

A MODELLING FRAMEWORK FOR COST-EFFICIENT DESIGN OF NET-ZERO AND POSITIVE ENERGY DISTRICTS

JOÃO PEDRO MARQUES CARDOSO

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Faculty of Engineering of the University of Porto

Supervisor

Professor Vítor Manuel da Silva Leal, Faculty of Engineering of the University of Porto

Co-supervisor

Professor Isabel Maria Gonçalves Azevedo, Faculty of Engineering of the University of Porto



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Abstract

This thesis investigates Net-Zero Energy Districts (NZED) and Positive Energy Districts (PED) as strategic pathways for the optimal design of urban energy systems and to support energy transition toward sustainable cities. Achieving these objectives requires assessment frameworks that go beyond the individual building scale and are able to capture the technical, economic and spatial interactions that characterise district energy systems. Despite increasing interest in district-level solutions, important gaps remain regarding the assessment of their techno-economic feasibility, optimal system dimensioning and applicability under real urban constraints.

A systematic review of international case studies is performed to characterise prevailing design practices, technological choices and performance levels. Then, a meta-analysis of European case studies reveals a strong focus on energy supply solutions, particularly PV and heat pumps, while demand-side measures, mobility and economic efficiency are often underexplored. Together, these analyses show that achieving zero or positive energy balances is frequently prioritised over cost-optimality, highlighting the need for an integrated techno-economic assessment.

To address these gaps, a comprehensive framework is developed to support the early-stage design and optimisation of urban energy systems targeting NZED, PED and different levels of energy self-sufficiency. The assessment framework integrates energy demand modelling with high temporal and spatial resolution, supply and end-use technology characterisation and long-term cost assessment through a linear optimisation model. It thus enables a systematic exploration of trade-offs between investment cost, operational performance, renewable integration and self-sufficiency. The framework was applied to two case studies, one for validation of a first version, and a second for the validation of the expanded version, which allowed to study the complementation of PV and electric energy storage with seasonal thermal storage and wind generation. Applications confirm that cost-optimal and NZED solutions achieve favourable economic performance, whereas high self-sufficiency targets entail disproportionately higher storage requirements and costs. The results demonstrate that, in comparison to building-level solutions, a district-level approach consistently improves self-sufficiency and renewable self-consumption, while the economic feasibility of NZED and PED strongly depends on external factors such as electricity tariffs, technology costs and available area for PV. The analysis further examined the integration of electric vehicle charging and PV carports, highlighting that PED conditions are favoured by demand profiles and solar production alignment and by alleviated spatial constraints.

Overall, the results position integrated district-level optimisation as a robust and decision-oriented approach to support cost-efficient pathways toward NZED and PED.

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Resumo

A presente tese investiga os conceitos de *Net-Zero Energy Districts (NZED)* e *Positive Energy Districts (PED)* como estratégias para o desenho otimizado de sistemas energéticos urbanos e apoiar a transição energética rumo a cidades sustentáveis. Concretizar estes objetivos requer modelos de avaliação que ultrapassem a escala do edifício individual, e capazes de captar as interações técnicas, económicas e espaciais que caracterizam os sistemas energéticos ao nível do bairro. Apesar do crescente interesse em soluções à escala do bairro, subsistem lacunas relevantes no que respeita à análise e optimização da sua viabilidade técnico-económica, ao dimensionamento ótimo dos sistemas e à sua aplicabilidade em contextos urbanos reais.

A tese começa por analisar a forma como os conceitos de NZED, PED e outros relacionados são definidos e operacionalizados na literatura. É realizada uma revisão sistemática de casos de estudo internacionais, com o objetivo de caracterizar as práticas de conceção predominantes, as opções tecnológicas e os níveis de desempenho alcançados. Uma meta-análise de casos de estudo europeus revela um forte foco em soluções do lado da oferta de energia, em particular sistemas fotovoltaicos e bombas de calor, enquanto as medidas do lado da procura, mobilidade e eficiência económica são frequentemente pouco exploradas. Evidencia-se ainda que a obtenção de balanço energético nulo ou positivo é, muitas vezes, priorizada em detrimento da optimização económica, salientando a necessidade de avaliação técnico-económica integrada.

Para colmatar estas lacunas, é desenvolvida uma metodologia abrangente destinada a apoiar o projeto e a optimização em fase inicial de sistemas energéticos urbanos orientados para NZED, PED e autossuficiência energética (SS). A metodologia integra modelação de necessidades energéticas, caracterização tecnológica e avaliação de custos de longo prazo num modelo de optimização linear, permitindo a exploração sistemática dos compromissos entre custo de investimento, desempenho operacional, integração de energias renováveis e autossuficiência. A metodologia é aplicada a dois casos de estudo, um para validação da primeira versão, e uma segunda validação à versão expandida, permitindo estudar a complementação de fotovoltaico e armazenamento elétrico com armazenamento térmico sazonal e energia eólica. As aplicações confirmam que metas altas de autossuficiência implicam necessidades de armazenamento e custos desproporcionadamente elevados, ao passo que soluções de custo ótimo e NZED apresentam desempenhos económicos favoráveis. Os resultados demonstram que a coordenação à escala do bairro melhora consistentemente a autossuficiência e a correspondência entre produção renovável e consumo, enquanto a viabilidade económica de NZED e PED depende fortemente de fatores externos, como tarifas de eletricidade, custos tecnológicos e área disponível para instalação fotovoltaica. A análise

avaliou posteriormente a integração de carregamento de veículos elétricos e de *carports* fotovoltaicos, salientando que as condições PED são favorecidas pelo alinhamento entre os perfis de procura e de produção solar e pela mitigação de restrições espaciais.

Globalmente, os resultados posicionam a otimização integrada à escala do bairro como uma abordagem robusta e orientada para a melhor decisão no desenvolvimento de NZED e PED.

List of contents

Acknowledgements.....	v
Abstract.....	vii
Resumo	ix
List of figures.....	xv
List of tables.....	xix
Chapter 1. Introduction	1
1.1 Context and motivation	1
1.2 Technical and economic challenges.....	2
1.3 Research objectives and questions.....	3
1.4 Thesis structure.....	5
1.5 Publications related to this thesis.....	6
Chapter 2. Literature review: current approaches	7
2.1 Energy-related concepts at district or neighbourhood level.....	7
2.2 Review of academic studies and real case applications	8
2.3 Methodology followed for the systematic review.....	11
2.4 Results and discussion	14
2.5 Insights from the literature review.....	39
Chapter 3. Meta-analysis of district-level energy solutions	41
3.1 An overview on district-level solutions.....	41
3.2 Methodology followed for the meta-analysis	44
3.3 Results and discussion	46
3.4 Insights from the meta-analysis.....	63
Chapter 4. Methodology and optimisation model	65
4.1 Current models and tools to achieve NZED and PED.....	65
4.2 Description of methodology	67
4.3 Urban Building Energy Modelling (UBEM): City Energy Analyst.....	68

4.4 Dynamic optimisation model based on Mixed Integer Linear Programming (MILP) ..	70
Chapter 5. Case study 1: small-scale district in Porto	81
5.1 Description of case study 1	81
5.2 Energy demand results for baseline and retrofit configurations.....	84
5.3 Energy systems: HVAC&DHW, photovoltaic and electric energy storage	86
5.4 Simulation	88
5.5 Results and discussion	88
5.6 Extended analysis: EV charging demand and PV area availability	96
5.7 Insights from the model application to the case study	103
Chapter 6. Expanded version of the optimisation model.....	105
6.1 Expanding the dynamic optimisation model	105
6.2 The new technologies included in the optimisation model.....	107
6.3 Incorporating the new technologies in existing model formulations.....	112
6.4 Economic and environmental performance	118
Chapter 7. Case study 2: urban district in Lisbon	121
7.1 Description of case study 2	121
7.2 Energy demand results	127
7.3 Selected technologies for HVAC&DHW, electricity generation and storage.....	129
7.4 Simulation	132
7.5 Results and discussion	133
7.6 Insights from the expanded model application to the case study.....	152
Chapter 8. Conclusions	153
8.1 Main findings and applications	153
8.2 Limitations.....	156
8.3 Future research.....	157
References	159
Annex A. Literature review complementary data (Chapter 2)	183
Annex B. Meta-analysis complementary data (Chapter 3).....	187

Annex C. Criteria for selecting CEA (Chapter 4)	191
Annex D. Photovoltaic production simulation module (Chapter 4)	193
Annex E. Selected design variables alternatives (Chapter 4).....	197
Annex F. Case study 1 end-use schedules (Chapter 5)	207
Annex G. Case study 2 end-use schedules (Chapter 7).....	209

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List of figures

Figure 2.1. Flow chart of the methodology followed to identify case studies for analysis. ...	12
Figure 2.2. Number of search results per type of study, for each of the six sets of keywords, and respective share of field related papers relative to the total number of papers retrieved.....	14
Figure 2.3. Distribution of energy-related concepts stated as objective or subject of study.	15
Figure 2.4. Total final energy demand for the zero energy and zero emissions case studies (ID).....	26
Figure 2.5. SH, SC, DHW and Electricity final energy demand for the zero energy and zero emissions case studies (ID).....	27
Figure 2.6. Total final energy demand per floor area for all case studies (ID).	30
Figure 2.7. Number of cases studies presenting design alternatives, by design feature.	33
Figure 2.8. Comparison between complexity of design practices and final energy demand.	38
Figure 3.1. Flow chart of the methodology followed to identify the case studies for analysis.	44
Figure 3.2. Case studies distribution by country.....	47
Figure 3.3. Partition regarding: (1) district typology; (2) project typology; and (3) type of case study.....	48
Figure 3.4. Distribution of occurrences by scope of intervention (centre) and by measures (corners).	51
Figure 3.5. Number of appearances of the measures most adopted (those appearing more than six times).	51
Figure 3.6. Share of measures and case studies evaluated at each impact category.	53
Figure 3.7. Quantification of the impact of measures, by impact category.	56
Figure 3.8. Index of measure occurrence in scenarios with high impact vs. share in total measures. [Figure 3.8 a) index of measure occurrence in scenarios with high impact vs. project location]	60
Figure 4.1. Methodology workflow, design variables and general procedures.	68
Figure 4.2. Illustration of CEA workflow.	70
Figure 4.3. Optimisation model diagram.	71
Figure 5.1. The geographical distribution of the district in Porto, Portugal (Google maps)..	81
Figure 5.2. Representation of the selected buildings in the case study 1 in CEA software...	82

Figure 5.3. Comparison of energy demand by end-use between baseline and retrofit configurations of the district.....	85
Figure 5.4. Annual energy results for the main scenarios (optimal, NZED and SS100).	90
Figure 5.5. Cost split across lifetime horizon for the main scenarios (optimal, NZED and SS100).....	90
Figure 5.6. Variation of total cost with the level of self-sufficiency for each scenario in the four modelling setups (dark graph zooms into lower total cost).....	91
Figure 5.7. Cumulative cash flow for viable scenarios by modelling setup.	94
Figure 5.8. Sensitivity analysis results for the optimal scenario in the Baseline-District setup.	95
Figure 5.9. Representation of the system configuration and distribution of the project.	97
Figure 5.10. Profiles of percentual demand of EV charging: daytime vs night-time	98
Figure 5.11. Total cost of each scenario in the setup variants (dark graph zooms into lower total cost).	99
Figure 5.12. Difference in total cost (optimal vs. NZED) and energy demand vs. PV (optimal).	100
Figure 5.13. Differences on energy parameters of scenarios of the five setup variants.....	101
Figure 5.14. Area occupied by PV and energy demand vs. PV (optimal).....	102
Figure 6.1. Diagram of the expanded optimisation model, with new technologies inputs and variables (STES in brown and Wind in green).	106
Figure 7.1. Map of the selected district in Lisbon, Portugal (QGIS).....	121
Figure 7.2. Representation of the buildings composing the selected district in the CEA software.	122
Figure 7.3. Group A buildings (representation in QGIS and CEA softwares, respectively). .	123
Figure 7.4. Group B buildings (representation in QGIS and CEA softwares, respectively). .	124
Figure 7.5. Group C buildings (representation in QGIS and CEA softwares, respectively). .	125
Figure 7.6. Group D buildings (representation in QGIS and CEA softwares, respectively). .	126
Figure 7.7. Useful energy demand of the district by end-use.	128
Figure 7.8. Annual energy results for the main scenarios (optimal, NZED and SS100).	134
Figure 7.9. Cost split across lifetime horizon for the main scenarios (optimal, NZED and SS100).....	135
Figure 7.10. Impacts of borefield size in energy and cost parameters for the Optimal scenario.	138
Figure 7.11. Impacts of borefield size in energy and cost parameters for the NZED scenario.	138

Figure 7.12. Impacts of borefield size in energy and cost parameters for the SS scenario.	138
Figure 7.13. Variation of total cost with the level of self-sufficiency for each borefield size (dark graph zooms into lower total cost).	141
Figure 7.14. Variation of entering fluid temperature across the year (case bh 200).	141
Figure 7.15. Variation of space heating COP across the year (case Bh 200).	142
Figure 7.16. Variation of domestic hot water COP across the year (case Bh 200).	142
Figure 7.17. Variation of space cooling EER across the year (case Bh 200).	142
Figure 7.18. PV area covered for the scenarios in each setup.	145
Figure 7.19. Variation of total cost with the level of self-sufficiency for each setup (dark graph zooms into lower total cost).	145
Figure 7.20. Sensitivity analysis on costs and tariffs for the optimal scenario.	147
Figure 7.21. Sensitivity analysis results for the optimal scenario.	149
Figure 7.22. Influence of discount rate alternatives in CAPEX and OPEX.	150
Figure 7.23. Influence on project lifetime carbon emissions of decarbonisation rates.	151

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List of tables

Table 2.1. Proposed nomenclature for energy or emissions efficiency concepts.	16
Table 2.2. Proposed nomenclature for the coverage of the concepts.	17
Table 2.3. List of the selected case studies.	18
Table 2.4. General characterisation of the case studies.	19
Table 2.5. Main technical features of the PED case studies.	21
Table 2.6. Main technical features of the zero energy or zero emissions case studies.	23
Table 2.7. Main technical features of the nZED case studies.	29
Table 2.8. Existence of a structured process of choice from alternatives for the key-design features.	31
Table 2.9. Methods and tools used for energy performance and best solutions evaluation.	36
Table 3.1. List of considered case studies.	46
Table 3.2. Key concept or objective stated in papers.	47
Table 3.3. Categorisation of measures identified in the case-studies.	50
Table 3.4. Impact evaluation methodologies regarding Method, Discretisation and Typology.	53
Table 3.5. Occurrence of evaluations by KPI, for measures and for case studies, in number and share of total measures/case studies assessed by the KPI.	55
Table 5.1. Characteristics of buildings in the selected district.	83
Table 5.2. Characterisation of the retrofit scenario.	84
Table 5.3. Annual energy demand results for the baseline configuration and the retrofit configuration.	85
Table 5.4. HVAC&DHW systems options.	86
Table 5.5. PV and ESS options.	87
Table 5.6. Energy and economic results for the three main optimisation goals for all setups.	89
Table 5.7. NPV, IRR and Payback Time (PB Time) for all scenarios, taking the grid-only optimal scenario as reference.	94
Table 5.8. Setup variants considered in the analyses (D – day; N – night; CP – carport)	99
Table 7.1. Characteristics of buildings in Group A.	123
Table 7.2. Characteristics of buildings in Group B.	124
Table 7.3. Characteristics of buildings in Group C.	125
Table 7.4. Characteristics of buildings in Group D.	126

Table 7.5. Annual energy demand results. SH, SC and DHW are expressed in thermal energy / useful energy.	127
Table 7.6. HVAC&DHW systems efficiencies and costs.	129
Table 7.7. PV, Wind, ESS and STES efficiencies and costs.	130
Table 7.8. STES simulation input parameters.	131
Table 7.9. Energy and economic results for the main optimisation goals for all approaches.	133
Table 7.10. Area available and covered by PV for the studied scenarios.	136
Table 7.11. Energy and economic results for the three main optimisation goals for all setups.	140
Table 7.12. Energy and economic results in the multiple scenarios for each setup.	144
Table 7.13. Energy and economic results for the three main optimisation goals considering all technologies.	146
Table 7.14. Energy demand results from building design and operation alternatives.	148
Table 7.15. Influence of discount rate in systems sizing.	150

List of abbreviations

ACH	Air changes per hour
AL	Appliances and lighting
ASHP	Air-source heat pump
BD	Building design
BE	Building envelope
CAPEX	Capital expenditure
CHP	Combined heat and power
COP DHW	Coefficient of performance of domestic hot water system
CS	Carbon sequestration
DH	District heating
DHC	District heating and cooling
DHW	Domestic hot water
EMCS	Energy management system
EPBD	Energy Performance of Buildings Directive
EU	European Union
ES	Energy supply
EST	Energy storage
ESS	Energy storage system
FE	Final energy
GHG	Greenhouse gases
GFA	Gross floor area
HVAC	Heating, ventilation, and air conditioning
IRR	Internal return rate
KPI	Key performance indicator
LCA	Life cycle assessment
MILP	Mixed integer linear programming
NPV	Net present value
NZE	Net zero energy
NZEB	Net-zero energy buildings
nZEB	Nearly-zero energy buildings
NZED	Net-zero energy districts
nZED	Nearly-zero energy districts

NZEN	Net-zero energy neighbourhoods
nZEN	Nearly-zero energy neighbourhoods
OPEX	Operational expenditure
PEB	Positive energy buildings
PED	Positive energy district
PS	Public space
PV	Photovoltaic system
SC	Space cooling
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
SH	Space heating
SS	Self-sufficiency
T	Transport
UBEM	Urban building energy modelling
UE	Useful energy
UFA	Useful floor area
WM	Waste management
ZEN	Zero emissions neighbourhood

List of symbols

A_{PV}	Installed PV surface area (m ²)
C_{Annual}	Annual cost of a given component (€)
C_{ASHP}	Investment cost of the ASHP (€/kW)
C_b	Battery investment cost (€/kWh)
$C_{b,tot}$	Total investment cost of the battery (€)
C_{bh}	Specific investment cost per borehole (€)
$C_{bh,tot}$	Total investment cost of the borefield (€)
C_e	Investment cost of the selected thermal equipment (€/kW)
$C_{e,tot}$	Total investment cost of the selected thermal equipment (€)
C_{GSHP}	Investment cost of the GSHP equipment (€/kW)
C_i	Revenue from electricity injected into the grid (€/kWh)
$C_{i,tot}$	Total revenue from electricity injected into the grid in lifetime (€)
C_{LCC}	Life cycle cost of a given component (€)
C_{pv}	Investment cost of the selected PV technology (€/m ²)
$C_{pv,tot}$	Total investment cost of the selected PV technology (€)
C_r	Cost of electricity imported from the grid (€/kWh)
C_{retro}	Retrofit cost (€)
$C_{r,tot}$	Total cost of electricity imported from the grid in lifetime (€)
C_w	Specific investment cost per turbine (€)
$C_{w,tot}$	Total investment cost of the selected wind system (€)
d	Constant annual decarbonisation rate (%/year)
$d_{b,avg}$	Battery average degradation factor (1/year)
d_e	Thermal equipment yearly degradation factor (1/year)
DF	Discount factor
$E_{bat,cap}$	Maximum battery storage capacity (kWh)
$E_{bat,ch}(t)$	Energy used to charge the battery at time step t (kWh)
$E_{bat,dis}(t)$	Energy discharged from the battery at time step t (kWh)
$E_{bat,level}(t)$	Battery energy level at time step t (kWh)
$E_{bat,size}$	Nominal battery storage size (kWh)
$EF(y)$	Emission factor in year y (kgCO ₂ e/kWh)
EF_0	Initial emission factor (kgCO ₂ e/kWh)
$E_{f,d}^{dhw}(t)$	Final energy demand for domestic hot water at time step t (kWh)

$E_{f,d}^{\text{lapp}}(t)$	Final energy demand for lighting and appliances at time step t (kWh)
$E_{f,d}^{\text{sc}}(t)$	Final energy demand for space cooling at time step t (kWh)
$E_{f,d}^{\text{sh}}(t)$	Final energy demand for space heating at time step t (kWh)
$E_{f,d}^{\text{total}}(t)$	Total district final energy demand at time step t (kWh)
$E_{f,d}^x(t)$	District final energy demand for end-use x at time step t (kWh)
$E_i(t)$	Electricity injected into the grid at time step t (kWh)
$E_{n,d}^x(t)$	District useful energy demand for end-use x at time step t (kWh)
$E_{n,i}^x(t)$	Energy demand of building i for end-use x at time step t (kWh)
$E_{\text{pv}}(t)$	PV electric energy production at time step t (kWh)
$E_r(t)$	Electricity imported from the grid at time step t (kWh)
$E_w(t)$	Wind electric energy production at time step t (kWh)
$G_{\text{eff}}(t)$	Effective irradiance at time step t (W/m^2)
H	Borehole length (m)
$L_{\text{bat,ch}}(t)$	Losses due to battery charging at time step t (kWh)
$L_{\text{bat,dis}}(t)$	Losses due to battery discharging at time step t (kWh)
L_t	Lifetime horizon for calculation (years)
LT_w	Long-term performance correction factor
M_b	Maintenance costs of the battery (€)
M_e	Maintenance costs of the selected thermal equipment (€)
M_p	Maintenance costs of the selected PV technology (€)
M_{tot}	Total maintenance and battery replacement costs (€)
M_w	Maintenance costs of the selected wind system (€)
n_{bh}	Number of boreholes selected
n_w	Number of turbines selected
P_{ASHP}	Peak thermal power of ASHP (kW)
P_{GSHP}	Peak thermal power of GSHP (kW)
P_p^{th}	Peak thermal power (space heating, cooling, and DHW) (kW)
$Q_{\text{ASHP}}^x(t)$	Useful energy demand covered by ASHP at time step t (kWh)
$Q_{\text{charge}}(t)$	Ground forced charged energy at time step t (kWh)
$Q_{\text{GSHP}}^x(t)$	Useful energy demand covered by GSHP at time step t (kWh)
r	Real discount rate
R_b	Replacement costs of the battery (€)
$R(t)$	Solar irradiance at time step t (kWh/m^2)
SS_{lvl}	Self-sufficiency level

T	Total number of time steps
t	Time step
$T_{\text{cell}}(t)$	PV cell temperature at time step t (°C)
$v(z)$	Wind speed at hub height z (m/s)
$v(z_{\text{ref}})$	Measured wind speed at reference height z_{ref} (m/s)
W_{ext}	Ground energy extraction limits (W/m)
W_{inj}	Ground energy injection limits (W/m)
$W_{\text{profile}}(t)$	Specific power output of a single turbine at time step t (kWh)
x	Energy use
α	Hellmann exponent
γ	Temperature coefficient (1/°C)
$\eta_{\text{ASHP}}^x(t)$	Efficiency of the ASHP equipment for end use x at time step t
$\eta_{\text{GSHP}}^x(t)$	Efficiency of the GSHP equipment for end use x at time step t
η_{pv}	Efficiency of the selected PV equipment
η_x	Efficiency of the selected equipment for that use
$\eta_{x,\text{nom}}$	Nominal efficiency of the selected equipment for that use
η_{inv}	Efficiency of the inverter

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Chapter 1. Introduction

1.1 Context and motivation

The buildings sector is responsible for a significant share of the world's energy demand, representing around 24% of total final energy consumption in 2023, similar to transport (25%), above feedstocks (8%), and just below industry sector (43%) (BP, 2025). In the European Union (EU), buildings (residential and services) are responsible for 40% of final energy consumption and 36% of energy-related CO₂ emissions, being the largest consumer sector (Directive (EU) 2024/1275 (EPBD), 2024). This significant share of total energy demand represented by buildings is expected to remain important with the perspective of continuous growth of cities and urban development, with an estimated 70% share of world's population living in cities in 2050 (EC, JRC, 2019). Adding to the fact that 75% of the European built environment is inefficient and only around 1% is renewed each year, large room for improvement of building energy performance is identified (Directive (EU) 2024/1275 (EPBD), 2024).

United Nations Sustainable Development Goals include the adoption of sustainable building practices and technologies, ensure access to adequate housing, enhance inclusive and sustainable urbanisation, efficient use of resources, waste generation reduction and improving energy efficiency (UN, 2015). Achieving these goals involves upgrading housing and infrastructure to be more sustainable, promoting the use of renewable energy sources for buildings, and addressing environmental impacts associated with urbanisation.

As settled in the 2030 Climate Target Plan, the EU committed to reduce carbon emissions to at least 55% below 1990 levels until 2030, with buildings playing a significant role in the achievement of this goal (EC, 2020). The recast of the Energy Performance of Buildings Directive (EPBD) establishes that all new EU buildings should be zero-emission by 2030, and existing buildings should achieve zero-emission by 2050 (Directive (EU) 2024/1275 (EPBD), 2024). EPBD recast paves the way for different approaches to enhancing energy efficiency and sustainability in urban communities (Directive (EU) 2024/1275 (EPBD), 2024). Selected approaches primarily involve reducing overall energy demand through sufficiency measures, adopting more efficient heating and cooling systems, and integrating distributed renewable energy sources.

Concepts like Net-zero Energy Building (NZEB) and Positive Energy Building (PEB) have been explored in the last years, focusing on the balance between energy demand and renewable energy supply at building level. Transitioning from the individual building to a district-level approach, Net-zero Energy District (NZED) and Positive Energy District (PED) concepts came forward in recent

years. NZED are based on achieving net-zero energy balance on the year, i.e., on-site energy supply being equal to energy demand, by decentralised renewable energy generation. PED aims at annual positive energy balance based on energy supply surplus. PEDs play a central role in the European Strategic Energy Technology Plan, in specific with the Action 3.2 aiming at planning and deploying at least 100 cases, as a strategic instrument for accelerating the transition towards climate-neutral and sustainable European cities (JPI Urban Europe, 2020). District or neighbourhood level solutions allow to consider an integrated vision, with interventions to be applied at both building and district level and based on community strategies. The system benefits and environmental gains from highly energy efficient buildings and local production of low or zero carbon energy are connected with the idea of the result being greater than the sum of the parts (Saheb et al., 2019). In practice, this means that the potential for optimisation at cluster level is higher than the sum of building-level optimisations. District scale solutions enable the centralisation of systems traditionally implemented at building-level, such as HVAC and DHW equipment or local renewable energy production as photovoltaics, while contributing to the decentralisation of energy production at national level (Shnapp et al., 2020). This intermediate scale further enables local engagement, fostering community buy-in, active citizenship and shared responsibility in the energy transition.

1.2 Technical and economic challenges

The large-scale deployment of NZED and PED is constrained by design stage limitations regarding modelling, dimensioning and assessment of the systems. From a modelling perspective, a central challenge lies in representing the interaction of multiple energy system components and balancing energy demand and supply with profiles that are frequently not temporally aligned. Renewable energy sources such as solar and wind are variable and weather-dependent, while thermal systems, energy storage, district heating and cooling networks and electric mobility exhibit distinct operational dynamics. Capturing these interactions in a consistent framework, while ensuring physically coherent energy balances over time, remains a complex task. Simplified or fragmented modelling approaches often fail to reflect the coupled behaviour of demand, generation and storage, leading to suboptimal or hypothetically misleading design conclusions.

A further difficulty concerns system sizing under different performance objectives. Designing a district to be cost-optimal, net-zero energy, positive energy, or to achieve high levels of self-sufficiency (share of final energy covered by self-consumed renewable energy) leads to fundamentally different system configurations. In practice, there is limited methodological support to explore these trade-offs systematically, particularly when spatial constraints, technology costs

and operational strategies interact. As a result, system sizing is often driven by predefined targets or heuristics rather than by optimisation grounded in techno-economic analysis.

From an economic perspective, while assessing long-term performance is key to fully understand trade-offs between different alternatives, it introduces additional complexity. High upfront investments in PV, storage, heat pumps and infrastructure must be evaluated against future operating costs and electricity price evolution. Many existing studies either neglect full cost assessment or rely on static assumptions, making it difficult to evaluate economic feasibility, payback periods and risk exposure over the system lifetime. The lack of integrated economic analysis undermines confidence in investment decisions and limits comparability between alternative district strategies.

Beyond these modelling challenges, NZED and PED must be understood as socio-technical systems embedded within regulatory, financial and institutional frameworks. While governance and policy conditions strongly influence feasibility, they also can be updated to better accommodate these solutions, if technical barriers are surpassed and cost effectiveness is proven.

These challenges motivate the development of the methodological framework proposed in this thesis. By integrating detailed energy modelling with long-term economic assessment and explicitly allowing alternative design objectives and multiple constraints, the methodology provides a structured means to dimension district-scale energy systems in a transparent, comparable and decision-oriented manner. This approach directly supports the research objectives and questions addressed in the following sections.

1.3 Research objectives and questions

The transition towards carbon neutral cities requires methodological frameworks capable of evaluating energy systems at scales beyond the individual building. Significant knowledge gaps remain regarding their technical feasibility, economic performance and integration within real urban contexts. This thesis addresses these gaps by pursuing a set of overarching research objectives, which are examined through a structured set of specific research questions.

1.3.1 Research objectives

The main objective of this thesis is to develop and apply a modelling framework for the cost-efficient design and assessment of Net-zero and Positive Energy Districts, supporting informed decision-making at the district-scale.

To achieve this main objective, the thesis pursues the following specific objectives:

- Develop a conceptual and methodological framework capable of analysing district-scale energy systems with consistent definitions and performance criteria for NZED and PED.
- Build a dynamic techno-economic optimisation model integrating multi-energy systems, energy storage, electric vehicle charging and alternative demand scenarios.
- Evaluate energy performance and economic outcomes of district energy designs under different energy goals, ranging from cost-optimal solutions to NZED and high self-sufficiency (SS) targets.
- Compare district and building-level approaches based on energy balances, renewable energy integration and system costs.
- Quantify the impacts of demand reduction measures, technology efficiencies and costs, storage options and spatial constraints on district energy systems design.
- Assess the applicability and benefits of district-level coordination in real European contexts and specifically for Portuguese urban districts.

These objectives define the scope and methodological ambition of the thesis.

1.3.2 Primary research questions

The research objectives are addressed through the following primary research questions:

1. How to develop a framework that can perform integrated techno-economic analysis, combining operational energy modelling with full investment and life-cycle cost perspectives?
2. Can the district-level approach offer measurable advantages over traditional building-level planning in terms of energy performance, renewable energy integration and system efficiency?
3. Are Net-zero Energy Districts (NZED) and Positive Energy Districts (PED) technically and economically feasible under realistic market, climatic and spatial conditions?

