaged in the framework to solve some conceptual gaps for a socially sustainable design. The review finds that, in some pilot projects, more attention is paid to citizen involvement during the planning phase than in others. Some critical issues concerned the involvement during the operational phase of the district and the difficulty of citizens in sharing their needs with planners and governors to request corrective or adaptation actions.

To achieve the SDG "making cities and human settlements inclusive, safe, resilient and sustainable leaving no one behind", it is essential that government policies set up adequate measures to combat green gentrification. Although specific KPIs are used to evaluate the phenomenon in some cases, this issue is not sufficiently discussed in the context of the experiences of innovative districts reviewed and stemmed through tailor-made solutions, such as citizen empowerment.

The social sustainability concept has evolved into a multi-layered complex and triggered an integrated network of stakeholders (Gollner et al., 2020). Coming originally from sustainability sciences, it is integrated into social sciences in an intrinsic way, which brings together several subjects into play, such as sociology, psychology, and anthropology, among others. Examples of methodologies coming from social sciences are the sociology of work (Grint, 2005) and work psychology which offer a rationale for understanding and investigating working conditions and social impacts on workers (Arnold, 2005). Environmental psychology provides methods to analyse the effect of the environment on people, creating a restorative and beneficial result for them (Collado et al., 2017). Finally, it is possible to mention methods from anthropology on how to investigate specific populations, considering their culture, values, etc., such as ethnography (Bjerregaard, 2011).

Each and every of them can bring important theoretical and methodological background to be applied to social sustainability, however, none of them comprise a comprehensive framework to assess social impacts on different stakeholders (Chabrawi et al., 2023). On the other hand, Social Life Cycle Assessment (S-LCA) is a methodology to assess the social impacts of products and services across their life cycle, offering a systematic assessment framework that combines quantitative as well as qualitative data, aiming ultimately for the well-being of stakeholders (UNEP, 2020). S-LCA is one of the three methodologies to assess the sustainability of the three pillars, focusing on the People Pillar (UNEP, 2020).

The approach is largely based on the framework of ISO 14040 and 14044 and comprises the social dimension of the LCSA, together with LCA and LCC. It entails several stakeholders, covering a wide variety of social topics that are interlinked to different social sciences, bridging the scopes among sustainability and social sciences (Chabrawi et al., 2023). Moreover, S-LCA is founded on international standards such as the norms and conventions of the International Labour Organization (ILO), and United Nations Children's Fund (UNICEF), when addressing the stakeholder workers, and children, respectively. Furthermore, S-LCA is also contemplated with a dedicated ISO norm (ISO 14075), in which the principles and framework for S-LCA are established, providing a consistent and standardised background, also based on knowledge yielded from social sciences to understand and measure the social phenomena.

Given the above-mentioned outcomes of the review, it is possible to conclude that aspects of social sustainability and its respective assessment methodology are lacking specifically in PED research. Methodological developments and case studies applying the Social Life Cycle Assessment (S-LCA) approach are clearly missing despite the more than 10 years of activities from the publication of the 2009 UNEP SETAC Guidelines of S-LCA of Products. The energy and in particular renewable energy relevance in PEDs indicate the importance of assessing social impacts across the entire life cycle.

4.1.3 Research gaps and conclusions

Although the KPI frameworks reviewed earlier are quite comprehensive, they do not systematically assess PEDs as complex, fully integrated developments. They also lack considerations for sustainability and life cycle assessments of PEDs. Furthermore, the defined indicators primarily focus on monitoring and evaluating specific technologies and actions within a particular Smart Cities and Communities SCC project rather than addressing sustainability and interdependencies within broader PED urban development.

Despite extensive research on social dimensions in energy projects and PED development, further efforts are needed in planning and designing socially sustainable PEDs, as well as in developing methodologies and indicators for assessing social sustainability. To advance these areas, it is essential to examine social, behavioural, and organisational barriers that hinder public support for Positive Energy Developments. Additionally, a more multidisciplinary approach—incorporating socio-technical, anthropological, cognitive, and behavioural perspectives—should be explored and tested to foster truly sustainable PED developments.

In this sense, it is recommended the application of S-LCA as a robust approach to contemplate the multi-diverse complexity of the social phenomena within a PED. The method is embedded in consistent methodological backgrounds coming from various social disciplines, benefitting from years of study and development coming from each field. Moreover, S-LCA is intrinsically aligned with international norms and standards, such as those coming from ILO, and has been largely organised and systematised by the UNEP/SETAC (2009) and UNEP (2020) Guidelines, and standardised by ISO 14075, granting consistency and robustness to the approach.

Regarding the scope of assessment of a PED, in general, all life cycle stages of the PED shall be considered: Acquisition and extraction of raw materials, construction/development of the PED, use of PED, and deconstruction/decommissioning. In addition, the supply chain of related materials and components should be included with a special focus to the energy and construction sector. An assessment of the mobility sector should be carried out depending on the goal of the study and other specific aspects including geographical location.

Authors

Rose Nangah Mankaa, Institute of Sustainability in Civil Engineering, RWTH Aachen University (rose.mankaa@inab.rwth-aachen.de)

Arij Mohamad Radwan Omar Chabrawi, Institute of Sustainability in Civil Engineering, RWTH Aachen University (arij.chabrawi@inab.rwth-aachen.de)

Marzia Traverso, Institute of Sustainability in Civil Engineering, RWTH Aachen University, Germany (marzia.traverso@inab.rwth-aachen.de)

4.2 Methodological framework for social impact assessment

4.2.1 Introduction

This document provides rules for the assessment of the social impacts of Positive Energy Districts (PEDs) and follows the framework of Product Category Rules for the environmental assessment of products. These rules make up a Social Impact Assessment Framework of PEDs (SIA Framework) and are meant to support practitioners in presenting transparent, consistent, and verified information about the social sustainability performance of PEDs or PED-related components. It should enable different practitioners to generate consistent results when assessing PEDs from humanities and social perspectives.

Social Life Cycle Assessment (S-LCA) has the ultimate objective of promoting the improvement of social conditions for all its stakeholders and achieving overall socio-economic performance (UNEP, 2020). The assessment considers positive and negative impacts on relevant stakeholders that occur in the entire life cycle of the product or service under study. There are four main stages in conducting S-LCA aligned to the Life Cycle Assessment (LCA) framework in ISO 14040/44 (2006): Goal and Scope Definition, Inventory Analysis, Impact assessment, and Interpretation. Moreover, the S-LCA methodology has been standardised by the recently published ISO 14075: 2024 (Environmental management — Principles and framework for social life cycle assessment) which builds on the LCA framework and recognises the fact that other tools can be combined with S-LCA to have a more extensive assessment of sustainability, such as Life Cycle Costing. S-LCA, according to ISO 14075, addresses the social impacts of products in line with major international agreements such as the Universal Declaration of Human Rights and the International Labour Organization (ILO) standards.

The rules provided in this SIA Framework are based mainly on the S-LCA methodology with the incorporation of tools and best practices developed in recent research activities relevant to PEDs, including but not limited to JPI UE activities, Energy culture, and Climate circular communities (ARV). Hence, the four steps of S-LCA for PEDs are illustrated in the following sections to guide the evaluation of social impacts over the entire life cycle of the PED. The entire life cycle of the PED must be considered, including the acquisition and extraction of raw materials, construction/development, use, and deconstruction/decommissioning. In particular, the implementation stage includes the construction of the buildings and other PED-related infrastructures.

4.2.2 Goal and scope definition

Goal and Scope (G&S) definition is the first phase of an S-LCA study where the purpose, the object, as well as the methodological framework, are determined. The objective is to provide a clear statement of the purpose of the study and define its breadth and depth. This is a crucial phase of the process, which will have a significant impact on how the study will be conducted and, ultimately, on the results. The G&S, and by extension the complete S-LCA, are often carried out iteratively – it may be revised due to unforeseen limitations, constraints, or because of additional information uncovered along the way. Such modifications made during the process, together with their justification, should be documented. In LCA, stakeholders' participation (stakeholders are defined as those affected in any way by the study and its results) in the development of the G&S is strongly encouraged. This is to ensure optimal decision-making at this crucial phase. In S-LCA, the importance of stakeholders is further strengthened by the fact that the social impact is assessed for various stakeholder categories.

4.2.2.1 Goal Definition

In defining the goal of the S-LCA various aspects must be considered with a focus on why the study has to be conducted. The answer to this question will also lead to the identification of the intended use(s), target audience, what needs to be assessed, the expected potential improvement, and the stakeholders involved. The goal(s) should be clearly defined to ensure successful outcomes. The goals sought by S-LCA case studies can vary. S-LCA applied to PEDs can examine potential social improvement options along the life cycle, support the sustainable planning, design, and implementation of PEDs by integrating social considerations into early-stage decision-making, help policymakers have a deeper knowledge of the city's alignment with sustainability, assess and compare the social impacts of PED models evaluating different PED designs to identify those that best promote inclusive urban development. These PED-specific S-LCA goals will ultimately lead to the identification of social hotspots within the PED pinpointing critical issues such as affordability, displacement risks, and unequal access to mobility and energy services.

4.2.2.2 Scope definition

The scope clarifies the object of the study and determines its methodological framework. It needs to be related to the goal of the study. For this purpose, and in the case of PEDs, the definition of PEDs and their function shall be stated. Consequently, the quantity of materials needed to develop the PED (reference flow) and the steps, activities, and organisations needed to comply with the functional unit (the product system) are defined. The scope definition shall also include the following as a minimum:

- Identifying which parts of the product system are part of the assessment (the system boundaries);
- Stakeholders included and affected, and the stakeholders' involvement strategy;
- Type of impact assessment method and impact categories and/or subcategories included;
- Data collection strategies (inventory indicators, data type, and data collection);
- Data quality requirements (reliability, completeness, temporal and geographical conformance, etc).

The requirements related to these aspects in applying S-LCA to PEDs are provided in the following paragraphs.
The function defines what is offered by the investigated product or service, which in this case refers to the PED. Following the definitions of PEDs proposed so far, the close relationship to energy efficiency and renewable energy use is evident. PEDs might also incorporate housing and mobility solutions which form part of the function provided.

Table 15: Requirements and Definitions for PEDs

Requirements of PEDs	Possible definition
Highly efficient buildings	The building's thermal energy demand is at least 10% lower than the national standard.
Minimum use of the local renewable energy potential	The local potential of renewable energies is determined. A PED must use at least 60% of the local potential (as long as a net import of energy is necessary for the annual balance).
Support of the surrounding energy system	Implement one of the following measures with a minimum capacity concerning the peak load of x %: 1. establishing a mechanism for electrical peak shaving in the neighbourhood depending on external electricity availability - either by installing batteries - or by sector coupling (heat pumps with heat storage or controlled charging of e-vehicles) - or by-demand side management including a corresponding control system 2. provision of electrical storage or controllable loads to provide balancing power demand outside the neighbourhood

The function of the PED needs to be consistent with the G&S of the S-LCA and also informs the identification of the functional unit. The functional unit (FU) defines quantitatively the object of a study, whose magnitude can be fixed arbitrarily but constitutes an important choice in conducting the S-LCA of PEDs. Some authors have argued that it is difficult to link qualitative S-LCA indicators with functional units (Arcese et al., 2013, Hu et al, 2013). Literature on FU gives us an overview of functional units used in LCA studies at the neighbourhood and urban district scale involving energy and mobility aspects, highlighting their diversity and impact on comparability. François & Coulombel (2024) link FU to annual travel demand, while Quest et al. (2022) consider yearly neighbourhood energy supply. Neighbourhood-wide approaches, like those of Sigurðardóttir et al. (2023), Nematchouaa et al. (2019), and Lausselet et al. (2019), define FU at the neighbourhood level, with debates on whether FU should be per neighbourhood, per person, or square meter. Building-focused studies, such as the ones of Mastrucci et al. (2020) and Schildt et al. (2023), use FU based on building stock or specific metrics, like floor area. Palumbo et al. (2019) incorporate dimensional characteristics of blocks, while Alberti et al. (2019) and Lotteau et al. (2015) review FU variations in LCA studies. PEDs could be considered at the project level to avoid disaggregation that could prove meaningless in the social context. In light of this, it is recommended to consider the entire district in applying S-LCA to PEDs (i.e., one positive energy district initiative comprising buildings, infrastructure, and associated systems). The humanities and social function of PEDs should also be included in the FU definition through per capita considerations.

System boundaries define which parts of the life cycle and processes belong to the analysed system (Moltesen et al., 2018). Credible life cycle assessment will preclude the use of equal and consistent system boundaries. In general, all life cycle stages of the PED shall be considered: Acquisition and extraction of raw materials, Construction/development of the PED, Use of PED, and Deconstruction/decommissioning. This should be in line with the goal of the S-LCA, and any exclusion of life cycle stages shall be justified.

In addition, the supply chain of related materials and components should be included. Considering the characteristics and main function of a PED, it is recommended to include materials and components related to, at least, the energy and construction sectors. An assessment of the mobility sector should be carried out depending on the goal of the study and other specific aspects including geographical location. For example, during the manufacturing or construction stage of the PED, materials and components serve as key inputs. The assessment of their impact should not only focus on the construction stage but also consider their broader life cycle, spanning from extraction and production to disposal or recycling.

This requires evaluating the social impacts of these materials throughout their entire supply chain - from labour conditions in raw material extraction to manufacturing processes, transportation, and the eventual end-of-life management. Moreover, when considering the mobility sector, the impact of materials used in public transport infrastructure and vehicles must be explored, as these will have significant social consequences, such as the potential for job creation, impacts on local communities, and access to mobility services. The social effects of transportation infrastructure during its life cycle, particularly its role in increasing or reducing social inequality in the production stage of public buses, influencing mobility access in the local community where fuel is extracted should also be addressed. Any exclusions must be justified and transparently reported alongside its effect on the results.

The LCA framework requires the involvement of stakeholders in the scope definition, therefore the identification and definition of relevant stakeholders is important in establishing the scope of the study. JPI Booklet reviewing 61 PED and Towards PED projects (Gollner, et al., 2020) and other scientific articles identify citizens, municipalities, researchers, the building sector, and industry as the main stakeholder groups related to the main phases of a PED.

In summary, the above-mentioned major stakeholder groups are common for the planning, implementation, and operation phases of the PED, and their cooperation and communication influence significantly the development of each phase. Occupants, end-users, energy utility and transportation service companies, researchers, and architectural companies in one or more phases of the PEDs, as reported in Table 1 of the appendix.

Stakeholders play a key role in S-LCA, as the social impact is evaluated on Stakeholder Categories recommended and defined in the Guidelines and adopted in ISO 14075 (Table 16).

The stakeholders are classified under defined stakeholder categories and can be relevant in various PED life cycle stages. For example, the employees of the building and construction company can be classified under the Worker stakeholder category of the construction or implementation phase while the employees of municipalities in charge of maintenance fall under the same Stakeholder Category but in the operation phase. The Consumer stakeholder category comprises the residents and non-residents benefitting from the services provided in the PED while the Local community may refer to PED inhabitants as well as the neighbouring communities depending on the context of the study.

Table 16: Stakeholder categories and subcategories in the UNEP 2020 Guidelines

	Worker	Local community	Value chain actors (not including consumers)	Consumer	Society	Children
Subcategories	Freedom of association and collective bargaining Child labor Fair salary Working hours Forced labor Equal opportunities/discrimination Health and Safety Social benefits / social security Employment relationship Sexual harassment Smallholders including farmers	Access to material resources Access to immaterial resources Delocalisation and migration Cultural heritage Safe and healthy living conditions Respect of Indigenous rights Community engagement Local employment Secure living conditions	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights Wealth distribution	Health and Safety Feedback mechanism Consumer privacy Transparency End-of-life responsibility	Public commitments to sustainability issues Contribution to economic development Prevention and mitigation of armed conflicts Technology development Corruption Ethical treatment of animals Poverty alleviation	Education provided in the local community Health issues for children as consumers Children's concerns regarding marketing practices

To ensure a robust social assessment, each selected impact and subcategory from the Goal and Scope section must be linked to appropriate inventory indicators.
These indicators should align with the chosen impact assessment approach to accurately reflect social conditions (ISO 14075).
Social inventory indicators, also known as social flows, are measurable variables that represent specific aspects of a life cycle stage or process (Vanclay, 2002).
Common examples include salary levels and workplace accident rates, which provide direct evidence of social conditions. The selection of these indicators determines the type of data required for analysis (UNEP, 2020).
An initial list of 56 harmonised indicators for PEDs was established drawing from multiple sources to ensure comprehensive, robust, and relevant indicators (Table 2 in the appendix). The harmonised indicators were further validated by different methods.
At first, a hotspot assessment was carried out for the sectors of Construction, Energy, and Transport for all countries throughout the world, to verify which indicators represent a hotspot for these sectors. Hence, the harmonised indicators which correspond to the indicators with high and very high impact were selected, resulting in a total of 49 indicators. After this, a panel of experts and researchers was involved in a second round of screening, resulting in the most relevant indicators selected for PEDs and PED-related projects (Table 17). Additional indicators can be included building on the selection process and methodology implemented (Table 3 in the appendix 2). Hence, specific product life cycle stages, sector-specific concerns, or regional social priorities can be incorporated.
Consequently, while the selected indicators serve as the baseline, practitioners should refine the selection further to reflect specific social dynamics, stakeholder concerns, and product system attributes, maintaining alignment with ISO recommendations.

Table 17: Selected Indicators

Stakeholder	Consumer	
Subcategory	**Health & Safety**	
	Indicator	Unit
	Thermal comfort	Five-point Likert scale
	Thermal Comfort-Predicted Mean Vote (PMV)	[#]
	Thermal Comfort-Predicted Percentage Dissatisfied (PPD)	[%]
	Indoor Air Quality	CO_2 [ppm]
	Noise Pollution	[dB], [%]
	Illuminance	[Lux]
	Daylight Factor	[%]
	Green space	[ha/100.000 inhab], [m^2/inhab.], [%]
	Public outdoor recreation space	[m^2/inhab.]
Subcategory	**Feedback mechanism**	
	Indicator	Unit
	Degree of satisfaction	[%] and/or Five-Point Likert Scale
Stakeholder	**Local Community**	
Subcategory	**Access to material resources**	
	Indicator	Unit
	Progress towards Energy Citizenship	Five-point Likert scale
	Access to public transport	[% of inhab]
	Access to vehicle-sharing solutions for city travel	[#/100.000 inhab], [#/inhabs.], [#], [km]
	Access to commercial amenities	[% of inhab]
	Access to public amenities	[% of inhab]
	Shared EV Penetration Rate	[%]
	EV charging stations	[#], [#/km^2], [%], [#/100,000]
	Length of the bike route network	[% in km], [km/100,000 inhab)], [m]
	Public Transport Network	[km/100,000 inhab]
Subcategory	**Access to immaterial resources**	
	Indicator	Unit
	Internet Penetration Rate	[% of inhab]
Subcategory	**Safe and healthy living conditions**	
	Indicator	Unit
	Thermal comfort	Five-point Likert scale
	Thermal Comfort-Predicted Mean Vote (PMV)	[#]

	Thermal Comfort-Predicted Percentage Dissatisfied (PPD)	[%]
	Indoor Air Quality	CO_2 [ppm]
	Noise Pollution	[dB], [%]
	Illuminance	[Lux]
	Daylight Factor	[%]
	Green space	[ha/100.000 inhab], [m^2/inhab.], [%]
	Public outdoor recreation space	[m^2/inhab.]
	Access to basic health care services	[% of inhab]
Subcategory	**Community engagement**	
	Indicator	Unit
	Active/proactive citizens' behaviour	[%] and/or Five-Point Likert Scale
	Increased consciousness of citizenship	Five-point Likert scale
	Social Cohesion	Five-point Likert scale
	Increased participation of vulnerable groups	Five-point Likert scale. The indicator provides a qualitative measure and is rated on a five-point Likert scale: No at all – 1 — 2 — 3 — 4 — 5 — Excellent 1. Not at all: the project has not increased the participation of groups not well represented in society. 2. Poor: the project has achieved little when it comes to the participation of groups not well represented in society. 3. Fair: the project has somewhat increased the participation of groups not well represented in society. 4. Good: the project has significantly increased the participation of groups not well represented in society. 5. Excellent: Participation of groups not well represented in society has been hugely improved due to the project.
	Number of awareness-engagement initiatives/events	[#/100 inhab], [#]
	Open Public Participation	[#/hab], [#/100,000 inhab] and/or Likert scale
Subcategory	**Local employment**	
	Indicator	Unit
	Job creation	[#], [%]
Subcategory	**Secure living conditions**	

	Indicator	Unit
	Crime rate	[#/100.000 inhab], [%]
	Living Conditions	[% of inhab]
	Affordability of Energy	[% of inhab], Likert scale
	Affordability of Housing	[% of inhab], Likert scale
Stakeholder	**Worker**	
Subcategory	**Health and Safety**	
	Indicator	Unit
	Access to basic health care services	[% of inhab]
	Noise Pollution	[dB], [%]
	Indoor Air Quality	CO_2 [ppm]
	Illuminance	[Lux]
Subcategory	**Equal opportunities /discrimination**	
	Indicator	Unit
	Gender Equity of New Jobs	[%]
Stakeholder	**Society**	
Subcategory	**Contribution to economic development, poverty alleviation**	
	Indicator	Unit
	Median Disposable (Household) Income	[€/household], [€/inhab.]
Additional		
	Indicator	Unit
	Accessible Design	10-point Likert scale and [% of barrier-free units] at the building level; [% of barrier-free units] at the district level
	Social factors	[%] and/or Five-Point Likert Scale

Considering the indicators identified above, the relevance of Consumer, Worker, Local Community, and Society stakeholder categories emerge. Hence, these stakeholder categories shall be assessed vis-à-vis the social impacts of PEDs. Any exclusions must be justified. The relevance and hence inclusion of the Children and Value Chain Actors stakeholder categories should be addressed, case by case.

In the supplementary sheets of this SIA Framework, subcategories related to these Stakeholder categories are defined, and information on why they are relevant for PEDs is provided based on the methodological sheets of the Guidelines.

In defining the scope of a S-LCA the type of impact assessment method must be specified considering the particular product and the defined goal. There are two main types of impact assessment approaches identified by ISO 14075 (2024). Both ISO 14075 (2024) and UNEP Guidelines (2020) give a comprehensive overview of the methods, which are the Reference Scale Assessment (formerly Type I or RS S-LCIA) and the Impact Pathway Assessment (formerly Type II or IP S-LCIA), each responding to different practitioner needs.

Reference Scale Assessment focuses on predefined reference scales for measuring social impacts. This approach primarily uses generic data established in databases to evaluate the potential social impacts associated with a product's life cycle. It is particularly useful when the objective is to assess impacts using established benchmarks. This method is suitable for practitioners needing straightforward assessments where data is easily accessible through databases, especially when working with well-defined impact categories and subcategories. In the context of PEDs, RS S-LCIA might be used to evaluate how the PED impacts community well-being compared to established benchmarks. This would involve identifying indicators to their corresponding stakeholder subcategories. In contrast, Impact Pathway Assessment is based on the social mechanisms that link causes to effects, representing impacts through a cause-effect chain. This approach can account for both midpoint and endpoint indicators, making it ideal for scenarios that require a more complex understanding of social impacts. IP S-LCIA is best utilised when assessing stakeholder impacts beyond just workers is critical, allowing for a more nuanced exploration of social mechanisms. It is also preferable when there is a need to integrate qualitative observations and findings from multiple disciplines. In the scale of PEDs, one might explore how energy efficiency measures and renewable energy projects affect social well-being through their impacts on air quality, which may subsequently influence health outcomes and equity within the community.

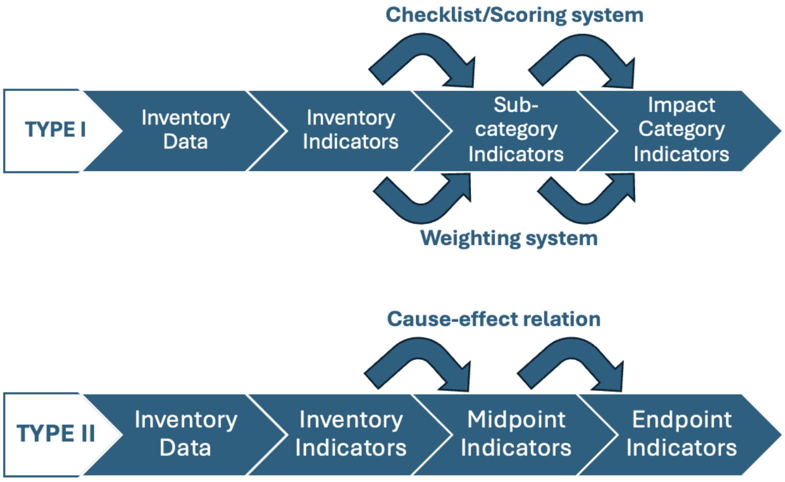

Figure 30: Impact Assessment Methods (adapted from Chhipi-Shrestha et al., 2015)

Figure 30 summarises both approaches. In other words, RS S-LCIA is more straightforward and suitable for scenarios with clear benchmarks, while IP S-LCIA is preferable for complex assessments requiring deep analysis of social mechanisms and broader stakeholder impacts. Both approaches provide a pathway to identify both positive and negative social impacts, such as potential displacement due to gentrification, or enhanced community cohesion through increased local engagement. Figure 31 shows the goal and scope steps regarding the impact assessment method. Each approach has its pros and cons, depending on the specific needs and context of the assessment. Additionally, in one study, one may apply both Type I and Type II for different impact categories, which can then be subsequently aggregated.

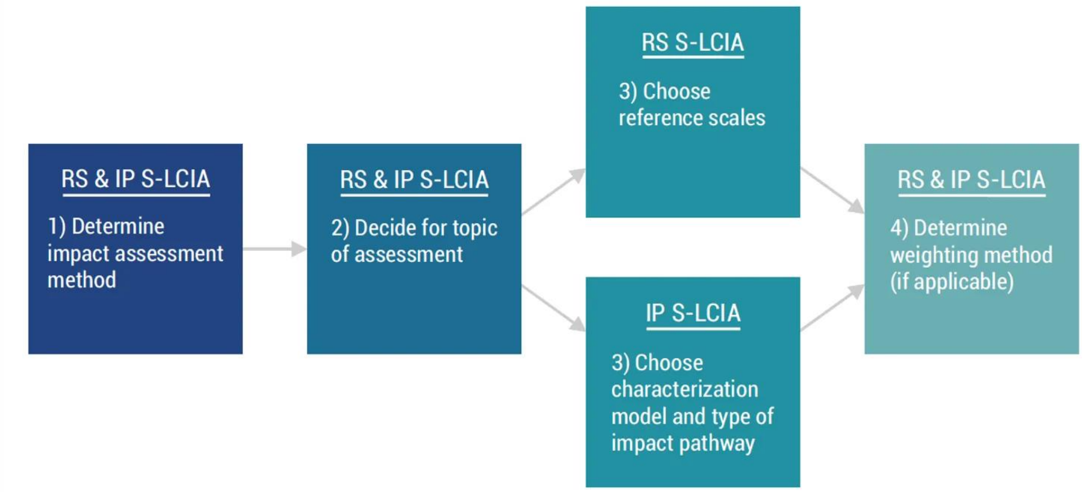

Figure 31: Steps in goal and scope (UNEP, 2020)

Type I and Type II can be applied for PEDs but for this SIA Framework, methodological and practical guidance is provided for the reference scale approach S-LCIA (Type I). This approach allows for a more straightforward assessment of social performance and risks by comparing observed impacts against established reference scales. The reference scale approach is clearly outlined in ISO 14075 (Figure 32), and this SIA Framework adheres to that guidance. In contrast, the impact pathway assessment (Type II) is less suitable at this stage as the specific cause-effect relationships within PEDs have not been clearly defined, indicating a need for further research to develop comprehensive impact pathways in this context.

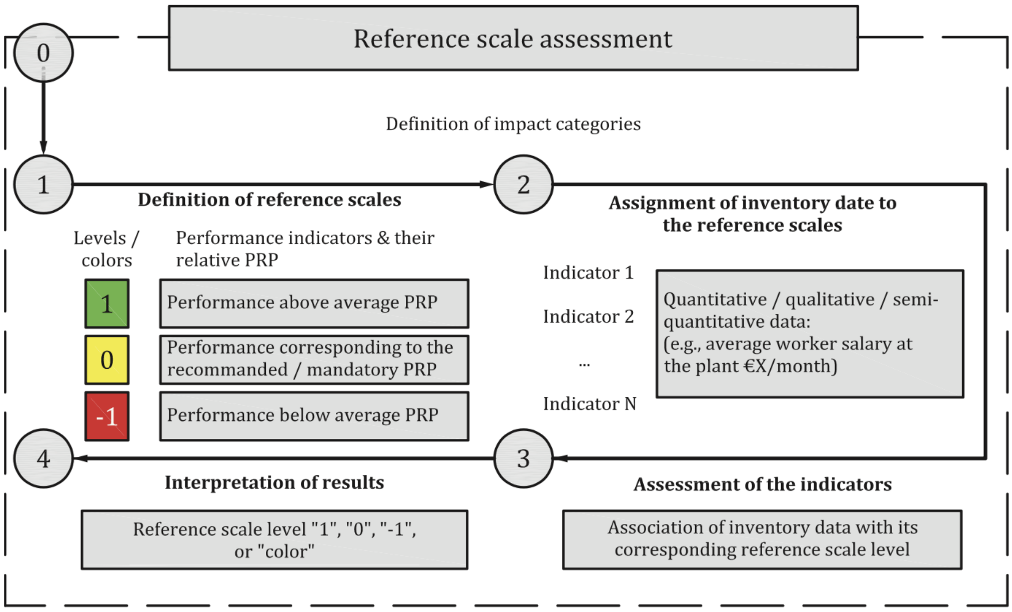

Figure 32: The reference scale assessment (ISO 14075:2024)

While choosing the indicators and creating the reference scales for PEDs, the effect of various energy culture groups should be considered. A useful framework for comprehending energy behaviours is the Energy Cultures Framework (Stephenson et al., 2010), which emphasises how material culture, cognitive norms, and energy practices influence energy-related decisions and results. The reference scales and indicators must take into account the variety of energy cultures found in various districts, as PEDs seek to promote sustainable and socially inclusive urban settings. This guarantees that evaluations include social acceptance, behavioural patterns, and cultural impacts on energy usage, in addition to technical achievement. Integrating the Energy Cultures Framework into the development of reference scales strengthens the evaluation approach, making it more comprehensive and contextually relevant, in alignment with the broader objectives of PEDs.

In the context of PEDs, the development and application of reference scales for social indicators must reflect the unique characteristics and sustainability goals of these districts. PEDs aim to create energy-efficient, inclusive, and high-quality urban environments, making social performance a key aspect of their evaluation (Hedman et al., 2021; Salom et al., 2021; Angelakoglou et al., 2020). Therefore, the indicators assessed must be aligned with the specific needs and challenges of PEDs. PED-relevant reference scales for each indicator shall be defined based on global or local (e.g., national or municipal) norms. In cases where predefined norms are lacking, alternative methodologies are to be applied, such as converting existing rating systems or using expert-defined ideal benchmarks to differentiate between performance levels. The reference scale may comprise five levels, ranging from a positive high social performance (score 2, green) to a negative and severe social risk or deficiency (score -2, red), as highlighted in Table 18. Building the reference scales should start with defining performance reference points (PRPs, score 0, yellow) using regulatory and scientific research.

To enhance and support the assessment of PEDs on social performance, reference scales have been defined and provided for use in this SIA Framework, addressing the final list of

the selected indicators that should ideally be assessed (Table 6 in the appendix). Performance reference points (PRPs) of this SIA Framework are firstly valid for urban area contexts but at the same time can be valid for different contexts. Some of the PRPs are developed for Europe-specific contexts, some are valid for all around the world. Depending on each specific PED, where it is located and locally available guidelines, regulations, or benchmarks, PRPs should be adjusted accordingly and transparent justification provided (Chabrawi et al., 2024).
In the case of the indicator "access to public transportation" measured by the number of inhabitants with a public transportation stop at less than 500m, the reference point is defined as "70% - 84% of inhabitants have a transport stop at less than 500m". The reference scale is, therefore, defined as follows.

Table 18: Example of reference scale of Access to public transportation

Stakeholder	Subcategory	Indicator	Unit	2	1	0	-1	-2
Local Community	Access to material resources	Access to public transport	[% of hab]	≥95% of inhabitants have a public transport stop within 500m.	85–94% of inhabitants have a public transport stop within 500m.	70–84% of inhabitants have a transport stop within 500m.	50–69% of inhabitants have a transport stop within 500m, meaning significant portions of the population lack easy access.	<50% of inhabitants have a transport stop within 500m, indicating a major accessibility issue.

Another example is "indoor air quality", where the reference point was defined as "CO_2 concentration between 551 – 800 ppm" meeting regulatory standards for adequate indoor air quality.

Table 19: Example of reference scale of Indoor air quality

Stakeholder	Subcategory	Indicator	Unit	2	1	0	-1	-2
Consumer	Health & Safety	Indoor Air Quality	CO2 [ppm]	CO_2 concentration ≤ 450 ppm Ideal air quality, optimal for health and comfort; virtually no discomfort.	CO_2 concentration between 451 – 550 ppm	CO_2 concentration between 551 – 800 ppm. Meets regulatory and industry standards for adequate indoor air quality.	CO_2 concentration between 801 – 1350 ppm Indoor air quality is below compliance, indicating insufficient ventilation. .	CO_2 concentration >1350 ppm Indoor air quality is severely inadequate, and classified as low quality.

The reference point of "affordability of energy" is defined as "household income spent on energy is 5.0% OR 50% of inhabitants finding energy costs affordable". In the option of generic data, household income spent on energy values can be used to identify the reference value. However, when specific data is collected, affordability can be assessed either by analysing actual household energy expenditures or through inhabitant perceptions using a Likert scale.

Table 20: Example of reference scale of Affordability of energy

Stakeholder	Subcategory	Indicator	Unit	2	1	0	-1	-2
Local Community	Secure living conditions	Affordability of Energy	[% of hab], Likert scale]	Household income spent on energy is ≤ 3.2% OR ≥ 75% of inhabitants finding energy costs affordable	Household income spent on energy is between 3.3% – 4.9% OR 51–74% of inhabitants finding energy costs affordable	Household income spent on energy iS 5.0% OR 50% of inhabitants finding costs energy affordable	Household income spent on energy is between 5.1% – 6.5% OR 30–50% of inhabitant finding costs affordable.	Household income spent on energy is > 6.5% OR < 30% of inhabitants finding costs affordable.

4.2.3 Life cycle inventory

The Social Life Cycle Inventory analysis (S-LCI) of a PED should follow closely the ISO 14040/44 (2006) framework. In addition, specific requirements provided in this document shall also be implemented when carrying out S-LCI. The specific requirements are based on the methodological sheets of the 2020 UNEP Guidelines on S-LCA of products and organisations (Guidelines) alongside findings on relevant social indicators for PEDs. Moreover, the S-LCI is required to be conducted in line with the provisions of ISO 14075.

Data collection is the most labor-intensive activity when carrying out an S-LCA. Therefore, different indicators may be used depending on data availability and the goal and scope of the study. The methodological sheets address each impact subcategory included in the stakeholder categories, defining generic and specific indicators and giving examples of sources for collecting both types of indicators. However, these methodological sheets are not product-specific. Hence, this SIA framework provides specific guidance for PEDs aiming to avoid misunderstandings about subcategories and to clarify their relation to stakeholder groups as well as providing examples of inventory indicators, units of measurement, and potential data sources for hotspot assessment to aid calculations of each subcategory.

In addition to the generic data sources provided in the methodological sheets and summarised for this SIA Framework (Table 4 in the appendix), PED-specific data sources shall be consulted for each subcategory.

In the case of the subcategory Freedom of association and collective bargaining under the worker stakeholder category, PED-specific data sources would include Documentation of Trade Union bodies related to workers of the construction companies, utility providers, and service providers. Human resource records will also provide supply-specific confirmation of the agreements signed by any organisation involved in the PED life cycle. Evidence of payment of working hours dedicated to activities in Trade unions represents support of the organisation for workers to be members of trade unions while specific interviews of workers will provide information on prejudice in participating in collective bargaining or a strike. A list of PED-specific data sources has been compiled for guidance and consultation in the planning and implementation of PED data collection for S-LCI (Table 5 in the appendix).

4.2.4 Social Life Cycle Impact Assessment

Social Life Cycle Impact Assessment (S-LCIA) is the process of aggregating inventory data to assist in understanding the magnitude and significance of the social data in respective contexts (UNEP, 2021). S-LCIA is highly challenging to accomplish as it involves value judgments across different categorisations including normalisation, weighting, and aggregation of social data (Hosseinijou et al., 2014, Sala et al., 2013, Hannouf and Assefa, 2018).

Based on the social impacts to be assessed, defined in the G&S stage, and once the data about the relevant indicators is collected, and the respective reference scales are developed, the impact assessment can be carried out. The exercise is quite straightforward: the indicators relating to a certain impact category should be compared against their reference scale, and their position in the scale is registered in terms of potential social impact score. In the above examples, the scores vary from +2 (when the highest performance is identified) and -2 (in cases of worst social performance).

As an example, the indicators “indoor air quality” and “affordability of energy” relate to health and well-being which is a Human Right as stated in paragraph 25 of the Universal Declaration of Human Rights “Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family…” (UN, 1948, p. 7). Therefore, securing adequate indoor air quality and affordable costs of energy in a PED –house or building– fall under the human rights impact category.

A value of indoor air quality of 579 ppm CO_2 concentration would correspond to an intermediary level of the developed reference scale (Table 19) and therefore would be assigned the social performance level “0”. In the case of “affordability of energy” adopting a 5-point Likert scale question (How do you rate the adequacy of your current living costs regarding electricity and heating costs?), if 45.5% of the interviewed inhabitants of a given PED state that the costs are “affordable”, this would correspond to a “ -1” level of social performance (Table 20).

This is also in the impact assessment phase where aggregation of the results may occur. Aggregation is a way of bringing together several pieces of information and synthesising them into a single score to facilitate understanding and communication of the S-LCA results (UNEP, 2020). Aggregation may occur alongside weighting. In the weighting process, values (weights) are applied to inventory, impact subcategory, or stakeholder category results, to represent their relative importance.

If aggregation takes place, the procedures to aggregate the results must be aligned with the G&S of the study, as well as weighting. An important remark is made to data transparency while aggregating and weighting the S-LCA results. Both should be conducted by using reliable and scientific methods where the combination of different types of data (units) is

made possible. An example is the aggregation of an indicator "access to public transportation" with the unit "% of inhab" and "indoor air quality" with the unit "CO_2, ppm". Thus, aggregating indicators with different units and dimensions may pose challenges that should rely on procedures, like normalisation, to transform them into a single unit, allowing for making mathematical operations like addition and multiplication, for instance.
Since aggregation combines different data altogether, the original values might be lost. Therefore, ISO 14075 recommends that aggregation should always be made transparently, reporting and justifying the methods and criteria adopted for conducting aggregation. Furthermore, the results of the study should always be complemented with the disaggregated data (UNEP, 2020, ISO 14075).

4.2.5 Interpretation

The interpretation phase of PED S-LCA comprises several analyses or elements (UNEP, 2020, ISO 14075):

- identifying significant issues based on the results of the S-LCI, and S-LCIA phases;
- evaluating completeness, sensitivity, and consistency;
- providing conclusions, limitations, and recommendations.

These elements shall be conducted against the goal and scope of the study.
In addition, the appropriateness of the definitions of the system functions, the functional unit and system boundary as well as limitations identified by the data quality assessment and the sensitivity analysis shall be analysed with regards to the stated goal.
In identifying significant issues, analyses shall be made considering information from the preceding S-LCA phases. The methodological choices on allocation and system boundaries as well as the value choices, roles, and responsibilities of different interested parties as defined in the G&S goal and scope. This information will lead to the identification of significant inventory data, impact categories, and contributions from life cycle stages or processes to the S-LCI or S-LCIA results.
Evaluation of the social results shall include completeness, sensitivity, and consistency checks to establish and enhance confidence in, and the reliability of the results, in particular in relation to the significant issues identified. This shall be conducted through a completeness, sensitivity and consistency check. The completeness check establishes if relevant information and data needed for the interpretation are available and complete. In case any relevant information necessary for determining the significant issues, is missing or incomplete, the preceding phases (S-LCI, S-LCIA) have to be repeated or the goal and scope definition should be adjusted. The sensitivity check aims to assess how the final results and conclusions are affected by uncertainties in the data, allocation methods or calculation or reference of category indicator results. This shall include sensitivity and uncertainty analyses performed in the S-LCI and S-LCIA phases and consider the sensitivity check shall include the results of the sensitivity analysis and uncertainty analyses and shall consider issues predetermined by the goal and scope of the study, the results from all other phases of the study and expert judgements and previous experiences. If the S-LCA is to be used for social comparative assertions intended to be disclosed to the public, the evaluation element shall include interpretative statements based on detailed sensitivity analyses. The consistency check is to establish whether the assumptions, methods and data are consistent with the goal and scope. This shall include differences in data quality along product life cycle and between different systems, regional and/or temporal differences, the consistent application of allocation rules and the system boundary and the consistent application of social impact assessment.
The last part of interpretation is to draw conclusions, identify limitations and make recommendations for the intended audience of the S-LCA.
Conclusions shall be made iteratively considering them based on the other elements of the interpretation phase. Hence a preliminary conclusion is drawn following the identification of significant issues and the evaluation of the results, checking its consistency with the requirements of the goal and scope of the study. In particular, the consistency of the conclusions with data quality requirements, predefined assumptions and values, methodological and study limitations, and application-oriented requirements are analysed. If the conclusions are not consistent the previous steps have to be repeated.

Recommendations shall be formulated on the final conclusions tested with the requirements of the goal and scope of the study.

4.2.6 Reporting of results

In line with the G&S definition, the intended audience needs to be informed of the results and conclusions of the PED S-LCA. This should be done without bias, including data, methods, assumptions, and limitations. The report shall be based on the principles of completeness, accuracy, transparency and provide sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the S-LCA while supporting decision-making.
Finally, the general requirements in ISO 14075 on preparing third-party reports and including limitations of S-LCA shall be considered.

Authors

Rose Nangah Mankaa, Institute of Sustainability in Civil Engineering, RWTH Aachen University (rose.mankaa@inab.rwth-aachen.de)
Arij Mohamad Radwan Omar Chabrawi, Institute of Sustainability in Civil Engineering, RWTH Aachen University (arij.chabrawi@inab.rwth-aachen.de)
Olubukola Tokede, School of Architecture and Built Environment, Deakin University, Australia (olubukola.tokede@deakin.edu.au)
Marzia Traverso, Institute of Sustainability in Civil Engineering, RWTH Aachen University, Germany (marzia.traverso@inab.rwth-aachen.de)

4.3 Case study application and insights

This work is part of a three-step approach to support social sustainability assessment for Positive Energy Districts (PEDs). The first one was dedicated to creating a State-of-the-Art (SoTA) report that aimed at mapping viable methodologies to conduct a social impact assessment of PEDs. Moreover, the SoTA report also mapped and harmonised an extensive list of inventory indicators and another on social impacts related to PEDs and PED-related projects. The second step was built upon the knowledge raised previously and focused on developing a self-explanatory framework activity (FA). The FA provided comprehensive guidance on how to conduct the four phases of a Social Life Cycle Assessment of PEDs, providing examples and hands-on tips for social sustainability practitioners.
Likewise, the third step was also built upon the previous ones and consists of a real-case social assessment to demonstrate the methods and procedures necessary to implement each phase of a S-LCA. For this illustrative exercise on how to conduct a social sustainability assessment, a real case study was selected, the “Friedrich-Inhauser-Straße”, an urban district in Salzburg, Austria. The district is part of the syn.ikia project (Fuchshofer et al., 2024) and comprises 99 apartments and a total gross floor area of 10.24 m². The initiative does not satisfy all requirements to be considered a PED but meets several specific characteristics of a PED, such as mobility alternatives, renewable energy integration, and easy access to public services.
This case study details the application of S-LCA to the “Friedrich-Inhauser-Straße” district following the four phases: Goal and Scope; Life Cycle Inventory; Life Cycle Impact Assessment; and Interpretation.

4.3.1 Goal and scope

As per the first step of the Social Life Cycle Assessment study, the goal and scope have the aim of setting the base for the activities that will be carried out. However, before initiating, some information about the case studies planning, such as the objective, functional unit, system boundaries, and other methodological aspects have to be defined. As mentioned above, the study under consideration is the “Friedrich-Inhauser-Straße” urban district in Salzburg, Austria. The housing project was first built in 1985, comprising 75 social apartments and it was totally renovated in 2019 and 2021, due to rotted wooden constructions in the roof and balcony. The renovation increased the number of apartments to 99 with 8,107 m² of living area. It also comprised an adaptation of the thermal insulation and the heating system was changed from gas to heat pump and pellets. Moreover, a large photovoltaic system on the roof was installed for electricity generation. The initiative did not extend the car parking area, but provides mobility services such as bicycle parking, car sharing, and rental bikes, as alternatives to cars. After the renovation, 30 families returned to the new complex in December 2021, and in March 2024 the residents were surveyed on their satisfaction.
The following aspects of Goal and Scope were defined:
1.1. GOAL: The aim of the S-LCA study is to investigate the positive and negative impacts on stakeholders of the housing project Friedrich-Inhauser-Straße, considered as a PED, identifying improvement potentials. The study serves as guidance on implementing the steps of S-LCA in a real case highlighting methodological choices and challenges.
1.2. SCOPE: The elements deemed relevant for the scope definition, given the goal of this case study were: functional unit, system boundaries, stakeholders, data collection strategy and definition of the type of impact assessment, impact categories, and subcategories. Moreover, Salzburg is situated in a spatial and geographical landscape of mountains, with height variations that can lead to temperature differences between the city and surrounding suburbs, especially during autumn and winter. In general, the city has evenly sunny and cloudy days, but a temperate climate prevails
1.2.1. Functional Unit: The FU defined in this case study is at the urban district level, and considers the main services related to a PED. The FU is therefore one urban district of 30m² living area per inhabitant, offering housing conditions and public services. The housing project has future prospects for improving energy generation and savings, energy and house affordability, and urban development design with a high level of residents’ satisfaction.
1.2.2. System boundary: The raw material extraction phase, the construction phase, the use occupation stage, and the demolition stage belong to the system boundary of the study.

Flows related to electricity use, water consumption, maintenance services, and public services such as public transportation in the PED fall within the system boundary. The indicators associated with these flows are assessed all through their life cycle. Likewise, it is important to bear in mind that for each life cycle stage considered within the goal and scope of the study, components, and materials should be considered not only within that particular stage but also in their entire supply chain. For example, during the use phase, while focusing on aspects such as electricity consumption, maintenance materials for buildings, and the upkeep of green spaces, it is crucial to also consider in the scope of assessment the impacts from the earlier life cycle stages, including raw material extraction, construction, and manufacturing. In the case of electricity consumed in the district, it is a product of energy generation, and its social impacts are also shaped by the conditions under which it was produced, i.e., labor rights violations during energy production, aspects related to safe and healthy living conditions of the communities surrounding the power plant, or the reduction of social inequalities in the distribution of energy access for consumers. However, because the renovation was completed two years ago, relevant social data related only to the use stage without the supply chain could be collected. Hence, the system boundary of this case study includes all unit processes related to the use of the Friedrich-Inhauser-Straße district, in Austria. The activities are focused on supporting the daily living of the residents through the supply and operation of residential, energy, and mobility-related services.

1.2.3. Stakeholders: In PEDs Worker, Consumers, Local community, Society, and Children are to be considered. However, due to data availability stakeholder categories considered in this case study are consumers and the local community due to data availability. In the use stage of PEDs the extent and complexity of an urban district encompass a broader perspective of users that are, on the one hand, consumers and, on the other hand, local community. Specific subcategories and indicators were assigned to each stakeholder category as detailed in the S-LCI phase.

1.2.4. Data collection strategy: Following the aim of the study expressed under the Goal, only site-specific data is allowed for inventory flows related to the use stage. Although not included in the Friedrich-Inhauser-Straße assessment, further social impacts related to the supply chain should be encompassed here. Thus, resuming from the example of electricity provided as a service, questionnaires to collect data regarding workers in the power plant, or possible issues related to the health and safety living conditions should be developed to also measure the associated social impacts throughout its supply chain.

1.2.5. Impact assessment method: The Reference Scale Approach was selected as a social performance assessment method for the Friedrich-Inhauser-Straße urban district. The method comprises defining reference values (Table 21) for each indicator to compare it against thresholds and classify the performance of the organisation accordingly. For the stakeholders Consumer and Local community, the corresponding indicators and subcategories are listed in Table 22.

Table 21: Selected stakeholders, indicators, and their data unit

Stakeholder	**Consumer**	
Subcategory	**Health & Safety**	
	Indicator	Unit
	Indoor Air Quality	CO_2 [ppm]
Subcategory	**Feedback mechanisim**	
	Indicator	Unit
	Degree of satisfaction	[%] and/or Five-Point Likert Scale
Stakeholder	**Local Community**	
Subcategory	**Access to material resources**	
	Indicator	Unit
	Access to public transport	[% of inhab]
	Access to commercial amenities	[% of inhab]
	Access to public amenities	[% of inhab]
Subcategory	**Safe and healthy living conditions**	
	Indicator	Unit
	Indoor Air Quality	CO_2 [ppm]
	Access to basic health care services	[% of inhab]
Subcategory	**Secure living conditions**	
	Indicator	Unit
	Affordability of Energy	[% of inhab], Likert scale
	Affordability of Housing	[% of inhab], Likert scale

Indoor air quality is assessed by CO_2 concentration level. According to EN 16798-1-2019, Occupational Safety and Health Administration (2011) and World Health Organisation (2021), the PRP of this indicator is determined as the CO_2 concentration value is between 551 – 800 ppm. Degree of satisfaction assessed by questionnaires. Impact assessment results are determined by the percentages of inhabitants answering with positive perceptions and/or average score value obtained by the questionnaires. According to the Product Social Impact Assessment Handbook (2018), PRP is when the average score from questionnaires is between 2.6 - 3.5 and/or 59-40% of inhabitants report positive perceptions (agree or strongly agree) across all key variables. Access to public transport is calculated by the percentage of inhabitants have a public transport spot within 500 m. PRP of this indicator is 70–84% of the inhabitants can reach the closest public transport spot with a 500 m walking distance. Their closeness to the district assesses Access to commercial amenities and Access to public amenities. In this SIA Framework and this case study proposed commercial amenities are 4 (Supermarket/ grocery store; Bank/ ATM; Commercial centre (mall, high street, etc.); Hospitality (Cafés, restaurants, bars, hotels, hostels, etc.)) and for public amenity, type is 8 (Primary School; Playground; Kindergarten; Public parks/gardens; Local public transport node; Community centre; Post office; Library). PRPs of both indicators mean that half of the amenities are within a 1 km range of the district. Access to basic health services indicator is assessed by the percentages of inhabitants who have access to a basic health service within 30 minutes of walking distance. When 70–84% of inhabitants can reach it, the impact assessment result would be the compliance value (0).
According to researchers - Wehrmann (2022), Hoppe et. al (2019) and IEA (2019) -, PRP of Affordability of energy is determined as Household income spent on energy is 5.0% OR 50% of inhabitants finding energy costs affordable. Similarly, PRP of Affordability of housing is determined as Household income spent on housing is 20% OR 50% of inhabitants finding housing costs affordable - Eurostat (2024).