These questions frame the core scientific contribution of the thesis.

1.3.3 Secondary research questions

To further investigate the underlying mechanisms and design trade-offs associated with NZED and PED implementation, the following secondary research questions are explored:

- a) How can NZED and PED be achieved through current design practices?

- b) How do energy demand reduction measures, equipment efficiencies and technology costs influence the feasibility and optimal configuration of NZED and PED solutions?
- c) How do varying self-sufficiency (SS) levels relate to NZED and PED status, and what trade-offs arise between autonomy, cost and renewable energy use?
- d) What are the comparative contributions of electrical and thermal energy storage to achieving NZED and PED targets, and how do they affect system cost and flexibility?
- e) To what extent can centralised and shared energy systems, particularly in the Portuguese context, enhance district-level performance, reduce costs and support decarbonisation?

1.4 Thesis structure

The thesis is organised into eight chapters, each contributing to a comprehensive examination of Net-zero and Positive Energy Districts.

Chapter 1 introduces the context and motivation for adopting district-level approaches in urban energy transitions, outlines the research gaps, and presents the research questions and goals guiding the work.

Chapter 2 and Chapter 3 describe distinct analyses based on two separate systematic literature reviews. Chapter 2 reviews current approaches and solutions used to design NZED and PED. Inconsistencies found in literature justified a clarification of concepts used to define approaches. The examination of the technological and methodological practices adopted to date revealed limitations and opportunities for improving district-level design frameworks. Chapter 3 presents a meta-analysis of European district-level case studies, classifying the implemented measures, assessing their impacts on energy, carbon and cost indicators, and identifying recurring patterns and areas where current practice remains limited.

Chapter 4 and Chapter 5 present the modelling framework and demonstrate its application to a theoretical case study, respectively. Chapter 4 develops the methodological core of the thesis, introducing an optimisation model for the economic-efficient design of NZED and PED. This chapter describes the mathematical formulation, data structure and evaluation criteria that support the subsequent analyses. Chapter 5 applies the model to a small-scale district, allowing controlled investigation of system behaviour, renewable integration, storage needs and economic outcomes under varying assumptions and targets. A sensitivity analysis focuses on costs variation and pinpoints the direct impact of profile aggregation at district-level. The chapter closes with an analysis on how electric vehicles charging and photovoltaic deployment influence the feasibility of NZED, PED and high self-sufficiency scenarios.

Chapter 6 describes the expanded version of the optimisation model, to incorporate a larger set of technologies, operation functions and performance indicators. While the model expansion preserves the original methodological structure, the new elements enable the evaluation of the integration of air and ground source heat pump systems, electric and thermal storage, and PV and wind energy supply. Chapter 7 assesses the application of the expanded model to a large and real case study, projected at district scale to combine heat pump technology with PV and electrical and thermal energy storage. The performance of different system configurations under realistic spatial and techno-economic constraints emphasise the potential of system centralisation, seasonal thermal energy storage and wind integration to target ambitious energy goals.

Chapter 8 synthesises the main findings of the thesis and respective implications for research, policy and practice, outlines the limitations of the work and proposes avenues for future research.

1.5 Publications related to this thesis

Parts of the work developed within this thesis have been published or submitted to peer-reviewed journals and international conferences.

The content of Chapters 2 and 3 is largely based on journal publications. The paper *“Designing carbon neutral, net-zero, nearly-zero and positive energy districts or neighbourhoods: current approaches and solutions”*, published in *Advances in Building Energy Research* (Cardoso et al., 2024), includes most of the content presented in Chapter 2. The paper *“Meta-analysis of district-level solutions towards energy, carbon and economic targets”*, published in *Energy and Buildings* (Cardoso et al., 2025), includes most of the analysis addressed in Chapter 3.

The content of Chapter 4 and Chapter 5 forms the basis of a manuscript submitted to the journal *Energy*, which was under peer review at the time of the submission of the thesis.

The analysis presented in the section 5.6 was accepted for presentation and publication as a conference paper at the *International Conference on Energy Economics and Energy Policy (ICEEEP)*, to be held in April 2026.

Chapter 2. Literature review: current approaches

This chapter is based on the peer-reviewed journal article “Designing carbon neutral, net-zero, nearly-zero and positive energy districts or neighbourhoods: current approaches and solutions” published in Advances in Building Energy Research (Cardoso et al., 2024). Section 1.1 of the original article is not included in this chapter, as its content is addressed in Chapter 1 of the present thesis. Minor editorial revisions were applied to ensure consistency across the thesis and to reflect the subsequent evolution of the research.

2.1 Energy-related concepts at district or neighbourhood level

A great variety of concepts is used throughout literature, with cases presenting different nomenclatures to similar meanings, or the same nomenclature used to describe cases with multiple minor scope variations. Some of the concepts vary on the threshold at which the energy balance must be achieved (Lindholm et al., 2021).

These neighbourhood/district-level concepts evolve from building-level concepts as Nearly-zero Energy Buildings (nZEB), Net-zero Energy Buildings (NZEB), Positive Energy Buildings (PEB), among other, as analogous concepts applied exclusively at building scale, aiming at energy demand reduction and management, and offsetting it with local energy supply. The district level allows to consider an integrated vision, with solutions to be applied based on community level plans, e.g., refurbishment of buildings, integrated renewable energy solutions (both electric and thermal), shared heating and cooling solutions, and public spaces and mobility.

Although a more thorough analysis on the most common concepts is presented in the next section, some of the concepts deemed as most important for the present study are:

- Net-zero Energy District (NZED), or Net-zero Energy Neighbourhood (NZEN), or Net-zero Energy (NZE) community: aims at obtaining a neutral balance, in a certain time-period, between energy demand and supply. I.e., the amount of energy consumed by the urban area is virtually the same as the energy the community is able to produce, be it directed to self-consumption, or supplied to the electric network to offset other imports.
- Nearly-zero Energy District (nZED) or Nearly-zero Energy Neighbourhood (nZEN): evolves from the Nearly-zero Energy Building (nZEB) concept, defined as “a building that has a very high energy performance (...) nearly zero or very low amount of energy should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produces on-site or nearby”

(Directive 2010/31/EU (EPBD), 2010). This concept evolved to be applied at neighbourhood/district level, considering that nZED is not merely the sum of nZEBs but reaching further to an aggregated energy management and including other elements, e.g. public spaces and mobility (Amaral et al., 2018).

- Positive Energy District (PED): “energy-efficient and energy-flexible urban areas or groups of connected buildings which (...) actively manage an annual local or regional surplus production of renewable energy” (JPI Urban Europe, 2020).
- Self-Sufficient District: the entirety of the operational electricity and heating/cooling demands are covered by renewable energy generated inside defined boundaries of the district (Laitinen et al., 2021).
- Zero Emission Neighbourhood (ZEN): expansion to the neighbourhood/district level of the concept of zero emission building (ZEB). This is defined as aiming to reduce and compensate its direct and indirect greenhouse gas (GHG) emissions towards zero over the analysis period (FME ZEN, 2022).

The variety of terms and expressions used to define energy or carbon emissions-related initiatives on clusters of buildings is extremely large, with “zero”, “low”, “net zero”, “nearly zero”, “positive” or “plus”, and the identification of the cluster as “district”, “neighbourhood”, “block” or “community” as the most frequent ones. Brozovsky et al. (2021) opted by naming the overall group of concepts as “climate friendly neighbourhoods” (CFN) (Brozovsky et al., 2021). Being the focus of the present study energy-related aspects of neighbourhood/district initiatives, examples based on concepts of NZEN/NZED, nZEN/nZED and PED were prioritised. Other examples, based on different concepts as ZEN or Self-sufficient District, were also examined in situations in which energy was also the main subject of study.

2.2 Review of academic studies and real case applications

Initiatives from both practitioners and academics of neighbourhood or district-level work are deemed important references to assess the current vision and state of the art. This includes the approaches regarding selection and combination of technical solutions, methodologies and tools to evaluate different options on multiple scenarios, implementation practices (Koutra et al., 2018).

There are multiple studies based on theoretical cases (i.e., designed but not built), covering the different concepts, e.g., nZEN (Nematchoua, Nishimwe, et al., 2021; Sougkakis et al., 2020; Sugár et al., 2020), NZED/NZEN (Becchio et al., 2018; Hachem-Vermette et al., 2019; Mittal et al., 2019; Natanian & Auer, 2020) and PED (Gouveia et al., 2021; Rehman et al., 2019; Sougkakis et al., 2020). Becchio et al. (2018) present an evaluation framework for alternative solutions for a NZED

in Turin, which included four strategies with varying retrofit alternatives for the building envelope, a district heating system, and multiple solutions on thermal and electrical energy supply (e.g., cogeneration, biomass, or PV) (Becchio et al., 2018). A study on strategies for converting an existing neighbourhood into net zero energy was performed in Valongo, Portugal, including three levels of energy efficiency (low, medium and high), retrofit solutions, and offset generation alternatives, which included building integrated photovoltaic, off-site large-scale photovoltaic, off-site large-scale wind turbines (Leal et al., 2015). Another example of a methodology for retrofitting existing districts was studied in Spain, based on District Sustainability Indicators, with four steps: district audit, energy conservation and optimisation measures evaluation, implementation of solution and measurement of savings (García-Fuentes et al., 2014).

At the level of the energy supply for NZEDs, studies compare different solutions, in some cases supported on a case study application, e.g., comparison between solar thermal, PV and hybrid systems (PV and thermal) (Good et al., 2015), analysis on hybrid renewable energy system with solar district heating (Kim et al., 2019) or different solar PV adoption (Mittal et al., 2019). He et al. (2021) included a solution with hydrogen. Developed within the MAKING-CITY project, a PED methodology was developed to improve replicability, considering needs, resources availability, and solutions (Alpagut et al., 2019; Gabaldón Moreno et al., 2021). PED recent development in Europe is also presented by Lindholm et al. (2021) and by the European Commission (EC, JRC, 2020).

Examples of real case application studies include nZEN/nZED (Aste et al., 2020), NZED/NZEN/Net Zero Energy Community (Kim et al., 2019; Sameti & Haghighat, 2018), Self-sufficient district (Laitinen et al., 2021) and PED (Bisello, 2020; Erba & Pagliano, 2021). Zero Emission Neighbourhood (ZEN) concept presents significant examples of real application, namely the FME ZEN Pilot Projects, e.g., Ydalir, Elverum (Lausset et al., 2021) and Evenstad (Pinel, 2020; Pinel et al., 2021), both in Norway.

EU energy and climate 2020 targets triggered several initiatives throughout Europe, with municipalities setting ambitious targets to reduce their energy demand and to increase the share of their energy supply from local renewable energy sources (Saheb et al., 2019). There are many examples, presented in the JRC Technical Report “From nearly-zero energy buildings to net-zero energy districts” (Saheb et al., 2019), of frontrunner municipalities in Europe with relevant achievements on addressing energy transition, including actions directed to both new and existing districts. The case studies focused mostly on assessing energy demand reduction, including renovation of existing buildings and new buildings, and supply with renewable energy generation (Saheb et al., 2019). The review of seven selected case studies demonstrated the potential of the zero-energy approach at local level. However, the challenge to scale up and normalise those

initiatives was highlighted in the lack of consistent terminology and targets, insufficient resident engagement and difficulties in investor confidence (Saheb et al., 2019).

Moreover, in the United States of America, National Renewable Energy Laboratory (NREL) report on NZED planning presents a variety of projects, representative of multiple building aggregation with the goal of achieving energy efficiency optimisation, and integration of district thermal energy and on-site renewable energy generation to offset energy use at district-scale (Pless et al., 2018). The diversity of case studies covers new and existing communities, different geographic locations, size and types of buildings. Some of the challenges identified in the study were related to difficulties in finding analysis tools for scaling zero energy solutions from individual buildings to the district and quantifying zero energy district benefits. Although the technologies exist, strategies to achieve best scenarios are still unclear. This is magnified by the resistance to setting zero energy goals and dealing with complex finance and governance structures (Pless et al., 2018). Through the project Net Zero Labs, NREL facilities are expected to be net-zero in a commitment to demonstrate and lead a path forward for other organisations, with one of the living laboratories, the “Flatirons Campus”, already achieving this status.

Previous literature review work presents important insights about this subject. Brozovsky et al. (2021) include review on ZEN, PED and other concepts related case studies, with an extended compilation of study typology, location or used methodologies. In Koutra et al. (2018), the author explores several approaches on sustainable and net-zero energy districts, presenting an overview of the existing assessment tools and methods comparing criteria and parameters. That overview covers different approaches from city, district and building level and based on the development of software, methodology, certification and tools (Koutra et al., 2018). In a similar way, Amaral et al. (2018) describe several initiatives on NZED projects with important inputs on energy performance calculation and metrics, and methodologies and tools already developed on this subject. PED examples are covered on their spatial, technological, economic, environmental and social (Derkenbaeva et al., 2022). Thus, large scope literature reviews on these concepts at district and neighbourhood level already exist and were published in recent years. However, from the authors’ perspective, there was still a need for a deeper analysis on what regards the design characteristics, practices, tools and performance results. This requires more information, and thus focusing on the few cases for which such information is available. In the other hand, the goal of encompassing examples of all the main studied concepts (i.e., nearly-zero, zero or positive energy and carbon balance) was kept. The present work is thus expected to take a step further from the referred analyses and address the identified gaps, by characterising a selected group of examples, presenting complete information on respective design practices, quantified energy demand and energy supply characterisation.

2.3 Methodology followed for the systematic review

This section described the methodology adopted for the systematic review conducted to assess the current development of approaches adopted to achieve nearly zero, net zero, positive energy or carbon neutral emissions status at neighbourhood/district level. This was supported by a systematic analysis of energy efficiency and decarbonisation initiatives at district-level to enable the identification and characterisation of design practices and technical solutions. The specific scope of this review can be summarised as:

- Clarify and systematise concepts used in literature, considering the goal stated in the papers. This is followed by the interpretation of results, discussion and proposals to uniformise these concepts.
- Characterise technical solutions being considered and chosen in nZEN/nZED, NZEN/NZED, PED, ZEN projects to date, as result of the analyses of selected case studies.
- Characterise design practices being used in nZEN/nZED, NZEN/NZED, PED, ZEN projects. This includes how design alternatives are identified/developed; how they are characterised; what criteria are adopted to choose; and the evaluation methodologies and tools used in the various case studies.

Focusing on the scope of this literature review, a set of guiding questions were defined as follows:

- Are the concepts nearly standardised / are expressions used to refer to the same concept?
- In case a large variability of language and concepts in literature is confirmed, is systematisation possible?
- What is the range of approaches seen in the design of nZEN/nZED, NZEN/NZED, PED, ZEN projects?
- Can patterns of energy demand intensity and technical solutions be identified across different concepts?
- Do current procedures in the design practices and procedures ensure that nZEN/nZED, NZEN/NZED, PED, ZEN performance is achieved in an economically efficient way, or is there room to improve this insurance?

The methodology was based on a literature review focused on identifying and collecting scientific peer-reviewed papers describing case studies aiming at reduced carbon emissions, reduced energy demand and/or increased energy efficiency, at district-level. The reviewed case studies include real cases with actual implementation and theoretical studies developed on real cases. Figure 2.1 shows the flow chart of the methodology followed by the authors to identify the case studies for the analysis.

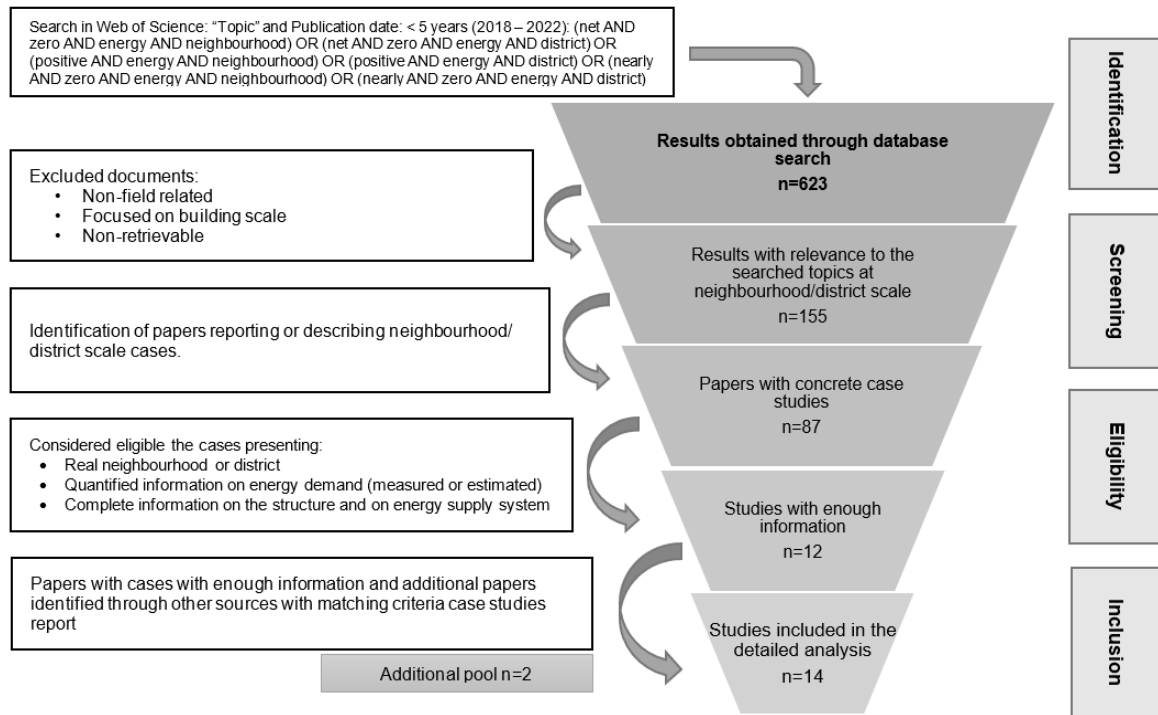


Figure 2.1. Flow chart of the methodology followed to identify case studies for analysis.

The use of terms commonly related to the concepts in study allowed to identify a significant number of papers, through Web of Science database. Some of the review papers referred in Introduction as inspiration to the development of this work, Amaral et al. (2018) and Koutra et al. (2018), were published in 2018, which encouraged the selection of a 5-year publication window, covering more recent works. Also, Topic filter, which includes the search in title, abstract and keywords, was selected in detriment to complete text filters. Even though this filter selection aimed to reduce the probability of retrieving completely subject-unrelated papers, a significant number of suggested papers were still non-relevant. The authors opted for separately searching for the following expressions: "net zero energy neighbourhood"; "net zero energy district"; "positive energy neighbourhood"; "positive energy district"; "nearly zero energy neighbourhood"; "nearly zero energy district". The search was performed by not restricting the order of the terms in each expression. A similar search with that restriction would not identify most of the case studies that are included in the final list in analysis, with exception of one case study: Aste et al. (2020). This is due to: 1) the significant number of concepts used in literature describing case studies that differ from the terms used (Brozovsky et al., 2021); 2) the fact that these concepts are frequently not referred in its complete form in the abstract or keywords; and 3) deficit in uniformisation of the concepts nomenclature in analysis, i.e., same nomenclature refers to different concepts and vice-versa. For these reasons, the search included the referred variability of terms. The six separated searches present the same results as a single search with the following phrase: (net AND zero AND

energy AND neighbourhood) OR (net AND zero AND energy AND district) OR (positive AND energy AND neighbourhood) OR (positive AND energy AND district) OR (nearly AND zero AND energy AND neighbourhood) OR (nearly AND zero AND energy AND district), however, by developing the search separately, an analysis of the results obtained by group of terms is possible.

The search on the referred terms resulted in a list of 623 publications, with a significant number of those being unrelated to the topic under analysis, i.e., describing works on other scientific fields that use similar wording. After a screening process, in which non-field related results, non-retrievable documents and topic related papers focusing on the building scale were excluded, a number of 155 results was achieved. The exclusion of building scale studies is justified by the intention to limit the analysis to an integrated district-level approach. The resulting / “filter passing” papers were individually analysed and characterised in terms of objective, purpose or aim, with a list of papers being selected for next stage when presenting case study report of neighbourhood level examples. In this step, the excluded papers would include review papers and documents describing methodologies, models or practices without referring to a specific case study. A group of 87 documents including a concrete case study was identified. The resulting list of papers that met these criteria is presented in Annex A (Table A.1). Using a systematic analysis, a final list of 12 very complete case studies in terms of characterisation of conditions to achieve the proposed energy status was obtained. The criteria used to select the 12 papers were, cumulatively: 1) only real districts /neighbourhoods were considered, regardless of whether the study was related to a real implementation case or theoretical study; 2) the intervention was mainly energy performance oriented; and 3) the characterisation of the cases was considered complete. The case studies were defined as complete when presenting indispensable information for the goal of the study, namely: 1) the description of district/neighbourhood structure, i.e., number of buildings, use(s) (residential and/or services) and areas; 2) a clear quantification of energy demand by use of the final/improved district, in total value or per area; and 3) a detailed description of energy supply systems, and respective energy production performance. Two additional case studies obtained from other sources were added for analysis to the resulting list of 14 case-studies, matching the same criteria. These two additional papers were added because both present complete information on relevant case studies (Lausset et al., 2019; Mavrigiannaki et al., 2021). Lausset et al. (2019) reports to the Zero Village Bergen a relevant Zero Emission Neighbourhood project in Norway and Mavrigiannaki et al. (2021) reports to an Italian pilot of Zero Energy Neighbourhood. The complete list of final case studies is presented in the following section.

2.4 Results and discussion

2.4.1 Search results analysis

As commented, opting by performing the literature search divided in six different combinations of terms allows to analyse the results separately, which is presented in Figure 2.2. The figure shows the share of field related papers relative to the total number of papers retrieved for each search, and those divided by three categories, namely papers with case studies to consider in this work, review papers, and other papers describing methodologies, models and other studies related to the subject. These results include repeated papers in the various searches, with a total number of 221 field related papers identified, which, excluding repeated results, accounted for the 155 examples stated in the second level in the flow chart of the methodology in Figure 2.1.

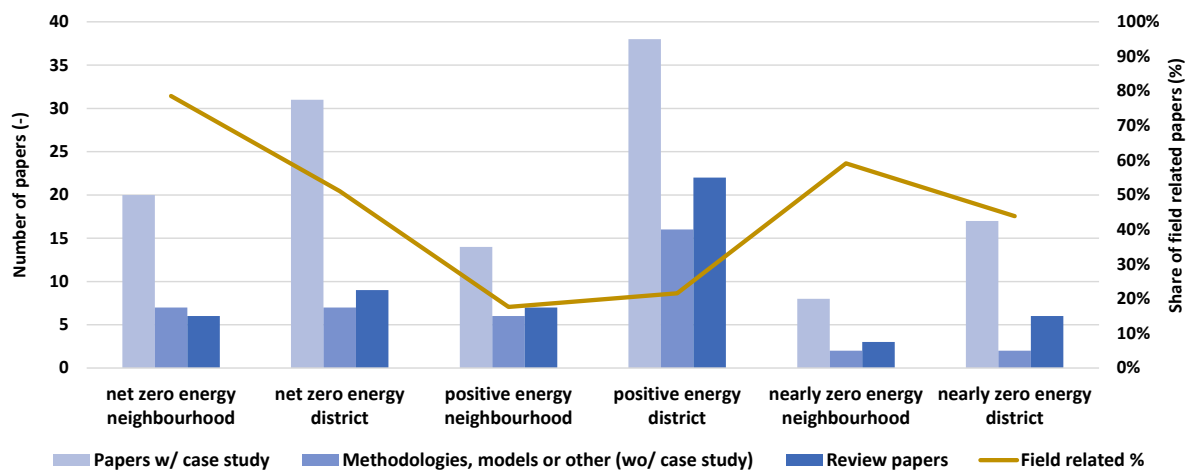


Figure 2.2. Number of search results per type of study, for each of the six sets of keywords, and respective share of field related papers relative to the total number of papers retrieved.

“Positive energy district” obtained more results, both for total results and field related results in absolute number. However, the low percentage of field related papers resulted in a significant number of results discarded by not being relevant to the subject in analysis, and an increased screening effort. On the contrary, the search for “net zero energy neighbourhood” terms resulted in the higher percentage of papers about the field in question and a significant amount in total result. The papers with case studies were the focus of the present work, accounting to 128 papers, which after filtering the repeated ones, allowed to achieve a group of 87 examples, distributed by the six combinations of terms.

An analysis on the energy/emissions-related expressions of objective/concept, as they were stated in the 87 case study papers, is presented in Figure 2.3. For each paper, one expression was selected, considering the definition given by the authors, which in multiple cases was not correlated

to the searched expression. For graphical representation, the expressions represented with only one case study were added together and defined as “Other”, which amounted to 17 cases. This analysis shows the large variability in the terms and expressions used to describe efficient/low energy/emissions related concepts, which validates the referred in Introduction. As commented, this variability exists for a number of reasons, and can be related to the energy/emissions balance goal defined by the authors of the studies or projects (e.g., positive, net zero, zero, or nearly zero energy/emissions), or by the physical elements considered, i.e., number of buildings or areas (district, neighbourhood, block, community). However, both these aspects are also subject to interpretation from the authors or regional definitions, i.e., there is a difficulty associated to the uniformisation of what is considered zero, net zero or nearly zero energy, or even the dimension of a district vs. a neighbourhood, just to highlight some examples.

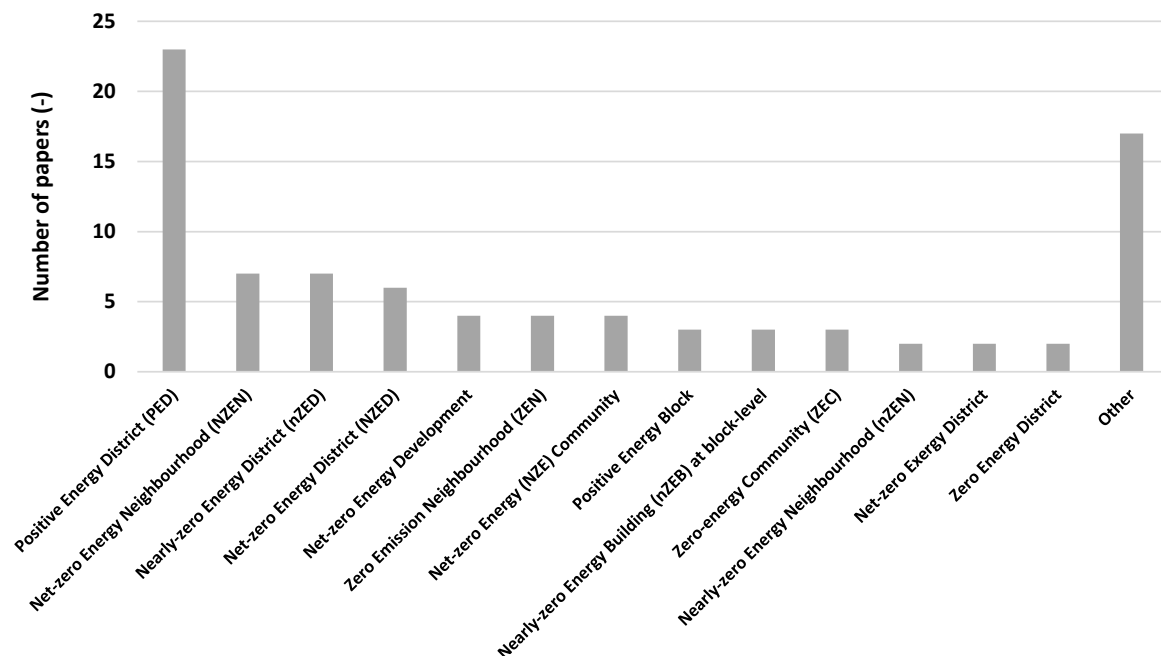


Figure 2.3. Distribution of energy-related concepts stated as objective or subject of study.

The expression “positive energy neighbourhood”, selected for one of the six searches, was not used in any of the case studies. For the “positive energy” scenario, the most common expression is clearly PED, followed by Positive Energy Block. Some of the expressions refer to “building”, however all of those cases were related to block-level approach, otherwise, they would be discarded in previous stages of the review. For the selection of the final list of case studies, the expression/concept used was not a factor of exclusion.

2.4.2 Proposal for the standardisation of concepts

Based on the literature review and the presented results, a proposition of definitions and nomenclature is presented in Table 2.1 and Table 2.2. The review showed that some aspects can be directly standardised, e.g., the nomenclature used to define a cluster of buildings, between “district”, “neighbourhood” or “block”, as long as the terms used are consensual in relation to the scope of elements they define, i.e., number and size of buildings, transport, and public areas. Also, the definition of the energy balance can be differentiated between “nearly zero”, “net zero” and “positive”, preventing the use of variations, as “near zero” or “plus”, or even hyphenations, as used in “net-zero”, as long as it refers to annual energy balance. To this set of definitions, the term “self-sufficient” is added to describe sustainable cases based on off-grid scenarios. Concepts based on carbon emissions related objectives would require a similar agreement.

In this way, a suggestion of a mapping of concepts is achieved, in order to contribute to the clarification of this subject.

Table 2.1. Proposed nomenclature for energy or emissions efficiency concepts.

Alternatives Currently Used	Proposed Nomenclature	Definition
Nearly-zero energy	Nearly-zero energy	Near zero energy balance in a specific period, usually one year, with low energy demand to be covered to a significant extent by energy supply produced locally from renewable sources, directed to self-consumption or supplied to the electric network to offset other imports.
Near-zero energy		
Low energy		
Net-zero energy	Net-zero energy	Neutral energy balance in a specific period, usually one year, with low energy demand to be covered by energy supply produced locally from renewable sources, directed to self-consumption or supplied to the electric network to offset other imports.
Zero energy		
Positive energy	Positive energy	Positive energy balance in a specific period, usually one year, between low energy demand and surplus energy supply produced locally from renewable sources, directed to self-consumption or supplied to the electric network to offset other imports.
Plus energy		
Self-sufficient	Self-sufficient	Electric and thermal energy demand is entirely covered by renewable energy generated inside the boundaries of the district or neighbourhood.
Zero energy		
Carbon neutral	Zero emission	Direct and indirect greenhouse gas emissions are reduced and locally compensated towards zero balance over a specific period, usually one year.
Zero carbon emissions		
Eco		

Table 2.2. Proposed nomenclature for the coverage of the concepts.