Table 22: Reference scale of case study indicators

Stakeholder	Subcategory	Indicator	Unit	+2	+1	0	-1	-2
Consumer	Health & Safety	Indoor Air Quality	CO_2 [ppm]	CO_2 concentration ≤ 450 ppm	CO_2 concentration between 451 – 550 ppm	CO_2 concentration between 551 – 800 ppm	CO_2 concentration between 801 – 1350 ppm	CO_2 concentration >1350 ppm
Consumer	Feedback mechanisim	Degree of satisfaction	[%] and/or Five-Point Likert Scale	≥ 80% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 4.6 – 5.	79-60% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 3.6 - 4.5	59-40% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 2.6 - 3.5	39-20% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 1.6 - 2.5	≤20% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 1 - 1.5
Local Community	Access to material resources	Access to public transport	[% of inhab]	≥95% of inhabitants have a public transport stop within 500m.	85–94% of inhabitants have a public transport stop within 500m.	70–84% of inhabitants have a transport stop within 500m.	50–69% of inhabitants have a transport stop within 500m, meaning significant portions of the population lack easy access.	<50% of inhabitants have a transport stop within 500m, indicating a major accessibility issue.
Local Community	Access to material resources	Access to commercial amenities	[% of inhab]	All 4 (Supermarket/ grocery store; Bank/ ATM; Commercial centre (mall, high street, etc.); Hospitality (Cafés, restaurants, bars, hotels, hostels, etc.)) commercial amenities are within 1 km (100% accessibility).	At least 3 commercial amenities (≥75%) are within 1 km.	At least 2 commercial amenities (≥50%) are within 1 km.	Only 1 commercial amenity (≤25%) is within 1 km.	None of the commercial amenities are within 1 km. (0% accessibility)
Local Community	Access to material resources	Access to public amenities	[% of inhab]	All 8 public amenities (Primary School; Playground; Kindergarten; Public parks/gardens; Local public transport node; Community centre; Post office; Library) are within 1 km (100% accessibility)	At least 6 public amenities (≥75%) are within 1 km.	At least 4 public amenities (≥50%) are within 1 km.	Less than 4 public amenities (≤50%) are within 1 km.	Most (≤25%) or none of the public amenities are within 1 km.
Local Community	Safe and healthy living conditions	Access to basic health care services	[% of inhab]	≥95% of inhabitants have a health center within 30 mins walking distance.	85–94% of inhabitants have a health center within 30 mins walking distance.	70–84% of inhabitants have a health center within 30 mins walking distance.	50–69% of inhabitants have a health center within 30 mins walking distance.	<50% of inhabitants have a health center within 30 mins walking distance.
Local Community	Secure living conditions	Affordability of Energy	[% of inhab], Likert scale	Household income spent on energy is ≤ 3.2% OR ≥ 75% of inhabitants finding energy costs affordable	Household income spent on energy is between 3.3 – 4.9% OR 51–74% of inhabitants finding energy costs affordable	Household income spent on energy is 5.0% OR 50% of inhabitants finding energy costs affordable	Household income spent on energy is between 5.1 – 6.5% OR 30–50% of inhabitant finding costs affordable.	Household income spent on energy is > 6.5% OR < 30% of inhabitants finding costs affordable.

4.3.2 S-LC Inventory Assessment

In 2016, a standardised questionnaire was developed by StadLandBerg and the SIR. The instrument has been used in 16 different projects in Salzburg, serving as a comparison between these projects. In 2024 the questionnaire was sent to residents of more than 16 years old, throughout the 99 apartments, totalling 270 people. Only 63 questionnaires were returned and served as the basis for the social assessment. Additionally, quantitative measurements were made for actual walking distances through Google Maps and for emission concentrations. For illustrative purposes of this case study, the selection of 8 indicators was made: 1. indoor air quality, 2. degree of satisfaction, 3. access to public transport, 4. access to commercial amenities, 5. access to public amenities, 6. access to basic health care services, 7. affordability of energy, 8. affordability of housing.
Air quality measurement is done with the AQM G3 measurement device from the company "Air Quality Monitor" with a measuring interval of 10 minutes. The results of air quality measurements are given in Figure 33.

RESULT AIR QUALITY MEASUREMENT SPRING: MEASUREMENT SERIES 1

Key data flat	
Flat type	3 rooms
Usable living space	64,5 m²
Number of persons	3
Move in	December 2022
Key data for air quality measurement	
Installation site	Living room
Start of measurement	10.05.2023, 00:00
End of fair	23.05.2023, 23:59
Measuring interval	10 minutes
Measuring device	AQM G3 from the company "AirQualityMonitor"
Further sources	Weather data GeoSphere Austria
Remark	Exhaust air system available
Air quality measurement results at a glance	
Average indoor air temperature	23,4 °C
Average air temperature outside	13,5 °C
Average indoor relative humidity	39 %rF
Mean value relative humidity outside	79 %rF
Average CO2 concentration	579 ppm

Figure 33: Air quality measurement results

Degree of satisfaction, affordability of energy, and affordability of housing are measured using the results of the questionnaires. For the degree of satisfaction, inhabitants answered the question "how satisfied are you currently with your personal living situation?" with answering options of "very satisfied", "satisfied", "not very satisfied" (Figure 34). 40% of inhabitants answered "very satisfied", 46% of people answered "satisfied" and 9% said "not very satisfied". For affordability of energy and affordability of housing, the question "how do you rate the adequacy of your current living cost?" answered by inhabitants with options of "affordable", "it's ok", "too high", "n/a" (Figure 35). Inhabitants were asked to answer this question for four different aspects: Rent costs, running and maintenance costs, heating costs and electricity costs. 49% of inhabitants answered “affordable” and 46% said “it’s ok” to rent costs. Running and maintenance costs resulted in 25% of inhabitants saying “affordable” and 48% saying “it’s ok”. Heating costs got 24% “affordable” and 32% “it’s ok” answers and electricity costs got 14% “affordable” and 21% “it’s ok” results from inhabitants.

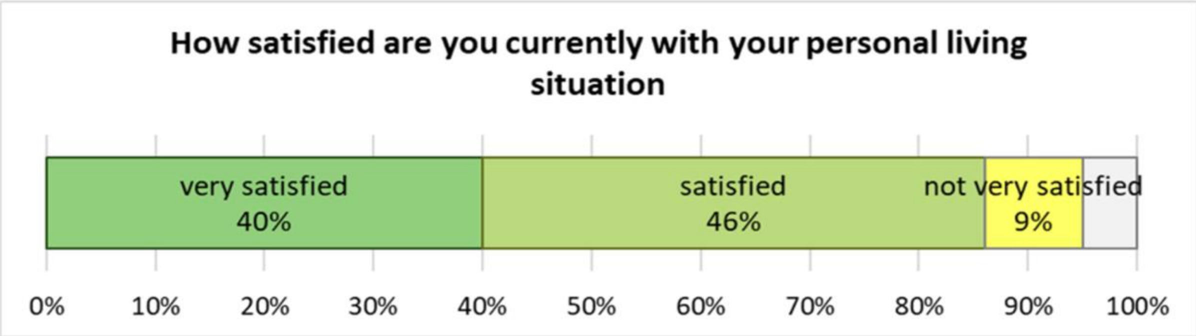

Figure 34: Answers of inhabitants to the question “How satisfied are you currently with your personal living situation?”

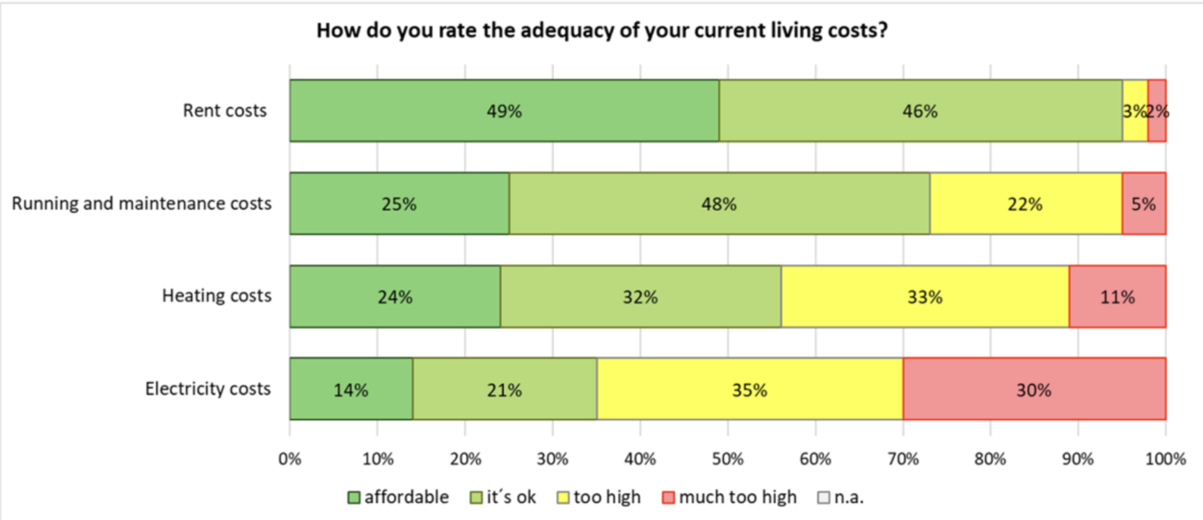

Figure 35: Answers of inhabitants to the question “How do you rate the adequacy of your current living costs?”

For the indicators, access to public transport, access to commercial amenities, access to public amenities and access to basic health care services, the distance from the inhabitants to the related indicator location is important.
Therefore, Google Maps is used to measure the walking distance from each of the houses in the housing unit to the related location that the relevant indicator assesses.

Figure 36: Google Maps view of the housing unit

4.3.3 S-LC Impact Assessment

With the collected inventory, the results are obtained and they are given in Table 23. Social Life Cycle Performance Assessment Results. For the consumer stakeholder category, two subcategories with corresponding two indicators are measured. Two subcategories with corresponding six indicators were measured in the local community stakeholder category.

For the consumer stakeholder category's health and safety subcategory, the indoor air quality indicator is assessed. Measurement of the average CO_2 concentration in the case study results of 579 ppm corresponds to a "0" impact assessment result. This means that for the indoor air quality indicator, this case study is aligned with international standards. For the feedback mechanism subcategory, the degree of satisfaction is assessed. "Very satisfied" and "satisfied" answers to "How satisfied are you currently with your personal living situation?" are used for this indicator. The sum of the percentages is equal to 86% positive perceptions which corresponds to a "+2" impact assessment result meaning ideal performance.

Local community stakeholder category's access to material sources subcategory is assessed by three different indicators. All the inhabitants of this housing unit can reach the public transport spot within 500 m. This means for the Access to public transport indicator the impact assessment result is "+2". Within 1 km of walking from this housing unit, inhabitants can reach a supermarket, an ATM and a hotel. This indicates "+1" impact assessment result to the indicator Access to commercial amenities which is progress beyond compliance. Primary school, kindergarten, public park, playground and a post office are within 1 km walking distance of the inhabitants of this housing unit. This means Access to public amenities indicator gets a "0" impact assessment result.

Safe and healthy living conditions subcategory is assessed with Access to basic health care services. A health care service is within 30 minutes walking distance from all the buildings of the unit. Due to this, this indicator gets a "+2" impact assessment result.

Affordability of energy and Affordability of housing are related to secure living conditions subcategory. Inhabitants answered the question "How do you rate the adequacy of your current living costs?" and Affordability of energy is calculated with "affordable" and "it's ok" answers to heating costs and electricity costs. On average, 45.5% of inhabitants gave positive perceptions. This means this indicator gets a "-1" impact assessment result which is a non-compliant situation. For Affordability of housing, the answers "affordable" and "it's ok" to rent costs and running and maintenance costs are used. Overall, 84% of inhabitants gave positive perceptions resulting in this indicator getting a "+2" impact assessment result.

Table 23: Social Life Cycle Performance Assessment Results

Stakeholder	Subcategory	Indicator	Unit	Result
Consumer	Health & Safety	Indoor Air Quality	CO_2 [ppm]	0
Consumer	Feedback mechanisim	Degree of satisfaction	[%]	+1
Local Community	Access to material resources	Access to public transport	[% of inhab]	+2
Local Community	Access to material resources	Access to commercial amenities	[% of inhab]	+1
Local Community	Access to material resources	Access to public amenities	[% of inhab]	0
Local Community	Safe and healthy living conditions	Access to basic health care services	[% of inhab]	+2
Local Community	Secure living conditions	Affordability of Energy	[% of inhab]	-1
Local Community	Secure living conditions	Affordability of Housing	[% of inhab]	+2

4.3.4 Interpretation

As stated under the Goal and Scope, the main aim of this study is to investigate the positive and negative impacts on stakeholders of the housing project Friedrich-Inhauser-Straße, considered as a PED, identifying improvement potentials. The study also serves as guidance on implementing the steps of S-LCA on a real-case highlighting methodological choices and challenges. The interpretation of the findings relates to the various elements of the stated aim and also the scope.

The S-LCA steps were applied to the housing project Friedrich-Inhauser-Straße, assuming that it is a PED, as it features PED-similar construction, energy and mobility aspects. However, due to the lack of a specific definition of PEDs at the moment of the case study, the PED nature of the housing project cannot be established. The social impacts are therefore to be interpreted bearing this limitation in mind.

With the purpose of providing guidance on implementing the steps of S-LCA, there was the need to simplify the complex nature of PEDs while maintaining the robustness of the methodology. Consequently, the system boundary was narrowed down to processes pertaining only to the use stage. Moreover, the life cycle perspective was not fully addressed for components, materials and other inputs related to the use stage. This is mostly as a result of data unavailability and the fact that the housing project was not planned with the aim of applying the S-LCA methodology. A sensitivity analysis to assess the effect of this simplification is not possible due to the very specific nature of the assessment and the lack of questionnaires addressing stakeholders related to the Construction/Manufacturing and raw material extraction/acquisition stages.
A sensitivity analysis was carried out on the choice of reference scales with a 5% increase and decrease in reference scale values. The analysis showed that for all of the indicators, the performance assessment results did not change (Table 7 of the Appendix 2).

Authors

Rose Nangah Mankaa, Institute of Sustainability in Civil Engineering, RWTH Aachen University (rose.mankaa@inab.rwth-aachen.de)
Arij Mohamad Radwan Omar Chabrawi, Institute of Sustainability in Civil Engineering, RWTH Aachen University (arij.chabrawi@inab.rwth-aachen.de)
Marzia Traverso, Institute of Sustainability in Civil Engineering, RWTH Aachen University, Germany (marzia.traverso@inab.rwth-aachen.de)

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Julia Kantorovich (VTT Technical Research Centre of Finland, Finland),
Ilaria Marotta, National Research Council of Italy - CNR (ilaria.marotta@cnr.it)
Fatima Zarrin (VTT Technical Research Centre of Finland, Finland),
Emanuela Giancola, CIEMAT, Department of Energy, Spain (emanuela.giancola@ciemat.es)
Iván Luque Segurai (IREC - Catalonia Energy Research Institute, Spain)
Maria Beatrice Andreucci (Sapienza University of Rome, Italy)
Magyari Ábel (ABUD I Advanced Building and Urban Design, Bulgaria)

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5. The multiple-benefits approach

Positive Energy Districts (PEDs) represent complex urban models whose full potential and overall impact are often not entirely understood by end-users. PEDs are frequently described and promoted by emphasising primarily technical aspects, such as energy efficiency and CO_2 emission reductions, while less immediate yet equally significant benefits tend to be undervalued or overlooked. However, to fully understand the value of PEDs, it is crucial to adopt an integrated perspective that considers all positive outcomes, including those less apparent or more challenging to quantify (Bertolami et al., 2024; Marotta et al., 2021).

In recent years, the concept of ESG standards (Environmental, Social, Governance) has emerged globally as a framework for measuring the social and environmental impacts of organisations and companies, prompting many to realign their operations towards more sustainable and responsible models (Croci, Edoardo et al., 2022). This tripartite approach (environmental, social, and governance) is not limited to organisations alone; it can also be applied to urban projects, including PEDs. ESG evaluation enables the quantification of impacts on the environment, communities, and decision-making processes, contributing to the structuring of an integrated sustainable urban development model.

Despite the several advantages of the ESG approach, there is a risk of overly compartmentalised evaluations, where each impact is rigidly categorised into one of the three primary dimensions, potentially ignoring significant, intersectional aspects relevant to local stakeholders and project partners. To address this limitation, a "multiple benefits" evaluation model is proposed. This model aims to explore the full spectrum of benefits generated by PEDs, not only within the environmental, social, and governance domains but also by accounting for the interconnections among these dimensions.

The "multiple-benefits" approach is a holistic and transversal method capable of capturing the range and depth of the positive effects PEDs can generate over time. The benefits of PEDs rarely concentrate on a single area of impact (Bertolami et al., 2024) (Bisello, 2017); instead, they develop across multiple dimensions, affecting various aspects of urban life. For example, infrastructural improvements designed to reduce energy consumption can produce additional benefits in terms of public health, through reduced air pollution, or in the social sphere, by promoting sustainable practices and civic engagement. Similarly, better governance within a PED can foster transparency and equity in decisions regarding land and resource management, creating an environment of trust that strengthens the bond between communities and local institutions.

The concept of "multiple-benefits" emerged on the international scene in 2014, when the International Energy Agency (IEA) published an article identifying the main multiple-benefits (including social, environmental, economic, and other domains) arising from improved energy efficiency (International Energy Agency, 2014).

Multiple-benefits are defined as all the positive impacts of a project, understood from a holistic perspective (Bisello, 2020) and therefore encompassing several areas, such as social, environmental, economic and governance. They include both the primary benefits of the project (explicitly stated and related to the project's objectives) as well as those not anticipated (Ürge-Vorsatz et al., 2014).

Since a PED or PED-to-be is a complex urban model involving multiple stakeholders with diverse perspectives and priorities, it is essential to analyse and address these differences to ensure effective and inclusive dialogue. According to Bertolami et al. (2024) the multiple-benefits analysis should be performed considering as well including stakeholders in the process. In the case of a project including multiple case studies, stakeholders should be engaged through a structured process, operating on two primary levels: project-wide and local.

5.1 Objective

The objective of conducting a multiple-benefits analysis for an urban project, such as a positive energy district (PED), is to comprehensively assess and highlight the wide range of positive impacts it generates. By adopting a holistic perspective, this analysis helps ensure that all potential benefits are recognised, ultimately leading to more effective and well-informed decision-making.

A stakeholder-focused approach further enhances this process by actively involving those who are directly affected by or have an interest in the project. By integrating their perspectives, priorities and needs, the analysis can identify and prioritise benefits that align with stakeholder expectations, thereby increasing the overall value and acceptance of the project. This approach fosters greater involvement, increases equity and improves the likelihood of successful implementation, ensuring that the project delivers significant and lasting benefits to the community.

5.2 Methodology

5.2.1 Literature review

The process, as described by Bertolami et al. (2024), begins with an analysis of the literature and comparable PED (or similar) projects in order to identify the most frequently mentioned multiple benefits. This initial step provides a general understanding of the positive impacts typically associated with such initiatives and allows for a comparison with the project in question. Figure 37 shows the most common multiple benefits derived from a literature review and project screening of different PED and smart cities projects (Bertolami et al., 2024).

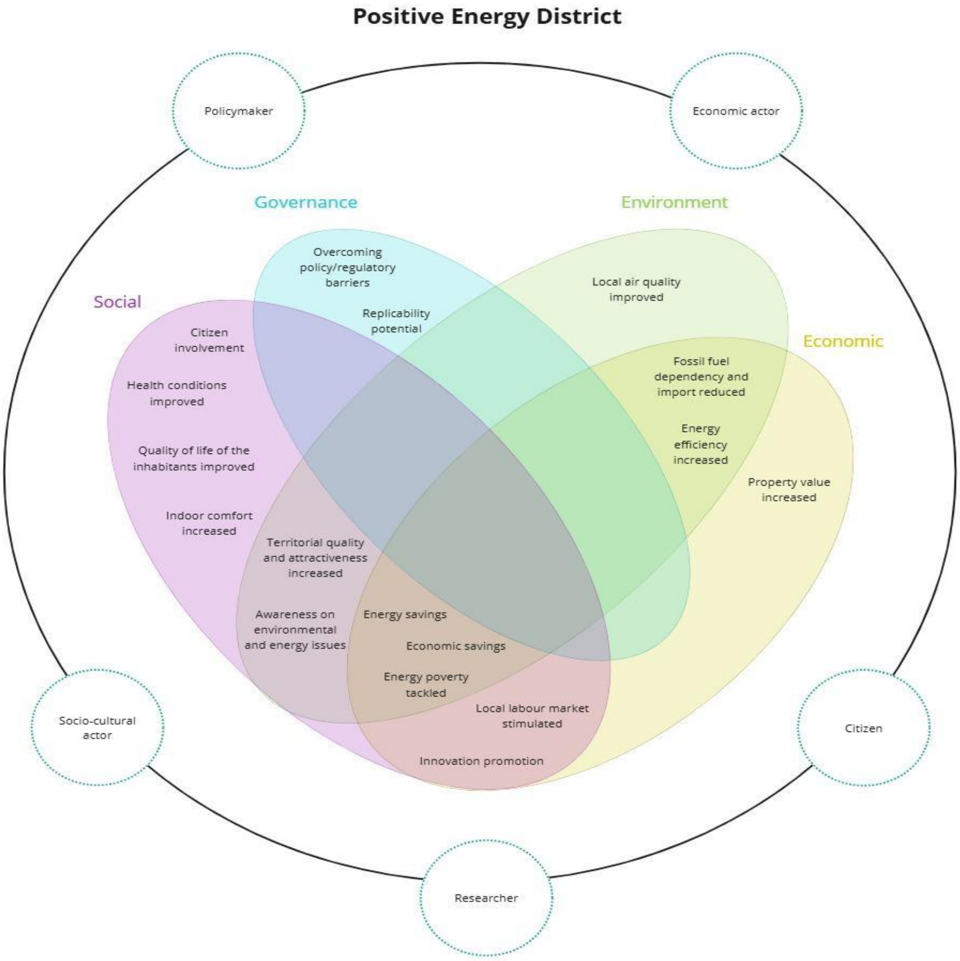

Figure 37: Most relevant multiple benefits in a PED according to the literature review

5.2.2 Involvement of project partners

Subsequently, the main multiple benefits of the project taken into consideration are identified. This phase is conducted collaboratively with all project partners to ensure no significant elements are omitted.

For projects involving multiple case studies, the analysis is conducted on two levels:

- Project-wide level: The target audience includes all project partners, regardless of their direct involvement in the case studies.
- Local level: Focused collaboration with local stakeholders directly or indirectly involved in the project.

At the project-wide level, partners participate in a collective brainstorming session to identify the multiple benefits deriving from the project, including those related to its case studies. These benefits can be organised into four main categories: social, governance, environmental, and economic. This classification serves two primary purposes:

1. It encourages participants to reflect on a diverse range of benefits.
2. It visualises the interconnections between different areas through a Venn diagram (Figure 37), highlighting benefits with positive impacts across multiple sectors.

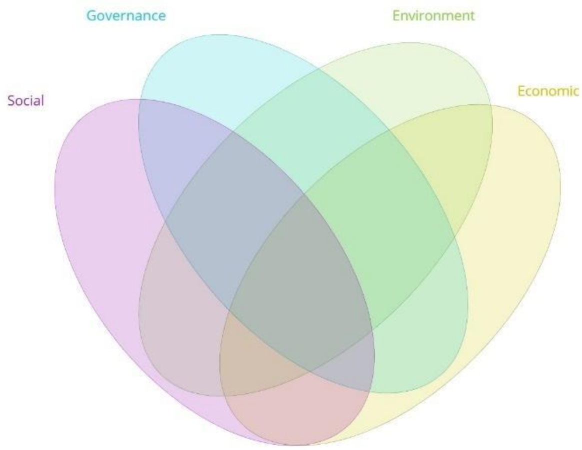

Figure 38: Diagram for the brainstorming on multiple benefits

The outcome of this brainstorming session is a structured list of the main benefits associated with the project's implementation.
For projects involving multiple case studies, it is crucial to progressively tailor the list of benefits to suit the specificities of each context. To this end, meetings with demonstration leaders and local decision-makers are organised to define a targeted list of benefits for each case study.

5.2.3 Involvement of stakeholders

Subsequently, the analysis of multiple benefits is enriched through the involvement of project partners and other local stakeholders in a more detailed evaluation by means of a questionnaire.
The questionnaire helps determine whether different stakeholder groups share common priorities or exhibit significant variations. By identifying patterns of alignment or divergence, the process improves communication strategies and simplifies project implementation. Prioritising widely valued benefits ensures efficient allocation of resources, while addressing discrepancies fosters greater stakeholder engagement and support. This step is therefore important because it integrates stakeholder insights into the decision-making process, improving the initiative's responsiveness and overall effectiveness.
The questionnaire presents respondents with a random selection of identified benefits, asking them to indicate the most and least relevant according to their perspective. This process, repeated for different benefit groups until a uniform evaluation is ensured, uses the Best Worst Scaling method. Best Worst Scaling (BWS) was developed by Louviere and Woodworth in 1990 to create user-friendly surveys. It helps respondents identify the "best" and "worst" items

from a set, based on Random Utility Theory (RUT). BWS is used within MCA (multicriteria analysis) frameworks to quantify preferences through normalised scores, aiding objective decision-making. Its advantages include simplicity, reduced bias, and strong discriminative power as well as the identification of a clear hierarchy of perceived priorities (Finn & Louviere, 1992) (Chrzan & Peitz, 2019).

5.2.4 Dissemination of the results

Finally, the dissemination of results is critical and pursues two main objectives:

1. Supporting project partners: The results provide valuable insights into local perceptions and preferences, enabling partners to make more informed and deliberate decisions in subsequent project phases.
2. Engaging stakeholders: Sharing the motivations and benefits of territorial transformations helps the community to better understand their value. This increased awareness fosters acceptance and support for the proposed changes. In addition, being aware of the priorities of the different stakeholder groups makes it possible to structure more targeted communication.

Dissemination is a multi-faceted process that combines various communication channels and strategies. Interactive tools, such as living labs and public events, offer stakeholders the opportunity to engage directly with the results. Simultaneously, digital platforms like social media, project partner websites, and other communication means amplify the reach, ensuring the message reaches a broader audience. This phase not only promotes transparency but also bridges the gap between decision-makers and the community, fostering understanding and harmonious integration of territorial changes.

5.3 Conclusions

This integrated approach enables a comprehensive examination of PEDs and highlights their large-scale effects. The “multiple-benefits” approach also allows the definition of both qualitative and quantitative metrics and evaluation methodologies, adaptable to different contexts and often expressed in monetary and non-monetary values, capable of reflecting the real impact on the environment, society, economy and governance.
Stakeholders are a central part of an urban project; they have the power to improve or worsen the project in question depending on their involvement. To maximise project effectiveness, it is crucial not only to communicate the potential benefits of implementation, but also to create opportunities for stakeholders to express their priorities and concerns. Meaningful dialogue and active engagement ensure that different perspectives are taken into account, fostering a collaborative approach that strengthens stakeholder support and improves project outcomes. Ultimately, integrating multi-benefit analysis with a stakeholder-driven perspective leads to more resilient and impactful urban projects. It reinforces the importance of balancing technical, economic, and social considerations to create positive energy districts that not only meet climate and energy goals, but also generate significant and lasting value for the communities they serve.

Authors

Irene Bertolami, Institute for Renewable Energy, Eurac Research, Italy (Irene.Bertolami@eurac.edu)
Adriano Bisello, Institute for Renewable Energy, Eurac Research, Italy (adriano.bisello@eurac.edu)

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6. Conclusions

6.1 Toward an integrated evaluation framework for PEDs

Positive Energy Districts (PEDs) embody a new paradigm in urban transformation, where energy production, consumption, and distribution are interwoven with social, economic, and environmental dynamics at the district scale. Unlike traditional energy efficiency interventions or high-performance buildings, PEDs are not isolated projects but rather complex socio-technical systems operating within a dense network of urban interdependencies. This complexity demands a fundamental shift in how we approach impact assessment.

Historically, impact evaluation in the built environment has followed sectoral lines: economic feasibility studies and environmental Life Cycle Assessments (LCAs), have typically been conducted in parallel or in isolation, while social impact assessment practices are only now beginning to appear in the evaluation landscape. However, this compartmentalised approach is no longer sufficient. PEDs necessitate an integrated framework that combines these dimensions into a unified methodology, capable of capturing interactions, synergies, and trade-offs across multiple domains.

The findings from research activities performed under the Subtask C supervision and coordination show that while several methodologies exist, ranging from Cost-Benefit Analysis (CBA) and Life Cycle Costing (LCC) to Multi-Criteria Decision Analysis (MCDA) they are rarely used in combination. Most studies adopt a single-method perspective, which can result in overlooking important cross-cutting effects. For instance, an intervention that appears economically advantageous may have negative distributional impacts or environmental rebound effects that are not captured through financial metrics alone. Conversely, some nature-based solutions that may perfectly fit into the overall PED design, substantially helping in achieving energy efficient results, also providing substantial co-benefits (e.g., air quality, urban cooling, biodiversity) may be undervalued if assessed only through conventional investment analysis.

An integrated evaluation framework must therefore evolve toward a hybrid model, combining quantitative and qualitative tools, static and dynamic indicators, and financial as well as non-market valuation techniques. Such a model should be designed not only to support decision-making but also to communicate the systemic value of PEDs to a broader audience of stakeholders, including policymakers, developers/investors, and citizens.

Moreover, this evaluation effort must be context-sensitive. PEDs are deeply embedded in local social, regulatory, climatic, and economic conditions. A one-size-fits-all framework risks generating misleading conclusions. Site-specificity is essential, both in terms of technological configurations and in the way value is constructed, perceived, and distributed among stakeholders. Key Performance Indicators (KPIs) must be carefully chosen and balanced to avoid skewing priorities. For example, over-reliance on short-term Return on Investment (ROI) or Payback Periods might disincentivise long-term benefits such as energy poverty reduction or climate adaptation capacity. A balanced scorecard approach that reflects a plural set of values and timeframes is recommended, e.g. through the integration and adaptation of existing sustainability protocols, which adequately consider the specific energy characteristics of PED, while taking a broad view in which the quality of urban life is a fundamental element together with environmental compatibility.

Spatial analysis and GIS-based tools are particularly promising in this domain. They can support integrated evaluation by overlaying environmental impacts, socio-demographic vulnerability, infrastructural needs, and economic potential across urban territories. This allows for data-driven prioritisation and a better understanding of how PED benefits and burdens are spatially distributed, tackling a key concern for inclusive and equitable development.

In conclusion, evaluation frameworks for PEDs should be more than accounting exercises. They must become instruments of strategic governance, capable of articulating a shared vision of urban sustainability. This means aligning assessments with broader policy objectives such as the European Green Deal, the Renovation Wave, or the Sustainable Development Goals (SDGs), and ensuring that metrics reflect not just cost-efficiency, but long-term public value creation and which can also be attractive to investors and users.

Therefore, an integrated evaluation approach for PEDs is both a methodological necessity and a political imperative. It offers a pathway to make the complexity of PEDs manageable, transparent, and actionable, turning ambitious concepts and pilot cases into replicable, desirable, and investable urban transformations.

6.2 The value of co-benefits in PED assessment

One of the key insights emerging from research activities in Subtask C is the essential role of co-benefits in defining the real value of Positive Energy Districts, because PEDs generate a much wider spectrum of impacts that often remain invisible in standard assessments. These include improved public health, increased urban resilience, enhanced social cohesion, higher property values, and the creation of local jobs, among others.

Recognising and accounting for these multiple, interrelated benefits is crucial not only to justify investments but also to foster social legitimacy and stakeholder engagement. Co-benefits are what make PEDs truly transformative: they turn a technical intervention into a strategic urban policy tool, capable of addressing complex challenges such as climate adaptation, demographic change, and economic inequality in an integrated manner.

A key challenge lies in the monetisation and comparison of these benefits, particularly when they span diverse domains and time horizons. For example, how can we compare avoided CO_2 emissions with improved learning outcomes in schools, or enhanced biodiversity with increased energy security? To address this, mixed methods able to capture the social, environmental, and economic value created by an intervention in monetary terms, offering a more comprehensive performance narrative are gaining interest. Among others, the Social Return on Investment (SROI) is a promising one. The identification of monetary values can be done by using proxies related to market values or adopting revealed or stated preferences of stakeholders (e.g., hedonic pricing techniques allow us to quantify how sustainable features, like proximity to green infrastructure or access to district energy systems, influence real estate markets. Conversely, Willingness to Pay - WTP can help assess how much citizens value certain outcomes, especially those not traded in the markets like cleaner air, reduced noise pollution, or increased safety). These techniques are not only useful for evaluation purposes but can also guide design and policy choices by revealing user priorities and preferences.

Another critical dimension is equity. Co-benefits are not evenly distributed, and this asymmetry can lead to unintended consequences, such as green gentrification or displacement of vulnerable groups. PED assessments should therefore include distributional analysis, asking who benefits, who pays, and who decides. Tools from welfare economics, such as equity-weighted cost-benefit analysis, can provide insights into how to design PEDs that are not only efficient and sustainable but also socially fair. The application of the concept of “public value” may provide a unifying lens for this integrated approach. Unlike private value, which is captured by individual actors, public value encompasses collective gains that contribute to the common good. This includes not only economic growth but also health, justice, environmental integrity, and cultural vibrancy. PEDs, when designed and evaluated through a public value perspective, can serve as platforms for societal innovation, creating shared benefits that extend well beyond the energy domain.

The application and adaptation of existing handbooks, such as “A practical guide to the New European Bauhaus self-assessment method and tool (https://publications.jrc.ec.europa.eu/repository/handle/JRC139118)” recently published by the European Community may be used as a reference.

Some of these co-benefits are interdependent and mutually reinforcing. For instance, green spaces integrated in PEDs improve stormwater management, reduce urban heat island effects, and promote physical and mental health, all of which can lower public health expenditures and enhance quality of life. Similarly, local energy generation and storage systems can increase community resilience to power outages while reducing dependence on external suppliers. This “chain of effects” is intriguing, but also easily lends itself to double-counting or overestimation of benefits, which must be avoided.

Aligning PED vision with overarching frameworks such as the New European Bauhaus can facilitate both strategic coherence and cross-sectoral collaboration, facilitating planning, funding, and evaluation systems.

6.3 PEDs as urban governance challenges

It has already been said that Positive Energy Districts are not merely technological projects; they are complex urban projects that also challenge existing governance models. Their implementation requires coordinated management across multiple sectors (e.g., energy, mobility, construction-planning, environment, social services) and the active involvement of a diverse range of public, private, and civic stakeholders. In this sense, PEDs represent a case of complex, multi-level governance.

Most local administrations still lack the tools and institutional capacity to plan, assess, and monitor such multifaceted interventions. PEDs demand a strong integration between energy planning and urban planning, which are often developed separately in policy and regulatory frameworks. This also calls for overcoming administrative silos and promoting interdepartmental and interinstitutional collaboration.

Another critical aspect is participatory governance. For PEDs to succeed, they must be co-designed with end-users: citizens, local businesses, and utility companies. Only through this approach can trust be built, social acceptance of new technologies increased, and equitable distribution of benefits ensured. Tools such as co-design workshops, urban living labs, and digital engagement platforms are essential to this process. At the same time, there is a need for new forms of public-private partnerships, capable of attracting investment and ensuring long-term economic sustainability. This requires innovative business models, flexible contracts, and regulatory incentives that recognise the contribution of PEDs to both the energy system and broader urban well-being. The use of KPI and wording aligned with corporate and investor sustainability reporting can help in this regard (e.g. referring to EFRAG, GRI, etc.).

The national and local regulatory frameworks also play a key role. In many cases, legal and policy barriers (such as limitations on energy sharing, building codes, or tax regimes) constrain the full potential of PEDs. A revision of legal instruments could be necessary in specific contexts to enable new energy governance models at the urban scale, including energy communities and local flexibility markets. In general, PEDs rollout requires a paradigm shift in urban governance: from linear, sectoral models to adaptive, collaborative, and public value-oriented systems. Only then will it be possible to scale up pilot initiatives into transformative and sustainable urban solutions.

6.4 Strategic implications for urban planning and key recommendations

Positive Energy Districts are not just an innovation in energy systems but a strategic opportunity for rethinking urban planning and urban-energy frameworks. The PED concept lies at the intersection of energy infrastructure design, environmental performance, economic regeneration, and social innovation. As such, its implementation requires a profound transformation of the tools and approaches traditionally used in urban development.

As a prerequisite, PEDs call for a new planning rationale that integrates energy requirements and performance criteria directly into land-use plans, zoning codes, and not only building regulations. Energy issues related to local clean generation potential, district heating and cooling opportunities, or infrastructure for flexibility and storage must become structural components of urban development strategies, not post hoc add-ons.

This also implies revisiting spatial planning instruments. Masterplans, urban regeneration projects, and Sustainable Urban Mobility Plans (SUMPs) should include energy objectives and be aligned with the vision of decarbonised, resilient, and self-sufficient urban districts, as cornerstones of municipal transition plans. PEDs can serve as spatial and institutional “testbeds” to experiment with this new generation of integrated plans, based on systemic thinking and place-based strategies. At the policy level, a key implication is the need for multi-sectoral alignment. Many of the benefits of PEDs, from reduced health costs to improved air quality and mobility integration, fall outside the traditional jurisdiction of energy departments and require a new approach in public budgeting, calling for cross-sector funding, fostering collaboration across environmental, economic, housing, and social sectors. Also, from an investment perspective, PEDs challenge existing funding schemes. Their long-term returns and distributed benefits do not always align with short-term financial logics or siloed budget lines. Therefore, new financing models, including blended finance, green bonds, climate funds, or results-based financing, should be tailored to the characteristics of PEDs. In such interconnected and high-tech systems. reliable data and digital tools become key enablers for planning, monitoring, and optimising PED performance. Therefore, cities should invest in interoperable platforms, open data standards, and spatialised energy models to support evidence-based decision-making and transparent impact evaluation. The adoption of international standards as a reference (see for example ISO smart cities related publications https://www.iso.org/sectors/environment/smart-cities) may facilitate this process.

Building on these insights and considerations, we propose the following key recommendations for practitioners, policymakers, and stakeholders involved in the development of PEDs:

1. Adopt integrated evaluation frameworks that combine economic, environmental, and social indicators, including qualitative and non-monetary dimensions, to assess the full range of impacts and trade-offs associated with PED implementation;
2. Center co-benefits and public value creation in project appraisal processes. This includes quantifying avoided costs, societal gains, and long-term benefits across different sectors (e.g., health, education, biodiversity, resilience);
3. Embed PED criteria in spatial planning instruments, ensuring alignment between energy objectives and land-use regulations, urban design principles, and infrastructure planning;
4. Foster regulatory innovation through flexible, adaptive, and participatory frameworks. Regulatory sandboxes and experimental planning zones can help test new solutions while reducing institutional inertia;
5. Promote collaborative governance models that enable co-creation, shared ownership, and multi-stakeholder engagement across the project lifecycle. Strong local leadership and empowered intermediaries are essential for navigating complexity and building trust;
6. Strengthen local capacities in integrated planning, data management, and project evaluation, especially within municipal governments. Capacity-building programmes, peer-to-peer exchange, and participation in international networks can support this objective;
7. Develop dedicated funding streams and investment tools tailored to the specific nature of PEDs, leveraging both public and private capital while ensuring fair distribution of risks and returns;
8. Align PED initiatives with broader policy agendas, such as the Green Deal, the Renovation Wave, the New European Bauhaus, and the Sustainable Development Goals (SDGs), to maximise impact and policy coherence;
9. Support replicability and upscaling by codifying lessons learned into actionable toolkits, open-source platforms, and standardisation protocols. A PED certification scheme could enhance investor confidence and benchmarking;
10. Integrate user feedback and behavioral insights into the design and operation of PEDs, recognising the central role of citizens not just as end-users but as active elements in the energy transition and social value creation.

In conclusion, PEDs are a powerful lever to operationalise a just, green, and smart urban transition. But to do so, they must be framed not only as optimised energy projects, but as catalysts of urban regeneration, policy innovation, and social transformation. Their successful implementation will require the ability to rethink how cities are planned, financed, governed, and evaluated.

Authors

Adriano Bisello, Institute for Renewable Energy, Eurac Research, Italy (adriano.bisello@eurac.edu)

Appendix 1

To delve into the different energy flows characterising PEDs, it is worth focusing on each of them singularly, starting from $E_{th}E_{th}$. Considering that it can be supplied by (DHN) networks as well as users' own plants, the PED's total thermal energy demand ($E_{th}^{PED}E_{th}^{PED}$) can be evaluated according to Equation 1:

$$E_{th}^{PED} = \sum_{i=1}^{NTP^{US}} E_{th_i}^{TP^{US}} + E_{th,net}^{DHN^{US}} \quad (1)$$

$E_{th_i}^{TP^{US}}E_{th_i}^{TP^{US}}$ quantifies the thermal energy supplied by each plant owned by single users, which is referred to by using the subscript i that ranges between 1 and the total number of TPs owned in total by users ($NTP^{US}NTP^{US}$). $E_{th,net}^{DHN}E_{th,net}^{DHN}$ represents instead the net thermal energy delivered to the users by the DHN. According to Equation 2, in addition to $E_{th}^{DHN^{US}}E_{th}^{DHN^{US}}$, the gross thermal energy delivered to the DHN ($E_{th,gross}^{DHN}E_{th,gross}^{DHN}$) includes the share of thermal energy exported outside of the PED boundaries ($E_{th,exp}^{DHN}E_{th,exp}^{DHN}$) and thermal energy losses ($E_{th,loss}^{DHN}E_{th,loss}^{DHN}$). From the generation side and according to Equation 3, $E_{th,gross}^{DHN}E_{th,gross}^{DHN}$ equals the sum of the thermal energy imported from non-local RESs-based TPs ($E_{th,imp}^{DHN}E_{th,imp}^{DHN}$) and the thermal energy produced by all TPs inside the PED (whose total number is equal to $NTP^{PED}NTP^{PED}$) net of each plant's energy demand for the activation of auxiliaries ($E_{th,net_i}^{TP^{PED}}E_{th,net_i}^{TP^{PED}}$).

$$E_{th,gross}^{DHN} = E_{th}^{DHN^{US}} + E_{th,exp}^{DHN} + E_{th,loss}^{DHN} \quad (2)$$

$$E_{th,gross}^{DHN} = E_{th,imp}^{DHN} + \sum_{i=1}^{NTP^{PED}} E_{th,net_i}^{TP^{PED}} \quad (3)$$

TPs' primary energy demand can be estimated by using efficiency values ($\eta_i^{TP}\eta_i^{TP}$). Likewise, the electric energy demand of electric-driven TPs can be estimated by using coefficients of performance ($COP_i^{TP}COP_i^{TP}$). As a result, the total primary energy demand of the PED relating to thermal energy supply ($E_p^{PED}E_p^{PED}$) can be evaluated according to Equation 4. The subscripts f and r account for the energy source exploited by each plant, that is fossil or renewable, respectively. The term $E_{p,exp_i}^{TP_r^{PED}}E_{p,exp_i}^{TP_r^{PED}}$ relates to the exports of thermal energy, and therefore acts like a subtractive term in the total balance. The overall emissions due to thermal energy supply and demand in PED ($m_{CO_2}^{th}m_{CO_2}^{th}$) can be evaluated according to Equation 5 by multiplying each term of Equation 4 by the EF of the source exploited in the corresponding TP ($\beta_i^{TP}\beta_i^{TP}$). As a result, the emissions due to the export of surplus thermal energy produced by RESs-based plants are subtracted to the total emission balance and act as an emission credit.

$$E_p^{PED} = \sum_{i=1}^{NTP^{NL}} E_{p_i}^{TP^{NL}} + \sum_{i=1}^{NTP_f^{PED}} E_{p_i}^{TP_f^{PED}} + \sum_{i=1}^{NTP_r^{PED}} \left(E_{p_i}^{TP_r^{PED}} - E_{p,exp_i}^{TP_r^{PED}}\right) + \sum_{i=1}^{NTP_f^{US}} E_{p_i}^{TP^{US}} + \sum_{i=1}^{NTP_r^{US}} E_{p_i}^{TP^{US}} \quad (4)$$

$$m_{CO_2}^{th} = \sum_{i=1}^{NTP^{NL}} \left(E_{p_i}^{TP^{NL}} \cdot \beta_i^{TP^{NL}}\right) + \sum_{i=1}^{NTP_f^{PED}} \left(E_{p_i}^{TP_f^{PED}} \cdot \beta_i^{TP_f^{PED}}\right) + \sum_{i=1}^{NTP_r^{PED}} \left(\left(E_{p_i}^{TP_r^{PED}} - E_{p_i}^{TP_r^{PED}}\right) \cdot \beta_i^{TP_r^{PED}}\right) + \sum_{i=1}^{NTP_f^{US}} \left(E_{p_i}^{TP_f^{US}} \cdot \beta_i^{TP_f^{US}}\right) + \sum_{i=1}^{NTP_{RES}^{US}} \left(E_{p_i}^{TP_r^{US}} \cdot \beta_i^{TP_r^{US}}\right) \quad (5)$$

The methods discussed so far can be applied also to the evaluation of emissions due to supply and demand for cooling energy ($m_{CO_2}^{co} m_{CO_2}^{co}$). In both cases, the emissions relating to the activation of electric-driven thermal/cooling energy production plants belonging to users ($E_{el}^{TP^{US}}$ $E_{el}^{TP^{US}}$ and $E_{el}^{CP^{US}}$ $E_{el}^{CP^{US}}$, respectively) as well as serving the DHN/DCN ($E_{el}^{TP^{PED}}$ $E_{el}^{TP^{PED}}$ and $E_{el}^{CP^{PED}}$ $E_{el}^{CP^{PED}}$, respectively) can be included in the total balance for electric energy supply/demand. In this regard, the total electric energy demand of the district (E_{el}^{PED} E_{el}^{PED}) can be determined according to Equation 6,

$$E_{el}^{PED} = E_{el}^{US} + E_{el}^{TP^{PED}} + E_{el}^{CP^{PED}} \quad (6)$$

Where the term E_{el}^{US} E_{el}^{US} represents the users' total electric energy demand (which also includes $E_{el}^{TP^{US}}$ $E_{el}^{TP^{US}}$ and $E_{el}^{CP^{US}}$ $E_{el}^{CP^{US}}$). From the generation side and as stated in Equation 7, E_{el}^{PED} E_{el}^{PED} equals the supply of electric energy from RESs-based plants outside of PED net of self-consumption due to auxiliaries' activation and grid losses ($E_{el,net,i}^{EP^{NL}}$ $E_{el,net,i}^{EP^{NL}}$), plus the supply from plants inside the PED ($E_{el,net,i}^{EP^{PED}}$ $E_{el,net,i}^{EP^{PED}}$) and belonging to users ($E_{el,net,i}^{EP^{US}}$ $E_{el,net,i}^{EP^{US}}$) net of their self-consumptions and reduced by potential exports. In addition, the imports from the external power grid (PG) must be also considered (E_{el}^{PG} E_{el}^{PG}).

$$E_{el}^{PED} = \sum_{i=1}^{NEP^{NL}} E_{el,net_i}^{EP^{NL}} + \sum_{i=1}^{NEP^{PED}} \left(E_{el,net_i}^{EP^{PED}} - E_{el,exp_o}^{EP^{PED}}\right) + \sum_{i=1}^{NEP^{US}} E_{el,net_i}^{EP^{US}} + E_{el}^{PG} \quad (7)$$

For quantifying the primary energy demand relating to $E_{el,net_i}^{EP^{PED}}$ $E_{el,net_i}^{EP^{PED}}$, the distinction between plants exploiting fossil fuels, thermal RESs and non-thermal RESs is required. The latter categorisation applies also to $E_{el,net,i}^{EP^{NL}}$ $E_{el,net,i}^{EP^{NL}}$ and is useful to evaluate the total emissions due to electric energy supply and demand in PEDs ($m_{CO_2}^{el} m_{CO_2}^{el}$), according to Equation 8. In this Equation, NEP identifies the total number of EPs distinguished based on their location and exploited source, by analogy with Equation 4. Indeed, in the case of thermal RESs-based plants (which are referred to by using the subscript tr), emissions can be evaluated multiplying their primary energy demand by the EF of the corresponding source (

$\beta_i^{EP}\beta_i^{EP}$). Of course, the primary energy demand of each plant can be determined by using its efficiency ($\eta_i^{EP}\eta_i^{EP}$) starting from its gross electric energy production ($E_{el,gross}^{EP}E_{el,gross}^{EP}$). Conversely, in the case of non-thermal RESs-based plants, emissions can be determined starting from their gross electric energy production ($E_{el,gross}^{EP}E_{el,gross}^{EP}$) by adopting the EF relating to the specific plant ($\alpha_i^{EP}\alpha_i^{EP}$). Indeed, these plants do not involve combustion processes and their emissions are non-zero only when adopting LC-based EFs thereby. In the case of RES-based plants within the PED or belonging to users, the eventual exports of electric energy outside of its boundaries must be considered as in the case of thermal/cooling energy production. Lastly, emissions due to electricity imports from the PG can be evaluated by using its own emission factor ($\alpha^{PG}\alpha^{PG}$), whose value can be considered constant during the year but also time and spatial dependent.