Proposed Nomenclature	Definition
District	Administrative area within a county.
Neighbourhood	Cluster of buildings located near each other. Typically includes service and/or residential buildings, possibly including also small public areas.
Block	Cluster of attached buildings limited by streets

Table 2.1 excludes terms not referring energy or emissions determined goals, as “smart”, “smart urban”, “energy balance”, or “zero-waste”, and Table 2.2 excludes terms without specific definition regarding typology of buildings or area coverage, as “community”, “development”, “settlement”, or “system”.

There must highlighted that, despite the suggested nomenclature, this thesis generally followed the current terminologies most commonly used to address these concepts, as illustrated in Figure 2.3.

2.4.3 Selected case studies

Following the described methodology, the papers with case studies were individually analysed, resulting in 12 examples to which two more case studies were added. This final list of the selected case studies is presented in Table 2.3.

Table 2.3. List of the selected case studies.

ID	Author of Publication	Title of Publication
1	(Volpe et al., 2022)	Optimal design and operation of distributed electrical generation for Italian positive energy districts with biomass district heating
2	(Neumann et al., 2021)	Analysis and evaluation of the feasibility of Positive Energy Districts in selected urban typologies in Vienna using a bottom-up district energy modelling approach
3	(Erba & Pagliano, 2021)	Combining sufficiency, efficiency and flexibility to achieve Positive Energy Districts targets
4	(Janzadeh & Zandieh, 2021)	Design feasibility of a net-zero energy neighborhood in Qazvin
5	(Kim et al., 2019)	Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community
6	(Mavrigiannaki et al., 2021)	Zero energy concept at neighborhood level: A case study analysis.
7	(Laitinen et al., 2021)	A techno-economic analysis of an optimal self-sufficient district
8	(Huang et al., 2019)	Transforming a residential building cluster into electricity prosumers in Sweden: Optimal design of a coupled PV-heat pump-thermal storage-electric vehicle system
9	(Pinel et al., 2021)	Impact of the CO ₂ factor of electricity and the external CO ₂ compensation price on zero emission neighborhoods' energy system design
10	(Lausset et al., 2021)	LCA and scenario analysis of a Norwegian net-zero GHG emission neighbourhood: The importance of mobility and surplus energy from PV technologies
11	(Lausset et al., 2019)	LCA modelling for Zero Emission Neighbourhoods in early stage planning
12	(He et al., 2021)	Transformation towards a carbon-neutral residential community with hydrogen economy and advanced energy management strategies
13	(Ascione et al., 2021b)	Knowledge and energy retrofitting of neighborhoods and districts. A comprehensive approach coupling geographical information systems, building simulations and optimization engines
14	(Aste et al., 2020)	A renewable energy scenario for a new low carbon settlement in northern Italy: Biomass district heating coupled with heat pump and solar photovoltaic system

A general characterisation of the selected case studies is presented in Table 2.4, including location, the project scale and the concept used in the publication. The scale of the project was divided by buildings floor area (small scale: $a < 10\,000\text{ m}^2$; medium scale: $10\,000\text{ m}^2 < a < 100\,000\text{ m}^2$; large scale: $a > 100\,000\text{ m}^2$).

Table 2.4. General characterisation of the case studies.

ID	Author of Publication	Location	Project Scale	Concept
1	(Volpe et al., 2022)	Sicily, Italy	Small	PED
2	(Neumann et al., 2021)	Vienna, Austria	Medium	PED
3	(Erba & Pagliano, 2021)	Milan, Italy	Small	PED
4	(Janzadeh & Zandieh, 2021)	Qazvin, Iran	Small	NZEN
5	(Kim et al., 2019)	Jincheon, South Korea	Medium	Net-zero Energy (NZE) Community
6	(Mavrigiannaki et al., 2021)	Emilia-Romagna, Italy	Small	Zero Energy Neighbourhood
7	(Laitinen et al., 2021)	Helsinki, Finland	Large	Self-Sufficient District
8	(Huang et al., 2019)	Ludvika, Sweden	Small	Electricity Prosumers Building Cluster
9	(Pinel et al., 2021)	Evenstad, Norway	Small	ZEN
10	(Laussetlet et al., 2021)	Elverum, Norway	Large	ZEN
11	(Laussetlet et al., 2019)	Bergen, Norway	Medium	ZEN
12	(He et al., 2021)	San Francisco, USA	Medium	Carbon-neutral Residential Community
13	(Ascione et al., 2021b)	Naples, Italy	Medium	nZED
14	(Aste et al., 2020)	Milan, Italy	Medium	nZED

The majority of the case studies are European, namely in Italy (5), Norway (3), Austria (1), Finland (1) and Sweden (1) Two examples are located in Asia, in Iran and South Korea, and another one in America, specifically in the USA. According to the defined scale, the scale of most of the projects was small and medium. The most common concepts were PED and ZEN. Three examples

of “net zero” or “zero” energy community or neighbourhood were also selected. Some variations were also represented, e.g., “Self-Sufficient District”, “Electricity Prosumers Building Cluster” or “Carbon Neutral Residential Community”. The list also includes two examples of nZED.

2.4.4 Technical solutions adopted

The main technical features of the case studies are presented, in the following tables, divided by three main categories. The first one includes only examples of Positive Energy District (PED). The second category includes Net-zero Energy District (NZED), Net-zero Energy Community, Zero Energy Neighbourhood, Energy Self-Sufficient District, and zero carbon examples, e.g., Zero Emission Neighbourhood (ZEN) and Carbon Neutral Community. The third category compiles examples of Nearly-zero Energy District (nZED).

This analysis included the identification of the typology of intervention, e.g. new construction or refurbishment, and the district structure, with details on the number of buildings or constructive elements and respective floor areas. Energy-related details were summarised, including the characterisation and quantification of energy demand, characterisation of energy supply, energy storage, energy management and control systems (EMCS) and mobility energy-related details. Energy demand description was focused on the energy needs of the district, when possible divided between space heating (SH), space cooling (SC) and domestic hot water (DHW) thermal energy, electric energy for lighting, appliances and other needs, and mobility. Energy demand details were divided by the elements of the structure, i.e., residential and non-residential buildings, when possible. Based on the information displayed in the papers, useful energy (UE) and/or final energy (FE) was presented. Annual energy demand values were presented by area. For the examples presenting total annual values, the demand per area was calculated. These values are identified in the tables as “calculated”. When several design versions were considered, the characteristics presented refer to the one that was actually selected/adopted.

Table 2.5 presents a summary of the main technical features of the PED case studies.

Table 2.5. Main technical features of the PED case studies.

Author / Project	District / Neighbourhood structure	Energy Demand				Energy Supply		Energy Storage	EMCS	Mobility
		Space Heating	Space Cooling	DHW	Electric Energy (lighting, appliances, etc.)	Heating / Cooling and DHW	Electricity			
ID: 1 (Volpe et al., 2022) Refurbishment Sicily, Italy	17 residential buildings: 10 433 m ² 3 commercial buildings: 1 426 m ²	SH and DHW UE: 37.1 kWh _{th} /m ² /yr (calculated)			Electricity UE: 31.6 kWh _{el} /m ² /yr (calculated)	Biomass boiler district heating network	PV and Electric grid	Biomass storage associated to the DH network (seasonal) Thermal storage water tank (daily)	N/D	N/A
ID: 2 (Neumann et al., 2021) Refurbishment Vienna, Austria	154 units of residential detached housing: 23 760 m ²	Total FE: 60.9 kWh/m ² y				Solar thermal collectors: 0.384 GWh/yr Heat Pump District heating network	PV: 1 054 GWh/yr Electric network	Excess heat to be locally stored and/or fed in a district heat network for seasonal compensation	N/D	N/A
		SH FE: 30.6 kWh/m ² /yr	SC FE: 1.2 kWh/m ² /yr	DHW FE: 12.8 kWh/m ² /yr	Appliances: 10.9 kWh/m ² /yr Lighting: 1.8 kWh/m ² /yr Cooking: 3.6 kWh/m ² /yr All FE					
ID: 3 (Erba & Pagliano, 2021) Refurbishment Milan, Italy	2 residential buildings: 4 633 m ²	Scenario B SH UE: 16.6 kWh _{th} /m ² /yr SH FE: 6.1 kWh _{el} /m ² /yr	Scenario B SC UE: 7.0 kWh _{th} /m ² /yr SC FE: 2.6 kWh _{el} /m ² /yr	Scenario B DHW UE: 12.0 kWh _{th} /m ² /yr DHW FE: 4.4 kWh _{el} /m ² /yr	Scenario B Electricity use (appliances, lighting, ICT, etc.) FE: 17.0 kWh/m ² /yr Cooking FE: 3.3 kWh/m ² /yr Ceiling fans FE: 0.2 kWh/m ² /yr Elevators FE: 1.8 kWh/m ² /yr Lighting in common areas FE: 0.6 kWh/m ² /yr Mechanical ventilation FE: 3.6 kWh/m ² /yr	Scenario B Heat pump (92 kW)	Scenario B PV in rooftop and façades: 215 kWh/m ² /yr	No	N/D	Electric vehicles and public transport Private car: 8.8 kWh/m ² /yr Public transport: 5.0 kWh/m ² /yr

The selected PED case studies are fairly comparable examples of refurbishment of districts, with total final energy demand values of 71,5 kWh/m²/yr (Volpe et al., 2022), 60,9 kWh/m²/yr (Neumann et al., 2021), and 39,6 kWh/m²/yr (Erba & Pagliano, 2021). These values were obtained by using the value presented by the authors or calculated by adding the different energy needs values. When only useful energy was presented, final energy was estimated based on equipment/systems efficiencies retrieved from the papers. In Annex A (Table A.2), conversion results and used information are described.

Volpe et al. (2022) present a value of final energy demand of 39,9 kWh/m²/yr in order to cover SH and DHW needs, by means of a biomass boiler-based district heating network, and an electric energy demand of 31,6 kWh/m²/yr, supplied by photovoltaic (PV) production and electrical grid, therefore, amounting to 71,5 kWh/m²/yr of total final energy demand. Neumann et al. (2021) present final energy demand of 60,9 kWh/m²/yr, including SH, SC, DHW, electric appliances, lighting and cooking. In Erba & Pagliano (2021), the final energy is 39,6 kWh/m²/yr, considering the electric final energy demand for SH, SC and DHW and other various electricity uses. For the three PED, SH and DHW final energy demand varies from 10,5 kWh/m²/yr in Erba & Pagliano (2021), to 39,9 kWh/m²/yr in Volpe et al. (2022) and to 43,4 kWh/m²/yr in Neumann et al. (2021). Volpe et al. (2022) present SH and DHW energy demand together, which means that a comparison with the other two examples is only possible by using SH and DHW thermal energy needs combined. Neumann et al. (2021) and Erba & Pagliano (2021) present a more comparable energy demand description, although the difference in the district structure from residential buildings to residential detached houses, and the difference in equipment efficiencies, may be responsible for difference in terms of energy demand values. The most significant difference is the higher SH energy demand and lower SC energy demand for Neumann et al. (2021) compared to Erba & Pagliano (2021), possibly justified by the case studies location, Vienna and Milan, respectively. Thermal energy supply of the PED case studies is based on different solutions, e.g., biomass boiler, solar thermal collectors or heat pumps, however, all of the cases included photovoltaic energy solutions for electric energy supply. Erba & Pagliano (2021) is the only example that includes mobility characterisation.

Table 2.6 presents the main technical features for the second category of case studies, composed by a significant variety of concepts representing examples aiming at zero energy or carbon emissions targets. This second category includes examples of Net-zero Energy Neighbourhood (NZEN), Net-zero Energy Community, Zero Energy Neighbourhood, Energy Self-sufficient District, Zero Emissions Neighbourhood (ZEN) and Carbon Neutral Community.

Table 2.6. Main technical features of the zero energy or zero emissions case studies.

Author / Project	District / Neighbourhood structure	Energy Demand				Energy Supply		Energy Storage	EMCS	Mobility
		Space Heating	Space Cooling	DHW	Electric Energy (lighting, appliances, etc.)	Heating / Cooling and DHW	Electricity			
ID: 4 (Janzadeh & Zandieh, 2021) Net-zero Energy Neighbourhood (NZEN) New construction Qazvin, Iran	8 two-story buildings: 5 120 m ²	SH FE: 26.6 kWh _{th} /m ² /yr (calculated)	SC FE: 5.2 kWh _{el} /m ² /yr (calculated)	DHW FE: 7.0 kWh _{th} /m ² /yr (calculated)	Lighting FE: 12.8 kWh _{el} /m ² /yr Room FE: 14.2 kWh _{el} /m ² /yr Fan FE: 1.3 kWh _{el} /m ² /yr Pumps FE: 1.3 kWh _{el} /m ² /yr (calculated)	24 solar collector units: 18 104 kWh/yr Chiller Natural gas system	PV: 230.9 kW	No	N/D	N/A
ID: 5 (Kim et al., 2019) Net-zero Energy (NZE) Community Refurbishment Jincheon, South Korea	200 residential houses 6 public buildings Total area covered of 72 000 m ² Floor area: 14 705 m ²	SH UE: 25.7 kWh/m ² /yr	SC UE: 7.9 kWh/m ² /yr	DHW UE: 12.8 kWh/m ² /yr	Plug FE: 18.6 kWh/m ² /yr	Proposed scenario: Hybrid renewable energy system (HRES) - Solar thermal system - Seasonal Thermal Energy Storage (STES) - Three multi-source heat pump (ground, sewage and STES) - Buffer tank District heating network system	PV (900 kWp): 2 092 MWh	Seasonal Thermal Energy Storage (STES)	N/A	N/A
ID: 6 (Mavrigiannaki et al., 2021) Zero Energy Neighbourhood New construction Emilia-Romagna, Italy	R1: One single- story residence (259 m ²) R2: one two-story residence (241 m ²) Six more residences planned Total area: 2 760 m ²	Total FE demand: R1: 37.6 kWh/m ² /yr R2: 41.4 kWh/m ² /yr				HVAC system: - Air-to-water heat pump with 8kW capacity - Low-temperature under floor heating system	PV Production and storage are shared PV panels with 12 kWp (6 kWp on each rooftop)	Battery with 4 kWh of storage capacity per residence (possible increase of capacity up to 12 kWh) for daily compensation	Load Control system and Home Energy Manageme nt System	N/A

Author / Project	District / Neighbourhood structure	Energy Demand				Energy Supply		Energy Storage	EMCS	Mobility
		Space Heating	Space Cooling	DHW	Electric Energy (lighting, appliances, etc.)	Heating / Cooling and DHW	Electricity			
ID: 7 (Laitinen et al., 2021) Self-Sufficient District New construction Helsinki, Finland	Apartment buildings 1 200 000 m² Offices 400 000 m² School 20 000 m²	SH UE: 28.2 kWh/m²/yr Ventilation UE: 3.6 kWh/m²/yr (calculated)	SC UE: 4.9 kWh/m²/yr Ventilation UE:1.7 kWh/m²/yr (calculated)	DHW UE: 28.2 kWh/m²/yr (calculated)	Total electricity FE: 44.9kWh/m²/yr (calculated)	Centralised heating system with electrically-driven heat pump	Self-sufficient scenario PV: 30 MWp Wind: 20 MWp	Self-sufficient scenario Centralised electric battery system: 715 MWh Centralised seasonal heat storage: 44 GWp	N/D	Electric vehicles
ID: 8 (Huang et al., 2019) Electricity Prosumers Building Cluster Refurbishment Ludvika, Sweden	3 apartment buildings 4 326 m²	SH UE: 91.3 kWh/m²·y/yr (calculated)	-	DHW UE: 18.6 kWh/m²/yr DHW circulation: 4.1 kWh/m²/yr (calculated)	Appliances and lighting FE: 20.6 kWh/m²/yr Operational electricity FE: 9.8 kWh/m²/yr (calculated)	Centralised heat pump using exhaust air and ground Back-up pellet boiler Ventilation radiators	PV (79.2 kWp) Grid	Daily hot water storage Electric batteries (possible)	Energy Hub microgrid	Electric vehicles (2 EVs): 4.8 MWh
		SH and DHW FE: 67.6 kWh/m²/yr (calculated)								
ID: 9 (Pinel et al., 2021) Zero Emission Neighbourhood (ZEN) Refurbishment Evenstad, Norway	Student housing (SHO): 4 200 m² Passive offices (PO): 1 141 m² Normal offices (NO): 3 375 m²	SH UE: SHO: 47.6 kWh/m²/yr PO: 39.2 kWh/m²/yr NO: 89.0 kWh/m²/yr (calculated)	-	DHW UE: SHO: 10.8 kWh/m²/yr PO: 5.7 kWh/m²/yr NO: 13.5 kWh/m²/yr (calculated)	Total electricity FE: SHO: 38.4 kWh/m²/yr PO: 128.0 kWh/m²/yr NO: 181.4 kWh/m²/yr (calculated)	Scenarios: Boiler (biomethane or electric) CHP Air Source Heat Pump, Ground Source Heat Pump Solar Thermal	Scenarios: PV CHP	Scenarios for daily storage: Electric storage Heat Storage	N/D	N/A

Author / Project	District / Neighbourhood structure	Energy Demand				Energy Supply		Energy Storage	EMCS	Mobility
		Space Heating	Space Cooling	DHW	Electric Energy (lighting, appliances, etc.)	Heating / Cooling and DHW	Electricity			
ID: 10 (Lausselet et al., 2021) Zero Emission Neighbourhood (ZEN) New construction and Refurbishment Elverum, Norway	1 000 residential buildings 100 000 m² Non-residential: - school 6 474 m² - kindergarten 2 140 m²	Total UE demand; Residential: 78 kWh/m²/yr Non-residential: 109 kWh/m²/yr			Total FE electricity: R: 33 kWh/m²/yr NR: 70 kWh/m²/yr (calculated)	District heating plant: 5,5 GWh/yr Biomass CHP: 6,3 GWh/yr (heat) Cooling - electricity	PV panels (18 000 m²): 2.5 GWh/yr Biomass CHP: 2.5 GWh/yr Grid	No	N/D	Electric vehicles Electric demand: 0.5 GWh/yr
R: 45 kWh/m²/yr NR: 35 kWh/m²/yr (calculated)										
ID: 11 (Lausselet et al., 2019) Zero Emission Neighbourhood (ZEN) New construction Bergen, Norway	695 residential dwelling: 85 164 m² (TH: 62 136 m² e AB: 23 028m²) Non-residential – services: 6 727 m²	SH UE (Sartori et al., 2016): TH: 11.8 kWh/m²/yr AB: 10.2 kWh/m²/yr Non-residential total thermal: 23.8 kWh/m²/yr		DHW UE (Sartori et al., 2016): TH: 24.8 kWh/m²/yr AB: 26.8 kWh/m²/yr	Electricity FE (Sartori et al., 2016): TH: 29.8 kWh/m²/yr AB: 30.6 kWh/m²/yr Non-residential: 104.8 kWh/m²/yr	Scenarios: District heating (DH) Biomass fired Combined Heat and Power (Bio CHP) Ground Source Heat Pump (GSHP)	PV energy (90%): 2 941 MWh/yr From grid (10%)	No	N/D	Personal vehicles Buses Light trail
ID: 12 (He et al., 2021) Carbon-neutral Residential Community San Francisco, USA	30 residential houses: 12 000 m²	Building FE demand: 21.9 kWh/m²/yr SH FE: 3.9 kWh/m²/yr				Electrical heaters Tankless heater	PV Grid	No	N/D	30 hydrogen vehicles Hydrogen station supplied by PV electricity

Total final energy demand was calculated for all cases, based on the available information displayed in Table 2.6. For some cases, the total value was presented in the paper and used directly in this analysis. Otherwise, the separated energy needs values were added to obtain the total energy demand. This included all energy needs presented by the authors. Also, when applicable, the weighted average between residential and non-residential energy demand was calculated based on the areas. As previously, when only useful energy (UE) values were available, final energy (FE) was estimated by using information retrieved from the articles, as described in Annex A (Table A.2).

This analysis, presented in Figure 2.4, allowed the identification of a range of total final energy demand between 21,9 kWh/m²/yr (He et al., 2021) and 148,6 kWh/m²/yr (Pinel et al., 2021). An important factor influencing energy demand is the structure of the district/neighbourhood, as case studies with higher amount of non-residential buildings, i.e., offices or service buildings, show higher energy demand, e.g., Laitinen et al. (2021) and Pinel et al. (2021). Also, in the case studies presenting separately residential and non-residential energy demand, the non-residential portion represents a larger energy demand share, e.g., Lausset et al. (2019, 2021) and Pinel et al. (2021), which supports the previous conclusion.

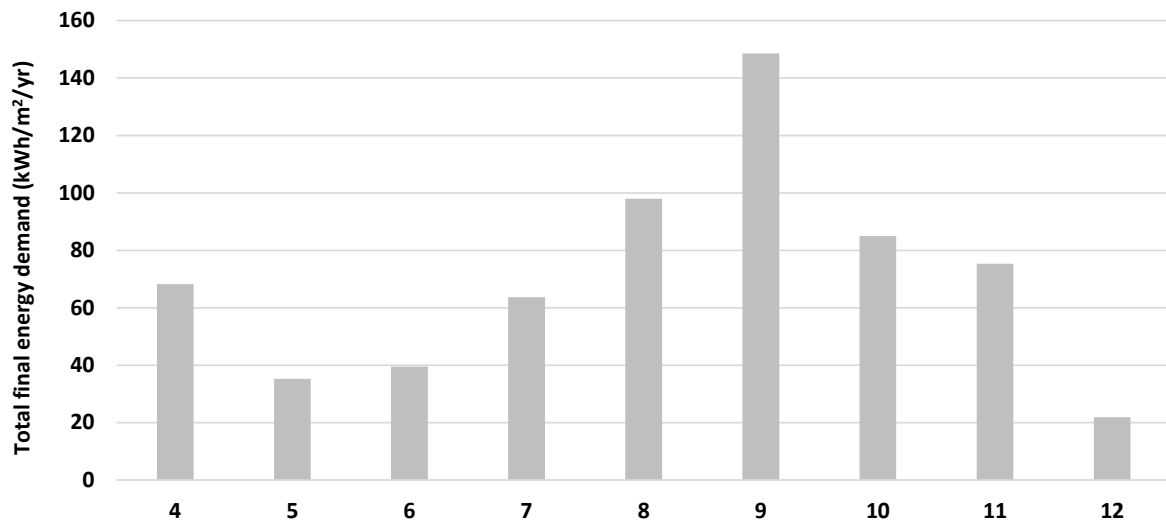


Figure 2.4. Total final energy demand for the zero energy and zero emissions case studies (ID).

Additional analysis to the final energy demand results obtained from the zero energy and zero emissions case studies focused on identifying energy demand by different energy needs, specifically SH (space heating), SC (space cooling), DHW (domestic hot water) and Electricity. The results are presented in Figure 2.5. Each dot in the graph corresponds to the final energy demand for the specific need of the complete district in study. When applicable, the weighted average between residential and non-residential energy demand based on the areas was calculated. Also,

the results only include cases presenting a specific value for the corresponding energy need, i.e., excluding aggregated values for more than one energy need or unclear data.

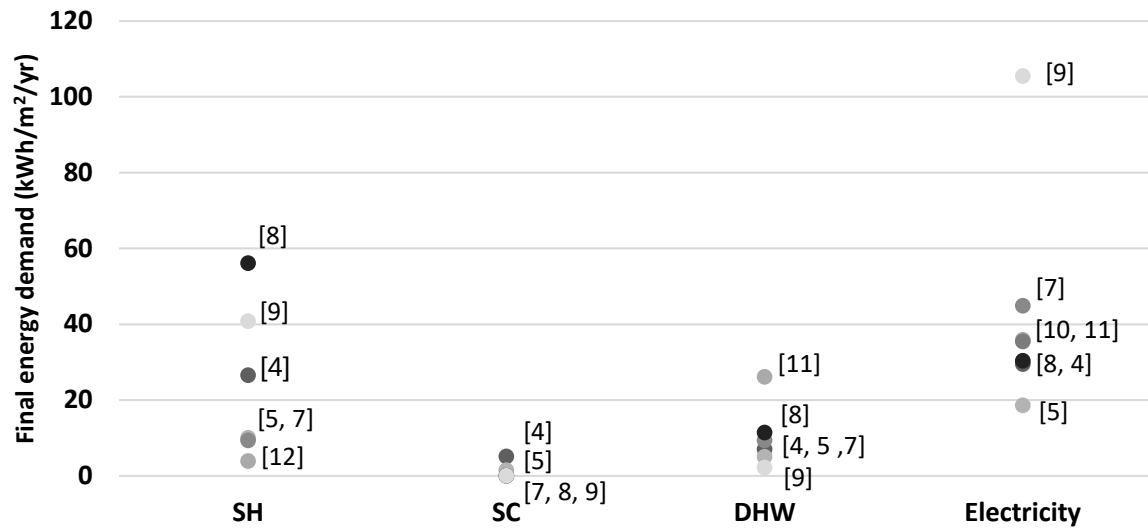


Figure 2.5. SH, SC, DHW and Electricity final energy demand for the zero energy and zero emissions case studies (identified by ID).

From the presented case studies, SH final energy demand values range from 3,9 kWh/m²/yr to 56,2 kWh/m²/yr, although from the six examples presenting specific SH demand values, only two cases are above 30 kWh/m²/yr (Huang et al., 2019; Pinel et al., 2021). These variations can be attributed to several factors, for instance, the geographical locations, as regions experiencing colder climates tend to exhibit higher heating demands. In fact, those two cases above 30 kWh/m²/yr are located in Sweden (Huang et al., 2019) and Norway (Pinel et al., 2021). Additionally, variations in the efficiency of building insulation, window quality, and overall housing structure impact the amount of energy required for heating and cooling purposes. Examples of cooling energy demand are generally lower, between 1,5 kWh/m²/yr and 5,1 kWh/m²/yr, with three cases explicitly identified with zero energy directed to SC, including the ones previously referred with higher heating energy demand (Huang et al., 2019; Pinel et al., 2021). The differences in cooling demands can be associated with local climate conditions as well as the presence of passive cooling techniques or highly efficient cooling systems installed in these homes. In a similar analysis, DHW final energy values vary from 2,2 kWh/m²/yr to 26,1 kWh/m²/yr. These variations might stem from factors such as the efficiency of the water heating systems, usage patterns of hot water by occupants, and the geographical availability of alternative energy sources for water heating, such as solar thermal systems. The main solutions employed to cover space heating and DHW energy demand include heat pumps, biomass boilers or Combined Heat Power units, which also represent a source of electric energy, solar thermal systems, and district heating. The choice of these solutions can be influenced by the local availability of energy sources, cost-effectiveness, and environmental

considerations. Thermal storage was considered for a small number of cases. Total electric energy demand for lighting, appliances and other needs presented in the case studies varied for most cases from 18,6 kWh/m²/yr to 44,9 kWh/m²/yr, although one example reached 105,5 kWh/m²/yr (Pinel et al., 2021). These discrepancies can be due to variations in the districts' structure, presence of large office areas, size of households, occupants' behaviour regarding energy consumption, and the types and efficiency of appliances used. For all cases, Photovoltaic systems were selected to cover electric energy demand in balance with the energy requested from the grid. In some cases, CHP was included in the system, as well as electric energy storage. Mobility was addressed in some of the case studies, mostly based in analysing the electric energy demand of a determined number of electric vehicles. In Lausset et al. (2019), buses and light rail systems were accounted for.

Table 2.7 presents the main technical features for the third category of case studies, composed of the Nearly-zero Energy Districts (nZED) case studies. Nearly-zero Energy case studies, presented in the Table 2.7, aim at a less ambitious energy balance goal, in which the energy demand is higher than the renewable energy supply. This is reflected in a higher energy demand and/or a lower share of renewable energy supply than examples of net zero or positive energy/carbon emissions. As before, final energy (FE) conversion was based on the presented values and the system characteristics, described in Annex A (Table A.2). For Ascione et al. (2021b), the selected scenario was the optimal solution with the minimal district's primary energy consumption (Ascione et al., 2021b). The total final energy demand values were 25,9 kWh/m²/yr (Aste et al., 2020) and 46,3 kWh/m²/yr (Ascione et al., 2021b). For Aste et al. (2020), contrarily to all the examples of PED and zero energy and emissions targets, SC final energy demand was higher than SH energy demand, being the larger parcel of energy demand compared to all the other needs, although the exclusion of electric energy demand for home appliances is expressed by the authors (Aste et al., 2020). Moreover, both the examples include residential and service buildings, which can help justify the increased SC energy demand. Heating, cooling and DHW solutions are similar to the other examples, i.e., heat pumps, biomass boiler or CHP and electric energy solutions also included PV systems.

Table 2.7. Main technical features of the nZED case studies.

Author / Project	District / Neighbourhood structure	Energy Demand				Energy Supply		Energy Storage	EMCS	Mobility
		Space Heating	Space Cooling	DHW	Electric Energy Needs (lighting, appliances, etc.)	Heating / Cooling and DHW	Electricity			
ID: 13 (Ascione et al., 2021b) Nearly-zero Energy Building - at blockt level Refurbishment Naples, Italy	4 buildings (residential and services): 21 396 m ²	Scenario RP 10: Total primary energy consumption: 90.3 kWh/m ² /yr				HVAC: electric heat pumps	Scenario RP 10: PV: reduction of 18.1 kWh/m ² /yr Final grid energy consumption: 72.3 kWh/m ² /yr	No	N/D	N/A
		Scenario RP 10: SH UE: 6 kWh/m ² /yr	Scenario RP 10: SC UE: 32.7 kWh/m ² /yr	N/D	N/D					
ID: 14 (Aste et al., 2020) Nearly-zero-Energy District New construction: Milan, Italy	Residential 64 490 m ² Tertiary buildings 24 600 m ²	SH UE: 15.2 kWh/m ² /yr	SC UE: 37 kWh/m ² /yr	DHW UE: 18 kWh/m ² /yr	Electricity for appliances in non-residential buildings FE: 6.1 kWh/m ² /yr Electricity demand for home appliances was not considered	Space heating and DHW: - Biomass boiler combined with a small CHP unit - Decentralised water to water heat pump (winter and mid-seasons) Space cooling: - Groundwater Heat Pump (GWHP)	CHP electric output (during its operation period), Photovoltaic systems (BIPV) integrated on the roofs By the grid, as last option	DHW storage systems: - Winter: storage tanks are heated when the space heating demand is low, using CHP energy - Summer and mid-seasons: storage tanks are heated when there is high PV generation	Energy Management System	N/A

A synthesis of total final energy demand of all the case studies is presented in Figure 2.6. This figure aims at displaying energy demand of the entire sample of selected cases in the most synthesised form, in order to evaluate distribution of this energy indicator through the varied studied energy balance concepts.