$$
\begin{aligned}
m_{CO_2}^{el} = {} & \sum_{i=1}^{NEP_{tr}^{NL}} \left(E_{p,i}^{EP_{tr}^{NL}} \cdot \beta_i^{EP}\right) + \sum_{i=1}^{NEP_{r}^{NL}} \left(E_{el,gross,i}^{EP_{r}^{NL}} \cdot \alpha_i^{EP}\right) + \sum_{i=1}^{NEP_{f}^{PED}} \left(E_{p,i}^{EP_{f}^{PED}} \cdot \beta_i^{EP}\right) \\
& + \sum_{i=1}^{NEP_{tr}^{PED}} \left(\frac{E_{el,gross,i}^{EP_{tr}^{PED}} - E_{el,exp,i}^{EP_{tr}^{PED}}}{\eta_i^{EP}} \cdot \beta_i^{EP}\right) + \sum_{i=1}^{NEP_{r}^{PED}} \left(\left(E_{el,gross_i}^{EP_{r}^{PED}} - E_{el,exp,i}^{EP_{r}^{PED}}\right) \cdot \alpha_i^{EP}\right) \\
& + \sum_{i=1}^{NEP_{tr}^{us}} \left(\frac{E_{el,gross,i}^{EP_{tr}^{us}} - E_{el,exp,i}^{EP_{tr}^{us}}}{\eta_i^{EP}} \cdot \beta_i^{EP}\right) + \sum_{i=1}^{NEP_{r}^{PED}} \left(\left(E_{el,gross_i}^{EP_{r}^{us}} - E_{el,exp,i}^{EP_{r}^{us}}\right) \cdot \alpha_i^{EP}\right) \\
& + E_{el}^{PG} \cdot \alpha^{PG}
\end{aligned}
$$

Appendix 2

Table 1: Main Stages in PEDs' Value Chain

	Main Stages in PEDs' Value Chain			Background	Ref.
	Planning	Implementation	Operation		
Stakeholder			occupants, residents, and end-users; citizens as energy producers and consumers	From three PEDs projects in Norway (ZEN/ +CityxChange/ syn.ikia)	Baer et al. 2021
	representatives from energy engineering and utility companies, the real estate, building and construction sector, financial intermediaries				
	The public sector (city authorities) through all stages				
		Policymaker, government, authorities		PEDs in Spain/ 60 projects in Europe from JPI UE Program	Hearn and Castaño-Rosa 2021; Bossi et al. 2020
	Municipality, citizens, real estate developers			61 PEDs Projects review (JPI UE programme)	Zhang et al. 2021
	citizens, professionals (researchers), urban planners, and municipal stakeholders			n.d.	Hedman et al. 2021
	Citizens, end-users, municipality			n.d.	Bossi et al. 2020
	(potential) customers			the lighthouse city: Leipzig in SPARCS project	Uspenskaia et al. 2021
		Utility company municipal planners, researchers, coordinating organisation and architectural company		two Smart Energy Community (SEC) projects in Oslo (implementation stage) and Bergen (planned)	Nielsen et al. 2018
	city planners				
	Planners, architects, researchers, and citizens			ZEN in Smart Cities	Wiberg et al. 2019

	Main Stages in PEDs' Value Chain			Background	Ref.
	Planning	Implementation	Operation		
	citizens, experts, professionals, researchers			two Lighthouse cities Espoo (Finland) and Leipzig (Germany), from European Horizon Europe (H2020) project	Fatima et al. 2021

Table 2: A harmonised KPI set for assessing the social impact of PEDs

Assessment Criteria	KPI	Unit	KPI Description	Source	Corresponding social impact from Literature and JPI UE Booklet (P: Project)
Safety	Crime rate	#/100.000	Number of violence, annoyances, and crimes per 100.000 population	CITYKeys Bosch et al. 2017	reduced crime rates (Shnapp et al. 2020)
Community	Increased consciousness of citizenship	Five-point Likert scale (No unit)	The extent to which the project has contributed to increasing consciousness of citizenship. The consciousness of citizenship is the awareness (consciousness) of one's community, civic rights, and responsibilities and contributes to the sense of community.	Angelakoglou et al. 2019	Common community purpose/a sense of community (Shnapp et al. 2020; Hearn and Castaño-Rosa 2021)
	Social Cohesion	n.d.	addressing the existence and the conditions for strong social networks, formed on trust-based bonds, with a capacity to absorb and build on diversity	Salom et al. 2021	Social cohesion (Hedman et al. 2021); the consensus among stakeholders (Shnapp et al. 2020; Hearn and Castaño-Rosa 2021)
Work	Job creation	%	Assessing the direct job creation through the implementation and operation of the respective solutions; Or the annual rate of contraction in all the sectors per year	Angelakoglou et al. 2019Matchup	Employment opportunities(P1,18); (Shnapp et al. 2020)
Health	Access to basic health care services	% of people	Share of population with access to basic health care services within 500m	CITYKeys Bosch et al. 2017	Health increasing (P2,9)
	Encouraging a healthy lifestyle	Likert	The extent to which policy efforts are undertaken to encourage a healthy lifestyle		

Assessment Criteria	KPI	Unit	KPI Description	Source	Corresponding social impact from Literature and JPI UE Booklet (P: Project)
Equity	Increased participation of vulnerable groups	Five-point Likert scale (No unit)	Vulnerable and other groups whose opinions or contributions are not reflected well enough in our society (like women, minorities, and the disabled) require special attention to be included in the community, thereby enhancing social cohesion and diversity	Angelakoglou et al. 2019	Social inclusiveness (Hedman et al. 2021)
	Living Conditions	n.d.	the use of "red flags" such as overpopulation and general bad living conditions monitored by Eurostat that in turn refers to SDGs 1, 6, and 11	Salom et al. 2021	living condition (P 2,3,13,16,19,20,23) Passive Haus (P2)
	Affordability of Energy	n.d.	the use of harmonised European "arrears" and "share of income spent on energy" indicators to measure energy poverty		Energy poverty (Haarstand and Wathne 2019; Hearn et al. 2021; Gouveia et al. 2021; Hedman et al. 2021)
	Affordability of Housing	% of people, Likert	the share of people with a housing cost overburden and mapping the income required to afford housing price		Gentrification (for those vulnerable groups or families) (Hedman et al. 2021; Gouveia et al. 2021; Yazar et al. 2020)
Access to services	Access to commercial amenities	% of people	Share of the population with access to at least six types of commercial amenities providing goods for daily use within 500m	CITYKeys Bosch et al. 2017	Enhancement of spatial qualities by the provision of amenities (P5)
	Access to public amenities	% of people	Share of the population with access to at least one type of public amenity within 500m		
Access to services	Access to public transport	% of people	Share of the population with access to a public transport stop within 500m	CITYKeys Bosch et al. 2017	citizen mobility becoming easier (P21)
	Access to vehicle-sharing solutions for city travel	#/100.000	Number of vehicles available for sharing per 100.000 inhabitants		

Assessment Criteria	KPI	Unit	KPI Description	Source	Corresponding social impact from Literature and JPI UE Booklet (P: Project)
	Length of the bike route network	% in km	% of bicycle paths and lanes concerning the length of streets (excluding motorways)		
Quality of housing and the built environment	Thermal comfort	Five-point Likert scale (No unit)	The quality of the delivered heating/cooling service is certainly a matter of technical aspects that can be measured with quantified technical indicators, but it is also a matter of the opinion of the service receivers	Angelakoglou et al. 2019	Indoor comfort (Hedman et al. 2021)
	Public outdoor recreation space	m2/cap	Square meters of public outdoor recreation space per capita	CITYKeys Bosch et al. 2017	Recreation, creation of attractive public space (shared space/playgrounds) (P13,20); well-organised recreational area (Uspenskaia et al. 2021)
	Green space	hectares/ 100.000	Green area (hectares) per 100.000 population		A green oasis, a community garden (P13, 20)
Social Acceptance	Active/proactive citizens' behaviour	% and/or 5-Point Likert Scale	The indicator addresses the question of whether and to which extent householders changed their behaviour regarding an action (e.g., willingness to invest in energy savings measures or pay more for RES or service, recommend the project to others	mySMARTLife, https://www.mysmartlife.eu/	Behaviour changing, realisation or increasing self-consumption, living an emission-friendly lifestyle (P2,9,19,20)
	Degree of satisfaction	% and/or 5-Point Likert Scale	Level of satisfaction and acceptance of people affected by the action in the topics analysed: 1. Technical point of view: perceived adequateness, perceived benefit (e.g., comfort), perceived usefulness, perceived ease of use, aesthetical solution satisfaction 2. Economic point of view: cost, risk, benefit		Social acceptance (Hedman et al. 2021) rasing awareness (Haarstand and Wathne 2019)

Assessment Criteria	KPI	Unit	KPI Description	Source	Corresponding social impact from Literature and JPI UE Booklet (P: Project)
	Social factors	% and/or 5-Point Likert Scale	Citizens' perception of the social factors identified (e.g., the divergence of interest, resistance to change, perception of the amount of information received, perception of involvement in decision-making, interviewed profile)		
	Number of people reached	% # (it is not known the size of the target group)	Percentage of people in the target group that has been reached and/or are activated by the project		social implementation, engagement activities carried out (P19)
	Percentage of citizens' participation in online decision-making	%	The indicator assesses the percentage of citizens who take part in online decision-making.	Angelakoglou et al. 2020	Increases citizen engagement (Giourka et al. 2020)

Table 3: Detailed Indicator Selection Process

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2-survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
Safety	Crime rate	Number of violence, annoyances, and crimes per 100.000 population	[#/100.000 hab], [%]	Society, local community	Implementation, Use	Corruption, Secure living conditions	Primary	2	Crime level in the area	Africa: 4 Asia: 4 South America: 4	Africa: 4 Asia : 5	Africa: 4 Asia: 5	4	Public report	15
Community	Increased level of consciousness of citizenship	The extent to which the project has contributed to increasing consciousness of citizenship. The consciousness of citizenship is the awareness (consciousness) of one's community, civic rights, and responsibilities and contributes to the sense of community. (Variables: civic rights and responsibilities, sense of community) [Surveys-based Likert scale]	Five-point Likert scale	Local community	Use	Community engagement	Primary/Secondary	2	The reference value is the base value recorded at the beginning of the project and which is then compared with the one monitored at a later stage of the project.	-	-	-	2	Surveys	9

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construct ion	Elec tricit y	Transport			
	Progress towards Energy Citizenship	(Variables: social acceptance of PED solution, personal attitudes and motivation, perceived incentives/barriers, level of trust, sense of community, technology perception, ICT literacy) [Surveys-based Likert scale]	Five-point Likert scale	Local community	Use	Access to material resources	Primary	2	The reference value is the base value recorded at the beginning of the project and which is then compared with the one monitored at a later stage of the project.	-	-	-	2	Surveys	16
	Social Cohesion	("D3.1_Methodology -framework-for-Plus-Energy-Buildings-and-Neighbourhoods" of the project folder and carefully read the calculation method on pages 90-91-92-93.) Addressing the existence and the conditions for strong social networks, formed on trust-based bonds, with a capacity to absorb and build on diversity (Variables: support network, care habits, belonging, cultural values, trust, discrimination)	Five-point Likert scale	Local community	Use	Community engagement	Primary	2	The reference value is the base value recorded at the beginning of the project and which is then compared with the one monitored at a later stage of the project.	Africa: 4 Asia: 4	Africa: 4 Asia : 4	Africa: 4 Asia: 4	2	Surveys	15

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
Work	Job creation		[#], [%]	Local community, Society, Value chain actors	All	Local employment, poverty alleviation	Secondary	2	Data can be derived from project documentation or interviews with the project leader and/or statistical authorities. Additionally, average data (e.g. average ratio of new jobs per million of euros invested in the building sector) can be applied for estimations. Once	Africa: 5 Asia: 4 South America: 4	Africa: 5 Asia: 4 South America: 4	Africa: 5 Asia: 4 South America: 4	5	e.g. OECD	20
	Median Disposable (Household) Income		[€/household], [€/hab]	Society	All	Contribution to economic development, poverty alleviation, wealth distribution	Secondary	2	Statistics, i.e. for Italy: http://dati.istat.it/Index.aspx?QueryId=42299&lang=en	Africa: 5 Asia: 4	Africa: 5 Asia: 4	Africa: 5 Asia: 4	5	e.g. Eurostat	19
Health	Access to basic health care services	(hab with a health center <500m)	[% of hab]	Local community, workers	All	Safe and healthy living conditions, health and safety	Primary/Secondary	1		Africa: 5 Asia: 4 South America: 4	Africa: 5 Asia: 4 South America: 4	Africa: 5 Asia: 4 South America: 4	4	Urban planning studies	9
	Encouraging a healthy lifestyle		Likert scale	Local community	All	Community engagement, safe and healthy living conditions	Primary	1	Statistics	-	-	-	2	Survey, WHO	6

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
Equity	Increased participation of vulnerable groups	(Variables: improved accessibility for wheelchairs, facilitating online access, financial aid to participate in sports or cultural activities, organisational quotums on the participation of underrepresented groups) [Surveys-based Likert scale] Vulnerable and other groups whose opinions or contributions are not reflected well enough in our society (like women, minorities and the disabled), require special attention to be included in the community, thereby enhancing social cohesion and diversity and tapping into underdeveloped social capital. One can think of many ways to increase this participation, for instance: I. Physical, e.g. improved accessibility for wheelchairs II. Digital, e.g. facilitating online access or providing information pages online III. Financial, e.g. financial aid to participate in sports or cultural activities IV. Organisational, e.g. through quotums on participation of underrepresented groups	Five-point Likert scale. The indicator provides a qualitative measure and is rated on a five-point Likert scale: No at all – 1 — 2 — 3 — 4 — 5 — Excellent	Local community	All	Community engagement	Primary	2	The reference value is the base value recorded at the beginning of the project and which is then compared with the one monitored at a later stage of the project.	-	-	-	2	Surveys and other data source	18

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Accessible Design	Universal design broadly refers to providing equal opportunities in terms of accessibility. In the EU context, this practically means providing barrier-free access to those with impaired motor, perceptive, and cognitive capabilities both inside buildings and sites, and within the neighbourhood. (*There are several definitions, a clear definition is reported in Synikia project: "D3.1_Methodology-framework-for-Plus-Energy-Buildings-and-Neighbourhoods" of the project folder and carefully read the calculation method on pages 86-87-89.)	10 point Likert scale and [% of barrier-free units] at the building level; [% of barrier-free units] at the district level	-	-	-	-	2		-	-	-	2	Architectural / Urban design studies	15
	Gender Equity of New Jobs		[%]	Workers	All or just supply chain + end of life?	Equal opportunities/ discrimination	Primary/Secondary	1		Africa: 5 Asia: 4 South America: 4	Africa: 5 Asia: 4 South America: 4	Africa: 5 Asia: 4 South America: 4	3	Public Report	8

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Living Conditions	Population living in inadequate housing (Variables: overcrowding, lack of facilities in the house, etc.) (*t "D3.1_Methodology-framework-for-Plus-Energy-Buildings-and-Neighbourhoods" of the project folder and carefully read the calculation method on pages 82-83-84.)	[% of hab]	Local community	Use	Secure living conditions	Secondary	2	Eurostat (read the reference document). 1) National Affordable Homes Agency, "721 Housing Quality Indicators (HQI) Form," 2007. 2) https://ec.europa.eu/eurostat/cache/metadata/en/sdg_11_10_esmsip2.htm 3) https://ec.europa.eu/eurostat/cache/metadata/en/sdg_01_60_esmsip2.htm 4) https://ec.europa.eu/eurostat/cache/metadata/en/sdg_06_20_esmsip2.htm	Africa: 5 Asia: 4	Africa: 5 Asia: 4	Africa: 5 Asia: 4	4	Published reports / Surveys	23
	Affordability of Energy	Energy Poverty/Affordability of Energy (Change in percentage points of gross household income spent on energy bills/Households unable to afford the most basic levels of energy/etc.) [%], [Surveys and equations based %] (*t "D3.1_Methodology-framework-for-Plus-Energy-Buildings-and-Neighbourhoods" of the project folder and carefully read the calculation method on pages 74-75-76.)	[% of hab], Likert scale	Local community, society	Use	Secure living conditions, contribution to economic development	Secondary	2	https://ec.europa.eu/eurostat/web/products-datasets/product?code=HBS_STR_T211	Africa: 5	Africa: 5	Africa: 5	2	Surveys	19

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Affordability of Housing	Housing Cost Overburden Rate- Affordability of Housing (Population living in households where the total housing costs represent more than 40% of disposable income) [%] or [Surveys-based] (* "D3.1_Methodology-framework-for-Plus-Energy-Buildings-and-Neighbourhoods" of the project folder and carefully read the calculation method on pages 76-77-78.)	[% of hab], Likert scale	Local community, society	Use	Secure living conditions, contribution to economic development	Secondary	2	The condition of housing poverty is used to describe households with a cost overburden, measured by comparing the share of income spent on housing (including rent, and utilities) with a benchmark. The specific benchmark varies for different countries, but in Eurostat, 40% is used	-	-	-	2	Surveys	16
Access to services	Access to commercial amenities	(*There are several definitions, a clear definition is reported for the KPI "access to amenities) in Synikia project: "D3.1_Methodology-framework-for-Plus-Energy-Buildings-and-Neighbourhoods" of the project folder and carefully read the calculation method on pages 69-70-71-72)	[% of hab]	Local community	Use	Access to material resources	Secondary	1		-	-	-	3	Urban planning studies	7
	Access to public amenities		[% of hab]	Local community	Use	Access to material resources	Secondary	1		-	-	-	3	Urban planning studies	7
	Internet Penetration Rate		[% of hab]	Local community	Use	Access to immaterial resources	Secondary	1		-	-	-	4	Published document	8
	Access to public transport	(hab with a transportation stop <500m)	[% of hab]	Local community	Use	Access to material resources	Secondary	2		-	-	-	3	Google Map	19

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Access to vehicle sharing solutions for city travel	(no. of shared vehicles/no. of car sharing locations/distance)	[#/100.000 hab], [#/hab], [#], [km]	Local community	Use	Access to material resources	Primary/Secondary	2		-	-	-	3	Urban planning studies	15
	Shared EV Penetration Rate	(no. of EVs in the platform and the car-sharing concept)	[%]	Local community	Use	Access to material resources	Primary/Secondary	1		-	-	-	3	Urban planning studies	8
	EV charging stations		[#], [#/km²], [%], [#/100,000]	Local community	Use	Access to material resources	Primary/Secondary	1		-	-	-	4	Published document	9
	Length of the bike route network		[% in km], [km/100,000 hab)],	Local community	Use	Access to material resources	Primary/Secondary	1		-	-	-	4	Published document/Google Map	10
	Public Transport Network	(Length of one-way public transport lines within boundaries)	[km/100,000 hab]	Local community	Use	Access to material resources	Primary/Secondary	1		-	-	-	4	Published document	10
Quality of housing and the built environment	Thermal comfort		Five-point Likert scale	Local community, Consumer	Use	Safe and healthy living conditions, health and safety	Primary	1		-	-	-	2	Surveys (with occupants) + Digital Twins	9
	Thermal Comfort-Predicted Mean Vote (PMV)		[#]	Local community, Worker, Consumer	Use, Implementation	Safe and healthy living conditions, health and safety	Primary	2	EN ISO 16798-1-2019	-	-	-	2	simulation environments (e.g. TRNSYS) or equation-based analytical approaches	17
	Thermal Comfort-Predicted Percentage Dissatisfied (PPD)		[%]	Local community, Consumer	Use, Implementation	Safe and healthy living conditions, health and safety	Primary	2	EN ISO 16798-1-2020	-	-	-	2	simulation environments (e.g. TRNSYS) or equation-based analytical approaches	17

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Indoor Air Quality		[ppm]	Local community, Consumer, Worker	Use, Implementation	Safe and healthy living conditions, health and safety	Primary	2	EN ISO 16798-1-2019	-	-	-	2	simulation environments or on-site measurements and surveys with equation-based analytical approaches	17
	Noise Pollution		[dB], [%]	Local community, Consumer, Worker	Use, Implementation	Safe and healthy living conditions, health and safety	Primary	2	EN ISO 16798-1-2019	-	-	-	2	simulation environments or on-site measurements and surveys with equation-based analytical approaches	15
	Illuminance		[Lux]	Local community, Consumer, Worker	Use, Implementation	Safe and healthy living conditions, health and safety	Primary	2		-	-	-	2	simulation environments (e.g energy plus) or other tools or on-site measurements	15
	Daylight Factor		[%]	Local community, Consumer	Implementation, Use	Safe and healthy living conditions, health and safety	Primary	2		-	-	-	2	simulation environments (e.g Energy Plus) or other tools	12
	Public outdoor recreation space	Square meters of public outdoor recreation space per capita	[m²/hab]	Local community, Consumer	Use	Safe and healthy living conditions, health and safety	Primary/Secondary	1		-	-	-	3	Urban planning studies	9
	Green space		[ha/100.000 hab], [m²/hab], [%]	Local community, Consumer	Use	Safe and healthy living conditions, health and safety	Primary/Secondary	1		-	-	-	3	Urban planning studies	9

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
Social Acceptance	Active/proactive citizens' behaviour	(e.g. willingness to invest in energy savings measures or pay more for RES or service; no. of citizens with increased ability to manage their energy consumption, no. of households who requested energy advice or information) [Surveys based]	[%] and/or Five-Point Likert Scale	Local community	Use	Community engagement	Primary	1		-	-	-	2	Surveys	8
	Degree of satisfaction		[%] and/or Five-Point Likert Scale	Consumer	Use	Feedback mechanisms	Primary	2		-	-	-	2	Surveys	17
	Social factors	(Variables: divergence of interest, resistance to change, satisfaction with information, satisfaction with involvement in decision-making) [Surveys-based Likert scale]	[%] and/or Five-Point Likert Scale	-	-	-	-	1		-	-	-	2	Surveys	9

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Connection to the Existing Cultural Heritage	The extent to which making a connection to the existing cultural heritage was considered in the design of the project. An important aspect in promoting the feeling of community/home is 'place-making'; the creation of place and identity. This identity can be created by building on local and regional history, culture, and character. This entails integrating urban design and heritage conservation so that it enhances or connects to the existing character of the place, e.g. preservation and/or adaptive reuse of historic buildings and cultural landscapes.	Likert scale. The indicator provides a qualitative measure and is rated on a five-point Likert scale: Not at all – 1 — 2 — 3 — 4 — 5 — Very much	Local community	All	Cultural heritage	Primary/Secondary	0	to be defined (as declared within Pocityf project outputs)	-	-	-	1	Surveys. The indicator provides a qualitative measure and is rated on a five-point Likert scale: Not at all – 1 — 2 — 3 — 4 — 5 — Very much 1..	0

Assessment Criteria	Indicators	Additional Information	Unit	Guidelines Stakeholder category compliant? Which? Cut-off criteria	Life Cycle Stage	Stakeholder Subcategory	Availability Primary X Secondary	Do we have reference values? -Quali or Quanti (Choose 0 "no" , 1 "not specific" and 2 "yes") Cut-off criteria	If yes state source or definition	Hotspot Assessment (Choose from 1 "no risk" to 5 "very high risk")			Data collection availability (Choose from 1 "not available" 2- survey need 4 case specific to 5 "available")	Which sources or methods for data collection?	Avg scoring Mandatory indicators = Red cells
										Construction	Electricity	Transport			
	Number of people (inhabitants) reached	Percentage of people in the target group that have been reached and/or are activated by the project. A project is usually most successful if the entire target group of a service participates. For example, if all electric car owners join in optimising their battery use to improve the energy system efficiency of the district. In addition, a high score on people reached can be seen as a signal of increased community engagement due to the project. The effort the project will make towards reaching the full extent of its target group can vary and with it the size of the target audience. Therefore, this effort and the target audience for each integrated solution have to be clearly defined before assessing the indicator.	[%] [#] (if is not known the size of target group)	Local community	Use	Access to material resources, access to immaterial resources and community engagement	Primary/Secondary	1		-	-	-	4	The LH managers create a log file to record people reached through: a) communication campaigns (press, social media), b) events organised by the project c) participation in third-party events, and d) an estimation of people reached through social media and the press is recorded; Step 2: Calculate the number of people in the project implementation area but also expand this to another scale of evaluation i.e. city if relevant	12
	Number of awareness-engagement initiatives/events		[#/100 hab], [#]	Local community, Society	Use, end of life	Community engagement, public commitments to sustainability issues	Primary/Secondary	1		-	-	-	4		11
	Open Public Participation	(no. of public participation processes, open data)	[#/hab], [#/100,000 hab] and/or Likert scale	Local community	Use, end of life	Community engagement	Primary/Secondary	1		-	-	-	4		8
	Percentage of citizens' participation in online decision-making		[%]	Local community, Society	Use, end of life	Community engagement, public commitments to sustainability issues	Primary	0	to be defined (as declared within Pocityf project outputs)	-	-	-	4	Published document	0

Table 4: Generic Data Sources

Generic data sources	
Data sources	Reference
For Each Stakeholders	
Psilca Database	https://psilca.net/
Social Hotspots Database	http://www.socialhotspot.org/
Worker	
Freedom of association and collective bargain	
International Trade Union Confederation	https://www.ituc-csi.org/documents?lang=en
ILO, ILOSTAT	https://ilostat.ilo.org/topics/collective-bargaining/
United Nations Association Coventry Branch	https://unacov.uk/human-freedom-index/
IndustriALL Global Union	https://www.industriall-union.org/who-we-are
German Union of Mining and Energy	https://igbce.de/igbce
The Federation of Electric Power Related Industry Worker's Unions of Japan	https://www.denryokusoren.or.jp/english/relationship.html
Child labor	
Monitoring the Situation of Children and Women – UNICEF	https://data.unicef.org/topic/child-protection/child-labour
The International Labour Organisation (ILO), UNICEF and the World Bank initiated inter-agency research project	https://ieg.worldbankgroup.org/sites/default/files/Data/reports/gppp_ucw_wp.pdf
US Department of Labor	https://www.dol.gov/
Fair salary	
ILO Global Wage Report	https://normlex.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C026
Minimum Wage Fixing Convention 1970 (No. 131)	https://normlex.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C131
Local Community	
Amnesty International country reports on human rights, including freedom of expression	https://www.amnesty.org/en/countries/
Ecolex environmental law	https://www.ecolex.org/
World Economic Forum annual country rankings for each subcategory relevant information	https://www.weforum.org/
Access to material resources	
FAO Global Forest Resources Assessment for industrial impacts on forest land	https://www.fao.org/forest-resources-assessment/en/
OECD Environmental Data Compendium for industrial impacts on material resources, including land, water, air and wildlife	https://www.oecd.org/en/topics/environmental-statistics-accounts-and-indicators.html
United States Department of Agriculture, Natural Resources Conservation Services, World Soil Resources Map Index	https://www.nrcs.usda.gov/

Generic data sources	
Data sources	**Reference**
World Bank data on biodiversity, extractive industries and water resources	https://data.worldbank.org/
Access to immaterial resources	
U.S. Department of State Country Reports on Human Rights Practices, including freedom of speech and press	https://www.state.gov/reports-bureau-of-democracy-human-rights-and-labor/country-reports-on-human-rights-practices/
World Economic Forum annual country rankings on specialised research and training programs and technology transfer	https://www.wipo.int/publications/en/series/index.jsp?id=37
World Intellectual Property Organization's World Intellectual Property Indicators	https://www.wipo.int/publications/en/series/index.jsp?id=37
Safe and healthy living conditions	
The World Bank Group's environmental data on emissions and pollution	https://www.worldbank.org/en/home
The World Bank Group and International Finance Corporation's reports on local and country-level construction safety regulations	https://www.ifc.org/wps/wcm/connect/corp_ext_content/ifc_external_corporate_site/home
World Health Organization's global burden of disease and health risks reports	https://www.who.int/
Community engagement	
U.S. Department of State annual country reports on human rights, including freedom of peaceful assembly and association and political participation	https://www.state.gov/reports-bureau-of-democracy-human-rights-and-labor/country-reports-on-human-rights-practices/
Local employment	
ILO Key Indicators of the Labour Market for employment statistics by country and sector	https://www.ilo.org/global/statistics-and-databases/research-and-databases/kilm/lang--en/index.htm
Secure living conditions	
The Business & Human Rights Resource Centre country and company reports on security	https://www.business-humanrights.org/en/
U.S. Department of State Country Reports on Human Rights Practices, including incidents of arbitrary arrest and detention	https://www.state.gov/reports-bureau-of-democracy-human-rights-and-labor/country-reports-on-human-rights-practices/
Consumer	
Health and Safety	
International Consumer Product Health and Safety Organization	https://www.oecd.org/sti/consumer/ECommerce-Recommendation-2016.pdf
U.S. Consumer Product Safety Commission	http://www.cpsc.gov/
Feedback Mechanism	
European Commission, Consumers Affairs	http://www.ec.europa.eu/consumers/redress_cons/collective_redress_en.htm

Generic data sources	
Data sources	Reference
Society	
Contribution to economic development	
CIA The World Factbook	https://www.cia.gov/the-world-factbook/
Economy Watch	https://www.economywatch.com/
Organisation for Economic Co-operation and Development	https://www.oecd.org/
World Bank	https://www.worldbank.org/ext/en/home
Poverty alleviation	
EUROSTAT	https://ec.europa.eu/eurostat
FAOSTAT	https://www.fao.org/faostat/en/#home
ILOSTAT	https://ilostat.ilo.org/
World Bank Open Data	https://datacatalog.worldbank.org/home
OECD Data	https://www.oecd.org/en/data.html

Table 5: Specific Data Sources for each stakeholder subcategory

Stakeholder category: Worker

Freedom of association and collective bargain

Specific data sources

Inventory Data or Indicator	Data sources
Density of workers unionised in energy organisations	● Verification on Unions' documentation (memberships on the renewable energy sectors, relating to a specific organisation or to the entire sector, for instance).
Collective bargaining coverage rate in energy organisations	● Verification on Unions' documentation (participation and reach of workers in collective bargaining, relating to a specific organisation or to the entire sector, for instance).
Ratio between the number of collective agreements fulfilled and the number of agreements signed throughout a certain period of time for specific organisation	● Human resources data; ● Verification of organisations' documents; ● Country specific union agreements; ● Agreement documents signed by both parties (employers and workers).
Collective agreements ratio (number between the agreements reached and number of collective negotiations initiatives)	● Verification on Unions' documentation; ● Verification of organisations' documents.
Ratio between the number of accomplished meetings and the number of times in which a trade union asked for meetings to collective negotiation purposes.	● Verification on Unions' documentation and e-mails; ● Verification of organisations' documents and e-mails; ● Interview with trade unions' representatives; ● Interview with directors or human resources officers.
Bargaining structure	● Channels to address workers' claims or negotiations; ● Mechanisms set up by the organisation to run collective bargaining with workers or trade union representatives.
Discrimination or prejudice against unionisation and/or collective bargaining and/or taken part in a strike	● Questionnaires or surveys filled out by workers to assess whether they have been discriminated or suffered prejudice for the reasoning of joining union, representing workers in a trade union, or participated in a collective bargaining or strike.
Organisations' support to workers unionise and play representative roles in trade unions	● Payment of working hours while the employees are playing a representative role in a trade union, etc.

Union activity is usually assessed through unions' membership and unions' participation in collective bargaining, which are measured through the union density rate and the collective bargaining coverage rate.

Stakeholder category: Worker

Child Labor

Specific data sources

Inventory Data or Indicator	Data sources
Percentage of working children under the legal age or 15 years old (14 years old for developing economies (%))	● Visit to facility ● Interview with directors or human resources officer ● Verification of organisation documents ● NGOs reports ● Verification with workers interviews or audits ● Interview with community members
Children are not performing work during the night (an example of unauthorised work by the ILO conventions C138 and C182)	● Visit to facility ● Interview with directors or human resources officer ● Verification of organisation documents ● NGOs reports ● Verification with workers interviews or audits

Records on all workers stating names and ages or dates of birth are kept on file	● Visit to facility ● Interview with directors or human resources officer ● Verification of organisation documents
Working children younger than 15 and under the local compulsory age are attending school	● Interview with directors or human resources officer ● Verification with workers interviews or audits ● NGOs reports ● Interview with local schools

Stakeholder category: Worker

Fair salary

<u>Specific data sources</u>

Inventory Data or Indicator	Data sources
Lowest paid worker, compared to the minimum wage and/or living wage	● Country minimum wage ● Interview with directors or human resources officer ● Verification of organisation documents: e.g., wage records ● Review of organisation-specific reports, such as GRI reports or audits
Number of employees earning wages below poverty line	● Interviews with workers ● Interview with local NGOs
Presence of suspicious deductions on wages	● Interviews with employees, management, and human resources ● Review of organisation-specific reports, such as GRI reports or audits agreement or contracts between organisations and employees ● Review of wage records
Regular and documented payment of workers (weekly, bi-weekly)	● Interviews with employees, governmental agencies, management, and NGOs ● Review of organisation-specific reports, such as GRI reports or audits ● Review of wage records

Stakeholder category: Local Community

Access to material resources

<u>Specific data sources</u>

Inventory Data or Indicator	Data sources
Has the organisation developed project-related infrastructure with mutual community access and benefit	● Site visit or site-specific audit ● Interviews with community members, employees, governmental agencies, management, and NGOs ● Review of organisation-specific reports, including GRI and COP reports and audits
Strength of organisational risk assessment with regard to potential for material resource conflict	● Site visit or site-specific audit ● Interviews with community members, governmental agencies, management, and NGOs ● Review of organisation- specific reports, including GRI and COP reports, audits, and social impact assessments
Does the organisation have a certified environmental management system	● Site visit or site-specific audit ● Interviews with management ● Review of organisation specific reports, including GRI and COP reports and audits
Progress towards Energy Citizenship (Variables: social acceptance of PED solution, personal attitudes and motivation, perceived incentives/barriers, level of trust,	● Site visit or site-specific audit ● Interviews with community members, governmental agencies, management, and NGOs

sense of community, technology perception, ICT literacy)	
Access to public transport (hab with a transportation stop <500m)	● Site visit or site-specific audit ● Interviews with community members, governmental agencies, management, and NGOs
Access to vehicle sharing solutions for city travel (no. of shared vehicles/no. of car sharing locations/distance)	● Site visit or site-specific audit ● Interviews with community members, governmental agencies, management, and NGOs

Stakeholder category: Local Community

Access to immaterial resources
<u>Specific data sources</u>

Inventory Data or Indicator	Data sources
Annual arrests connected to protests of organisation actions	● Site visit or site-specific audit ● Interviews with governmental agencies, management, and NGOs ● Review of organisation-specific reports, including GRI and COP reports and audits
Do policies related to intellectual property respect moral and economic rights of the community	● Site visit or site-specific audit ● Interviews with community members, employees, governmental agencies, management, and NGOs ● Review of organisation-specific audits, such as ISO 26000, and social impact assessments
Presence/strength of community education initiatives	● Site visit or site-specific audit ● Interviews with community members, employees, governmental agencies, management, and NGOs ● Review of organisation-specific reports, including GRI and COP reports, audits, and social impact assessments
Percentage of people in the target group that have been reached and/or are activated by the project	● Site visit or site-specific audit ● Interviews with community members, employees, governmental agencies, management, and NGOs

Stakeholder category: Local Community

Safe and healthy living conditions
<u>Specific data sources</u>

Inventory Data or Indicator	Data sources
Management oversight of structural integrity	● Site visit or site-specific audit ● Interviews with management, community members, employees, governmental agencies, and NGOs ● Review of organisation-specific reports, such as GRI or COP reports
Organisation efforts to strengthen community health (e.g. through shared community access to organisation health resources)	● Site visit or site-specific audit ● Interviews with management, community members, employees, governmental agencies, and NGOs ● Review of organisation-specific reports, such as GRI or COP reports and Social Impact Assessments
Management effort to minimise use of hazardous substances	● Site visit or site-specific audit ● Interviews with management, community members, employees, governmental agencies, and NGOs ● Review of organisation-specific reports, such as GRI or COP reports
Thermal comfort (Five-point Likert scale)	● Site visit or site-specific audit ● Interviews with management, community members, employees, governmental agencies, and NGOs

Indoor Air Quality (ppm)	• Site visit or site-specific audit • Interviews with management, community members, employees, governmental agencies, and NGOs
Noise Pollution (dB, %)	• Site visit or site-specific audit • Interviews with management, community members, employees, governmental agencies, and NGOs
Illuminance (Lux)	• Site visit or site-specific audit • Interviews with management, community members, employees, governmental agencies, and NGOs
Daylight Factor (%)	• Site visit or site-specific audit • Interviews with management, community members, employees, governmental agencies, and NGOs
Green space (ha/100.000 hab, m^2/hab, %)	• Site visit or site-specific audit • Interviews with management, community members, employees, governmental agencies, and NGOs

Stakeholder category: Local Community

Community engagement
Specific data sources

Inventory Data or Indicator	Data sources
Strength of written policies on community engagement at organisation level	• Site visit or site-specific audit • Interviews with community members, employees, management, and NGOs • Review of organisation-specific reports, such as GRI reports or audits
Diversity of community stakeholder groups that engage with the organisation	• Site visit or site-specific audit • Interviews with community members, employees, management, and NGOs • Review of organisation-specific reports, such as GRI reports or audits
Number and quality of meetings with community stakeholders	• Site visit or site-specific audit • Interviews with community members, employees, management, and NGOs • Review of organisation-specific reports, such as GRI reports or audits
Organisational support (volunteer-hours or financial) for community initiatives	• Site visit or site-specific audit • Interviews with management and NGOs • Review of organisation-specific reports, such as GRI reports or audits
Percentage of people in the target group that have been reached and/or are activated by the project.	• Site visit or site-specific audit • Interviews with management and NGOs • Review of organisation-specific reports, such as GRI reports or audits
The extent to which the project has contributed to increasing consciousness of citizenship. (The consciousness of citizenship is the awareness (consciousness) of one's community, civic rights and responsibilities and contributes to the sense of community)	• Site visit or site-specific audit • Interviews with management and NGOs • Review of organisation-specific reports, such as GRI reports or audits
Increased participation of vulnerable groups (Variables: improved accessibility for wheelchairs, facilitating online access, financial aid to participate in sports or cultural activities, organisational quotums on participation of underrepresented groups)	• Site visit or site-specific audit • Interviews with management and NGOs • Review of organisation-specific reports, such as GRI reports or audits

Stakeholder category: Local Community

Local employment
Specific data sources

Inventory Data or Indicator	Data sources
Percentage of workforce hired locally	• Site visit or site-specific audit • Interviews with management • Review of organisation-specific reports, such as GRI or COP reports
Strength of policies on local hiring preferences	• Site visit or site-specific audit • Interviews with community members, employees, governmental agencies, management, and NGOs • Review of organisation-specific reports, such as GRI or COP reports
Percentage of spending on locally-based suppliers	• Site visit or site-specific audit • Interviews with management • Review of organisation-specific reports, such as GRI or COP reports

Stakeholder category: Local Community

Secure living conditions
Specific data sources

Inventory Data or Indicator	Data sources
Management policies related to private security personnel	• Site visit or site-specific audit • Interviews with management, community members, employees, governmental agencies, and NGOs • Review of organisation-specific reports, such as GRI or COP reports and social and/or human rights impact assessments
Number of legal complaints per year against the organisation with regard to security concerns	• Site visit or site-specific audit • Interviews with management, governmental agencies, and NGOs
Number of casualties and injuries per year ascribed to the organisation	• Site visit or site-specific audit • Interviews with management, governmental agencies, and NGOs
Number of violence, annoyances, and crimes per 100.000 population	• Site visit or site-specific audit • Interviews with management, governmental agencies, and NGOs
Population living in inadequate housing (Variables: overcrowding, lack of facilities in the house, etc.)	• Site visit or site-specific audit • Interviews with management, governmental agencies, and NGOs
Affordability of Energy (Energy Poverty/Affordability of Energy)	• Site visit or site-specific audit • Interviews with management, governmental agencies, and NGOs
Housing Cost Overburden Rate-Affordability of Housing (Population living in households where the total housing costs represent more than 40% of disposable income)	• Site visit or site-specific audit • Interviews with management, governmental agencies, and NGOs

Stakeholder category: Consumer

Health and Safety

Specific data sources

Inventory indicator	Data sources
Number of consumer complaints	• Interviews or questionnaire filled by management, retailers, and NGOs • Review of enterprise-specific reports, such as audits and/or GRI reports • Consumer organisations
Presence of Management measures to assess consumer health and safety	• Interviews or questionnaire filled by management, retailers, consumers, and NGOs • Review of enterprise-specific reports • Consumers organisations
Presence of a Quality and/or Product Safety Management System such as ISO 9001:2015	• Review of enterprise-specific documents. • Interviews or questionnaire filled by management, retailers, consumers, and NGOs

Stakeholder category: Consumer

Feedback mechanism

Specific data sources

Inventory indicator	Data sources
Presence of a mechanism for customers to provide feedback	• Site visit or site-specific audit • Interview with directors or marketing officer • Verification of enterprise documents • Consumer protection office • Consumers organisations
Management measures to improve feedback mechanisms	• Site visit or site-specific audit • Interview with directors or human resources officer • Verification of enterprise documents
GRI PR5 Practices related to customer satisfaction, including results of surveys measuring customer satisfaction	• Site visit or site-specific audit • GRI Sustainability report • Interview with directors or marketing officer • Verification of enterprise documents • Consumer protection office • Consumers organisations

Stakeholder category: Society

Contribution to economic development

Specific data sources

Inventory indicator	Data sources
Contribution of the product/service/organisation to economic progress (e.g., annual growth rate of real GDP per employed person)	• Interviews with community members, governmental agencies, management and NGOs • Review of enterprise-specific reports, such as GRI reports or audits
Proportion of informal employment in non-agriculture employment, by sex	• Interviews with governmental agencies, management and NGOs • Review of enterprise-specific reports, such as GRI reports or audits
Average hourly earnings of female and male employees, by occupation, age, and persons with disabilities	• Interviews with governmental agencies, management and NGOs • Review of enterprise-specific reports, such as sustainability reports or audits

Stakeholder category: Society

Poverty alleviation

Specific data sources

Inventory indicator	Data sources
The organization carries out a poverty alleviation program	• Interviews with management • Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports
Contingency planning measures, disaster, emergency management plan, training programs, and recovery/ restoration plans	• Interviews with management • Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports
Formalized commitment of the organisation to reduce poverty	• Interviews with management • Review of enterprise-specific reports, such as GRI reports, SA8000 certifications, and annual reports

Stakeholder Subcategories and Their Relevance for PEDs (Based on Methodological Sheets of the Guidelines)

Stakeholder category: Worker

Examples of relevant subcategories include Freedom of association and collective bargaining, Child labor, Fair salary

Freedom of association and collective bargaining

Freedom of association is defined on ILO's Convention nº 87 as a right that all workers and employers have, without distinction, to establish and join organizations of their choice without having to require previous authorisation. In the same way, workers' and employers' organisations shall have the right to establish and join federations and confederations (ILO, 1948).

Collective bargaining is also covered in the ILO's convention (nº 154) and is understood as a process of negotiation between independent unions and employers in order to establish terms and conditions of work, employment, working hours, wages and the relations between the parties. It also includes negotiations with the workers' representatives and the establishment of rules of procedure agreed between associations of employers and workers.

When assessing freedom of association and collective bargaining, several aspects should be addressed alongside checking the density of workers unionised or the collective bargaining coverage. These include but are not limited to bargaining power of unions, the outcome of the negotiations, the treatment of the right to collective bargaining, the extension of collective agreements, the bargaining structure, the level of bargaining, the degree of bargaining coordination (ILO, 2018) and the right to strike. In order to have a full picture of workers and employers' relations it is necessary to map and interpret relevant indicators related to freedom of association and collective bargaining together as they are interlaced. Furthermore, understanding the country's context and legal framework on unionisation and the company's patterns to run collective bargaining are important to get a more accurate view of how negotiations are conducted. For instance, a company might be open to negotiations while not signing or fulfilling collective agreements.

Besides official organisation documents and reporting another important source of data is the workers themselves.

When data availability permits, it can also be combined to create indicators among different sectors. For example, in the case of PEDs data with the different energy, construction and transportation sectors can be used for comparison and best practice identification purposes.

The relevance of the subcategory Freedom of association and collective bargaining to PEDs is closely linked to the workers or employees involved in the construction activities and the energy and transportation service providers, including those in their respective supply chains. For example, construction workers for the infrastructures pertaining in the PED as well as those in the solar panel production factory, in case the PED includes solar energy.

Child labour

Children may carry out several types of work and not all of them should be considered as child labour. It depends on many criteria such as the child's age, country where the work is performed, type and characteristics of the tasks and activities, working hours, conditions in which the child is subject. Child labour is often attributed to the work that deprives children of their childhood, potential, and dignity. Work has to be considered harmful to physical and mental development, being mentally, physically, morally and socially dangerous and harmful to the child. Furthermore, it affects schooling by one of the following situations: deprivation of the opportunity to attend school, obligation to leave school prematurely, requires the child to attempt to combine school attendance with excessively long and heavy work (Hilowitz et al., 2004).

In the Minimum Age Convention (C 138, 1973), ILO establishes international standards for the work children may perform, although countries are free to establish their own legal framework regarding this matter. The convention establishes criteria for light work, permitted for children from 13 to 15 years old, according to national laws and regulation from each signatory country, and has to meet the following conditions: work not likely to be harmful to children's health or development, and not prejudice attendance at school and participation in vocational and training programs. For developing countries, the defined ages for light work can be substituted by 12 and 14 (ILO, 1973).

However, it is not the light work that should be targeted for elimination. In the same convention, ILO also defines hazardous work as the one whose nature or the circumstances in which it is carried out is likely to jeopardise the health, safety or morals of young persons who should not be less than 18 years old. Examples of hazardous labour carried out by children in the energy sector may be mining, agricultural production for bioenergy purposes, civil construction for renewable energy production and consumption, etc. Developing countries may adopt the minimum age of 16 years for hazardous work.

Beyond the hazardous work, ILO acknowledged the existence of the worst forms of child labour on the convention 182, subject to prohibition and elimination by all the signatory countries and considers as child any person under the age of 18. Thus, the worst forms of child labour was defined as all forms of slavery practices or similar to slavery, and any involvement of a child in sex related activity or content, any use or involvement of a child in illicit activities (ILO, 1999).

In order to better assess if the tasks and activities performed by a child may be classified as a light work, it is relevant to observe the following aspects: if the organisation checks the age of the children, if they are receiving training before starting to work, if food is provided by the organisation, with they have protective equipment, when necessary, if their work is supervised by an adult, and if the organisation makes sure that children are attending school regularly (Fallon & Tzannatos, 1998). The last topic is a mandatory matter and even light work can be targeted as an activity to be abolished if it is preventing children from attending school.

As per hazardous work, the following are evidences of it: children working long hours, with no time off to go to school, working in dangerous conditions, facing humiliating situations at work, making greater physical efforts than they are capable of, having no access to clean and drinking water, working with dangerous materials and/or with heavy equipment. Regarding the worst forms of child labour, the definition is quite explicit, but other characteristics may support classifying child labour as such: children being assaulted or offended at work, suffering psychologically due to work, being forced to work against their will, working under threats, children who were kidnaped and forced to work and to have a debt bondage working relationship (Hillowitz et al., 2004).

Assessing child labour may not be an easy task, especially when collecting primary data. Different strategies should take place particularly where a hotspot is identified. Interviewing the community on the surroundings of the organisation and applying confidential questionnaires on workers can be fruitful sources of information. In terms of data validity, triangulating the findings with other sources of information would be a good practice.

Fair salary

Fair salary is a wide concept comprehending different characteristics and factors, such as minimum wage, living salary, equal remuneration, among others. Wage is only the basic salary whereas remuneration comprehends also additional emoluments (ILO, 1951).

The Universal Declaration of Human Rights foresees that everyone who works has the right to just and favorable remuneration ensuring for himself and his family an existence worthy of human dignity, and supplemented, if necessary, by other means of social protection (United Nations, 1948). In the same direction, minimum wage has been defined as the minimum amount of money that an employer is required to pay workers for the work performed during a given period, which cannot be reduced by collective agreement or individual contract (ILO, 1970).

Fixing the minimum wage has to take into consideration the needs of workers and their families, considering the general level of living in a given country, costs of living, social security benefits, and relative living standards of other social groups.

Finally, the Equal Remuneration Convention, nº 100 determines equal remuneration to all men and women workers for work of equal value and acknowledges that equal remuneration is a fundamental right, relevant to all countries, without exception, though it may vary in terms of how it is implemented from country to country.

There is not a specific convention or recommendation that addresses specifically fair salary or fair wage, being understood as a notion that encompasses the minimum wage, living wage and equal remuneration principles, though its extent is wider. According to ILO (International Labour Conference, 2014) fair wages must lead to a balanced wage structure, free of discrimination, and take into account different levels of education, jobs tasks and responsibilities, skills and professional experience, and reward individual and collective performance.

When it comes to minimum wage and living wage, even though both concepts seem interchangeable on the Minimum Wage Fixing Convention, in a large portion of countries the value fixed for minimum wage would not equate the costs of affording the basic needs of workers and their families. In this sense, it is important to separate the assessment of minimum wage, fixed according to a country legal framework, from living wage, which is due to a country's socioeconomic development contexts and conditions (purchasing power, health and social security systems, etc.).

Stakeholder Category: Consumer

Examples of relevant subcategories can be given as Health and Safety and Feedback Mechanism.

Health and safety

Consumer health and safety refers to the consumers' rights to be protected against products and services that may be hazardous to health or life (ISO 26000, 2008). Customers (end users) expect products and services to perform their intended functions satisfactorily and not pose a risk to their health and safety. Moreover, consumers have the right to "early warnings when unsafe products are on the market or are subject to a ban or recall" (OECD, 2020).

In the context of PEDs, this definition extends to the protection of individuals living in or utilising the district from potential hazards associated with the built environment, energy systems, and services. This includes ensuring that the energy infrastructure and associated services operate reliably and safely, avoiding electrical hazards, pollution, or other environmental risks. Residents and users within PEDs expect safety from crime and accidents (Guarino et al, 2021). Additionally, there is an expectation for transparent

communication regarding any potential safety concerns, as well as timely warnings and corrective actions in the event of system failures, unsafe practices, or other dangers specific to the innovative technologies employed in PEDs.
This subcategory helps to identify the existence and scope of systematic efforts to address consumer health and safety across the organisations involved in the life cycle of a product and/or service. In the case of PEDs, this refers to consumers related to the organisations involved in the life cycle of PEDs as well as consumers of the energy and services provided in a PED. It could include assessing not only the crime rate and safety incidents but also the existence of instruments and measures to address the related risks for example safety features in the transportation system or the energy related appliances available for inhabitants in the PEDs.