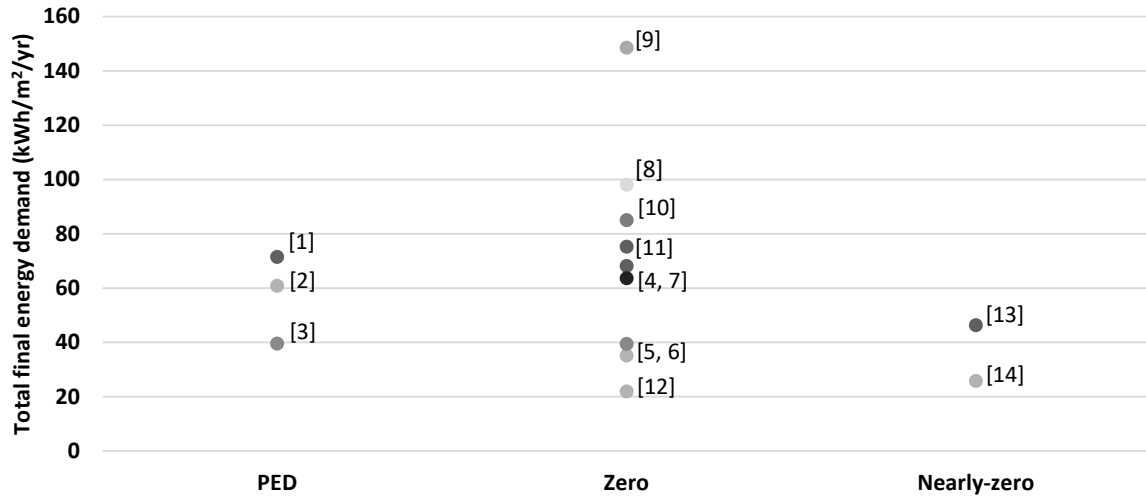


Figure 2.6. Total final energy demand per floor area for all case studies (identified by ID).

A significant part of examples presents final energy demand around 60 and 90 kWh/m²/yr. An apparent relation between the concept of energy balance and final energy demand of the cases is not clear, although, for this analysis, the number of cases only allows indicative conclusions. Theoretically, lower final energy demand would facilitate the achievement of neutral or positive energy balance, by requesting lower renewable energy supply.

2.4.5 Design Practices

It was investigated if several alternatives for key design features were considered and compared, or if a certain solution was adopted without a structured decision process. The criteria of choice and technical tools used to evaluate and test alternatives were also identified.

In Table 2.8, the consideration of multiple design alternatives was described with “Yes” or “No”, considering if different scenarios or only one were stated in the study. “N/A” was applied in Energy Storage and Mobility characterisation when this element was not part of the study.

Table 2.8. Existence of a structured process of choice from alternatives for the key-design features.

Case studies	Multiple design alternatives presented						Selection Criteria (or analysis when only one alternative is presented)	Tools used
	Envelope	Appliances and lighting	Energy service equipment	Energy “generation” equipment	Energy storage	Mobility		
ID: 1 (Volpe et al., 2022) Sicily, Italy	No	No	Yes	Yes	No	N/A	Energy performance and storage space Dimensioning based on the distance between buildings, accesses and area PV depending on available area	MATLAB: to implement the optimisation model
ID:2 (Neumann et al., 2021) Vienna, Austria	No	No	No	No	No	N/A	N/A	MAPED model
ID: 3 (Erba & Pagliano, 2021) Milan, Italy	Yes	Yes	Yes	Yes	N/A	Yes	Overall energy balance	Energy-Plus for building performance simulation
ID: 4 (Janzadeh & Zandieh, 2021) Qazvin, Iran	Yes	No	No	No	N/A	N/A	Energy performance Energy consumption reduction	DesignBuilder for building simulation T-SOL for solar thermal system
ID: 5 (Kim et al., 2019) Jincheon, South Korea	No	No	Yes	Yes	Yes	N/A	Techno-economic performance	TRNSYS for building performance simulation
ID: 6 (Mavrigiannaki et al., 2021) Emilia-Romagna, Italy	Yes	Yes	Yes	Yes	Yes	N/A	Optimisation for achieving simultaneously the targets of: - renewable energy production - regulated energy consumption - investment cost reduction	Dynamic Thermal Simulation (DTS) tools for energy performance simulation EnergyPlus and Design Builder Life Cycle Cost Analysis (LCCA) Meteonorm

Case studies	Multiple design alternatives presented						Selection Criteria (or analysis when only one alternative is presented)	Tools used
	Envelope	Appliances and lighting	Energy service equipment	Energy “generation” equipment	Energy storage	Mobility		
ID: 7 (Laitinen et al., 2021) Helsinki, Finland	No	No	Yes	Yes	Yes	No	Cost and net energy results Self-sufficiency rates	Rule-based method and the optimisation method IDA-ICE and TRNSYS for building performance simulation
ID: 8 (Huang et al., 2019) Ludvika, Sweden	No	No	No	Yes	Yes	Yes	PV and storage final capacity Self-sufficiency and self-consumption LCOE results	LCOE Sketchup and TRNSYS EV load: Grahn-Munkhammar model
ID: 9 (Pinel et al., 2021) Evenstad, Norway	No	No	Yes	Yes	Yes	N/A	Scenarios to test the importance of choice of CO ₂ factor of electricity	ZENIT model for cost-optimal energy system by Mixed Integer Programming
ID: 10 (Lausset et al., 2021) Elverum, Norway	Yes	No	No	Yes	N/A	Yes	Scenarios to reach net-zero GHG emissions	Life Cycle Assessment (LCA)
ID: 11 (Lausset et al., 2019) Bergen, Norway	No	No	Yes	Yes	N/A	No	Key Performance Indicators (KPI): Zero energy and emissions target System cost (investment and operational)	PVSyst
ID: 12 (He et al., 2021) San Francisco, USA	No	No	No	No	No	No	Energy consumption and cost	TRNSYS for building performance simulation
ID: 13 (Ascione et al., 2021b) Naples, Italy	Yes	No	Yes	Yes	N/A	N/A	Energy demand and primary energy consumption Global cost	SketchUp and DesignBuilder EnergyPlus for dynamic energy simulation MATLAB
ID: 14 (Aste et al., 2020) (Aste et al., 2017) Milan, Italy	No	No	Yes	Yes	No	N/A	Minimise total primary energy demand Ensure low running costs Best cost/benefit performance together with social and environmental impacts High level of sustainability	Energy-Plus for building performance simulation

This systematic analysis of the case studies allows for the identification of the design practices used in the different examples, including the tools identified to best analyse the results and to select most adequate solutions. Also, an analysis structured according to design feature offers insights on the areas of intervention for which additional scenarios or alternatives were considered.

Figure 2.7 presents the number of case studies that considered design alternatives for each design feature. This usually included an analysis using well defined criteria of choice and tools to evaluate and select the best solution, which were collected in Table 2.8. The cases without evaluation of alternative design choices directly identified the solution or characteristic of the feature used in the neighbourhood/district in the paper in analysis, without clarifying if that process happened in a previous stage.

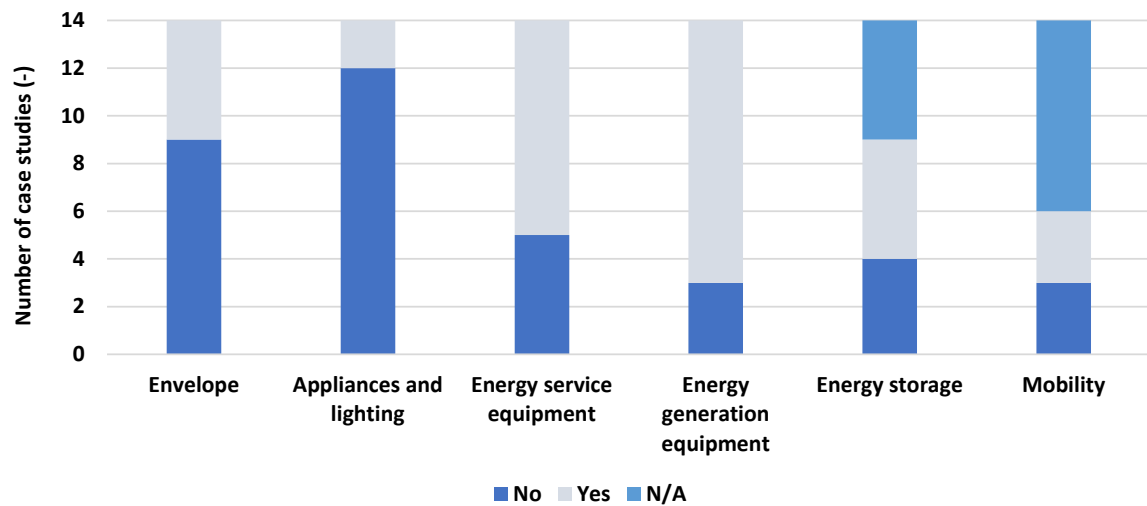


Figure 2.7. Number of cases studies presenting design alternatives, by design feature.

Approaches varied significantly between case studies, with various ways of testing alternatives. In some cases, the design features alternatives were tested separately, even if a final set of alternatives is compiled and a final result is reached. In other cases, complete scenarios are built with different solutions covering the multiple design features, e.g., in Erba & Pagliano (2021), two scenarios were presented, and, in Ascione et al. (2021b), a total of 10 retrofit packages were tested.

For the case studies in analysis, *Envelope* and *Appliances and Lighting* design features were in most cases based on the definition and characterisation of a single scenario. Economic cost represents an important factor as an intervention on *Envelope* usually presents larger return on investment periods, promoting prioritisation the intervention on other aspects. Additionally, the intervention in the envelope may require more time and resources. Examples of *Envelope* solutions usually include improving insulation of building's structure - e.g., walls, roof, windows - with

thermal insulator materials, and window glasses and frames (Ascione et al., 2021b; Janzadeh & Zandieh, 2021; Mavrigiannaki et al., 2021). Only two studies considered more than one solution to Appliances and Lighting (Erba & Pagliano, 2021; Mavrigiannaki et al., 2021). Usually, the intervention on this feature focuses on using *LED* lights, efficient lighting control, and energy efficient appliances, therefore, a single intervention or scenario is considered for most cases. A smaller number of different solutions and reduced difference in terms of impact on energy efficiency between solutions justifies the small number of cases with more than one scenario. Also, in refurbishment cases, maintaining the previous characteristics was frequently considered as a baseline scenario.

Contrarily, *Energy service equipment* (SH, SC and DHW equipment) and *Energy generation equipment* (energy supply equipment) were more frequently discussed, with different alternatives considered in the studies. This is justified by a greater impact variation of solutions in the final energy or emissions balance, as different alternatives present different results, depending on the conditions of the district/neighbourhood, energy consumption profiles, location or available resources. Also, multiple combinations of energy service equipment and energy generation equipment can be tested and present various results. Thus, combining heat pump with PV was a common solution, featuring in 10 of the 14 analysed case studies. CHP was considered in all the ZEN cases, all of them located in Norway, in order to cover both electric and thermal energy needs of the districts/neighbourhoods. To cover electric energy needs, PV was combined with CHP. In two of the ZEN cases, district heating network was combined with the biomass-based CHP, and in the other ZEN example, solar thermal was considered.

In general, combining thermal and electric storage, solar thermal energy production, and district heating, with each other and with other solutions was frequent. Similarly, in addition to the study of different technical solutions, and respective combinations, the design practices frequently considered different sizing for the same solution, such as different sizes of PV fields or heat pumps with different electrical powers.

When applicable, studies often considered alternative *Energy storage* and *Mobility* solutions. However, these features were not always included in the scope of the study or the characteristics of district/neighbourhood, justifying the relevant number of case studies in which the evaluation of alternatives for these features was defined in this analysis as not applicable (N/A). *Energy storage* solutions vary between using thermal and electric energy storage and different scenarios were considered regarding the quantity of storage considered, e.g., electric energy storage capacity (Mavrigiannaki et al., 2021). Electric energy storage is still very influenced by its expensive cost, although representing an important potential in increasing efficient use of renewable energy and annual energy balance. Mobility solutions included scenarios for different private and public

transport balances (Erba & Pagliano, 2021), car-sharing solutions (Lausset et al., 2021), or different level of penetration of electric vehicles in the neighbourhood (Huang et al., 2019).

Erba & Pagliano (2021) and Mavrigiannaki et al. (2021) cases present alternatives in a larger number of design features, excluding only energy storage (Erba & Pagliano, 2021) and mobility (Mavrigiannaki et al., 2021), as the respective studies do not include analysis of those features. On the other side, although Ascione et al. (2021b) or Lausset et al. (2021) cover less design features – three and two, respectively – the studies include a larger number of scenarios, comparing over 10 combinations of alternative design features. A connection between the number of alternatives or design features and energy demand is not clear, although none of the four referred cases are among the examples with higher annual energy demand per area, between 39 kWh/m²/yr (Mavrigiannaki et al., 2021) and 85 kWh/m²/yr (Lausset et al., 2021). Also, Huang et al. (2019) and Pinel et al. (2021), the two case studies with higher energy demand values, do not present alternatives in *Envelope* and *Appliances and Lighting* design features and only Pinel et al. (2021) present alternatives for *Energy Service Equipment*. The two cases consider alternatives for Energy “Generation” and Storage, which is not impactful in energy demand reduction, and a focus on alternatives to reduce energy demand in the other design features was to be expected.

The evaluation of best solutions for the cases studies was based on multiple methods and tools. Optimisation models, simulation of energy performance, renewable energy systems design and life cycle level-based tools were some of the main approaches identified in the studies, and a summary of the tools used is presented in Table 2.9.

Table 2.9. Methods and tools used for energy performance and best solutions evaluation.

Methods and tools		(Volpe et al., 2022)	(Neumann et al., 2021)	(Erba & Pagliano, 2021)	(Janzadeh & Zandieh, 2021)	(Kim et al., 2019)	(Mavrigiannaki et al., 2021)	(Laitinen et al., 2021)	(Huang et al., 2019)	(Pinel et al., 2021)	(Lausselet et al., 2021)	(Lausselet et al., 2019)	(He et al., 2021)	(Ascione et al., 2021b)	(Aste et al., 2020)
Energy system optimisation methods, and cost and/or financial analysis	Rule-based methods, optimisation and cost-optimal models	X	X					X	X	X				X	
	LCOE								X						
	Grahn-Munkhammar model (EV load)								X						
	LCCA						X								
Energy performance simulation	EnergyPlus			X			X							X	X
	Design Builder				X		X							X	
	TRNSYS					X		X	X				X		
	IDA-ICE							X							
	Sketchup								X					X	
	Meteonorm						X								
Renewable energy simulation	T-Sol				X										
	PVSyst											X			
Life cycle Environmental assessment	LCA										X				

Optimisation of the energy system, cost optimal analysis, and energy performance simulators were the main and most frequent tools used in the case studies to assess energy performance and best solutions. Optimisation models aim to find the best combination of design parameters to maximise energy efficiency or cost-optimal results, and provide quantitative solutions based on mathematical modelling, however they are highly dependent on the accuracy of input data and assumptions. There are a number of models developed for specific case studies, e.g., ZENIT (Zero Emission Neighbourhood Investment Tool) model, which searches for the cost-optimal energy system through a MILP optimisation, used in Pinel et al. (2021), and MAPED (Model for Energy Analysis of Positive Energy District) model, based on bottom-up energy modelling, enabling a simplified energy demand-supply analysis, and used in Neumann et al. (2021). These models are important scientific developments, usually applied without synergies with other tools, and being fitted to evaluate solutions for a specific study. Specific methods tend to allow having a better suited evaluation for each case study, although issues of biased results and lack of flexibility might be raised.

Other approaches included using a set of different tools, usually commercially available, as energy performance simulators or building design simulators, e.g., Energy Plus, TRNSYS, Design Builder or Sketchup. These simulators are based on various inputs like climate data, buildings characteristics, and occupancy patterns, and can assess the impact of various factors on energy consumption and efficiency, however they may be less precise than optimisation methods.

For some cases, the combination of optimisation models with energy performance simulators was selected, as observable in Table 2.9, e.g., rule-based method and optimisation with TRNSYS and IDA-ICE (Laitinen et al., 2021), MATLAB with Sketchup, Design Builder and Energy Plus (Ascione et al., 2021b), and levelised cost of electricity (LCOE) with Sketchup and TRNSYS (Huang et al., 2019).

Criteria of choice of design solutions were similar among the studied cases, with the most frequent focus being on achieving a net energy balance with a low energy demand, followed by the selection of the most cost-effective solutions. This also included increased renewable energy share (Huang et al., 2019; Mavrigiannaki et al., 2021; Volpe et al., 2022), GHG emissions reduction (Lausset et al., 2019, 2021; Pinel et al., 2021) and self-sufficiency rate (Huang et al., 2019). It was noticed that efficacy in achieving zero or positive energy balance is being prioritised in comparison to economic and resource efficiency. In some of the case studies, economic analysis was not evidenced in the paper, with the focus being the energy performance analysis. This unbalance does not ensure economically efficient design choices. More systematic consideration of alternatives and their assessment in terms of investment costs, running costs and consumption of materials would be expected and would increase the quality and value of the decarbonising strategies.

The critical analysis on the effectiveness of the described design practices was deepened by comparing the complexity of the design practices to the final energy demand values. The complexity of the design practices was determined by two factors: number of design features with alternatives and the variety of used tools. Three levels of complexity were defined as: high level for cases considering both optimisation tools and energy simulation performance tools; medium level for cases using only one type of tool and studying at least three alternative design features; and low level for cases with evidence of only one tool and two or less alternative design features. Figure 2.8 presents the results of this exercise.

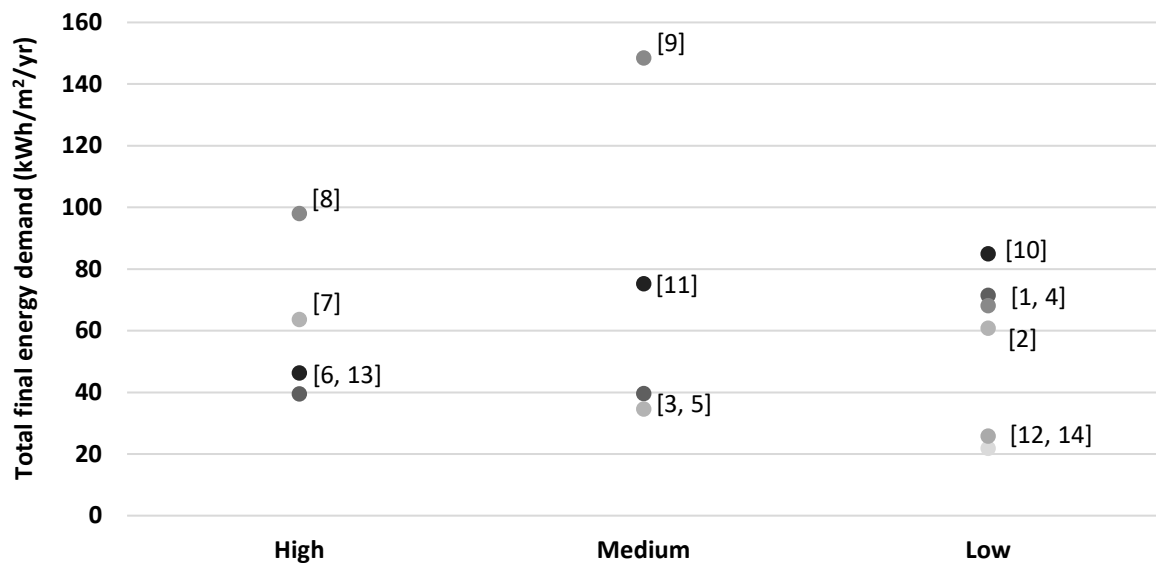


Figure 2.8. Comparison between complexity of design practices and final energy demand.

The results show a significant homogeneity, although the median of final energy demand values increases slightly from high complexity design process, with 55 kWh/m²/yr, to low complexity design process, with 64,6 kWh/m²/yr. In general, a more complex design practice, with the combination of different tools and methods, together with the study of alternatives in a larger number of design features, could be expected to allow more efficiency and better results. This expectation was slightly confirmed, but not in a definitive way. This may be due confounding factors like e.g. climate diversity among the case studies. On the other hand, the evaluation of performance through final energy demand is only one of the sensible possibilities. Others would be possible, such as the number of local renewables and their cost.

2.5 Insights from the literature review

The results of the systematic search, a collection of scientific papers addressing the study of real and theoretical cases, confirm the large variability of concepts and nomenclature currently used to characterise integrated solutions focused on the neutrality of energy demand and/or carbon emissions applied to clusters of buildings. In an attempt to answering the need to clarify these concepts, a proposal of standardisation is presented in this chapter, related to energy or emissions objectives and to the geographical dimension of the cluster of buildings and elements included in the scope of study. This normalisation is important to allow better comparability between different cases.

The analysis of case studies enabled the characterisation of design practices, adopted solutions and resulting energy demand and supply levels. The analysis of energy demand showed that the majority presented total final energy demand between 60 and 90 kWh/m²/yr. A significant difference between the average values for the PED, Zero or nZED cases was not noticed. However, a higher variation between cases was observed in space heating energy demand than that observed in domestic water heating and space cooling. As could be expected, geographical location has an important effect, as the cases with higher heating demand and lower cooling demand were located in colder climates.

Most frequently considered solutions for space heating and domestic hot water included heat pumps (present in 10 cases), biomass boilers, biomass-based combined heat power units (CHP) and solar thermal systems. In order to cover electric energy needs through renewable energy sources, PV (present in all the cases), wind energy and biomass-based CHP were the solutions adopted. Combinations of solutions were common, with the most frequent being heat pump combined with PV. Biomass-based CHP was considered in the Zero Emission Neighbourhood cases, all located in Norway, which was combined with the district heating network in two of the cases, and with solar thermal in the other example. Electric energy storage is not yet a frequent solution, although with the expected reduction of costs it may greatly improve the daily balance capacity of renewable energy supply systems. Resorting to offset through export to the grid (annual energy balance approach) may become less necessary, once energy storage systems become widely implemented. Mobility was considered in just six cases, mainly addressing electric mobility and public transport. The option to include mobility features is relevant for the design of cases, as it may represent a significant energy demand increment, and even influence the design of solutions for the district.

To achieve specific goals of energy or carbon emissions balances, several alternative features were frequently considered when designing the buildings. Only two out of the 14 cases presented

a single solution for every design feature. On the other hand, few cases presented alternative solutions for every design feature. A large number of cases considered different alternatives for *Energy Service Equipment* and *Energy Generation Systems*; however, few studied alternatives for *Envelope* and *Appliances and Lighting* equipment. Specially for case studies with higher energy demand, considering alternative solutions on *Envelope* should be expected in order to potentially reduce energy demand, which was not the case. For *Energy Service Equipment*, different type of equipment and different dimensions of the same equipment were covered. For *Energy Generation Systems*, different PV sizing was the most significant variable studied. The study of alternatives was mostly focused on the energy supply, overlooking the energy demand.

Design choices were based on a significant range of methods and tools, mainly focusing on energy performance evaluation, followed by energy system optimisation and cost optimal models. The expectation that more complex design processes and analysis could lead to lower energy-intensity solutions was slightly confirmed, with a numerical expression that is not conclusive. This may be due confounding factors like climate diversity among the case studies, or due to consumption offset through renewables being cheaper than further energy-efficiency in some cases. Overall, it was found that currently the focus is still more on demonstrating the efficacy of the design solutions in achieving the zero or positive balance than in achieving such balance at the lowest costs (i.e., with economic efficiency). In order to accelerate the deployment of these districts and neighbourhoods to the scale needed for a significant contribution to the decarbonisation efforts, it is necessary to develop new approaches and tools where the consideration of investment costs is ensured in a systematic and systemic manner - as well as life-cycle costs and, desirably, the usage of materials. Moreover, the support on the identification of decarbonisation solutions and strategies is expected to have policy implications. By understanding the evolution trends and efficiency of actions on a district-level, incentives for standardised categories of measures and a more accurate identification of application agents may occur.

A more extensive identification of measures to improve energy efficiency or decarbonising cluster of buildings and a reflection on key performance indicators to assess technical measures impact were targeted in following chapter. Furthermore, from the presented assessment, there seemed to exist a need for developing methodologies centred in achieving zero and positive energy balance in the most economic efficient way, as materialised in the work developed in this thesis.

Chapter 3. Meta-analysis of district-level energy solutions

This chapter is based on the peer-reviewed journal article “Meta-analysis of district-level solutions towards energy, carbon and economic targets” published in Energy and Buildings (Cardoso et al., 2025). Content from section 1 of the original article overlapping with the introductory material of the thesis has been omitted. Minor editorial revisions were applied to ensure consistency across the thesis and to reflect the subsequent evolution of the research.

3.1 An overview on district-level solutions

A promising path for progress lies in the implementation of technical interventions and cutting-edge technologies at district or neighbourhood level, offering the potential to revolutionise urban landscapes, fostering energy sustainability, reducing carbon footprints, and creating resilient communities. Literature review studies in recent years have been compiling technical interventions and strategies applied in the urban environment at district-level, e.g., Brozovsky et al. (2021) and Saheb et al. (2019). Projects with large scope of intervention like the European Programme “Positive Energy Districts and Neighbourhoods for Sustainable Urban Development”, which aims at planning and achieving 100 Positive Energy Districts, present relevant samples of technologies considered for the respective case studies (Bossi et al., 2020). Technical measures and technologies applied at the district or neighbourhood level provide a pathway toward sustainable and energy-efficient communities, namely through energy-efficient buildings, renewable energy generation, district heating and cooling, smart grids, electric mobility infrastructure and green transport modes promotion, and intelligent waste management (Nematchoua, Sadeghi, et al., 2021). District-level initiatives benefit from the capacity to consider energy interactions between individual buildings and the broader energy system at local level, potentiating synergies that are not captured by building-level actions (Leal et al., 2015). Specifically, management of load profiles, and production and storage capabilities are improved by a broader perspective, with increasing efficiency of implementation (Amaral et al., 2018). A larger scope of cross-sectorial planning is possible, and public engagement and economic incentives can be more easily accessed and promoted (Saheb et al., 2019). Relevant investment and maintenance costs benefits may be achieved from economies of scale effects. Public space and transport related interventions can also be included in the projects’ framework, importantly influenced by the urban form of districts and cities, which can be improved by efficient planning and development (Silva et al., 2018).

At the core of any sustainable district or neighbourhood lies the concept of energy-efficient buildings. By incorporating advanced building design principles, such as effective insulation, energy-efficient windows, and optimised lighting systems, significant reductions in energy consumption can be achieved (Oliveira Panão et al., 2013). Additionally, technologies like smart thermostats, occupancy sensors, and automated building management systems can enhance energy efficiency by dynamically adjusting heating, cooling, and lighting based on real-time conditions (Osello et al., 2013). Harnessing renewable energy sources is an integral component of decarbonisation efforts of the built environment, being its efficiency reinforced at the district or neighbourhood level by the capability to share resources and costs (Brozovsky et al., 2021). Solar energy harnessing, both thermal and photovoltaic, wind turbines, and geothermal systems can enable localised power generation, reducing reliance on fossil fuels and lowering greenhouse gas emissions. Moreover, through the implementation of microgrids and energy storage systems, surplus renewable energy can be stored and distributed efficiently, fostering a more resilient and decentralised energy infrastructure (Huang et al., 2021).

District heating and cooling centralised systems also offer a viable solution for improving energy efficiency in district and neighbourhoods. These systems involve the centralised production and distribution of thermal energy, providing heating, cooling, and hot water to multiple buildings within a given area (Masip et al., 2023). By leveraging waste heat recovery technologies, such as combined heat and power (CHP) plants, these systems can significantly reduce energy waste and promote the use of low-carbon energy sources (Aste et al., 2020). District heating systems coupled with renewable energy sources, as biomass or solar photovoltaic systems can enhance the benefits of these technologies (Aste et al., 2020). Smart grid technology has been incorporated in energy systems of urban environment infrastructure and, by incorporating advanced metering infrastructure, intelligent grid management systems, and real-time data analytics, smart grids optimise energy distribution, facilitate demand response programs, and enable efficient load balancing (Chui et al., 2018). Such systems empower communities to actively manage their energy consumption, integrate renewable energy sources, and make informed decisions to enhance energy efficiency (Koirala et al., 2016). Transport accounts for a significant share of urban energy consumption and carbon emissions. To address this challenge, the development of environmentally friendly and efficient mobility infrastructure at the district-level is crucial, including electric mobility, walking and cycling infrastructures. By establishing electric vehicle charging stations, promoting electric vehicle adoption, and implementing shared mobility services, communities can reduce reliance on fossil fuel-powered vehicles and create sustainable transport ecosystems (Castillo-Calzadilla et al., 2022). Waste management also plays a vital role in achieving energy efficiency and decarbonisation goals and by implementing intelligent waste management systems

that encompass waste segregation, recycling, and waste-to-energy conversion technologies, communities can minimise landfill waste, generate renewable energy from organic waste, and reduce greenhouse gas emissions associated with waste disposal. Impact assessment strategies are recurrently reviewed from energy, environmental, economic or social evaluation perspectives (Hashempour et al., 2020).

Assessment comprises indicators covering energy consumption, demand and savings, carbon emissions, life cycle impact, life cycle cost, investment costs or thermal comfort, among many others (De Boeck et al., 2015). Cost-effectiveness of projects is assessed, contributing to decision making processes (Dolšak, 2023). Thus, there is great variety of performance indicators to evaluate measures and technologies applied at district-level. Energy consumption and CO₂ emissions can be characterised in absolute value, per capita, per floor area or per end-use (e.g., heating, lighting, DHW and cooking) (Komninos, 2022). The same variability is shown when characterising energy consumption and CO₂ emissions regarding mobility, e.g., as total values or by mode, e.g., public transport, private car or electric mobility (Komninos, 2022). Energy demand per capita or per household, as well as the share of energy produced by renewable sources compared to energy from the grid, are indicators used to characterise case studies in the Project SPARCS (Uspenskaia et al., 2021).