Feedback mechanism
Feedback mechanisms are paths by which consumers communicate with organisations, such as surveys, return policies, quality assurances, guarantees, warranties, etc. These mechanisms help reveal consumer satisfaction related to the consumption and use of the product or service (UNEP, 2021). In the context of sustainability, customer satisfaction provides insight on what type of relationship the organisation establishes with its customers (GRI, 2020). Customers and hence consumers have a right to channel their complaints on the product and service through communication mechanisms foreseen, established and managed by the organisations. These management measures aim to “provide transparent and effective procedures that address consumer complaints and contribute to fair and timely resolution of consumer disputes without undue cost or burden” (OECD, 2000).
In the context of PEDs, feedback mechanisms are crucial for capturing the experiences and satisfaction levels of residents and users with respect to the district's energy systems, infrastructure, and services. It's essential to integrate participatory methods that create a strong feedback loop, aligning innovative progress with local planning and decision-making processes to ensure community-centered development (Krangsås et al., 2021). With feedback channels, consumers can report issues such as system malfunctions, inefficiencies, or safety concerns, and suggest improvements for the district's operations. Effective feedback mechanisms in PEDs also allow for continuous improvement and adaptation of technologies and services to better align with the evolving needs and preferences of the community, thereby enhancing overall satisfaction and engagement.
Assessments are geared towards evaluating the effectiveness of management measures to support consumer feedback. This also includes customer feedback, such as the level and quality of organisational responsiveness. In addition, consumer satisfaction could be indirectly assessed by evaluating the mechanisms provided by the enterprise to achieve this goal.

Stakeholder Category: Local Community
Examples of relevant subcategories include Access to material resources, Access to immaterial resources, Safe and healthy living conditions, Community engagement, Local employment and Secure living conditions.

Access to material resources
Material resources (natural and man-made) available in a certain locality need to be shared by the communities as well as production facilities and business activities. Scarcity in terms of quantity as well as in quality might lead to conflict over natural material resources (e.g. water, forest land, homelands). There is the need to assess the risk of potential conflict over material resources and engage with the local community over sustainable methods for sharing resources that should include plans for preventing, mitigating, and controlling environmental damage. Guidelines and principles in line with Environment management systems can help to improve material resource conservation. It also important to bear in mind the positive long-term effects on local communities through improving the quality of local infrastructure such as roadways and waste disposal systems. (UNEP, 2021)
Material resources in PEDs include renewable energy sources, advanced building materials, and infrastructure designed for energy efficiency and resilience (Bruggeman, 2023). It is essential that the development and operation of PEDs do not lead to the overexploitation of local natural resources or create conflicts over their use. PEDs should rather serve as models for sustainable resource management by prioritising the efficient use of resources, recycling, and the integration of circular economy principles (Derkenbaeva et al., 2022). Moreover, the infrastructure developed within PEDs—such as energy storage systems, smart grids, and waste management facilities—should be designed to benefit the wider community, enhancing local economic development and improving the quality of life. Risk assessments in PEDs should focus on ensuring that the demand for materials and resources does not compromise the district’s sustainability goals or negatively impact local communities.
Assessments to understand the extent to which organisations respect, work to protect, to provide or to improve community access to local material resources (i.e. water, land, mineral, and biological resources) and infrastructure (i.e. roads, sanitation facilities, schools, etc.) require information from various sources. Documents of the PED planning, implementation and use can be consulted to identify the existence of a risk management plan and alignment to environmental management principles. Similar investigations could be conducted for the manufacturing activities related to products used in PEDs for example the mining of minerals essential for the renewable energy generation components.

Access to immaterial resources
Immaterial resources include community services, intellectual property rights, freedom of expression, and access to information. Community services addressing health care, education, and lending programs can be enhanced and the access to these services is facilitated by sharing information and knowledge and transferring technology and skills to the community. Intellectual property rights should be respected as well as the moral and economic rights of the creators of intellectual property. Organisations could limit access to immaterial resources by restricting freedom of expression among employees or community members such as in the case of being complicit in suppressing local opinion if community members are arrested for protesting corruption within the organisation and if journalists are arrested for reporting on organisation corruption. (UNEP, 2021)
In PEDs, access to immaterial resources is crucial for fostering a community-oriented and knowledge-driven environment. Immaterial resources in PEDs extend to the availability of energy-related education, capacity-building activities and transparent access to energy consumption and production data (Baer et al., 2021; Bosh et al., 2017). PEDs can actively promote the dissemination of knowledge and skills related to renewable energy technologies and sustainable living practices, empowering residents to participate in the management of their energy systems. Furthermore, PEDs must ensure that intellectual property generated within the district, such as innovations in energy technology is handled in a manner that respects the rights of creators while encouraging the sharing of knowledge for the community's benefit.
Freedom of expression and access to information are particularly important in PEDs, where community involvement is key to the district's success. Transparent communication and the free flow of information help to build trust and ensure that the community remains engaged and supportive of the district's goals (Olokundun et al., 2018). PEDs must also be vigilant against practices that could restrict these freedoms, ensuring that all voices within the community are heard and respected.

Safe and healthy living conditions
Safety repercussions of operations or activities of the organisations can impact the local community such as in the case of project-related land use changes that can lead to landslides, poor water drainage can lead to stagnant water and spread of malaria. The outbreak of communicable diseases from influx of workers and the generation and/or use of hazardous material and pollution emissions may lead to adverse health impacts. The existence of an environmental risk management system for preventing, mitigating, and controlling health damage is one of the relevant indicators for assessing this subcategory. However, this subcategory supports the evaluation on how an organisation contributes to the health of local communities, for example by shared access to employee health services. An indicator to assess the remediation or compensation efforts for negative health effects could also communicate on improvements. (UNEP, 2021)
Safe and healthy living conditions within PEDs include the careful planning and management of energy infrastructure to prevent accidents, structural failures, and other risks associated with energy technologies. PEDs must consider the implications of land use changes to ensure that such changes do not lead to environmental hazards. The integration of green spaces and the promotion of sustainable urban mobility (e.g., walking, cycling, public transport) can also contribute to healthier living conditions by reducing pollution and promoting physical activity.
Organisations operating within PEDs should implement comprehensive environmental and health risk management systems that not only prevent and mitigate potential health risks but also enhance overall community well-being (Gouveia et al., 2021; Bisello, A. 2020*)*. This includes transparent communication with residents about any potential health and safety impacts, as well as active engagement in remediation or compensation efforts if adverse effects occur.

Community engagement
Community stakeholders consist of individuals or groups within the community who may be impacted by an organisation's actions or products. When formulating and implementing business policies, particularly those related to the local environment, health, and well-being, organisations should take these stakeholders into account to comply with ISO 9001:2015 Clause 4 on the organisation's context. It is essential for organizations to engage with a diverse group of stakeholders to ensure a balanced representation of community interests. Community engagement should offer a platform for members and leaders to express their concerns, which organisations should address through a strategic action plan. After all, community participation in decision-making is a fundamental aspect of sustainable development (Agenda 21). This ongoing process requires participation from representatives across all organisational levels. Additionally, organisations can promote community engagement by actively participating in local initiatives or providing financial support for community projects such as Earth Day events, recycling programs, and school visits. (UNEP, 2021)
In the PEDs context, community engagement is pivotal to the success and sustainability of the district. Given the innovative and transformative nature of PEDs, it is essential to involve community stakeholders early and continuously in the planning, development, and operational phases (Derkenbaeva et al., 2022; Gollner et al., 2020). This engagement ensures that the district's energy strategies and infrastructure align with the community's needs, values, and expectations.
PEDs can enhance community engagement through direct involvement in local sustainability projects, educational programs, and partnerships with local organisations to support broader community development efforts (Ornetzeder & Regen, 2023; Baer et al., 2021; Gollner et al., 2020).

Additionally, PEDs should foster active participation by creating inclusive forums and channels through which residents and local groups can voice their concerns, provide input, and contribute ideas regarding the district's energy systems, environmental impacts, and social implications. This could include regular town hall meetings, participatory workshops, and digital platforms that allow for transparent communication and feedback (Ornetzeder & Regen, 2023; Baer et al., 2021; Thapa et al., 2019). This also empowers residents to take ownership of the district's sustainability goals and ensure the success of long-lasting adoption (Gollner et al., 2020).

Local employment

Prioritising local hiring creates valuable income and training opportunities for community members. Local employees have unique knowledge of important community issues and can help the organisation build strong community relations. By building relationships with local suppliers, organisations can further promote local employment and economic growth. Additionally, training local employees in technical and transferable skills supports long-term community development. The impact is especially significant when organisations appoint local employees to senior management roles, as this fosters open communication, trust, and stronger community ties. (UNEP, 2021)

To ensure the successful development of PEDs, it's crucial that capacity building, education, and training encompass all relevant stakeholders, including professionals, citizens, and especially key personnel responsible for community engagement and capacity building within the district. By equipping stakeholders, particularly these key personnel, with the necessary knowledge, skills, and experience in stakeholder engagement, citizen participation, and capacity building, social innovation within PEDs can be directed and sustained over time (Baer et al., 2021). Additionally, fostering employment and business opportunities within the district further contributes to a secure and resilient living environment for all residents (Guarino et al., 2021).

Secure living conditions

Organisations with inadequate security oversight can contribute to unsafe living conditions, community tensions, and regional conflicts. However, when operating in insecure regions, organisations can enhance living conditions by ensuring private security personnel act responsibly. While states have the primary duty to uphold human rights, organisations must also respect and protect them. Security forces may be employed to safeguard employees and assets, but this protection should also extend to human rights in surrounding communities. In some regions, state-led security forces, such as police and military, have a history of human rights violations, and organisations have sometimes been complicit in these abuses (UN Global Compact, Security Forces & Human Rights). Therefore, it is crucial to assess whether an organisation has directly or indirectly benefited from such violations. Furthermore, failing to act in response to human rights abuses constitutes silent complicity. Organisations should train and oversee security personnel to ensure compliance with international law enforcement principles, including the UN Code of Conduct for Law Enforcement and the UN Basic Principles on the Use of Force and Firearms by Law Enforcement Officials. Additionally, organisations should collaborate with host governments and communities to promote best security practices. (UNEP, 2021)

In the PEDs context, ensuring secure living conditions is critical to fostering a safe, resilient, and harmonious community environment. PEDs, by their nature, involve the integration of advanced technologies, energy infrastructure, and new urban designs, which necessitate careful consideration of security measures. These include effective and accessible local services, safety from crime and accidents, and a visually appealing environment while prioritising the safety and well-being of all residents. Moreover, affordable housing, opportunities for social participation, and good environmental conditions, such as clean air and low noise levels, are vital (Guarino et al., 2021). Moreover, PEDs enhance the availability of safe, affordable, and accessible sustainable transport systems, fostering inclusive and sustainable urbanisation. It is also stated that the use of renewable energy through participation and strengthening the institutional capacity of the community will promote environmental quality improvement toward an inclusive, safe, resilient, and sustainable direction (Surya et al., 2021).

Stakeholder Category: Society

Examples of relevant subcategories include contribution to economic development and poverty allevation

Contribution to economic development

Economic development is essential in the fight against poverty and hunger, as generating sufficient wealth to meet basic material needs is fundamental to human well-being. Organisations can either compete by exploiting lower-tier suppliers and employees or invest in developing skilled suppliers and productive workers, fostering long-term economic growth. They can contribute to economic development in various ways, such as generating revenue, creating jobs, providing education and training, making investments, and advancing research. (UNEP, 2021)

In PEDs, economic development is driven through various means, including job creation, investment in sustainable infrastructure, support for innovation and research, and the promotion of local businesses. PEDs contribute to economic resilience by generating revenue, enhancing workforce skills through education and training, and fostering a circular economy aligned with sustainable urban growth.

Poverty alleviation

Poverty can be either absolute or relative. Absolute poverty occurs when individuals lack the basic necessities for survival, such as food, clean water, shelter, healthcare, and education. It is influenced not only by income but also by access to essential social services (United Nations, 1995). The World Bank defines extreme poverty as living on less than $1.90 per day in 2011 PPP (purchasing power parity)-adjusted terms. Relative poverty, on the other hand, is defined in comparison to others within a given society, where individuals experience financial and social disadvantages (Eskelinen, 2011). Global poverty increased in 2020 for the first time in two decades due to the combined effects of COVID-19, climate change, and conflicts. Poverty reduction requires both practical measures to address immediate material needs and strategic approaches to tackle underlying causes at local, national, and international levels. Since poverty cannot be eliminated instantly, it must be gradually alleviated by addressing its most severe components. Alleviating poverty is key to promoting economic stability, environmental protection, and sustainable development. Policymakers should prioritise partnerships for poverty alleviation and sustainable development. The World Bank (2001) suggests a three-pillar framework for sustainable economic growth: Promoting opportunity, facilitating empowerment, and Enhancing security. Investing in these areas fosters human capital development, which is essential for long-term economic stability (UNEP, 2021). PEDs contribute to poverty alleviation by fostering equitable access to energy, infrastructure, and economic opportunities. By integrating affordable and sustainable energy solutions, PEDs can help reduce energy poverty, lower household costs, and improve living conditions. Additionally, PEDs promote inclusive urban development through job creation, skills training, and access to essential services such as education, healthcare, and digital connectivity. Addressing both absolute and relative poverty, PEDs play a crucial role in enhancing social equity and resilience by ensuring that disadvantaged communities benefit from sustainable urban transformation.

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
Consumer	Health & Safety	Thermal comfort	Five-point Likert scale	Average score from questionnaires of this indicator is between 4.6 - 5	Average score from questionnaires of this indicator is between 3.6 - 4.5	Average score from questionnaires of this indicator is between 2.6 - 3.5	Average score from questionnaires of this indicator is between 1.6 - 2.5	Average score from questionnaires of this indicator is between 1 - 1.5	Product Social Impact Assessment Handbook (2018)
Consumer	Health & Safety	Thermal Comfort-Predicted Mean Vote (PMV)	[#]	PMV value is between -0.1 and +0.1	PMV value is between -0.2 and +0.2	PMV value is between -0.5 and +0.5	PMV value is between -0.7 and +0.7	PMV value is between -1.0 and +1.0	EN ISO 16789-1-2019
Consumer	Health & Safety	Thermal Comfort-Predicted Percentage Dissatisfied (PPD)	[%]	PPD value is < 5%	PPD value is between 5-10%	PPD value is 10%	PPD value is between 10-15%	PPD value is < 15%	EN ISO 16789-1-2019
Consumer	Health & Safety	Indoor Air Quality	CO_2 [ppm] ; $PM_{2.5}$ [μg/m³]; PM_{10} [μg/m³]; O_3 [μg/m³]; NO_2 [μg/m³]; SO_2 [μg/m³]; CO [mg/m³].	CO_2 concentration ≤ 450 ppm. $PM_{2.5}$ is <10 μg/m³. PM_{10} is <40 μg/m³. Ozone (O_3) is <85 μg/m³. Nitrogen dioxide (NO_2) is <20 μg/m³. Sulfur dioxide (SO_2) is <35 μg/m³. Carbon monoxide (CO) is < 2 mg/m³	CO_2 concentration between 451 – 550 ppm, $PM_{2.5}$ is 10-14 μg/m³. PM_{10} is 40-44 μg/m³. Ozone (O_3) is 85-99 μg/m³. Nitrogen dioxide (NO_2) is 20-24 μg/m³. Sulfur dioxide (SO_2) is 35-39 μg/m³. Carbon monoxide (CO) is 2-3 mg/m³.	CO_2 concentration between 551 – 800 ppm. $PM_{2.5}$ is 15 μg/m³. PM_{10} is 45 μg/m³. Ozone (O_3) is 100 μg/m³. Nitrogen dioxide (NO_2) is 25 μg/m³. Sulfur dioxide (SO_2) is 40 μg/m³. Carbon monoxide (CO) is 4 mg/m³.	CO_2 concentration between 801 – 1350 ppm. $PM_{2.5}$ is 16-20 μg/m³. PM_{10} is 46-50 μg/m³. Ozone (O_3) is 101-125 μg/m³. Nitrogen dioxide (NO_2) is 26-30 μg/m³. Sulfur dioxide (SO_2) is 41-45 μg/m³. Carbon monoxide (CO) is 5-6 mg/m³.	CO_2 concentration >1350 ppm. $M_{2.5}$ is 16-20 μg/m³. PM_{10} is >50 μg/m³. Ozone (O_3) is >125 μg/m³. Nitrogen dioxide (NO_2) is >30 μg/m³. Sulfur dioxide (SO_2) is >45 μg/m³. Carbon monoxide (CO) is >6 mg/m³.	EN 16798-1-2019; Occupational Safety and Health Administration (2011); World Health Organisation (2021)
Consumer	Health & Safety	Noise Pollution	[dB], [%]	Exposure levels are kept well below the lower exposure action values, such as LEX,8h ≤ 70 dB(A) and LpC,peak ≤ 125 dB(C), with effective noise reduction measures consistently applied and monitored.	Exposure levels below the lower exposure action values but not reaching the best practice level. For instance, LEX,8h ≤ 75 dB(A) and LpC,peak ≤ 130 dB(C).	LEX,8h = 85 dB(A) and LpC,peak = 137 dB(C) for upper exposure action values, and LEX,8h = 80 dB(A) and LpC,peak = 135 dB(C) for lower exposure action values.	Exposure levels may reach around LEX,8h = 90 dB(A) and LpC,peak = 140 dB(C).	Exposure levels may reach or exceed LEX,8h = 95 dB(A) and LpC,peak = 145 dB(C) or more, indicating severe non-compliance.	Noise and vibrations - Occupational Safety and Health Ordinance

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
Consumer	Health & Safety	Illuminance	[Lux]	Illuminance complies with the recommended levels for specific activities and is regularly monitored and maintained to ensure consistent quality. Proactive adjustments are made for changing conditions (e.g., occupancy or time of day), and lighting systems use energy-efficient solutions (e.g., LED). Smart technology is implemented for adaptive lighting, optimising energy use and user comfort.	Illuminance complies with the recommended levels for specific activities and is periodically checked Lighting is energy-efficient, but no adaptive or smart technology is used. Minor improvements have been made in areas requiring better visual conditions, but further optimisation is possible.	Illuminance is within the range of compliance according to the Lighting standards. Basic lighting systems with no enhancements.	Illuminance levels fall below recommended ranges for some tasks (e.g., public spaces have less than 20–50 lux, or medium contrast tasks fall under 500 lux). Poor quality lighting systems with inefficient energy use or no optimisation for specific tasks. Irregular or inadequate maintenance leading to inconsistent performance.	Illuminance is inadequate or absent, falling far below the recommended levels for even basic tasks. Lighting systems are outdated, inefficient, and poorly maintained, resulting in safety and usability concerns. No data or plan exists to address illumination shortfalls.	IESNA Lighting Handbook (2000); AS/NZS 1680.1; Kofod (2017)
Consumer	Health & Safety	Daylight Factor	[%]	Daylight factor is 5% or more, ensuring sufficient natural light for tasks and areas.	Daylight factor is 2 - 5 % at everywhere, ensuring sufficient natural light for tasks and areas.	Average daylight factors is at least 1.5% in living rooms, 1% in bedrooms and 2% in kitchens even when predominantly daylit appearance is not necessary, meeting the minimum threshold for adequate daylighting according to regulations.	Daylight factor is between 1% and 2%, falling short of compliance.	Daylight factor is below 1%, significantly insufficient for the space's needs.	BS 8206-2: 1992; U.S. Green Building Council; Jakobiak (2024); Kofod (2017)
Consumer	Health & Safety	Green space	[ha/100.000 inhab], [m^2/inhab], [%]	Green space exceeds 50 m² per capita, achieving the ideal Urban Green Space value.	Green space is between 25–49 m² per capita, with sufficient recreational	Green space meets the minimum threshold of 9 m² per individual, aligning with	Green space is between 5–8 m² per capita, falling short of compliance.	Green space is less than 5 m² per capita, with minimal or no accessible outdoor	Russo and Cirella (2018); Ståhle (2018)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
					and ecological areas for the community.	international standards.		areas for the community.	
Consumer	Health & Safety	Public outdoor recreation space	[m²/inhab]	Public outdoor recreation space exceeds 100 m² per capita, greatly surpassing the ideal benchmark for recreational quality.	Public outdoor recreation space is between 75–99 m² per capita, offering ample opportunities for physical activity, relaxation, and social interaction.	Public outdoor recreation space meets the minimum threshold of 50 m² per capita, adhering to international standards.	Public outdoor recreation space is between 25–49 m² per capita, falling short of compliance.	Public outdoor recreation space is less than 25 m² per capita, with minimal or no accessible recreational areas.	Russo and Cirella (2018); Ståhle (2018)
Consumer	Feedback mechanism	Degree of satisfaction	[%] and/or Five-Point Likert Scale	≥ 80% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 4.6 - 5.	79-60% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 3.6 - 4.5	59-40% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 2.6 - 3.5	39-20% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 1.6 - 2.5	≤20% of inhabitants report positive perceptions (agree or strongly agree) across all key variables AND/OR Average score from questionnaires of this indicator is between 1 - 1.5	Product Social Impact Assessment Handbook (2018)
Local Community	Access to material resources	Progress towards Energy Citizenship	Five-point Likert scale	Average score from questionnaires that assess all key variables (Variables: social acceptance of PED solution, personal attitudes and motivation, perceived incentives/barriers, level of trust, sense of community, technology perception, ICT literacy) of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018)
Local Community	Access to material resources	Access to public transport	[% of inhab]	≥95% of inhabitants have a public transport stop within 500m.	85–94% of inhabitants have a public transport stop within 500m.	70–84% of inhabitants have a public transport stop within 500m.	50–69% of inhabitants have a transport stop within 500m, meaning significant portions of the population lack easy access.	<50% of inhabitants have a transport stop within 500m, indicating a major accessibility issue.	Poelman et al. (2020)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
Local Community	Access to material resources	Access to vehicle sharing solutions for city travel	[#/100.000 inhab], [#/inhab], [#], [km]	There are >35 cars and >160 bikes per 100.000 inhabitants as a vehicle sharing concept.	There are 23-35 cars and 136-160 bikes per 100.000 inhabitants as a vehicle sharing concept.	There are 18-22 cars and 125-135 bikes per 100.000 inhabitants as a vehicle sharing concept.	There are 10-18 cars and 100-125 bikes per 100.000 inhabitants as a vehicle sharing concept.	There are <10 cars and <100 bikes per 100.000 inhabitants as a vehicle sharing concept.	European Environment Agency (2024)
Local Community	Access to material resources	Access to commercial amenities	[% of inhab]	All[ii] 4 (Supermarket/ grocery store; Bank/ ATM; Commercial centre (mall, high street, etc.); Hospitality (Cafés, restaurants, bars, hotels, hostels, etc.)) commercial amenities are within 1 km (100% accessibility).	At least 3 commercial amenities (≥75%) are within 1 km.	At least 2 commercial amenities (≥50%) are within 1 km.	Only 1 commercial amenity (≤25%) is within 1 km.	None of the commercial amenities are within 1 km. (0% accessibility)	Elldér et al. (2022); Hidalgo et al. (2020)
Local Community	Access to material resources	Access to public amenities	[% of inhab]	All[ii] 8 public amenities (Primary School; Playground; Kindergarten; Public parks/gardens; Local public transport node; Community centre; Post office; Library) are within 1 km (100% accessibility)	At least 6 public amenities (≥75%) are within 1 km.	At least 4 public amenities (≥50%) are within 1 km.	Less than 4 public amenities (≤50%) are within 1 km.	Most (≤25%) or none of the public amenities are within 1 km.	Elldér et al. (2022); Hidalgo et al. (2020)
Local Community	Access to material resources	Shared EV Penetration Rate	[%]	The share of electric vehicles in car sharing fleets is ≥50%, demonstrating a strong commitment to sustainability and low-emission urban mobility.	The share of electric vehicles in car sharing fleets is 21 - 49%, showing steady progress toward cleaner shared mobility.	The share of electric vehicles in car sharing fleets is 20%	The share of electric vehicles in car sharing fleets is 10-19%, indicating slow adoption and continued reliance on fossil-fuel vehicles.	The share of electric vehicles in car sharing fleets is <10%, reflecting a lack of electrification efforts and high dependence on conventional vehicles.	Statistica (2023)
Local Community	Access to material resources	EV charging stations	[#], [#/km^2], [%], [#/100,000]	More than 800 EV charge points per 100,000 people in the neighbourhood	200 - 800 EV charge points per 100,000 people in the neighbourhood	150-200 EV charge points per 100,000 people in the neighbourhood and all parked cars have access to private	50 - 150 EV charge points per 100,000 people in the neighbourhood and there are maximum 3 private home	No data available, or fewer than 50 EV charge points per 100,000 people with no actions to address the deficiency	GrdiX Charging Report 2024, IEA (2024)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
						home charging stations.	charging stations for every 10 cars.		
Local Community	Access to material resources	Length of the bike route network	[% in km], [km/100,000 inhab)], [m]	Bicycle network density (dividing the area of the city or municipality by the length of all bike paths) is ≤250 m	Bicycle network density is between 250 - 400 m	Bicycle network density is between 400 - 500 m	Bicycle network density is between 500 - 1000 m	Bicycle network density is >1000 m	Weikl and Mayer (2023)
Local Community	Access to material resources	Public Transport Network	[km/100,000 inhab]	Public transport coverage is ≥150 km per 100,000 inhabitants, ensuring widespread, convenient access for residents	Public transport coverage is 106-149 km per 100,000 inhabitants, providing strong connectivity but with potential gaps in certain areas	Public transport coverage is 105 km per 100,000 inhabitants, meeting basic accessibility and mobility needs.	Public transport coverage is 55-104 km per 100,000 inhabitants, leading to reduced accessibility, longer travel times, and potential reliance on alternative transportation.	Public transport coverage is <54 km per 100,000 inhabitants, resulting in poor connectivity, social exclusion risks, and heavy dependence on private vehicles.	International Association of Public Transport (n.d.)
Local Community	Access to immaterial resources	Internet Penetration Rate	[% of inhab]	Internet penetration rate exceeds 95% of inhabitants. The district also offers free or affordable high-speed internet in public spaces, ensuring accessibility for disadvantaged groups.	Internet penetration rate is between 85% and 95% of inhabitants. Efforts are made to increase affordability and accessibility, with programs targeting underserved populations. Public spaces have partial access to free or subsidised internet.	Internet penetration rate is between 85% and 95% of inhabitants. Public spaces does not offer free internet access.	Internet penetration rate is between 50% and 85% of inhabitants. Public spaces does not offer free internet access.	Internet penetration rate is below 50% of habitants. Public spaces does not offer free internet access.	Eurostat (2024), European Comission (2020), Council of Europe (2014)
Local Community	Safe and healthy living conditions	Thermal comfort	Five-point Likert scale	Average score from questionnaires of this indicator is between 4.6 - 5.	Average score from questionnaires of this indicator is between 3.6 - 4.5	Average score from questionnaires of this indicator is between 2.6 - 3.5	Average score from questionnaires of this indicator is between 1.6 - 2.5	Average score from questionnaires of this indicator is between 1 - 1.5	Product Social Impact Assessment Handbook (2018)
Local Community	Safe and healthy	Thermal Comfort-Predicted	[#]	PMV value is between -0.1 and +0.1	PMV value is between -0.2 and +0.2	PMV value is between -0.5 and +0.5	PMV value is between -0.7 and +0.7	PMV value is between -1.0 and +1.0	EN ISO 16789-1-2019