This analysis explores the diverse range of technical measures and technologies that can be harnessed to enhance decarbonisation at district or neighbourhood scale, based on European case studies. By focusing on this granular level, communities can effectively address energy-related challenges, maximise resource utilisation, mitigate the environmental impact of urban areas. District and neighbourhoods are reasonably homogeneous areas within themselves, which constitute a defined matrix to analyse the effectiveness of technical interventions, allowing a fair comparison between cases. In addition, at district-level, citizen involvement is more easily promoted, contributing to the relevance of analysis at this scale. The integration of such interventions and technologies can pave the way for the development of smart, sustainable communities that are poised to adapt to future energy demands. This review describes the systematic selection of cases studies characterise them based on geographical distribution, objectives nomenclature and project and buildings typologies. The measures characterisation is based on a matrix of analysis for categorisation and on the quantification of occurrences of measures. The impact evaluation includes the analysis of the key performance indicators (KPIs) used in the various studies. A meta-analysis of impact results supported the identification of measures and technologies with higher potential to achieving energy performance, carbon emissions and economic targets. In this context, “impact results” refers to the percent change in relation to baseline indicators for the scenarios analysed. The case study scenarios, based on the

application of measures and technologies, were compared to the respective base case or worst-case scenario. The indicators selected for this analysis were based on the previously developed characterisation of KPIs. The results suggest the measures with better performance, supported by frequent application in diverse case studies, but also potentially identify less frequently applied measures with relevant impact results, which may encourage further study.

3.2 Methodology followed for the meta-analysis

The methodology to identify technical measures and low-carbon technologies to be applied on district-level case studies was based on a comprehensive literature review. The literature search specifically targeted identifying scientific papers that described or reviewed the application of these solutions in neighbourhoods, districts, blocks or communities, depending on the designation used in the paper, allowing for the compilation of a substantial collection of technical measures observed in numerous case studies. By analysing the identified examples, it became possible to organise and characterise a significant number of measures according to key attributes deemed important for their description, and respective categorisation based on their adequacy to different cases. This process aimed to assess their usefulness and applicability across various scenarios and conditions. The literature search process is depicted in Figure 3.1.

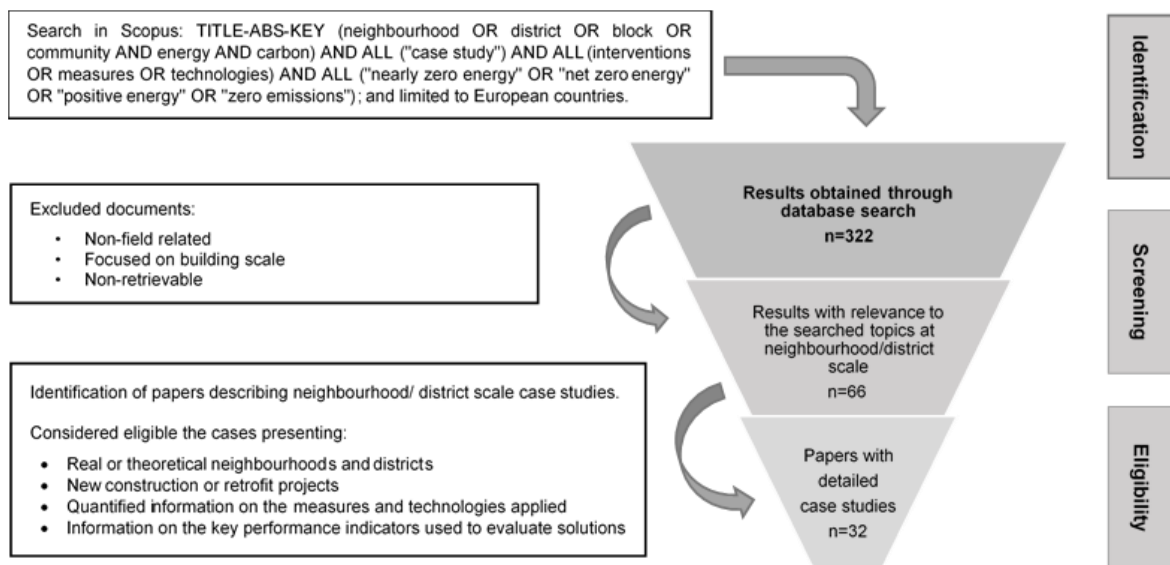


Figure 3.1. Flow chart of the methodology followed to identify the case studies for analysis.

The literature search involved identifying a combination of relevant terms to ensure the inclusion of a substantial number of projects that encompassed interventions and technologies representing the current landscape of sustainable and energy-efficient practices applicable to buildings.

The search was limited to European case studies allowing to reduce significant disparities in construction materials or techniques, although enabling some variations of measures that may be common in some parts of Europe and not in others, e.g., district heating systems, providing a comprehensive overview of measures with potential for large-scale application. The results obtained from the literature search were filtered, by excluding papers not related to the subject under analysis, or at different scales than district scale (e.g., building-level or city-level), or inaccessible papers. The results filtered were then analysed in order to retrieve papers describing case-studies and associated measures, resulting in 32 papers with case studies to analyse. The case studies were characterised by use typology of the buildings composing the districts, including residential, services or mixed neighbourhoods and by typology of project they were describing, i.e., new construction or retrofit. The case studies were also distinguished between real implementation cases or theoretical studies.

Measures presented in the case-studies were identified and information was collected on their impacts across different indicators. A meta-analysis of impact results retrieved from a significant portion of the selected case studies was performed and graphically presented. The main analysis was based on the percentual difference between an applied measure/technology or combination of measures/technologies and the base case or worst-case scenario. Therefore, the analysis was restricted to cases presenting a comparison of impact results, and also to the numerical results presented in the papers. A complete catalogue of solutions was obtained, embodied in a ranked list of technical measures and low-carbon technologies, individually or combined, according to their impact on energy (e.g. energy savings) and non-energy (e.g. economic cost) dimensions, in order to evaluate the efficiency, effectiveness and feasibility of these actions. For the purpose of the present study, the term “measure” encompasses the variety of single technologies or management options.

3.3 Results and discussion

3.3.1 Case studies characterisation

The application of the search methodology resulted in the identification of 32 suitable district-level case-studies, with a geographical distribution presented in Figure 3.2, identified according to list in Table 3.1. From the 32 selected papers, the same number of case studies were identified. Hainoun et al. (2022) covered three locations in different countries: Austria, Germany and France. For the purpose of the analysis on the present review, the three locations were considered different scenarios of the same case study. Aside from only targeting European case studies, no further geographical restrictions were made. Nonetheless, resulting cases were mainly located in Northern, Southern and Western Europe, which indicates either that these regions have more cases or, at least, that they report more on it in international peer-reviewed literature (based on the search terms used).

Table 3.1. List of considered case studies.

ID	Reference	ID	Reference
1	(Becchio et al., 2018)	17	(Pinel et al., 2021)
2	(Testi et al., 2019)	18	(Lausset & Brattebø, 2021)
3	(Guerrieri et al., 2019)	19	(Kauko et al., 2022)
4	(Aste et al., 2020)	20	(Zwickl-Bernhard & Auer, 2021)
5	(Minuto et al., 2021)	21	(Hainoun et al., 2022)
6	(Haneef et al., 2021)	22	(Ristimäki et al., 2013)
7	(Ascione et al., 2021a)	23	(Rehman et al., 2020)
8	(Sibilla, 2021)	24	(Uspenskaia et al., 2021)
9	(Capone et al., 2021)	25	(Virupaksha et al., 2019)
10	(Cirone et al., 2022)	26	(Buckley et al., 2021)
11	(Pompei et al., 2023)	27	(van den Dobbelsteen et al., 2018)
12	(Famiglietti et al., 2023)	28	(Tsirigoti et al., 2021)
13	(Lizana et al., 2017)	29	(Blumberga et al., 2020)
14	(Garriga et al., 2020)	30	(Barbosa et al., 2022)
15	(Castillo-Calzadilla et al., 2022)	31	(Ş. Kılış et al., 2017)
16	(Masip et al., 2023)	32	(Middelhauve et al., 2021)

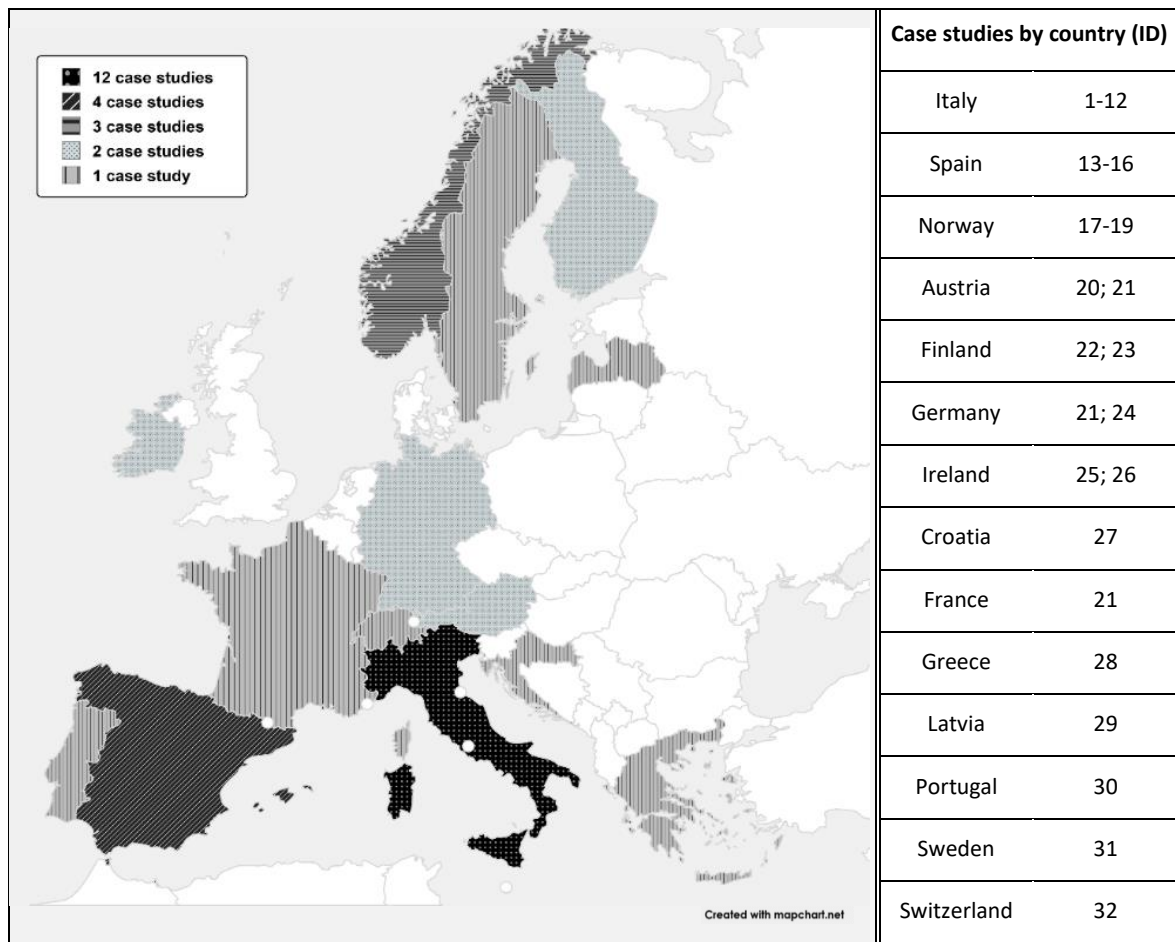


Figure 3.2. Case studies distribution by country.

From the case studies under analysis, the most frequently cited concepts towards energy or carbon targets are resumed in Table 3.2.

Table 3.2. Key concept or objective stated in papers.

Stated objective or concept	Quantity of papers
Zero Emissions/carbon-neutral Neighbourhood (ZEN)/District/Community	5 (16%)
Positive Energy District (PED)/Block	4 (13%)
Energy Community	4 (13%)
Near-zero/ Low Carbon Neighbourhood	3 (9%)
Net-zero Energy District (NZED)	2 (6%)
Nearly-zero Energy/Low Energy District/campus	2 (6%)
Smart Building Clusters	1 (3%)
Sustainable Residential Development	1 (3%)
Undefined	10 (31%)
TOTAL	32 (100%)

The terms used varied significantly, which was expected considering that the review included any case study with energy efficiency or decarbonisation improvement measures at district-level. Thus, a third of the case studies were not referring to any specific goal, being included in Table 3.2 as undefined. The many discrepancies present in the literature regarding the definition of the concepts must also be considered (Cardoso et al., 2024).

Figure 3.3 presents a characterisation of main aspects of the case studies, namely: 1) the typology of the buildings composing the district in analysis, e.g., residential, services or mixed use; 2) the project typology, e.g., new construction or a retrofitting of an existing district); 3) type of case study, i.e., if the paper reports a real implementation case or a theoretical study.

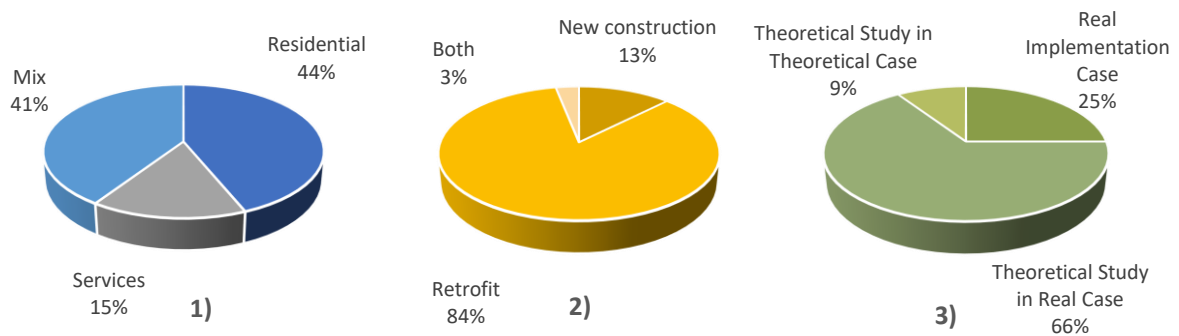


Figure 3.3. Partition regarding: (1) district typology; (2) project typology; and (3) type of case study.

The typology of buildings composing the districts was mostly residential or mixed use, with only five examples of services exclusive districts. Also, from the 32 case studies, 27 described retrofit projects, with only four being related to a new construction. One example presented both characteristics by including the renovation of existing buildings and the construction of new ones. The selected case studies include a majority of theoretical cases, with only 25% being about a real implementation. The theoretical case studies are divided between the study of a real case, i.e., existing district, and theoretical cases, exclusively designed for the study.

3.3.2 Measures characterisation

From the identification and cataloguing of different measures, a total of 164 occurrences were identified in the 32 case studies, divided into 33 different measures, and categorised according to the matrix presented in Table 3.3, in order to improve the analysis of results of the current literature review. Still, the matrix can be extended or adapted to analyse other studies and review different case studies.

The matrix covers a significant number of measures, classified by categories, to be applied at district-level to promote energy and carbon emissions efficiency improvement. The categorisation was designed as a tree structure to systematically organise the selection of measures, from the broadest category in terms of scope of intervention, narrowing progressively to the most specific category, referring to individual measures. The intermediate levels, subject of intervention and object of intervention, serve to provide clarity and granularity by detailing the intervention and by identifying the object or system being acted upon, respectively. This layered approach ensures a logical flow from general to specific, enhancing usability and precision in identifying relevant measures. As stated before, the selected studies were designed to improve buildings at a district-level, and the identified measures reflect this approach, e.g., considering shared energy production and storage or district heating systems. However, in general, most measures are suitable to be dimensioned for both building or district-level. This flexibility is one of the main benefits of district-level approach by allowing to identify the best solution from multiple variations of similar interventions both at building or district-level.

A quantitative analysis of the occurrence of measures is displayed in the following figures. Also, a complete quantification of measures, i.e., the number of times each measure is represented within the 32 case studies and how many case studies included each measure in its analysis, is presented in Annex B (Table B.1).

Figure 3.4 presents the quantification of occurrences of measures by scope of intervention in the central pie chart, with deeper quantification by measures in the four complementary pie charts. Figure 3.5 positions measures by prevalence in the selected case studies, grouping the results by the combinations of district and project typologies described in Figure 3.3, i.e., by type of building use (residential, services and mixed) and intervention project (new construction, retrofit and both).

Table 3.3. Categorisation of measures identified in the case-studies.

Scope of intervention	Subject of intervention	Object of intervention	Measures
BE: Building Envelope	Insulation	External	BE-1: Envelope (external walls)
		Internal	BE-2: Envelope (internal walls/floor)
		Rooftop	BE-3: Envelope (rooftop)
			BE-4: Green roofs
		Windows	BE-5: Windows
BD: Building Design	Shading	External	BD-1: Shading systems
AL: Appliances and Lighting	Efficient Equipment and Lighting	Lighting	AL-1: Efficient lighting system
		Appliances	AL-2: Efficient appliances
HVAC&DHW: Heating, Ventilation and Air Conditioning and Domestic Hot Water	Space and Water Cooling	Space and Water Cooling Equipment	HVAC&DHW-1: Cooling system
	Space Heating	Space Heating Equipment	HVAC&DHW-2: Heat exchanger system
		Heat Recovery System	HVAC&DHW-3: Heat recovery system
	Space Heating & DHW	Space and Water Heating Equipment	HVAC&DHW-4: Biomass boiler
			HVAC&DHW-5: Efficient boiler
	Space Heating /Cooling and DHW	Space Heating/Cooling and Water Heating Equipment	HVAC&DHW-6: District heating system
ES: Energy Supply	Renewable Energy Sources Integration	Electric and Thermal Energy Supply	ES-1: CHP/CCHP
			ES-2: Photovoltaic thermal units (PVT)
		Photovoltaic System	ES-3: Photovoltaic system
		Solar Thermal System	ES-4: Solar thermal system
		Wind Energy System	ES-5: Wind energy micro system
		Hydrogen System	ES-6: Hydrogen production by electrolyzer
		Geothermal Energy System	ES-7: Geothermal energy system
EST: Energy Storage	Energy Storage	Electric Energy Storage	EST-1: Electric energy storage
		Thermal Energy Storage	EST-2: Thermal energy storage
			EST-3: Hydrogen storage
EMCS: Energy Management and Control Systems	Energy Management System	Energy Management System	EMCS-1: Energy management system
WM: Waste Management	Waste Treatment	Recycling	WM-1: Recycling incentives
CS: Carbon Sequestration	Natural Carbon Sequestration	Reforestation	CS-1: Urban forestry
PS: Public Space	Public Equipment and Lighting	Public Lighting	PS-1: Efficient public lighting system
T: Transport	Electric Mobility	Electric Vehicles	T-1: Electric vehicles
		Electric Vehicles Infrastructure	T-2: Electric vehicles charging station
	Public Transport and Soft Modes	Soft Modes of Transport	T-3: Soft modes of transport incentive
		Public Transport	T-4: Public transport incentive

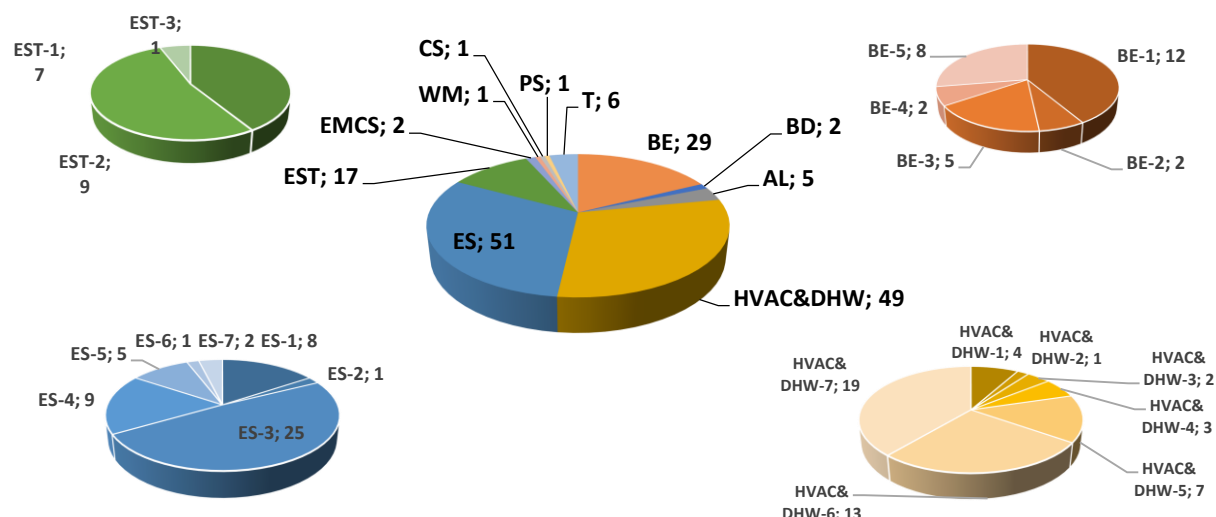


Figure 3.4. Distribution of occurrences by scope of intervention (centre) and by measures (corners).

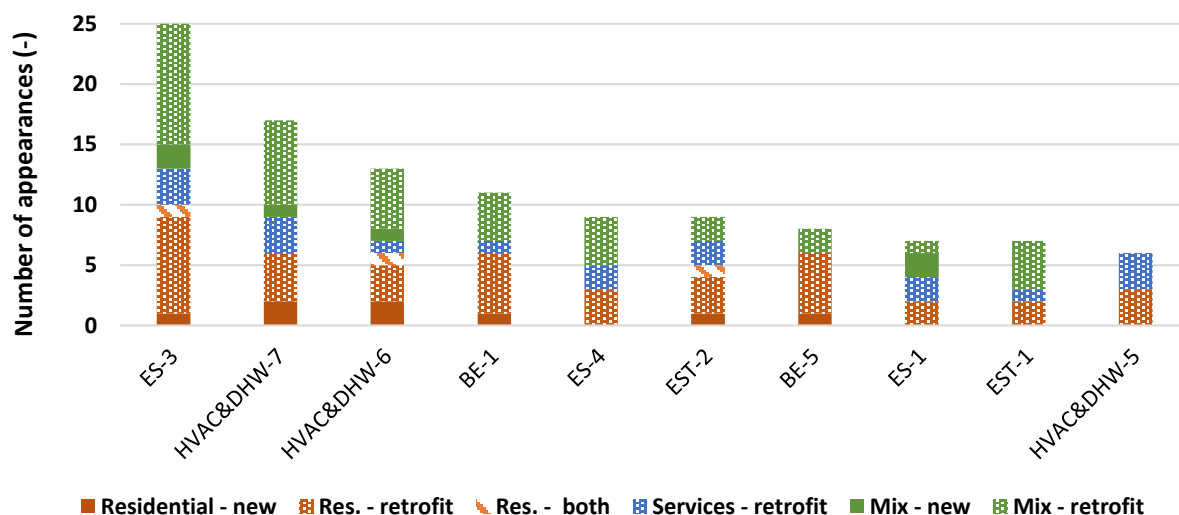


Figure 3.5. Number of appearances of the measures most adopted (those appearing more than six times).

Figure 3.4 and Figure 3.5 show photovoltaic systems (ES-3), heat pump (HVAC&DHW-7) and district heating systems (HVAC&DHW-6) as the three most common solutions by measure and by case study, respectively. For both accounts, external walls improvement (BE-1), solar thermal systems (ES-4) and thermal energy storage (EST-2) are the measures that follow. Additionally, a similar distribution is verified by type of case study, with photovoltaics being present in 75% of real implementation cases, and heat pumps, district heating and thermal energy storage in 50% of those cases.

By deepening the analysis of measures, Energy Supply (ES) is the most common scope of intervention category, with photovoltaic systems being present in 78% of the case studies. This frequent selection of photovoltaic may be justified by its high applicability and increasingly enticing economic payback, as well as external incentives. HVAC&DHW category is represented in 75% of the case studies, with most common technologies being district heating systems and heat pumps. This result was expected considering that energy related studies of the built environment regularly focus on HVAC and DHW due to those being high energy demanding systems. Energy Storage (ES) category is also frequent, with the contribution from electric and thermal energy storage systems. On district-level approaches, storage systems may represent better results, which justifies their high occurrence in the covered studies. The fourth most common category is Building Envelope (BE), with highlight to external walls and windows efficient solutions. Transport (T) measures were included in some of the case studies, covering electric vehicles increase or incentives to the installation of charging stations, public transport or soft modes of transport. Many transport related interventions involve, in fact, a district-level, or higher scale, approach. The percentage of case studies including Transport measures was lower than expected in the case studies analysed. This low occurrence can be justified by transport still being more associated to a city or national-level approach, or, having lesser economic support available, discouraging its study at this scale. The low occurrence of other measures, e.g., heat exchange and heat recovery systems or photovoltaic thermal units, may be justified by economic reasons. However, other factors, such as familiarity or cultural influences, could also play a role. Measures still in the early adoption phase, such as hydrogen-related measures, may become more common in future projects as the robustness of results improves.

Occurrence of measures by combination of district and project typologies represented in Figure 3.5 show a balanced distribution. As previously presented, retrofit interventions largely surpass the number of new construction cases, which is reflected in the distribution of measures by project typology, e.g., solar thermal systems (ES-4), electric energy storage (EST-1) and efficient boiler (HVAC&DHW-5) installation are not represented in new construction cases. The distribution of measures between residential and services uses is also balanced, with only efficient windows installation not occurring in services uses, although represented in mixed use cases.

3.3.3 Impact evaluation and key performance indicators characterisation

Within the assessed studies, the evaluation of impacts was performed using different methodologies, as presented in Table 3.4. All case studies were evaluated quantitatively, including simulation or numerical estimations. The discretisation of the evaluation of measures was evenly

shared between an analysis by measure, by combination of measures and by total result evaluation. The evaluation was based on the comparison between multiple scenarios results in 63% of the total occurrences of measures considered, a before vs. after intervention comparison of results in 28%, and by presenting and analysing only the final result in just 9%. Two case studies, Cirone et al. (2022) and Rehman et al. (2020), applied the comparison of scenarios and before vs. after evaluations for different measures, which resulted in being accounted in both typologies.

Table 3.4. Impact evaluation methodologies regarding Method, Discretisation and Typology.

	Evaluation	Number of measures evaluated	Number of case studies evaluated
Method	Calculation	164 (100%)	32 (100%)
	Measurement	0	0
Discretisation	Measure	41 (25%)	7 (22%)
	Combination of measures	74 (45%)	13 (41%)
	Total result	49 (30%)	12 (38%)
Typology	Multiple scenarios	104 (63%)	22 (69%)
	Before vs. after	46 (28%)	9 (28%)
	Evaluation of final result only	14 (9%)	3 (9%)

A list of categories was determined covering energy, carbon emissions, economic and environmental impacts. The quantification of occurrences of measures and case studies evaluated by impact category is summarised in Figure 3.6.

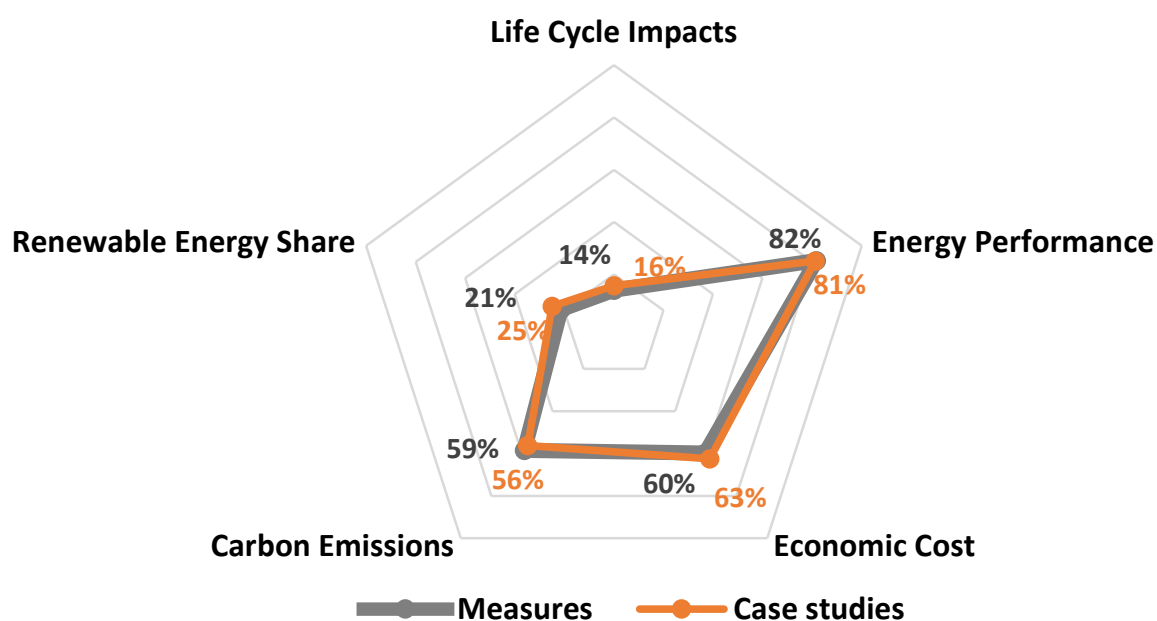


Figure 3.6. Share of measures and case studies evaluated at each impact category.

Around 82% of the occurrences of measures were assessed in terms of energy performance, with more than half being evaluated regarding economic cost and carbon emissions. Moreover, a significant number of measures was evaluated on carbon Life Cycle Assessment (LCA) impacts and renewable energy share. A similar distribution occurred for case studies. The analysis of final impacts evaluated for each measure resulted in an identification of the most frequent impact categories assessed by scope of intervention category, which is presented in detail in Annex B (Table B.2). For all scope of intervention categories, Energy Performance was the most recurrently assessed final impact. Energy performance was assessed for all the measures in more than half categories, and for the large majority of measures in the other categories. Carbon Emissions and Economic Cost were consistently assessed as the second and third impacts for all categories, though their order varied. These impacts were frequently analysed in association with, or resulting from, Energy Performance. In fact, Energy Performance and Renewable Energy Share impacts have direct influence on the other final impacts, especially in Carbon Emissions and Life Cycle Impacts, but also in Economic Cost impact, particularly by influencing energy related costs. The relevance of Life Cycle Impact evaluation must be highlighted for Building Envelope (BE) related measures, as the origin of materials used is considered an important factor in a significant number of case studies. Energy Supply (ES) and Energy Storage (EST) measures present relevant evaluation on Renewable Energy Share impact, together with Energy Performance, which was expected due to the influence of increasing renewable energy source integration in the energy balance of the case studies.