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
	living conditions	Mean Vote (PMV)							
Local Community	Safe and healthy living conditions	Thermal Comfort-Predicted Percentage Dissatisfied (PPD)	[%]	PPD value is < 5%	PPD value is between 5-10%	PPD value is 10%	PPD value is between 10-15%	PPD value is < 15%	EN ISO 16789-1-2019
Local Community	Safe and healthy living conditions	Indoor Air Quality	CO_2 [ppm] ; $PM_{2.5}$ [µg/m³]; PM_{10} [µg/m³]; O_3 [µg/m³]; NO_2 [µg/m³]; SO_2 [µg/m³]; CO [mg/m³].	CO_2 concentration ≤ 450 ppm. $PM_{2.5}$ is <10 µg/m³. PM_{10} is <40 µg/m³. Ozone (O_3) is <85 µg/m³. Nitrogen dioxide (NO_2) is <20 µg/m³. Sulfur dioxide (SO_2) is <35 µg/m³. Carbon monoxide (CO) is < 2 mg/m³	CO_2 concentration between 451 – 550 ppm, $PM_{2.5}$ is 10-14 µg/m³. PM_{10} is 40-44 µg/m³. Ozone (O_3) is 85-99 µg/m³. Nitrogen dioxide (NO_2) is 20-24 µg/m³. Sulfur dioxide (SO_2) is 35-39 µg/m³. Carbon monoxide (CO) is 2-3 mg/m³.	CO_2 concentration between 551 – 800 ppm. $PM_{2.5}$ is 15 µg/m³. PM_{10} is 45 µg/m³. Ozone (O_3) is 100 µg/m³. Nitrogen dioxide (NO_2) is 25 µg/m³. Sulfur dioxide (SO_2) is 40 µg/m³. Carbon monoxide (CO) is 4 mg/m³.	CO_2 concentration between 801 – 1350 ppm. $PM_{2.5}$ is 16-20 µg/m³. PM_{10} is 46-50 µg/m³. Ozone (O_3) is 101-125 µg/m³. Nitrogen dioxide (NO_2) is 26-30 µg/m³. Sulfur dioxide (SO_2) is 41-45 µg/m³. Carbon monoxide (CO) is 5-6 mg/m³.	CO_2 concentration >1350 ppm. $M_{2.5}$ is 16-20 µg/m³. PM_{10} is >50 µg/m³. Ozone (O_3) is >125 µg/m³. Nitrogen dioxide (NO_2) is >30 µg/m³. Sulfur dioxide (SO_2) is >45 µg/m³. Carbon monoxide (CO) is >6 mg/m³.	EN 16798-1-2019; Occupational Safety and Health Administration (2011); World Health Organisation (2021)
Local Community	Safe and healthy living conditions	Noise Pollution	[dB], [%]	Exposure levels are kept well below the lower exposure action values, such as LEX,8h ≤ 70 dB(A) and LpC,peak ≤ 125 dB(C), with effective noise reduction measures consistently applied and monitored.	Exposure levels below the lower exposure action values but not reaching the best practice level. For instance, LEX,8h ≤ 75 dB(A) and LpC,peak ≤ 130 dB(C).	LEX,8h = 85 dB(A) and LpC,peak = 137 dB(C) for upper exposure action values, and LEX,8h = 80 dB(A) and LpC,peak = 135 dB(C) for lower exposure action values.	Exposure levels may reach around LEX,8h = 90 dB(A) and LpC,peak = 140 dB(C)..	Exposure levels may reach or exceed LEX,8h = 95 dB(A) and LpC,peak = 145 dB(C) or more, indicating severe non-compliance.	Noise and vibrations - Occupational Safety and Health Ordinance

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
Local Community	Safe and healthy living conditions	Illuminance	[Lux]	Illuminance complies with the recommended levels for specific activities and is regularly monitored and maintained to ensure consistent quality. Proactive adjustments are made for changing conditions (e.g., occupancy or time of day), and lighting systems use energy-efficient solutions (e.g., LED). Smart technology is implemented for adaptive lighting, optimising energy use and user comfort.	Illuminance complies with the recommended levels for specific activities and is periodically checked, but without a proactive maintenance schedule. Lighting is energy-efficient, but no adaptive or smart technology is used. Minor improvements have been made in areas requiring better visual conditions, but further optimisation is possible.	Illuminance is within the range of compliance according to the Lighting standards[i]. Basic lighting systems with no enhancements.	Illuminance levels fall below recommended ranges for some tasks (e.g., public spaces have less than 20–50 lux, or medium contrast tasks fall under 500 lux). Poor quality lighting systems with inefficient energy use or no optimisation for specific tasks. Irregular or inadequate maintenance leading to inconsistent performance.	Illuminance is inadequate or absent, falling far below the recommended levels for even basic tasks. Lighting systems are outdated, inefficient, and poorly maintained, resulting in safety and usability concerns. No data or plan exists to address illumination shortfalls.	IESNA Lighting Handbook (2000); AS/NZS 1680.1; Kofod (2017)
Local Community	Safe and healthy living conditions	Daylight Factor	[%]	Daylight factor is 5% or more, ensuring sufficient natural light for tasks and areas.	Daylight factor is 2 - 5 % at everywhere, ensuring sufficient natural light for tasks and areas.	Average daylight factors is at least 1.5% in living rooms, 1% in bedrooms and 2% in kitchens even when predominantly daylit appearance is not necessary, meeting the minimum threshold for adequate daylighting according to regulations.	Daylight factor is between 1% and 2%, falling short of compliance.	Daylight factor is below 1%, significantly insufficient for the space's needs.	U.S. Green Building Council; Jakobiak (2024); Kofod (2017)
Local Community	Safe and healthy living conditions	Green space	[ha/100.000 inhab], [m^2/inhab], [%]	Green space exceeds 50 m² per capita, achieving the ideal Urban Green Space value.	Green space is between 25–49 m² per capita, with sufficient recreational	Green space meets the minimum threshold of 9 m² per individual, aligning with	Green space is between 5–8 m² per capita, falling short of compliance.	Green space is less than 5 m² per capita, with minimal or no accessible outdoor	Russo and Cirella (2018); Ståhle (2018)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
					and ecological areas for the community.	international standards.		areas for the community.	
Local Community	Safe and healthy living conditions	Public outdoor recreation space	[m²/inhab]	Public outdoor recreation space exceeds 100 m² per capita, greatly surpassing the ideal benchmark for recreational quality.	Public outdoor recreation space is between 75–99 m² per capita, offering ample opportunities for physical activity, relaxation, and social interaction.	Public outdoor recreation space meets the minimum threshold of 50 m² per capita, adhering to international standards.	Public outdoor recreation space is between 25–49 m² per capita, falling short of compliance.	Public outdoor recreation space is less than 25 m² per capita, with minimal or no accessible recreational areas.	Russo and Cirella (2018); Ståhle (2018)
Local Community	Safe and healthy living conditions	Access to basic health care services	[% of inhab]	≥95% of inhabitants have a health center within 30 min walking distance.	85–94% of inhabitants have a health center within 30 min walking distance.	70–84% of inhabitants have a health center within 30 min walking distance.	50–69% of inhabitants have a health center 30 min walking distance.	<50% of inhabitants have a health center within 30 min walking distance.	Florio et al. (2023)
Local Community	Community engagement	Active/proactive citizens' behaviour	[%] and/or Five-Point Likert Scale	Average score from questionnaires that assess all key variables (willingness to invest in energy savings measures, willingness to pay more for RES/services, recommend the project to others) of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018)
Local Community	Community engagement	Increased consciousness of citizenship	Five-point Likert scale	Average score from questionnaires that assess all key variables (knowing civic rights and responsibilities, feeling the sense of community) of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
Local Community	Community engagement	Social Cohesion	Five-point Likert scale	Average score from questionnaires that assess all key variables (having a support network, care habits, feeling belonging, cultural values, trust, discrimination) of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018)
Local Community	Community engagement	Increased participation of vulnerable groups	Five-point Likert scale.	Average score from questionnaires that assess all key variables of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018)
Local Community	Community engagement	Number of awareness-engagement initiatives/events	[#/100 inhab][iii] , [#][iii]	All targeted initiatives/events organised as multiple, diverse, large-scale with deep community involvement, measurable positive impact, and ongoing feedback integration.	Multiple targeted initiatives are executed that result in clear stakeholder engagement and positive community impact.	Number of events/initiatives are planned and reported for the specific needs of the PED.	Organises events/initiatives, with limited reach or unclear impact, and does not fully meet engagement expectations.	Fails to organise any number of initiatives/events	Whiting et al. (2004)
Local Community	Community engagement	Open Public Participation	[#/inhab[iii]], [#/100,000 inhab][iii] and/or Likert scale	Average score from questionnaires that assess all key variables of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018);
Local Community	Local employment	Job creation	[#], [%]	Increase in employment by 5% or more after the PED estabishment.	Increase in employment by 2%–5% after the PED estabishment.	Increase in employment by less than 2% or no measurable increase after the PED estabishment.	Decrease in employment by up to 5% after the PED estabishment.	Decrease in employment by more than 5%after the PED estabishment.	Chen et al. (2023)
Local Community	Secure living conditions	Crime rate	[#/100.000 inhab], [%]	Reduction of >20% crime rates before the PED estabishment..	Reduction of 10–20% in crime rates before	Reduction of less than 10% or no change in crime	No effective measures or data	An increase in crime rates before	Alonso et al. (2019)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
					the PED estabishment.	rates before the PED estabishment.	collection to improve safety.	the PED estabishment.	
Local Community	Secure living conditions	Living Conditions	[% of inhab]	Average score from questionnaires that assess all key variables (overcrowding, poor living conditions) of this indicator is between 1 - 1.5	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 4.5 - 5.	Product Social Impact Assessment Handbook (2018)
Local Community	Secure living conditions	Affordability of Energy	[% of inhab], Likert scale	Household income spent on energy is ≤ 3.2% OR ≥ 75% of inhabitants finding energy costs affordable	Household income spent on energy is between 3.3– 4.9% OR 51–74% of inhabitants finding energy costs affordable	Household income spent on energy is 5.0% OR 50% of inhabitants finding energy costs affordable	Household income spent on energy is between 5.1 – 6.5% OR 30–50% of inhabitant finding costs affordable.	Household income spent on energy is > 6.5% OR < 30% of inhabitants finding costs affordable.	Wehrmann (2022); Hoppe et. al (2019); IEA (2019)
Local Community	Secure living conditions	Affordability of Housing	[% of inhab], Likert scale	Household income spent on housing is ≤ 12%, OR ≥ 75% of inhabitants find housing costs affordable.	Household income spent on housing is between 13% – 19%, OR 50–74% of inhabitants find housing costs affordable.	Household income spent on housing is 20% OR 50% of inhabitants finding housing costs affordable	Household income spent on housing is between 21% – 30%, OR 30–49% of inhabitants find housing costs affordable.	Household income spent on housing is > 30%, OR < 30% of inhabitants find housing costs affordable	Eurostat (2024)
Society: Contribution to economic development, poverty alleviation, wealth distribution		Median Disposable (Household) Income	[$/household], [$/inhab]	Median disposable income is ≥ USD 49,000 per capita per year, ensuring strong financial security, high purchasing power, and access to quality goods and services.	Median disposable income is between USD 37,000 – 49,000 per capita per year, providing financial stability with discretionary spending capacity.	Median disposable income is USD 25,000-37,000 per capita per year, meeting basic financial needs but with limited excess for savings or luxury.	Median disposable income is between USD 13,000 – 25,000 per capita per year, indicating financial strain, reduced disposable income, and limited access to non-essential goods and services.	Median disposable income is ≤ USD 13,000 per capita per year, leading to economic insecurity, difficulty covering basic needs, and potential reliance on social assistance.	OECD (2023)
Worker	Health and Safety	Access to basic health care services	[% of inhab]	≥95% of inhabitants have a health center within 30 min walking distance.	85–94% of inhabitants have a health center within 30 min walking distance.	70–84% of inhabitants have a health center within 30 min walking distance.	50–69% of inhabitants have a health center 30 min walking distance.	<50% of inhabitants have a health center within 30 min walking distance.	Florio et al. (2023)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
Worker	Health and Safety	Indoor Air Quality	CO_2 [ppm] ; $PM_{2.5}$ [µg/m³]; PM_{10} [µg/m³]; O_3 [µg/m³]; NO_2 [µg/m³]; SO_2 [µg/m³]; CO [mg/m³].	CO_2 concentration ≤ 450 ppm. $PM_{2.5}$ is <10 µg/m³. PM_{10} is <40 µg/m³. Ozone (O_3) is <85 µg/m³. Nitrogen dioxide (NO_2) is <20 µg/m³. Sulfur dioxide (SO_2) is <35 µg/m³. Carbon monoxide (CO) is < 2 mg/m³	CO_2 concentration between 451 – 550 ppm, $PM_{2.5}$ is 10-14 µg/m³. PM_{10} is 40-44 µg/m³. Ozone (O_3) is 85-99 µg/m³. Nitrogen dioxide (NO_2) is 20-24 µg/m³. Sulfur dioxide (SO_2) is 35-39 µg/m³. Carbon monoxide (CO) is 2-3 mg/m³.	CO_2 concentration between 551 – 800 ppm. $PM_{2.5}$ is 15 µg/m³. PM_{10} is 45 µg/m³. Ozone (O_3) is 100 µg/m³. Nitrogen dioxide (NO_2) is 25 µg/m³. Sulfur dioxide (SO_2) is 40 µg/m³. Carbon monoxide (CO) is 4 mg/m³.	CO_2 concentration between 801 – 1350 ppm. $PM_{2.5}$ is 16-20 µg/m³. PM_{10} is 46-50 µg/m³. Ozone (O_3) is 101-125 µg/m³. Nitrogen dioxide (NO_2) is 26-30 µg/m³. Sulfur dioxide (SO_2) is 41-45 µg/m³. Carbon monoxide (CO) is 5-6 mg/m³.	CO_2 concentration >1350 ppm. $M_{2.5}$ is 16-20 µg/m³. PM_{10} is >50 µg/m³. Ozone (O_3) is >125 µg/m³. Nitrogen dioxide (NO_2) is >30 µg/m³. Sulfur dioxide (SO_2) is >45 µg/m³. Carbon monoxide (CO) is >6 mg/m³.	EN 16798-1-2019; Occupational Safety and Health Administration (2011); World Health Organisation (2021)
Worker	Health and Safety	Noise Pollution	[dB], [%]	Exposure levels are kept well below the lower exposure action values, such as LEX,8h ≤ 70 dB(A) and LpC,peak ≤ 125 dB(C), with effective noise reduction measures consistently applied and monitored. Additional measures may include continuous noise monitoring, isolated work zones, and proactive noise control technologies.	Exposure levels below the lower exposure action values but not reaching the best practice level. For instance, LEX,8h ≤ 75 dB(A) and LpC,peak ≤ 130 dB(C). Enhanced noise reduction practices are in place, and noise exposure is managed with policies to improve comfort and health, though not necessarily at exemplary levels.	LEX,8h = 85 dB(A) and LpC,peak = 137 dB(C) for upper exposure action values, and LEX,8h = 80 dB(A) and LpC,peak = 135 dB(C) for lower exposure action values. Indicates that standard practices are followed to meet regulatory requirements without additional proactive measures.	Exposure levels may reach around LEX,8h = 90 dB(A) and LpC,peak = 140 dB(C). Noise control measures are insufficient, possibly indicating occasional protective measures, but not enough to meet regulatory standards consistently.	Exposure levels may reach or exceed LEX,8h = 95 dB(A) and LpC,peak = 145 dB(C) or more, indicating severe non-compliance. Few to no effective noise controls are in place, and exposure to high noise levels poses a serious risk to health and safety.	Noise and vibrations - Occupational Safety and Health Ordinance
Worker	Health and Safety	Illuminance	[Lux]	Illuminance complies with the recommended levels for specific activities[i] and is regularly monitored and maintained to ensure consistent quality. Proactive adjustments are made for changing conditions	Illuminance complies with the recommended levels for specific activities[i] and is periodically checked, but without a proactive maintenance schedule. Lighting is energy-efficient, but no	Illuminance is within the range of compliance according to the Lighting standards[i]. Basic lighting systems with no enhancements.	Illuminance levels fall below recommended ranges for some tasks (e.g., public spaces have less than 20–50 lux, or medium contrast tasks fall under 500 lux).	Illuminance is inadequate or absent, falling far below the recommended levels for even basic tasks. Lighting systems are outdated, inefficient, and poorly maintained,	IESNA Lighting Handbook (2000); AS/NZS 1680.1; Kofod (2017)

Table 6

Stake-holder	Subcate-gory	Indicator	Unit	+2	+1	0	-1	-2	Reference
				(e.g., occupancy or time of day), and lighting systems use energy-efficient solutions (e.g., LED). Smart technology is implemented for adaptive lighting, optimising energy use and user comfort.	adaptive or smart technology is used. Minor improvements have been made in areas requiring better visual conditions, but further optimisation is possible.		Poor quality lighting systems with inefficient energy use or no optimisation for specific tasks. Irregular or inadequate maintenance leading to inconsistent performance.	resulting in safety and usability concerns. No data or plan exists to address illumination shortfalls.	
Worker	Equal opportunities /discrimination	Gender Equity of New Jobs	[%]	Gender wage gap is ≤ 2%	Gender wage gap is 3-10%	Gender wage gap is 10-12%	Gender wage gap is 12-20%	Gender wage gap is > 20%	OECD (2023)
Additional		Accessible Design	10 point Likert scale and [% of barrier-free units] at the building level; [% of barrier-free units] at the district level	Average score from questionnaires that assess all key variables of this indicator is between 4.6 - 5 AND 100% of public spaces, roads, and buildings fully comply with universal design checklist.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5 AND 85-99% of public spaces, roads, and buildings comply with universal design checklist.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5 AND 70-84% of public spaces, roads, and buildings comply with universal design checklist.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5 AND 50-69% of public spaces, roads, and buildings comply with universal design checklist.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5 AND Below 50% of public spaces, roads, and buildings comply with universal design checklist.	Product Social Impact Assessment Handbook (2018); UN-Habitat (2018)
Additional		Social factors	[%] and/or Five-Point Likert Scale	Average score from questionnaires that assess all key variables (divergence of interest, resistance to change, satisfaction with information, satisfaction with involvement in decision-making) of this indicator is between 4.6 - 5.	Average score from questionnaires that assess all key variables of this indicator is between 3.6 - 4.5.	Average score from questionnaires that assess all key variables of this indicator is between 2.6 - 3.5.	Average score from questionnaires that assess all key variables of this indicator is between 1.6 - 2.5.	Average score from questionnaires that assess all key variables of this indicator is between 1 - 1.5.	Product Social Impact Assessment Handbook (2018)

[i] Please note that these amount of amenities are recommended values of this SIA Framework. Depending on the location and the size of the assessed PED, they can be changed and adapted for the specific case.
[iii] Each PED should define their quantitative values of these indicators. These values varies based on factors such as community size, diversity and specific goals (Whiting et al. 2004).

Table 7: Sensitivity Analysis Results

Indoor air quality:

Scale	Original Range (ppm)	5% Decrease (ppm)	5% Increase (ppm)
+2	≤ 450	≤ 428	≤ 473
+1	451 – 550	428 – 523	473 – 578
0	551 – 800	523 – 760	578 – 840
-1	801 – 1350	761 – 1283	841 – 1418
-2	> 1350	> 1283	> 1418

- 5% decrease: Multiplying all values by 0.95
- 5% increase: Multiplying all values by 1.05

Case study: 579 ppm, 0 in all the cases

Degree of satisfaction:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	≥ 80%	≥ 76%	≥ 84%
+1	79 – 60%	75 – 57%	83 – 63%
0	59 – 40%	56 – 38%	62 – 42%
-1	39 – 20%	37 – 19%	41 – 21%
-2	≤ 20%	≤ 19%	≤ 21%

- 5% decrease: Multiplying all values by 0.95
- 5% increase: Multiplying all values by 1.05

Case study: 86%, +2 in all the cases

Access to public transport:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	≥ 95%	≥ 90%	≥ 100%
+1	85 – 94%	81 – 89%	89 – 99%
0	70 – 84%	67 – 80%	74 – 88%
-1	50 – 69%	48 – 66%	53 – 73%
-2	< 50%	< 48%	< 53%

- 5% decrease: Multiplying all values by 0.95
- 5% increase: Multiplying all values by 1.05

Case study: 100%, +2 in all the cases

Access to commercial amenities:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	All 4 (100%)	All 4 (95%)	All 4 (100%)
+1	≥ 3 (≥ 75%)	≥ 3 (≥ 71%)	≥ 3 (≥ 79%)

0	≥ 2 (≥ 50%)	≥ 2 (≥ 48%)	≥ 2 (≥ 53%)
-1	≤ 1 (≤ 25%)	≤ 1 (≤ 24%)	≤ 1 (≤ 26%)
-2	None (0%)	None (0%)	None (0%)

- 5% decrease: Multiplying the percentage thresholds by 0.95
- 5% increase: Multiplying the percentage thresholds by 1.05

Case study: 100%, +2 in all the cases

Access to public amenities:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	All 8 (100%)	All 8 (95%)	All 8 (100%)
+1	≥ 6 (≥ 75%)	≥ 6 (≥ 71%)	≥ 6 (≥ 79%)
0	≥ 4 (≥ 50%)	≥ 4 (≥ 48%)	≥ 4 (≥ 53%)
-1	< 4 (≤ 50%)	< 4 (≤ 48%)	< 4 (≤ 53%)
-2	≤ 2 (≤ 25%) or none	≤ 2 (≤ 24%) or none	≤ 2 (≤ 26%) or none

- 5% decrease: Multiplying the percentage thresholds by 0.95
- 5% increase: Multiplying the percentage thresholds by 1.05

Case study: 100%, +2 in all the cases

Access to basic health care services:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	≥ 95%	≥ 90%	≥ 100%
+1	85 – 94%	81 – 89%	89 – 99%
0	70 – 84%	67 – 80%	74 – 88%
-1	50 – 69%	48 – 66%	53 – 73%
-2	< 50%	< 48%	< 53%

Explanation:

- 5% decrease: Multiplying all values by 0.95
- 5% increase: Multiplying all values by 1.05

Case study: 100% +2 in all the cases

Affordability of Energy:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	≥ 75%	≥ 71%	≥ 79%
+1	51 – 74%	48 – 70%	54 – 78%
0	50%	48%	53%
-1	30 – 50%	29 – 48%	32 – 53%
-2	< 30%	< 29%	< 32%

Explanation:

- 5% decrease: Multiplying all values by 0.95
- 5% increase: Multiplying all values by 1.05

Case study: 45.5% -1 in all the cases

Affordability of Housing:

Scale	Original Range (%)	5% Decrease (%)	5% Increase (%)
+2	≥ 75%	≥ 71%	≥ 79%

+1	50 – 74%	48 – 70%	53 – 78%
0	50%	48%	53%
-1	30 – 49%	29 – 47%	32 – 52%
-2	< 30%	< 29%	< 32%

Explanation:

- 5% decrease: Multiplying all values by 0.95
- 5% increase: Multiplying all values by 1.05

Case study: 84% +2 in all cases

ANNEX 83

EBC

Energy in Building and Communities Programme

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