In Table 3.5, Key Performance Indicators (KPIs) used in the multiple case studies evaluation are identified and accounted in order to obtain a complete description of the indicators. To evaluate similar impacts, different KPIs were used and, in some cases, multiple KPIs were used to assess the same typology of impact. The variety of KPIs highlights the need for some level of harmonisation in impact measurement for comparability purposes on this kind of studies. Harmonisation should be supported by future research focusing on identifying the most suitable indicators for objectively assess the impact of solutions, enabling sustained comparisons between cases across different locations and built environments or technology levels, and minimising or at least facilitating the discussion of potential biases. In general, for Energy Performance evaluation, useful, final and primary annual energy consumption indicators were used, in total or per floor area. Less commonly, annual energy savings were also accounted. Economic Cost impact was accounted under a very varied set of indicators, namely economic cost and economic savings per year and/or per square meter of area, net present value and intervention cost, as total value or per square meter of area. Carbon emissions were evaluated through reduced kg. or ton. of CO₂ equivalent indicators, also in total or per square meter of area. Life Cycle Impacts were usually evaluated by sets of indicators, as result of studies of Life Cycle Assessment (LCA). Renewable Energy Share impact was analysed

through renewable energy ratios or energy production. The limited use of certain KPIs, such as efficiency and self-sufficiency, may be due to their narrower application compared to those used for quantifying energy, carbon or economic values. Other indicators, such as net present cost, may be chosen less frequently than net present value and direct economic cost or savings due to a preference for more commonly used indicators. However, further investigation may help clarify these preferences.

Table 3.5. Occurrence of evaluations by KPI, for measures and for case studies, in number and share of total measures/case studies assessed by the KPI.

	Key Performance Indicators (KPI)	Number of measures evaluated by KPI	Number of case studies evaluated by KPI
Energy Performance	Final energy or useful energy (kWh/yr or kWh/m ² /yr)	94 (57%)	17 (53%)
	Final or useful energy savings (kWh/yr or kWh/m ² /yr)	27 (17%)	4 (13%)
	Primary energy (kWh/yr or kWh/m ² /yr)	12 (7%)	2 (6%)
	Primary energy savings (kWh/yr or kWh/m ² /yr)	4 (2%)	1 (3%)
	Efficiency	2 (1%)	2 (6%)
Economic Cost	Intervention economic cost (€ or €/m ²)	43 (26%)	8 (25%)
	Net present value (€)	24 (15%)	6 (19%)
	Economic cost (€/yr or €/m ² /yr)	24 (15%)	4 (13%)
	Energy cost savings (€/kWh)	16 (10%)	2 (6%)
	Economic cost savings (€/yr)	4 (2%)	1 (3%)
	Net present cost (€/m ² /yr)	3 (2%)	1 (3%)
Carbon Emissions	Carbon emissions (CO ₂ ton/yr or CO ₂ ton/m ² /yr)	85 (52%)	15 (47%)
	Carbon emissions savings (CO ₂ kg/yr)	14 (9%)	4 (13%)
Renewable Energy Share	Renewable Energy Ratio	22 (13%)	6 (19%)
	Renewable energy production (kWh/yr)	13 (8%)	2 (6%)
	Self-sufficiency (%)	5 (3%)	2 (6%)
Life Cycle Impacts	LCA impacts (impact/m ² /yr)	23 (14%)	5 (16%)

3.3.4 Impact results

Figure 3.7 describes the impact results for a number of solutions based on measures or combination of measures application retrieved from the cases studies to allow the identification of the most impactful approaches and additional discernible patterns.



Figure 3.7. Quantification of the impact of measures, by impact category.

Impact results were based on the calculation of the percent difference on the results of each specific indicator between an applied measure or combination of measures and the base case or

worst-case scenario. Therefore, the analysis was only possible to examples presenting a before vs. after result or a comparison of multiple scenarios, i.e., only cases with a comparison of impact results. The analysis was also limited to the numerically available results, as some of the results were only graphically represented and others were commented but not integrally presented. In an additional note, it should be observed that only measures applied to achieve the presented impact result are identified in the graph, considering that there are technologies common to all the scenarios of a case study and, therefore, not responsible for the described difference. Measures or combinations of measures are displayed on the vertical axis and organised by case study in chronological order, from older (on top) to recently published papers (on bottom). Case studies are identified by the ID. Results are represented by data points positioned on the respective percentual distance to the base/worst case, in the horizontal axis. Competitive scenarios based on the same combination of measures are represented by each point connected in the same line. Also, data points formatting represents the impact category being characterised, according to the legend of the figure. When possible, multiple impact categories are represented in the same line. However, to improve readability, some impact results from the same solution were presented in two consecutive lines.

For Energy Performance, Carbon Emissions and Life Cycle Impacts, results are always better for higher negative percentage as they represent a reduction in energy consumption, carbon emissions or life cycle impacts, respectively. Even though different KPIs were used to represent those impact results, the percentual approach was applied to assure some degree of comparability. For Renewable Energy Share category, a higher positive percentage represents higher renewable energy share, therefore signifying an improvement. For Economic Cost category, the majority of KPIs represent a cost, thus, a negative percentage represents higher cost reduction. The exception is Net Present Value by being characterised as a positive indicator. For this case, a higher positive percentage represents a higher economic benefit, justifying the separate identification of this KPI in the graph.

The large variability of case studies characteristics, measures dimensioning and combination, and indicators used to evaluate results must be reminded. Therefore, the individual analysis of the papers is still recommended, especially when the objective is to compare impact results between case studies with accuracy. Nonetheless, this graphical representation of impacts quantification is expected to efficiently demonstrate the distribution of values between different solutions and approaches allowing to attain valuable considerations. Some questions may be discussed in combination with the graphical analysis:

3.3.4.1 Which are the measures or combination of measures that present better results?

For Energy Performance category, the combination of district heating system, photovoltaic system and electric energy storage, presented impact results from 83% to 93% (Buckley et al., 2021), and the combination of external envelope and windows improving measures, efficient lighting, district heating and heat pump, photovoltaic system and thermal and electric energy storage, was able to reach a maximum of 69% of impact in the evaluated indicators (Hainoun et al., 2022). In both cases, the impact result was associated to final or useful energy reduction. The occurrence of individual measures with higher impact percentage were related to BD-1, BE-4 and BE-1, i.e., shading system, green roofs and external envelope measures, respectively (Tsirigoti et al., 2021). For Carbon Emissions, the most significant results came from the combination of photovoltaic system and electric energy storage, with the best scenario representing 87% reduction from the base case (Cirone et al., 2022). Other combinations characterised with high impact results were heat recovery system, district heating and heat pump (Masip et al., 2023), or district heating and heat pump combined with PV and thermal energy storage (Rehman et al., 2020). These two examples also included the scenarios with higher results in Economic Cost, from 51% to 72% reduction in economic cost (Masip et al., 2023), and from 41% to 64% of economic cost reduction (Rehman et al., 2020). Net Present Value (NPV) results, represented in the graph with a positive percentage, presented the higher percentual differences to worst case scenario in Minuto et al. (2021), with the highest result being related to PV. The photovoltaic scenario reached a 185% higher NPV than other combinations of measures studied for this case. However, the PV scenario is not the best case for other impact categories, as represented in the graph, with the combination of PV and battery storage being the best result in renewable energy share, and the combination of PV and electric storage with heat pump presenting higher percentage in emissions reduction. This case study, among others, presents the opportunity to compare scenarios results through the lenses of different impact categories. The highest result in Renewable Energy Share category, also represented by positive impact percentage values, was associated to a single measure of photovoltaic system, covering 100% of energy demand (Middelhaue et al., 2021). Life Cycle Impacts quantified results were only possible to retrieve for one case study, with the combination of district heating, CHP, PV and public transport incentives representing a range of results from 22% to 42% of life cycle impacts reduction (Lausselet & Brattebø, 2021).

3.3.4.2 Did combinations of measures present better results than individual measures? And, when combined, how can the contribution from each measure be quantified in the overall impact result?

The correlation between combination of measures and better results is not entirely clear. Analysing the graph, the best results are indeed associated to combinations of measures. However, in some cases, the application of one single measure was sufficient to achieve relevant impact results, based on the dimensioning of the solution, e.g., substantial interventions on insulation of buildings or large photovoltaic systems in Tsirigoti et al. (2021) and Middelhauve et al. (2021). For combinations of measures, the contribution of each measure on the combined solutions impact result cannot be accurately determined in the present analysis. The percentual differences in the graph follow the same disaggregation level of the results presented in the papers, thus, estimating the contribution of each measure for the impact of a combined solution would result in high errors.

3.3.4.3 Is it possible to infer a relationship between the presence of specific measures in solutions with high impact and their frequency of occurrence across all solutions?

Further analysis of the most prevalent measures among solutions with high impact was needed to determine whether they tend to be more frequent in solutions with high impact or whether they are consistently present in those solutions due to their high frequency overall. This question was addressed despite being a challenging one due to the complexities inherent in studying the impact of individual measures within combinations of solutions. The conservative approach taken focused on calculating the occurrence share of each measure, whether individually or as part of a combination, in the total number of measures included in the scenarios of solutions within a defined impact range and comparing it to the same share in the overall number of scenarios. Importantly, this approach considers only the presence of each measure, not their specific contribution to the overall impact. To explore this approach, the scenarios of solutions with an impact greater than positive or negative 50%, corresponding to the best 25% scenarios, were identified. Within this subset, the occurrence shares of measures were quantified and compared to the occurrence shares across all scenarios of solutions. The calculation is represented by the *Index of measure occurrence in scenarios with high impact*, $Idx.$ (1).

$$\text{Index of measure occurrence in scenarios with high impact} = \frac{\text{measure occurrence in scenarios with } >|50\%| \text{ impact}}{\text{measure occurrence in total scenarios}} \bigg/ \frac{\text{total measures in scenarios with } >|50\%| \text{ impact}}{\text{total measures in total scenarios}} \quad (\text{Idx.1})$$

Therefore, Figure 3.8 presents the index between occurrence share of measures in the scenarios with impact greater than $\pm 50\%$, compared to its occurrence share across all scenarios, on the vertical axis. In the horizontal axis of the main graph, the share of occurrence in total measures represents a quantification indicator. Detailed data used to create the figure is available in Annex B (Table B.3).

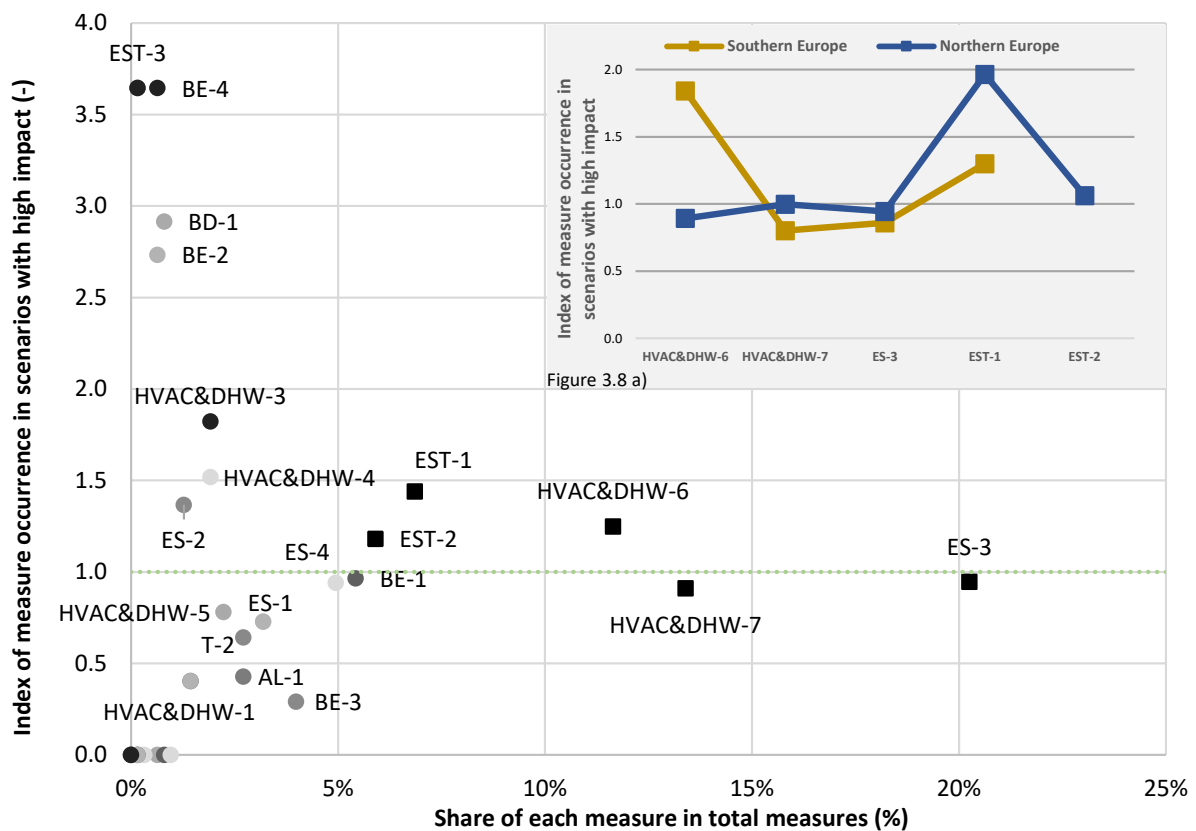


Figure 3.8. Index of measure occurrence in scenarios with high impact vs. share in total measures. [Figure 3.8 a) index of measure occurrence in scenarios with high impact vs. project location]

Measures with a higher ratio, meaning they are more frequent in scenarios with high impact than in total, also show low overall occurrence. These include hydrogen storage (EST-3), green roofs (BE-4), shading systems (BD-1), and internal wall and floor insulation (BE-2). These measures appear in only one case study each, where scenarios showed high impact results, explaining the ratio. This ratio suggests that in the only cases where these measures were present, significant impacts were

achieved; however, further validation is needed to confirm their individual effectiveness and readiness to general implementation.

On the other hand, the measures with the highest overall occurrence share in total scenarios of solutions are photovoltaic systems (ES-3), representing 20% of total measures, followed by heat pumps (HVAC&DHW-7) at 13%, district heating (HVAC&DHW-6) at 12%, electric energy storage (EST-1) at 7% and thermal energy storage (EST-2) at 6%. These measures have similar occurrence share in scenarios with more than 50% impact, as indicated by ratio values close to 1. By being based on more occurrences, results obtained in this analysis are more reliable and solid for these measures. And by presenting ratios close to 1, or higher in the case of district heating and electric storage, these measures show stronger individual tendency to be present in solutions with high impact.

The more significant amount of impact results for these measures allowed further comparison of the results across different geographies, as presented on the side graph, Figure 3.8 a). For this purpose, case studies were classified into Southern Europe: Italy, Spain, Portugal, Croatia and Greece; and Northern Europe: Norway, Sweden, Finland, Ireland and Latvia, following the United Nations division (UN, 1999). The same ratio between occurrence share in the scenarios with an impact greater than $\pm 50\%$, compared to its occurrence share across all scenarios, was calculated for each geographical zone. Differences were found in the case studies results from different geographies. Interestingly, district heating systems measures were more prevalent in scenarios with high impact in southern European cases than in northern European cases. This tendency can be justified by the lower implementation in southern European countries, therefore, being more frequently included in studies aiming at high energy efficiency or decarbonisation improvement indicators at district-level. Electric energy storage and heat pumps were more prevalent in scenarios with high impact in the northern European cases. Thermal energy storage was not represented in the southern European case studies with detailed impact data. Also, photovoltaic systems present similar prevalence in scenarios with high impact between Southern and Northern Europe, which is supported by a significant number of cases.

3.3.4.4 Do real implementation cases results validate the overall impact results? Do measures with high occurrence in impactful scenarios overall show similar tendency in real cases?

Specifically examining the results from the cases describing real implementation of measures can support, or question, the results taken from the overall results. From the cases with numerically retrievable results, five cases described real implementation. Considering the small number of

cases, this validation is expected to be indicative. Looking at the data, a first conclusion is that measures with higher share of occurrence in the overall measures show similar frequency in real implementation cases, with PV being present in all the five real cases, and district heating and heat pumps, in three and two of the real cases, respectively. A second item of analysis looks at the measures highlighted in the overall impact results to evaluate their presence in real implementation cases. The combination of PV and electric energy storage show percentages from 39% to 87% for both renewable energy share and carbon emissions reduction in the scenarios from Cirone et al. (2022). This combination is also present in Hainoun et al. (2022), together with district heating and heat pumps and other measures, including building envelope measures and thermal energy storage. On this case, the scenarios reach percentages between 25% and 69% improvement on energy performance. In Kauko et al. (2022), scenarios based on the combination of district heating, PV and thermal energy storage do not present percentual differences above 27%. The results from this case differ from the overall results, as all those measures presented high occurrence in scenarios with impact greater than $\pm 50\%$. Aste et al. (2020) presents a single scenario reaching 89% of renewable energy ratio, which includes biomass boiler, a measure occurring in the high impact scenarios, but with small share in total measures to support that result. The combination is also composed by heat pumps, CHP and PV. This observation indicates that results from real implementation cases are in line, for most cases, with the results considering both real and theoretical cases. This issue should nevertheless be kept under vigilance as more real cases emerge in the future.

3.3.4.5 Can the solutions efficiency, i.e., a relation between investment cost and impact results, be assessed?

In the present study, investment cost was identified as one of the key performance indicators to assess impact results from a specific solution. In the selected case studies, investment cost assessment was present in 25% of the case studies, however, a very limited number of values was retrieved for the present impact results analysis, due to previously described data availability issues. This difficulty prevented a systematic comparison between investment costs and other indicators to assess the efficiency of solutions. Although carbon emissions and energy related costs are directly related to, and usually dependent from, energy impact results, investment cost frequently vary inversely to other indicators results. E.g., in Rehman et al. (2020), higher investment costs related to different combinations of measures, including building renovation, HVAC and renewable energy supply, were associated to higher carbon emission reductions and lower energy related costs. For this case, a better result in investment cost impact, i.e. lower value, indicated a worse

result in other indicators. Despite the systematic assessment of solutions efficiency was not possible for this case, its importance is clear and must be pointed. Thus, the need for the integrated assessment of indicators is also highlighted, due to their frequent correlation.

3.4 Insights from the meta-analysis

For the identified set of cases studies, originated from 14 different European countries, available technical measures and technologies were assessed and thoroughly compared under different objective criteria. The systematisation in categories of measures contributed to the analysis, covering a large range of district-level solutions currently considered in the renewal or new build of clusters of buildings to achieve energy-related sustainability objectives. Literature search specifically targeted European case studies, in order to limit design disparities. Resulting cases were mainly located in Northern, Southern and Western Europe, although no restrictions were made within European borders. The limitation regarding geographical coverage also indicates less examples reported in other regions based on the terms used.

The most prevalent measures were insulation of external walls to enhance the building envelope, district heating and heat pumps installation to promote district-level space and water heating systems and respective electrification, and installation of photovoltaic systems for integrating renewable energy. The number of examples of transport related interventions was lower than expected, which may represent a subject of specific analysis. The growing electrification of the transport sector, new shared mobility solutions as well as the development of soft mobility infrastructure may strongly benefit from district-level approaches in the future. It is also expected that district-level approaches provide important economies of scale and support further decarbonisation efforts, which become especially relevant with the increasing complexity and interconnectedness of local energy systems.

Energy impact indicators were the most commonly evaluated, and a strong connection between energy indicators and carbon and economic indicators was found, as, expectedly, carbon emissions and economic costs reductions are mostly calculated from energy related results. The impact assessments conducted in the analysed papers aimed to evaluate the efficiency, effectiveness, and feasibility of the actions based on their effects on energy and non-energy dimensions. Considering that the totality of cases was evaluated by simulation or calculation methods, there is a need for an increase in studies supporting real measurement evaluation of results, which would increase their robustness.

The main analysis of percentual differences was restricted to cases presenting a comparison of numerical results. The analysis indicated measures as photovoltaic systems, district heating, heat

pump technology and energy storage, with consistent results in contributing to energy, carbon or economic targets. This represented a basis for the selection of technologies to integrate in the optimisation model developed and presented in the following chapters. Low occurrence measures with potential to be part of impactful solutions were also identified, as hydrogen storage and green roofs, which may be subject of further study to validate readiness for general implementation and exploring drivers to higher uptake of these solutions. By providing an insight into the impacts of different types of measures discussed in literature, using real or hypothetical examples, this analysis offers an overview of the work conducted in Europe on this subject. It aims at contributing to the maximisation of economic and process efficiency in future interventions, with valuable information for strategies related to district interventions assisting in the achievement of decarbonisation targets for 2030 and 2050. Additionally, there seems to be a need for quantifying co-benefits of energy efficiency measures for different impacts, as well as harmonising the Key Performance Indicators (KPIs) used to assess impacts.

The systematic literature reviews presented in Chapters 2 and 3 provided the foundation for the methodological developments that follow. The identification of current design practices and gaps in district-level approaches, together with the analysis of relevant technological solutions and KPIs, supported the modelling choices made during the framework development. Beyond a brief review of existing models, the subsequent chapters focus on the practical development and application of the proposed modelling framework.

Chapter 4. Methodology and optimisation model

This chapter reproduces, with adaptations and extensions, material submitted for publication to the journal Energy under the title “A methodology for economic-efficient design of net-zero, nearly-zero and positive energy districts considering adjustable levels of self-sufficiency”, which was under peer review at the time of completion of this thesis. The content has been complemented with additional material and annexed information to ensure completeness within the context of the thesis.

4.1 Current models and tools to achieve NZED and PED

Bringing NZED and PED into practice requires robust tools capable of simulating integrated district-scale energy strategies across multiple building typologies, demand profiles, technologies, regulatory scenarios, and centralised solutions in different urban contexts. In order to complement the methods and tools presented in Chapter 2, for the examined case studies, a broad analysis of the current modelling literature was developed.

Building energy simulation tools such as Design Builder, SketchUp and EnergyPlus are commonly used in district-level approaches (Natanian & Auer, 2020; Nematchoua, 2020). GIS-based tools and processing engines, e.g., MATLAB, also support PED development (Ascione et al., 2021b). The energy model for retrofitting optimisation presented in Ascione et al. (2021b) is based on a GIS tool coupled with SketchUp to generate geometrical models, while the envelope thermophysical definition is performed under DesignBuilder. EnergyPlus is used as dynamic energy simulator, while MATLAB works as the external postprocessing engine. Design Builder was also selected for energy optimisation of net zero energy neighbourhoods in tropical regions (Nematchoua, 2020), or to estimate the energy consumption decrease through passive strategies (Janzadeh & Zandieh, 2021). (Natanian & Auer, 2020) presents an environmental workflow with Ladybug plugin tools and Grasshopper as the main interface, through which data is obtained and streamed to simulation programs, including EnergyPlus, Radiance, Envi-met and Urban Weather Generator (UWG). Other examples include using steady-state calculations to obtain buildings energy needs (Mutani & Todeschi, 2020; Rose et al., 2022).

Recent studies have expanded techno-economic modelling for zero-energy and self-sufficiency (Castillo-Calzadilla et al., 2023; Laitinen et al., 2021; Pinel, 2020) and to select optimal energy system and supply solutions (Hachem-Vermette & Singh, 2020, 2021; Sougkakis et al., 2020). Hachem-Vermette & Singh (2020, 2021) present a methodology to optimise the mix of energy resources for a neighbourhood, focusing on the selection of the best energy supply solutions to achieve self-sufficiency or net zero status, assuming a specific high-performance energy demand.

Research frequently focus on technologies such as district heating, heat pumps, PV and energy storage, exemplified by the GreenSCIES Project (Revesz et al., 2022) and the Milano 4 You project, based on smart-grid, biomass district heating with heat pumps and solar photovoltaic systems to achieve energy self-sufficiency (Aste et al., 2020). Coupled PV-heat pump-thermal storage-electric vehicle system for electricity prosumers was studied in Sweden (Huang et al., 2019). Research initiatives include the study of favourable locations for PV-based PEDs (Bruck, Díaz Ruano, et al., 2022a), and coupling local production and energy storage at district level (Fichera et al., 2021).

Large EU projects have stimulated integrating methodologies for sustainable districts and PEDs. MAKING-CITY Project developed a methodology to achieve a positive annual energy balance at the design stage of a district. The methodology includes the calculation of energy balance, based on current standards, covering a large number of parameters, e. g, buildings' energy needs, energy systems and renewable energy supply solutions, however, estimations on energy needs and use were considerable and calculation was simplified, with some elements being excluded, e.g., appliances (Gabaldón Moreno et al., 2021). PEDRERA project focused on the design of a PEDs oriented renovation model (Civiero et al., 2021), and SPARCS Project achieved enhanced energy efficiency of buildings through advanced modelling techniques, contributing to sustainable urban development and resource optimisation (Uspenskaia et al., 2021). As part of the EU H2020 Smart Cities and Communities POCITYF project, the cities Alkmaar and Évora supported the deployment and market uptake of districts and demonstrate innovative and integrated technologies to enable flexibility in the energy system (Maas et al., 2020).

Multi-criteria decision-making approaches support the analysis of retrofit scenarios (Becchio et al., 2018; García-Fuentes et al., 2018; Isaac et al., 2020; Leal et al., 2015; Sibilla & Abanda, 2022), PED strategies for historic districts (Blumberga et al., 2020), or optimisation approaches for energy systems (Falke et al., 2016; Jing et al., 2018), including specific cases, from tropical NZED retrofits (Chacón et al., 2022) to high-altitude PEDs (Rehman et al., 2019). Optimisation modelling examples include the ZENIT optimisation model focusing on the Zero Energy Neighbourhoods (ZEN) concept (Pinel, 2020), a rule-based control method for techno-economic analysis of an optimal self-sufficient district (Laitinen et al., 2021), and optimisation for distributed energy resource systems coupled with district energy networks, emphasising cost-effectiveness and environmental impact (L. Li et al., 2016). LCA- based models evaluate environmental impacts across the entire life cycle for zero-emission neighbourhoods (Lauselet et al., 2020, 2021). A model for transition of city districts to NZEDs covers carbon and economic analysis of buildings, streetlighting and mobility parameters, although the input data and calculations are based on statistics and published metrics (Komninos, 2022).

Despite this progress, most projects remain case-specific, limiting broader applicability, or lack integration between demand modelling and cost-optimal design. Few studies systematically compare building- and district-level configurations or assess adjustable self-sufficiency targets. This highlights the need for flexible, optimisation-based tools capable of evaluating alternative district-scale design strategies.

4.2 Description of methodology

The modelling framework aims to support the efficient design of energy systems for urban districts. It is implemented by a defined methodology that evaluates and optimises the integration of multiple energy technologies while meeting sustainability-driven performance targets, namely net-zero (NZED) and positive energy districts (PED), and adjustable energy self-sufficiency (SS) levels up to 100%. While, NZED and PED are based on annual on-site renewable energy supply being equal or higher than energy demand, respectively, self-sufficiency levels are based on the share of annual demand covered by self-consumed renewable energy. The methodology combines detailed energy demand modelling with technology characterisation and cost parameters within a linear optimisation model that selects and sizes systems under multiple constraints. Although general in formulation, the methodology is demonstrated through its application to a mixed-use urban district to illustrate the resulting energy and economic outcomes under different design strategies.

The framework methodology combines Urban Building Energy Modelling (UBEM), implemented via the City Energy Analyst (CEA) (The CEA Team, 2025), with a dynamic Mixed-Integer Linear Programming (MILP) optimisation model. This integration enhances the ability to simulate combinations of technologies, at both building and district-level, and to achieve specific optimisation goals. The model focuses on selecting and sizing electric-based heating, ventilation, and air-conditioning (HVAC) and domestic hot water (DHW) systems, photovoltaic (PV) generation, and electric energy storage system (ESS). Optimisation minimises the life-cycle cost, encompassing both capital investment (CAPEX) and operational energy expenses and maintenance (OPEX), which is in this study is called total cost.

Figure 4.1 outlines the workflow, including relevant design variables and procedures, aiming a large spectrum of design issues:

1. District-level vs. building-level design
2. Baseline vs retrofit (Energy demand / envelope efficiency)
3. High-efficiency vs. low efficiency HVAC&DHW and PV equipment
4. Energy supply options: Grid-only vs. Grid + PV + ESS vs. PV + ESS
5. Cost-optimal vs. NZED vs SS levels

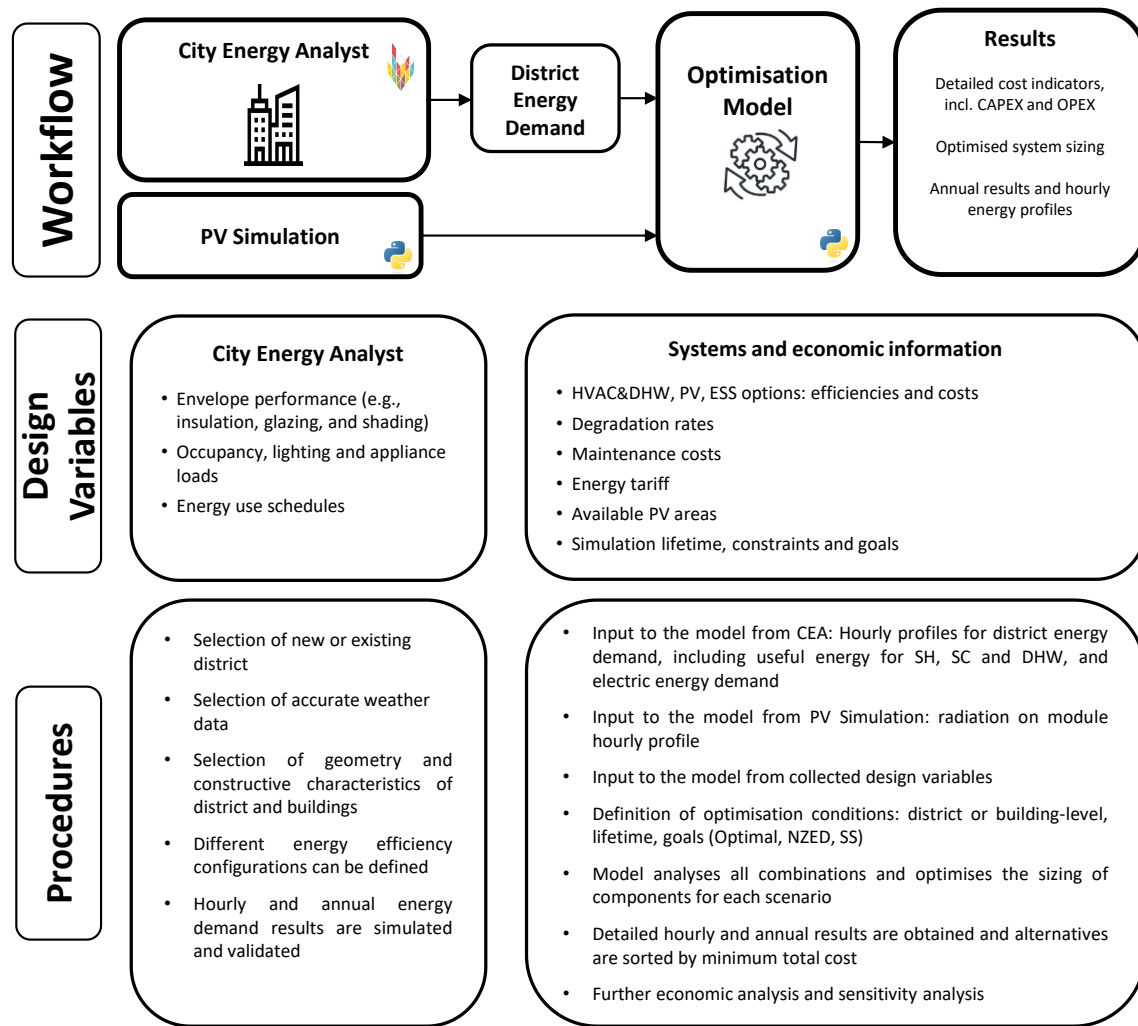


Figure 4.1. Methodology workflow, design variables and general procedures.

Developing a tailored optimisation model allowed additional control of the simulation requirements to the complete fulfilment of the defined goals. This justified limiting the use of CEA to the district energy demand calculations steps.

4.3 Urban Building Energy Modelling (UBEM): City Energy Analyst

Reinhart and Cerezo Davila coined the term "Urban Building Energy Modelling" (UBEM), in 2016, defining it as a "nascent field (Reinhart & Cerezo Davila, 2016). Given that traditional single building models require high amount of data and computational time for large-scale applications, UBEM foster a new approach to multiple building modelling. This approach is based on integrating geometric and physical data from GIS, archetype-based characteriation and simplified physical modelling routines, balancing between simplicity, the number of input parameters, and required computing efforts (Johari et al., 2020). UBEM methods are frequently categorised into two basic

groups: "Top-Down" and "Bottom-Up" models. Top-down models focus on aggregated energy demand of an entire region or country, relying on historical data and are often used in macroeconomic or socio-economic studies. In contrast, bottom-up models simulate the energy consumption of individual buildings and groups of buildings, allowing distinctions between different end uses such as heating, cooling, and lighting (Reinhart & Cerezo Davila, 2016). Bottom-up models can be based on statistical methods or engineering techniques (physical methods), or even a combination of both. Physics-based approaches are also divided in detailed multi-zone dynamic thermal simulations and reduced-order resistance capacitance (RC) (Ferrando et al., 2020).

The City Energy Analyst – CEA (The CEA Team, 2025) was selected to simulate building energy demand. CEA is an open-source UBEM platform for detailed energy performance assessments of multiple buildings within a urban context (Fonseca et al., 2016). The selection of CEA was justified by its comprehensive and up-to-date framework, allowing a complete assessment of energy performance of multiple buildings, illustrated in the comparison to other alternatives presented in Annex C. Previous applications of CEA include a case study aiming to establish the first Danish PED employing dynamic energy modelling (Jepsen et al., 2022), the design of improvement packages (Jradi et al., 2023), as well as to study urban energy infrastructure in a Portuguese district (Jewell et al., 2022).

Following the workflow illustrated in Figure 4.2, CEA integrates multiple sources of spatial and climatic data, enabling the spatial mapping of building attributes, such as geometry, orientation, and area, together with localised climatic conditions (Sola et al., 2020). A robust building stock characterisation leverages an library of building archetypes, completely adaptable to new data, allowing to model large and heterogeneous districts with realistic detail (Sola et al., 2020). Each building is characterised by one or more use-types, such as residential, office or retail, which define occupancy patterns, internal gains and end-use schedules. The dynamic energy use and demand simulation considers detailed occupancy and system characterisation, producing hourly energy demand profiles (Ferrando et al., 2020). The software outputs energy demand by end-use, including space heating (SH), space cooling (SC), domestic hot water (DHW), and lighting and appliances electric use. These outputs are stored aggregated and by building, and are structured to support further analyses.

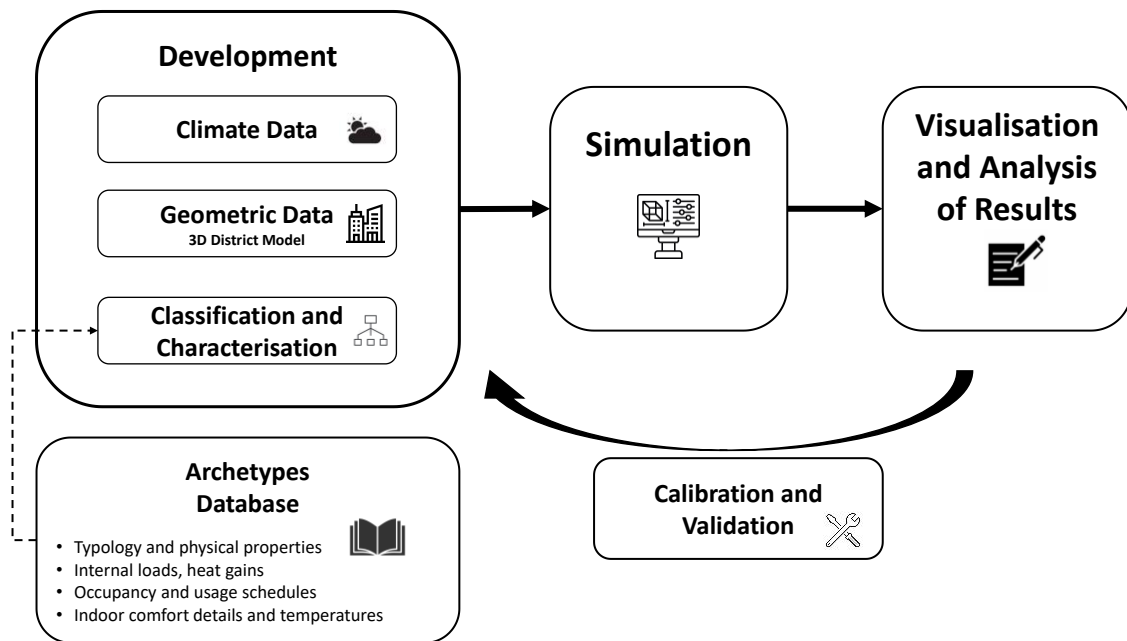


Figure 4.2. Illustration of CEA workflow.

4.4 Dynamic optimisation model based on Mixed Integer Linear Programming (MILP)

The model optimises the design and operation of integrated energy systems, following the workflow detailed in Figure 4.3. Hourly demand profiles from CEA and HVAC&DHW efficiencies determine final energy demand and solar radiation data is incorporated to assess PV generation potential. ESS operation is constrained by physical limitations, such as maximum battery energy capacity and allowable charging and discharging rates, as well as by operational restrictions, including preventing simultaneous charging and discharging. The complete set of battery-related constraints is presented in the following sections, together with the overall optimization constraints, including energy balances and limits, and the PV production. The ESS may consist of multiple physical batteries, being modelled as a single equivalent battery system. HVAC and DHW technologies, PV and ESS options vary in efficiency and investment costs.

The integrated energy system is sized to comply with the optimisation goal at minimum cost, ensuring energy balance requirements. These requirements encompass constraints at the hourly timeframe, fundamentally ensuring a time sensitive balance between district energy demand and supply, which combines PV renewable generation, battery storage and grid interactions at each time step, as well as annual scale restrictions, such as the achievement of annual net-zero energy or self-sufficiency levels. Notably, the self-sufficiency constraint can be either enforced fully (100% SS) or relaxed (below 100% SS) to explore trade-offs between autonomy and cost.

The methodology applies to both building-level and district-level analyses, thus enabling a comparison between optimising individual systems for each building independently, or through centralised HVAC&DHW technology, as District Heating and Cooling systems, and shared PV and ESS. Each scenario yields hourly profiles for energy demand, PV generation, grid exchange, ESS operation and storage levels, as well as detailed costs during the entire simulation lifetime.

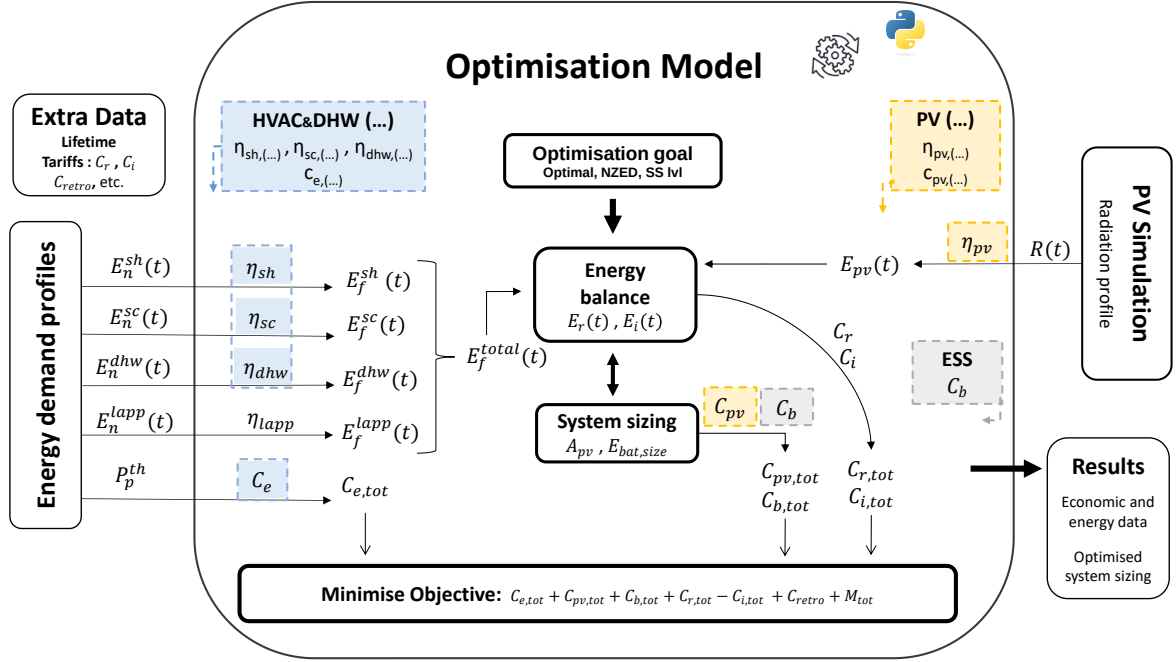


Figure 4.3. Optimisation model diagram.

4.4.1 Objective function

The objective of the optimisation is to minimise the total cost of the energy system while satisfying all energy demands, technology constraints, and (optional) self-sufficiency targets. The total cost function includes capital expenditures for HVAC&DHW, PV and ESS, as well as operational expenditures related to grid energy imports, revenues from grid injections, maintenance and replacement. Retrofit costs related to improvement of the buildings' energy efficiency (e.g., envelope, lighting) can also be included.

This cost function is subject to a comprehensive set of operational and technical constraints (e.g., energy balance, technology efficiency, PV generation, battery dispatch), and is solved using MILP techniques.

The total cost function to be minimised is expressed in the equation Eq (1).

$$\text{Total Cost} = C_{e,tot} + C_{pv,tot} + C_{b,tot} + C_{r,tot} - C_{i,tot} + C_{retro} + M_{tot} \quad (1)$$

Where:

$C_{e,tot}$ is the total investment cost of the selected thermal equipment (€);
 $C_{pv,tot}$ is the total investment cost of the selected PV technology (€);
 $C_{b,tot}$ is the total investment cost of the ESS battery (€);
 $C_{r,tot}$ is the total cost of electricity imported from the grid (€) in lifetime;
 $C_{i,tot}$ is the total revenue from electricity injected into the grid (€) in lifetime;
 C_{retro} is the retrofit cost (€);
 M_{tot} is the total maintenance and battery replacement costs (€).
 All costs are for the entire assumed duration of the project/simulation.

Each component of the total cost function is calculated as expressed in Eq. (1.1 – 1.6).

$$C_{e,tot} = C_e \cdot P_p^{th} \quad (1.1)$$

Where:

$C_{e,tot}$ is the total investment cost of the selected thermal equipment (€);
 C_e is the investment cost of the selected thermal equipment (€/kW);
 P_p^{th} is the peak thermal power (space heating, cooling, and DHW) (kW).

$$C_{pv,tot} = C_{pv} \cdot A_{PV} \quad (1.2)$$

Where:

$C_{pv,tot}$ is the total investment cost of the selected PV technology (€);
 C_{pv} is the investment cost of the selected PV technology (€/m²);
 A_{PV} is the installed PV surface area (m²).

$$C_{b,tot} = C_b \cdot E_{bat,size} \quad (1.3)$$

Where:

$C_{b,tot}$ is the total investment cost of the ESS battery (€);
 C_b is the battery investment cost (€/kWh);
 $E_{bat,size}$ is the nominal battery storage size (kWh).

$$C_{r,tot} = L_t \sum_{t=1}^T (C_r \cdot E_r(t)) \quad (1.4)$$

Where:

$C_{r,tot}$ is the total cost of electricity imported from the grid (€) in lifetime;
 L_t is the lifetime horizon for calculation (years);
 T is the total number of time steps (t);

C_r is the cost of electricity imported from the grid (€/kWh);

$E_r(t)$ is the electricity imported from the grid at time step t (kWh).

$$C_{i,tot} = L_t \sum_{t=1}^T (C_i \cdot E_i(t)) \quad (1.5)$$

Where:

$C_{i,tot}$ is the total revenue from electricity injected into the grid (€) in lifetime;

L_t is the lifetime horizon for calculation (years);

T is the total number of time steps (t);

C_i is the revenue from electricity injected into the grid (€/kWh);

$E_i(t)$ is the electricity injected into the grid at time step t (kWh).

$$M_{tot} = M_e + M_p + M_b + R_b \quad (1.6)$$

Where:

M_{tot} is the total maintenance and battery replacement costs (€);

M_e is the maintenance costs of the selected thermal equipment (€);

M_p is the maintenance costs of the selected PV technology (€);

M_b is the maintenance costs of the battery (€);

R_b is the battery replacement costs (€).

Maintenance cost calculation was similar for all components, with an annual percentual rate multiplied by the investment cost and by the simulation's lifetime. The replacement cost of the battery is calculated as a fraction of the investment cost proportional to the difference between the simulation period and the battery's lifetime.

4.4.2 District energy demand

To represent the total district energy demand, individual energy profiles from all selected buildings are aggregated by category. Each building i has an associated hourly energy demand profile for space heating (sh), space cooling (sc), domestic hot water (dhw), and lighting and appliances (lapp). The aggregated district energy demand $E_{n,d}^x(t)$, for each energy category $x \in \{sh, sc, dhw, lapp\}$, is computed in Eq. (2):

$$E_{n,d}^x(t) = \sum_i E_{n,i}^x(t) \text{ for } x \in \{sh, sc, dhw, lapp\} \quad (2)$$

Where:

$E_{n,d}^x(t)$ is the district useful energy demand for end-use x at time step t (kWh);

$E_{n,i}^x(t)$ is the energy demand of building i for end-use x at time step t (kWh).

This allows the model to compute the district demand dynamically, based on the buildings selected for analysis. The resulting aggregated profiles are then used in all subsequent optimisation procedures, including HVAC&DHW system sizing, cost calculation, and energy balance estimation.

It is important to note that, for a building-level approach optimisation, all the methodology steps and model equations (e.g. equipment sizing, PV production, energy balances) apply similarly, but only one building is considered at each time.

4.4.3 Thermal equipment (HVAC&DHW) sizing

The model calculates the overall peak power demand, the thermal power required for heating and DHW, and the thermal power required for cooling. Peak values serve as the basis for sizing energy conversion systems and estimating investment costs. The required thermal equipment capacity, P_p^{th} , is determined as the maximum value between the aggregated SH and DHW peak power, and the SC peak power. To avoid overestimation due to outliers, the thermal capacity required is calculated as the 99.9th percentile of the hourly profile's values over the simulation period.

4.4.4 Final energy demand from thermal equipment efficiency

To calculate the final energy demand $E_{f,d}^x(t)$ for each energy use $x \in \{sh, sc, dhw\}$ and each time step t , the model departs from the useful energy demand $E_{n,d}^x(t)$ and includes the influence of constant thermal equipment efficiency as presented in Eq. (3).

$$E_{f,d}^x(t) = \frac{E_{n,d}^x(t)}{\eta_x} \text{ for } x \in \{sh, sc, dhw\} \quad (3)$$

Where:

$E_{f,d}^x(t)$ is the district final energy demand for end-use x at time step t (kWh);

$E_{n,d}^x(t)$ is the district useful energy demand for end-use x at time step t (kWh);

η_x is the efficiency of the selected equipment for that use.

The efficiency coefficient is defined for the centralized DHC system in the district-level approach, and for each individual building system in the building-level approach. Likewise, Eq. (3) applies to both approaches: i) in the district-level approach, it is applied to the single centralized DHC system to convert the useful energy profiles (SH, SC and DHW) into final energy profiles; ii) in the building-level approach, the same conversion is applied independently to each building.

District-level efficiency accounts for the efficiency of the overall DHC system. In DHC composed by multiple heating/cooling equipment, e.g. more than one heat pump, a weighted average should be calculated and used. Building-level efficiencies may be differentiated by building or assumed identical, with the latter being preferable for comparability.

Efficiency of the thermal equipment is affected by degradation, d_e , through lifetime, L_t , as in Eq. (4).

$$\eta_x = \eta_{x,nom} \cdot \left(1 - \frac{d_e \cdot L_t}{2}\right) \text{ for } x \in \{\text{sh, sc, dhw}\} \quad (4)$$

Where:

$\eta_{x,nom}$ is the nominal efficiency of the selected equipment for that use;

d_e is the thermal equipment yearly degradation factor (1/year);

L_t is the lifetime horizon for calculation (years).

For lighting and appliances (lapp), the demand is already expressed in final energy, and no conversion is applied.

The expression for the total district final energy demand is defined in Eq. (5).

$$E_{f,d}^{\text{total}}(t) = E_{f,d}^{\text{sh}}(t) + E_{f,d}^{\text{sc}}(t) + E_{f,d}^{\text{dhw}}(t) + E_{f,d}^{\text{lapp}}(t) \quad (5)$$

Where:

$E_{f,d}^{\text{total}}(t)$ is the total district final energy demand at time step t (kWh);

$E_{f,d}^{\text{sh}}(t)$ is the final energy demand for space heating at time step t (kWh);

$E_{f,d}^{\text{sc}}(t)$ is the final energy demand for space cooling at time step t (kWh);

$E_{f,d}^{\text{dhw}}(t)$ is the final energy demand for domestic hot water at time step t (kWh);

$E_{f,d}^{\text{lapp}}(t)$ is the final energy demand for lighting and appliances at time step t (kWh).

4.4.5 Energy flow constraints

The balance between production, consumption, imports and exports is given by Eq. (6).

$$E_{f,d}^{\text{total}}(t) = E_{\text{pv}}(t) + E_r(t) - E_i(t) + E_{\text{bat,dis}}(t) - E_{\text{bat,ch}}(t) \quad (6)$$

Where:

$E_{f,d}^{\text{total}}(t)$ is the total district final electric energy demand at time step t (kWh);

$E_{\text{pv}}(t)$ is the PV electric energy production at time step t (kWh);

$E_r(t)$ is the electric energy drawn from the grid at time step t (kWh);

$E_i(t)$ is the electric energy injected into the grid at time step t (kWh);

$E_{\text{bat,dis}}(t)$ is the energy discharged from the battery at time step t (kWh);

$E_{\text{bat, ch}}(t)$ is the energy used to charge the battery at time step t (kWh).

Electricity can only be injected if there is PV production available: $E_i(t) \leq E_{\text{pv}}(t)$, and grid import must be non-negative: $E_r(t) \geq 0$.

4.4.6 Photovoltaic (PV) production

The PV electric energy production at each time step is defined by the product of the PV system efficiency, solar irradiance, PV area, and inverter efficiency, expressed in Eq. (7).

$$E_{\text{pv}}(t) = \eta_{\text{pv}} \cdot R(t) \cdot A_{\text{pv}} \cdot \eta_{\text{inv}} \cdot \Delta t \quad (7)$$

Where:

$E_{\text{pv}}(t)$ is the PV electricity production during time step t (kWh);

η_{pv} is the efficiency of the selected PV equipment;

$R(t)$ is the solar irradiance at time step t (kW/m²) (calculated by the PV Simulation module);

A_{pv} is the decision variable representing the PV area (m²);

η_{inv} is the efficiency of the inverter;

Δt is the duration of the time step t (h).

The PV Simulation module estimates the energy production of a PV system. Using climate data for the system's location obtained from a weather file and the PV system specifications, the module relies on the Python library *pvl* to calculate energy production over time (Anderson et al., 2023). This calculation considers the PV system's dimensions, technical details of the solar panels, panel tilt, incident solar radiation, and photovoltaic cell temperature. By integrating the *pvl* library, the simulation incorporates advanced methodologies to estimate solar position, solar radiation, and energy conversion. The PV module is detailed in Annex D.

Considering that efficiency and area are variables to the optimisation model, $R(t)$ accounts for the effective irradiance and the influence of cell temperature on solar module's efficiency, as in Eq. (8) (Anderson et al., 2023):

$$R(t) = G_{\text{eff}}(t) \cdot [1 + \gamma \cdot (T_{\text{cell}}(t) - 25)] \cdot 10^{-3} \quad (8)$$

Where:

$G_{\text{eff}}(t)$ is the effective irradiance at time step t (W/m²);

γ is the temperature coefficient (1/°C);

$T_{\text{cell}}(t)$ is the PV cell temperature at time step t (°C).

Total area used by the PV systems is limited by the available for installation, which is an input of the model.

Efficiency of the PV system is affected by degradation through lifetime, L_t , similarly to the thermal equipment expressed in Eq. (4).

4.4.7 Electrical energy storage (ESS) battery constraints

To ensure proper accounting of the battery State of Charge (SoC) over time, the model imposes constraints on the evolution of the battery charge level and its allowable discharge. The battery level in each time step t is defined recursively, considering energy charged and discharged, as well as potential energy losses associated with both operations. Additionally, a lower bound is imposed on the initial battery SoC to prevent infeasible initial conditions. The model also ensures that the energy discharged, including discharge losses, does not exceed the available energy from the previous time step.

For the initial time step $t = 1$, Eq. (9) is applied.

$$E_{\text{bat,level}}(1) \geq 0.01 \cdot E_{\text{bat, cap}} + E_{\text{bat,ch}}(1) - E_{\text{bat,dis}}(1) - L_{\text{bat,ch}}(1) - L_{\text{bat,dis}}(1) \quad (9)$$

For all other time steps $t > 1$, Eq. (10) and Eq. (11) are used.

$$E_{\text{bat,level}}(t) = E_{\text{bat,level}}(t - 1) + E_{\text{bat,ch}}(t) - E_{\text{bat,dis}}(t) - L_{\text{bat,ch}}(t) - L_{\text{bat,dis}}(t) \quad (10)$$

$$E_{\text{bat,dis}}(t) + L_{\text{bat,dis}}(t) \leq E_{\text{bat,level}}(t - 1) \quad (11)$$

Where:

$E_{\text{bat,level}}(t)$ is the battery energy level at time step t (kWh);

$E_{\text{bat, cap}}$ is the maximum battery storage capacity (kWh);

$E_{\text{bat,ch}}(t)$ is the energy charged into the battery at time step t (kWh);

$E_{\text{bat,dis}}(t)$ is the energy discharged from the battery at time step t (kWh);

$L_{\text{bat,ch}}(t)$ is the losses due to battery charging at time step t (kWh);

$L_{\text{bat,dis}}(t)$ is the losses due to battery discharging at time step t (kWh).

To prevent the battery from charging and discharging simultaneously, binary flags were introduced. Battery energy charging/discharging losses are modelled as a function of the efficiency of the storage system, proportionally to the amount of energy exchanged with the storage. Importantly, a constraint assures the same initial SoC for the following year, guaranteeing a multi-year continuity. Moreover, the charging/discharging rate (C-rate) is limited to a defined fraction of the maximum capacity of the battery.

Battery degradation over time was accounted for through a degradation factor, $d_{b,avg}$, which reflects the average reduction in effective capacity due to aging, assuming a linear annual degradation rate d_b . Two scenarios were considered. If the estimated battery's lifetime is higher or

equal than the simulation's lifetime, no battery replacement is required and the average degradation factor is computed as the midpoint degradation over the full period. If the battery's lifetime is lower than the simulation's lifetime, a battery replacement is assumed, and the average degradation factor is calculated accordingly.

Finally, the battery size is adjusted by applying the average degradation factor, $d_{b,avg}$, ensuring the required energy storage needs across the project lifetime, as expressed in Eq. (12).

$$E_{bat,size} = \frac{E_{bat,cap}}{d_{b,avg}} \quad (12)$$

Where:

$E_{bat,size}$ is the nominal battery storage size (kWh);

$E_{bat,cap}$ is the battery storage capacity (kWh);

$d_{b,avg}$ is the battery average degradation factor.

4.4.8 Net zero energy balance constraint

The net-zero energy constraint ensures that the total annual final energy demand $\sum_{t=1}^T E_{f,d}(t)$ matches the total annual PV energy production $\sum_{t=1}^T E_{pv}(t)$, as expressed in Eq. (13).

$$\sum_{t=1}^T E_{f,d}(t) = \sum_{t=1}^T E_{pv}(t) \quad (13)$$

Where:

$E_{f,d}^{total}(t)$ is the total district final electric energy demand at time step t (kWh);

$E_{pv}(t)$ is the PV electric energy production at time step t (kWh);

T is the total number of time steps (t).

This constraint is essential for implementing a Net Zero Energy District (NZED) scenario, where the district's total final energy demand over the period, e.g. one year, is met by the energy produced by PV systems. Although a positive energy balance constraint is not included in the model, the optimal or SS level scenarios may result in a positive energy balance. This result is represented by an annual PV energy surplus compared to final energy demand, i.e., higher annual energy grid exports than imports.

4.4.9 Self-sufficiency energy balance constraint

To ensure a certain level of self-sufficiency, the following Eq. (14) applies.

$$\sum_{t=1}^T E_r(t) \leq (1 - SS_{lvl}) \cdot \sum_{t=1}^T E_{f,d}(t) \quad (14)$$

Where:

$E_r(t)$ is the energy drawn from the grid at time step t (kWh);

$E_{f,d}(t)$ is the total final energy demand (including heating, cooling, hot water, and appliances) at time step t (kWh);

SS_{lvl} is the self-sufficiency level, where $0 \leq SS_{lvl} \leq 1$;

T is the total number of time steps (t);

To ensure the system's complete self-sufficiency, the total energy imported from the grid E_r must be zero at all times and SS_{lvl} is 1. The SS_{lvl} must be set as fraction between 0 and 1 to optimize the system sizing to meet any SS level below 100%, e.g. for the 90% SS level, $SS_{lvl}=0.9$, with a maximum of 10% of the final energy demand being allowed from grid imports.

4.4.10 Additional data analysis equations

The annual renewable energy used for self-consumption, $E_{ren,self}$ is expressed in Eq. (15).

$$E_{ren,self} = E_{pv,annual} + E_{bat,level}(T) - E_{bat,level}(1) - E_{i,annual} - L_{bat,annual} \quad (15)$$

Where, $E_{pv,annual}$ is the total annual PV production (kWh);

$E_{bat,level}(T)$ is the battery level at the final time step $t = T$ (kWh);

$E_{bat,level}(1)$ is the battery level at time step $t = 1$ (kWh);

$E_{i,annual}$ is the total injected energy to the grid (kWh);

$L_{bat,annual}(t)$ is the annual battery energy loss (kWh);

T is the total number of time steps (t).

The self-sufficiency rate is the share of final energy covered by self-consumed renewable energy, as presented in Eq. (16).

$$\text{Self-sufficiency rate} = \frac{E_{ren,self}}{E_{f,d,annual}^{total}} \cdot 100 \quad (16)$$

Where $E_{f,d,annual}^{total}$ is the annual final energy demand (kWh/year).

To calculate the self-consumption share as the percentage of renewable energy consumed locally, the Eq. (17) applies.

$$\text{Self-consumption share} = \left(\frac{E_{\text{ren,self}}}{E_{\text{pv,annual}}} \cdot 100 \right) \text{ if } E_{\text{pv,annual}} > 0 \quad (17)$$

In order to complement the methodology described in this chapter, selected design variables alternatives were compiled in Annex E. These alternatives cover variables for energy demand and energy systems for application of the methodology.

Chapter 5. Case study 1: small-scale district in Porto

This chapter reproduces, with adaptations and extensions, material submitted for publication to the journal Energy under the title “A methodology for economic-efficient design of net-zero, nearly-zero and positive energy districts considering adjustable levels of self-sufficiency”, which was under peer review at the time of completion of this thesis. The content has been expanded to improve clarity and completeness within the context of the thesis. Section 5.6 of the present chapter is based on material submitted to and accepted for publication and oral presentation at the ICEEEP 2026 conference, to be held in Porto, Portugal, from 10 to 12 April 2026.

5.1 Description of case study 1

An existing district located in Porto, Portugal, was selected as case study. The selected district is composed by one University building (Faculty of Dental Medicine - FMD), one mixed-use building - mostly multifamily residential with a share of office and retail use-types (RES MF), and one university students residence building (RES UNI), as described in Figure 5.1. The district is illustrative of the mixed-use urban area in which it is located.



Figure 5.1. The geographical distribution of the district in Porto, Portugal (Google maps).

The simulation used a typical meteorological year (TMY) weather file in EnergyPlus Weather File (EPW) format from the Energy Plus Database (U.S. DOE, 2025), corresponding to the Porto Sá Carneiro airport, located less than 10 km from the case study area. Figure 5.2 illustrates the selected buildings in CEA.



Figure 5.2. Representation of the selected buildings in the case study 1 in CEA software.

5.1.1 Baseline definition

Geometric characteristics were based on available data (e.g., height, number of floors, floor area) and by visual analysis (e.g., windows-to-wall ratio). The constructive characteristics of the buildings were estimated from reference data for buildings with their typology and construction age. By using standardised values, the characterisation becomes more representative, aligning better with the study's objectives. Thermal bridges were accounted as a thermal transmittance factor of 1.6 for opaque envelope and of 1.1 for glazing surfaces. Table 5.1 describes the characteristics assumed for each building considered in this case-study, including physical dimensions, construction details, internal loads and indoor comfort. Heating is considered available from October to April, and cooling from May to September.

The air ventilation rate was estimated so that, when combined with natural air infiltration, the total air change rate would reach 0.6 air changes per hour (ACH) for all buildings under assessment. Hourly schedules for occupancy, appliances, lighting, heating, cooling and hot water were compiled for each building, considering respective use-types, and are presented in Annex F.

Table 5.1. Characteristics of buildings in the selected district.

	FMD	RES MF	RES UNI
Construction year	1997	2008	2018
Number of floors above ground (average)	2	6	6
Number of floors below ground	1	0	0
Height above ground (average) (m)	9	18	18
Gross floor area (GFA) (m ²)	12 560	20 662	20 111
Useful floor area (UFA) (m ²)	10 676	15 053	14 652
Rooftop area (m ²)	4 187	2 952	2 873
External wall area (m ²)	2 942	4 600	4 770
North window area (m ²)	70.6	460.9	458
South window area (m ²)	173.4	300	245.3
East window area (m ²)	2.4	503.1	500.1
West window area (m ²)	46.6	571.5	442.1
Average air changes per hour ¹	0.6	0.6	0.6
Roof ^{1, 2, 3, 4}	40 mm XPS (80%) + glazing (20%) U-value = 1.02	60 mm XPS U-value = 0.47	80 mm XPS U-value = 0.36
Walls ^{1, 2, 3}	30 mm XPS U-value = 0.8	40 mm XPS U-value = 0.58	60 mm XPS U-value = 0.47
Windows ^{1, 2, 4}	Clear double glazed, Al frame U-value = 3.79 g-value = 0.75	Clear double glazed, Al frame with thermal cut / PVC U-value = 3.05 g-value = 0.71	Clear double glazed, Al frame with thermal cut / PVC U-value = 3.05 g-value = 0.71
Shading coefficient when shading device is active ^{2, 3}	0.08 (venetian blind)	0.12 (shutter)	0.12 (shutter)
Occupancy (m ² /p) ³	10	32.9	33.5
Appliances (W/m ²) ³	8	8.3	8.4
Artificial lighting (W/m ²)	4	4	4
Daily hot water consumption (ldp) ^{2,3}	2	30.3	33.9
Cooling Setpoint (°C) ²	25	25	25
Temperatures Setback point (°C)	30	30	30
Heating Setpoint (°C) ²	20	20	20
Temperatures Setback point (°C)	10	17	17
Min. outdoor air ventilation rate for Air Quality (l/s/p)	3.4	7.3	8.2

¹ U values in W/m².K

² (ADENE, 2021)

³ (ISO 13790, 2007)

⁴ (Raimundo et al., 2021)

⁵ For RES MF and RES UNI are the resulting weighted average by use-type. A value of 40 litres per person was considered for daily hot water consumption in residential use-type

5.1.2 Retrofit energy demand measures

A retrofit configuration was defined to include scenarios where the energy performance of the buildings is improved before supply systems are adopted, with measures such as improved insulation, glazing, lighting and appliances. Total costs related to this retrofit intervention aiming at buildings' performance improvement were estimated to be 5 532 497€. For comparison, a reference intervention was considered to occur during the simulated lifetime with a refurbishment of similar characteristics to the ones identified in the baseline configuration. This maintenance intervention was estimated to cost 2 882 171€. Therefore, the net retrofit cost was estimated to be 2 650 326€. Retrofit measures for both interventions and how they are characterised in the simulation inputs are presented in Table 5.2.

Table 5.2. Characterisation of the retrofit scenario.

Retrofit measure	Description	Characterisation	Retrofit cost	Reference baseline cost
Rooftop refurbishment	120 mm PUR polyurethane	U-value = 0.2 ^(1, 2)	55 €/m ² ⁽³⁾	35 €/m ² ⁽³⁾
Walls refurbishment	120 mm PUR polyurethane	U-value = 0.2 ^(1, 2)	55 €/m ² ⁽³⁾	35 €/m ² ⁽³⁾
Windows replacement	Two double glazed windows (one coloured) and Al frame with thermal cut / PVC	U-value = 0.55 <i>g-value</i> = 0.38 ⁽⁴⁾	300 €/m ² ⁽⁴⁾	120 €/m ² ⁽⁴⁾
Efficient lighting and appliances	High efficiency solutions	Reduction of 30% W/m ² ^(3, 5)	68 €/m ² ⁽³⁾	36 €/m ² ⁽³⁾

¹ U values in W/m².K

² (BPIE, 2023; IEA, 2013; PHI, 2018)

³ Market survey of different providers

⁴ (Raimundo et al., 2021)

⁵ (BEUC, 2023)

5.2 Energy demand results for baseline and retrofit configurations

The energy demand results obtained from the CEA simulation for the baseline configuration of the district are presented in Table 5.3, as well as the results for the configuration with the energy efficiency retrofit.

Results are presented both for the individual buildings and the district, by end-use and total demand, and expressed per gross floor area (GFA) and useful floor area (UFA). Space heating (SH),

space cooling (SC) and domestic hot water (DHW) energy demand ensures comfort conditions. Electric energy demand relates to electricity demand for lighting, appliances and ventilation.

Table 5.3. Annual energy demand results for the baseline configuration and the retrofit configuration.

Electric energy (kWh/m ² /yr)			SH (kWh/m ² /yr)		DHW (kWh/m ² /yr)		SC (kWh/m ² /yr)		Total energy demand (kWh/m ² /yr)	
by GFA/UFA	GFA	UFA	GFA	UFA	GFA	UFA	GFA	UFA	GFA	UFA
Baseline configuration										
FMD	20.7	24.3	45.1	53.1	2.4	2.8	8.3	9.8	76.5	90.0
RES MF	17.4	23.9	30.9	42.4	12.9	17.8	9.6	13.2	70.9	97.3
RES UNI	15.7	21.6	27.9	38.4	13.8	19.0	9.1	12.4	66.6	91.4
District	17.6	23.2	33.1	43.8	10.8	14.3	9.1	12.0	70.6	93.2
Configuration with retrofit										
FMD	15.2	17.9	36.9	43.5	2.4	2.8	9.1	10.7	63.7	74.9
RES MF	12.6	17.2	15.4	21.2	12.9	17.8	9.1	12.5	50.0	68.7
RES UNI	11.4	15.7	15.5	21.3	13.8	19.0	8.8	12.1	49.5	68.0
District	12.8	16.8	20.5	27.1	10.8	14.3	9.0	11.9	53.1	70.1

Total annual energy demand distribution by end-use for both configurations is presented in Figure 5.3.

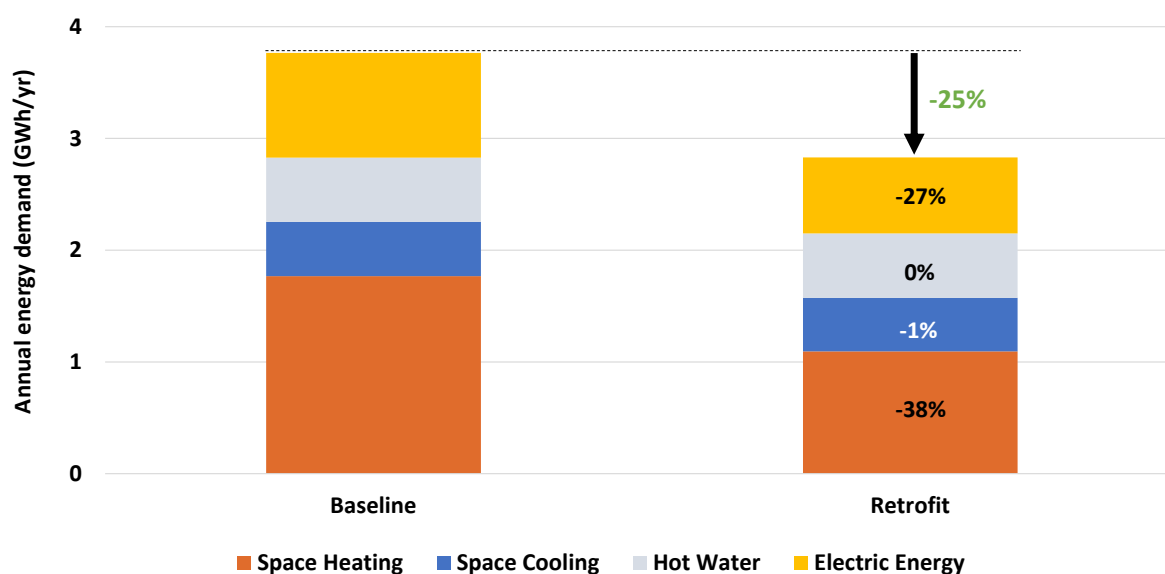


Figure 5.3. Comparison of energy demand by end-use between baseline and retrofit configurations of the district.

5.3 Energy systems: HVAC&DHW, photovoltaic and electric energy storage

Data on both district-level and building-level HVAC&DHW solutions, and PV and ESS technologies, was compiled based on commercially available solutions, including installation costs. For HVAC&DHW, particular attention was given to air-source heat pump (ASHP) technologies due to their relevance in all-electric high-efficiency solutions. This technologies were selected, along with insulation enhancing measures considered in the retrofit configuration, for their prevalence in high-impact scenarios in multiple previously published studies (Cardoso et al., 2025).

For HVAC&DHW and PV, high-efficiency / high-cost and low-efficiency / low-cost solutions were selected, resulting in the dataset summarised in Table 5.4. Costs and efficiency of district-level HVAC&DHW solutions are highly influenced by the systems typology, inlet/outlet temperature differences and sources, and network size which includes substations and piping. Building-level HVAC&DHW installation cost relative to equipment cost ranges from 20% for smaller systems (around 5 kW) to 50% for larger systems (approximately 9 kW) (EC, JRC, 2023b).

Table 5.4. HVAC&DHW systems options.

HVAC&DHW		District-level ¹		Building-level ²	
		Efficiency	Cost (€/kW)	Efficiency	Cost (€/kW)
1 - High-efficiency ASHP	SCOP	5.0		5.9	
	SEER	7.5	1 200	9.5	1 676
	COP DHW	3.5		3.9	
2 - Low-efficiency ASHP	SCOP	3.5		4.0	
	SEER	5.0	550	6.1	654
	COP DHW	2.2		2.6	

¹ literature review on centralised solutions (Buffa et al., 2019; EC, JRC et al., 2017; Ivančić et al., 2021; Mazhar et al., 2018; Vilén et al., 2023; Wirtz et al., 2020)

² (Bosch, 2017; Daikin, 2023)

PV total cost for both high and low efficiency solutions included a fixed cost for installation and auxiliaries of 645 €/kWp (138€/m²). A maximum of 75% of the total rooftop area was deemed available for PV, with south orientation and 30° tilt, without solar tracking. Additional parameters include a PV module normal operating cell temperature of 48°C, temperature coefficient of -0.0044 and inverter efficiency of 90%. A single ESS solution was selected from the reviewed alternatives. Reference values include: round-trip efficiency of 95%, CAPEX, including equipment and

installation, of around 600 €/kWh, and C-rate (maximum charging capacity per hour) of 0.5C. The resulting alternatives for PV and ESS are summarised in Table 5.5.

Table 5.5. PV and ESS options.

	Technology	Efficiency	Cost	
PV ¹	1 - High-efficiency	0.23	895 €/kWp	196 €/m ²
	2 - Low-efficiency	0.18	796 €/kWp	165 €/m ²
ESS ²		0.95 (round-trip)	600 €/kWh	

¹ Real application examples and PV module market survey (*Europe-Solarstore*, 2025)

² (EC, DG ENER et al., 2023; *Europe-Solarstore*, 2025; Minuto et al., 2021)

The degradation of components was accounted for. HVAC&DHW equipment and PV system are mainly affected in their efficiency parameters, with an estimated 0.25% yearly efficiency degradation (Lee et al., 2022) for HVAC&DHW, and a 0.55% yearly efficiency degradation for PV (*Europe-Solarstore*, 2025). ESS is affected with 2% yearly degradation of battery storage capacity (EC, DG ENER et al., 2023). Similarly, yearly maintenance costs were estimated for each component, with an average of 1% of investment cost for all components. For ESS system, a maximum lifetime of 15 years was estimated for a normal operation in standard conditions (including degradation losses) (EC, DG ENER et al., 2023), therefore battery replacement was considered for larger simulation lifetimes. Electric energy cost of 0.17€/kWh was based on Portuguese energy market in 2024 (Eurostat, 2025). A value for energy injection compensation was conservatively estimated to be 0.01€/kWh. The total lifetime of simulation, i.e., the time horizon to consider for the optimisation was set at 20 years.

5.4 Simulation

The optimisation model run under the Python-based PuLP programming modeler framework (Mitchell et al., 2011) on an Intel core i5 with 16 GB RAM, with the Gurobi solver (Gurobi Optimization, LCC, 2024) being used to solve the optimisation problem. To each alternative on energy demand, “baseline” and “retrofit” configurations, both district energy system design approaches, district- and building-level, were considered, resulting in four modelling setups: “Baseline-District”, “Baseline-Building”, “Retrofit-District” and “Retrofit-Building”.

Simulations included combinations of previously described solutions for HVAC&DHW, PV and ESS, with varied efficiencies and costs, dimensioned by the optimisation model to achieve predefined economic and energy goals: cost-optimal (Optimal) result (lower total cost), NZED (lower total cost to achieve net zero energy) and self-sufficient targets (80%, 85%, 90%, 95%, 97.5% and 100%). As predefinition, the use of both PV and ESS was allowed for all the optimisation goals. Nonetheless, the simulation comprised scenarios excluding PV and/or ESS, to enable comparisons between: 1) only grid; 2) grid with PV; 3) grid with PV and ESS; and 4) PV with ESS, excluding grid import.

The results section that follows presents the performance of the tested scenarios in terms of energy balances, system sizing and economic indicators. Building on these results, a subsequent analysis is conducted as an extension of the same case study, exploring the potential integration of electric vehicle (EV) charging stations and the expansion of PV capacity through carport solutions.

5.5 Results and discussion

The following sections present and discuss the results of the energy optimisation model applied to the described case study.

5.5.1 Main optimisation goals and self-sufficient targets

Table 5.6 summarises the energy and economic results obtained for the three main optimisation goals (cost-optimal, NZED and 100% self-sufficiency - SS100), for the four simulation setups, Baseline-District, Baseline-Building, Retrofit-District and Retrofit-Building. The best combination of technologies (HVAC&DHW and PV) alternatives is detailed for each scenario.

Results include total cost, divided into CAPEX and OPEX, as well as the respective cost components. Costs values are presented for the 20-year lifetime. Annual energy results include demand and supply values, together with self-consumption and self-sufficiency rates. Annual

carbon emissions were calculated using the Portuguese emission factor for 2023 of 0.107 tCO₂/MWh (APA, 2025), and consider only imported energy, i.e., without offsetting energy injected into the grid. System sizing details are reported to allow the assessment of the impact of different scenarios on each technology.

Table 5.6. Energy and economic results for the three main optimisation goals for all setups.

Scenario	Baseline-District			Baseline-Building			Retrofit-District			Retrofit-Building		
	Opt.	NZED	SS100	Opt.	NZED	SS100	Opt.	NZED	SS100	Opt.	NZED	SS100
HVAC&DHW - PV options	2 - 1	2 - 1	1 - 1	2 - 1	2 - 1	1 - 1	2 - 1	2 - 1	1 - 1	2 - 1	2 - 1	1 - 1
Total cost (M€)	5.55	5.56	111.43	5.74	5.77	114.66	6.73	6.74	31.70	6.90	6.93	33.13
CAPEX (M€)	2.02	2.40	77.65	2.39	2.65	80.12	4.16	4.33	23.43	4.48	4.66	24.61
HVAC&DHW (M€)	1.09	1.09	2.37	1.46	1.46	3.74	0.78	0.78	1.70	1.08	1.08	2.78
PV (M€)	0.91	1.04	1.47	0.87	0.97	1.47	0.68	0.78	1.47	0.66	0.73	1.47
ESS (M€)	0.03	0.11	73.81	0.06	0.22	74.91	0.04	0.11	17.60	0.09	0.20	17.71
Retrofit (M€)	0	0	0	0	0	0	2.65	2.65	2.65	2.65	2.65	2.65
OPEX (M€)	3.53	3.32	33.78	3.52	3.13	34.53	2.57	2.41	8.27	2.42	2.27	8.52
Grid energy use (M€)	3.12	2.84	-0.20	2.86	2.54	-0.22	2.26	2.05	-0.28	2.03	1.82	-0.30
Maintenance (M€)	0.41	0.48	33.98	0.49	0.58	34.75	0.31	0.36	8.56	0.39	0.45	8.82
Final energy (GWh/yr)	1.82	1.82	1.53	1.70	1.70	1.45	1.37	1.37	1.14	1.27	1.27	1.07
PV production (GWh/yr)	1.59	1.82	2.58	1.52	1.70	2.58	1.20	1.37	2.58	1.15	1.27	2.58
Self-consumption (GWh/yr)	0.86	0.93	1.53	0.81	0.90	1.45	0.67	0.73	1.14	0.64	0.70	1.07
Exported (GWh/yr)	0.72	0.89	1.00	0.70	0.80	1.09	0.52	0.64	1.41	0.51	0.57	1.48
Imported (GWh/yr)	0.96	0.89	0.00	0.88	0.80	0.00	0.69	0.64	0.00	0.63	0.57	0.00
Self-sufficiency rate (%)	47	51	100	48	53	100	49	53	100	50	55	100
Self-consumption rate (%)	54	51	60	54	53	56	56	53	44	56	55	42
Carbon emissions (tCO ₂ e/yr)	102.72	95.23	0.00	94.16	85.60	0.00	73.83	68.48	0.00	67.41	60.99	0.00
System sizing												
Heating capacity (MW)	1.98	1.98	1.98	2.23	2.23	2.23	1.42	1.42	1.42	1.66	1.66	1.66
Cooling capacity (MW)	0.49	0.49	0.49	0.57	0.57	0.57	0.50	0.50	0.50	0.57	0.57	0.57
PV capacity (MWp)	1.01	1.16	1.64	0.97	1.08	1.64	0.76	0.87	1.64	0.74	0.81	1.64
ESS nominal size (MWh)	0.04	0.19	123.01	0.01	0.36	125	0.07	0.20	29.40	0.15	0.33	29.52

Figure 5.4 and Figure 5.5 illustrate the differences in the results obtained in the main optimisation goals' scenarios for each setup, and foster further comparison between district and building-level approaches, and between baseline and retrofit configurations.

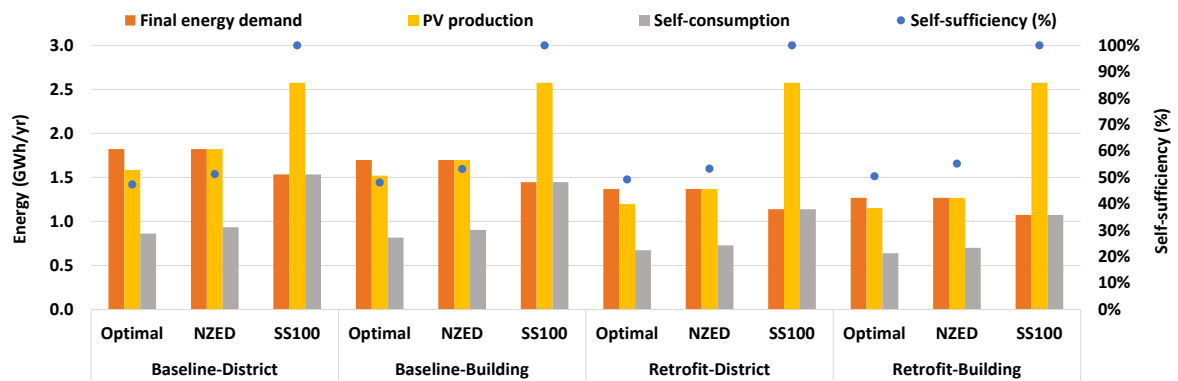


Figure 5.4. Annual energy results for the main scenarios (optimal, NZED and SS100).

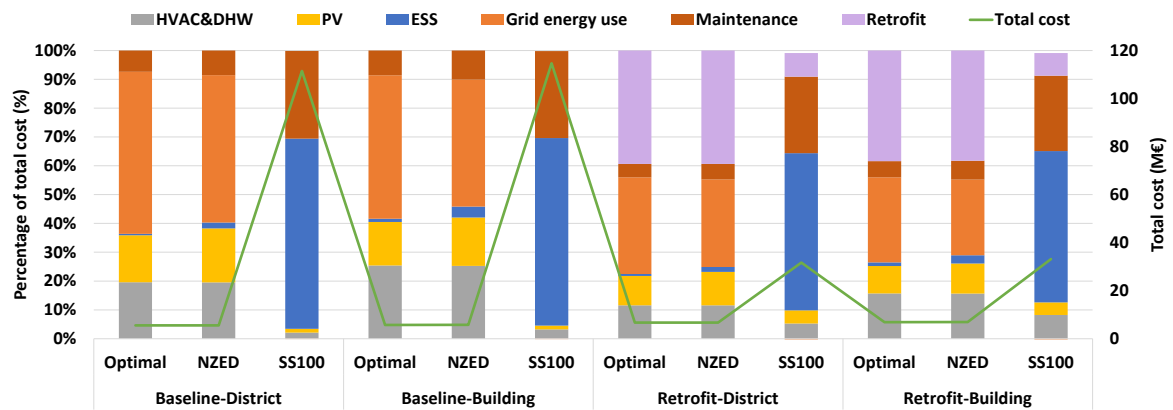


Figure 5.5. Cost split across lifetime horizon for the main scenarios (optimal, NZED and SS100).

The obtained results indicate that the cost-optimal scenario for the case study under analysis does not fully meet the NZED target, in which the renewable energy locally produced for one year is, at least, equal to the district final energy demand. This implies that achieving net zero energy balance would correspond to higher costs over the simulation timeframe. The optimal solution depends on the balance between additional capital investment, and associated maintenance costs, and the increase in achievable reductions in grid energy use. Nonetheless, the difference in terms of total cost between the optimal and the NZED scenarios is lower than 1% for all setups, considering that the CAPEX increase is nearly compensated by the OPEX decrease during the simulated lifetime. Given the uncertainty inherent to input assumptions, particularly related to energy costs, efficiencies, and degradation, it is reasonable to consider that the optimal scenario could fall within the margin of error of the NZED threshold.

On carbon emissions, cost-optimal scenarios represent the worst case for each setup, associated with the higher energy import from grid. Even though the factor is expected to decrease with the decarbonisation of the electrical grid system, this decrease was not considered in the

present analysis. In general, NZED scenarios represent a 7-10% reduction of carbon emissions from grid imported energy compared to optimal.

On the other hand, to achieve full self-sufficiency, the self-consumed PV energy must match the total demand, which required not only maximising PV production capacity by covering the entire available area, but also increasing significantly ESS capacity and associated costs. Increasing ESS capacity enables a higher self-consumption rate of PV production by storing surplus PV energy during periods of high generation and using it to cover demand during periods of low or no production. In this case, the available PV installation area and the relationship between energy surplus and deficit profiles allowed self-sufficiency to be achieved, albeit with very high ESS-related costs. However, under different conditions, achieving self-sufficiency may become infeasible. Also, although this study validates system behaviour feasibility, the physical viability of such large storage systems would require further assessment. Another important consideration in high-SS designs is the acceptable share of energy surplus. To maintain economic feasibility while targeting close to 100% SS, some level of discarded generation may be necessary, especially if storage costs are high or energy injection is economically compensated.

The exploration of increasing self-sufficiency targets revealed several key insights. The total cost variations across the multiple scenarios studied for each modelling setup are illustrated in Figure 5.6. The darker background graph zooms into the lower total cost section of the general figure to increase detail.

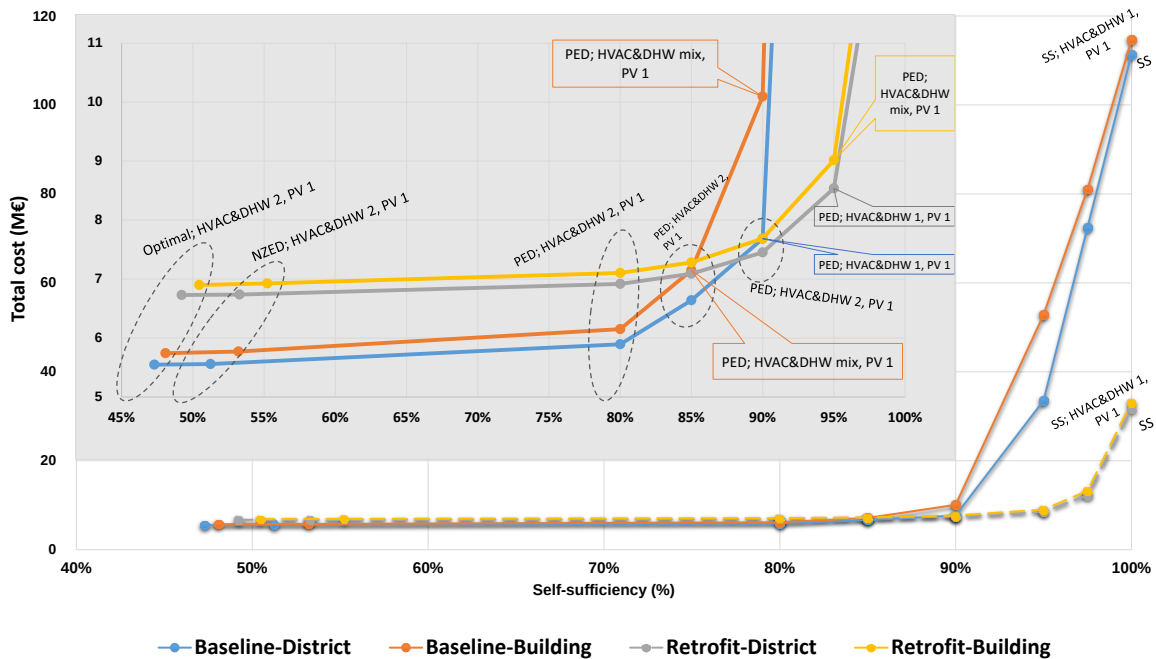


Figure 5.6. Variation of total cost with the level of self-sufficiency for each scenario in the four modelling setups (dark graph zooms into lower total cost).

5.5.1.1 District-level vs Building-level

For both baseline and retrofit configurations, district-level approach is advantageous when compared to building-level, with Table 5.6 showing a 3-4% reduction in total cost for optimal and NZED scenarios. For higher SS targets, the benefits of the district-level approach tend to increase, as displayed in Figure 5.6. In fact, for the baseline configuration, the difference between district-level and building-level total cost reaches 8%, at the SS85 target, and 58% at the SS95. For the retrofit configuration, the higher difference in total cost is 8% observed for the SS97.5 scenarios. This is mostly due to the aggregated flexibility and load balancing enabled by centralised energy systems, especially at high SS levels. However, the analysis included different systems to each approach, with specific efficiencies which may inherently favour one over the other. To understand the isolated influence of aggregating profiles, further analysis was developed in 5.7.3.2.

5.5.1.2 Baseline vs Retrofit

Moreover, looking at the evolution of the total cost across the optimisation goals, in Figure 5.6, Baseline-District scenarios present the best result from the optimal to the SS85 target. Retrofit scenarios present the lower total cost for targets over the SS90. For cost-optimal and NZED scenarios, retrofit configuration presents around 17-18% higher total costs than baseline, for both district and building-level. Retrofit scenarios benefit from lower energy demand due to energy efficiency improvement measures, which entails an intervention cost, quantified in Table 5.6. Under the proposed assumptions, the benefits of downsizing energy systems, along with the associated reductions in investment, maintenance, and grid energy demand resulting from retrofit, do not offset the cost of the efficiency improvement measures.

Figure 5.6 illustrates the significant impact of energy efficiency improvement measures in total cost, however, the associated cost is only compensated after the SS90 target. Retrofit interventions add value at higher SS levels, as demand reduction measures reduce the scale of on-site generation and storage needed to reach the target. Financial incentives or other support policy mechanisms could increase the attractiveness of these interventions. A financial compensation of 43-45% of the retrofit cost would be sufficient to turn retrofit interventions viable in optimal and NZED scenarios. For higher SS targets, the incentive needed would decrease significantly to the point that it wouldn't be necessary to achieve viability.

5.5.1.3 High vs low efficiency solutions

In Figure 5.6, labels detailing the combination of solutions for each result enable to analyse the evolution of the best alternative selected for the various results. Across all results, the high-efficiency PV solution was selected, indicating that the increase in cost justified the benefit in the efficiency increase for the analysed case study. However, for HVAC&DHW equipment, the trade-off was only justified for high SS targets. As SS targets rise, investments in high-efficiency equipment and PV systems become more economically justified, as these technologies reduce dependency on external supply and ESS capacity, which is still the most expensive component of the system.

5.5.2 Economic feasibility and long-term investment analysis of renewable energy integration

A long-term economic assessment of renewable energy integration was performed by comparing the inclusion of PV and ESS technologies to grid-only configuration. For this purpose, additional simulations were performed for grid-only and PV only (i.e., excluding ESS) variants of the optimal and NZED scenarios. Across all setups, PV based configurations outperform grid-only alternatives, reducing total costs by 16 to 26%. While ESS remains relatively expensive, its inclusion, particularly at small scale, slightly improves outcomes in optimal and NZED scenarios and proves essential to achieving high SS levels.

Table 5.7 presents the long-term economic assessment of the simulated scenarios using Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time over a 20-year period, with the grid-only configuration serving as the baseline. The objective is to examine how higher initial investments, from PV and ESS, and in some cases from HVAC&DHW alternatives, translate into economic benefits through reduced operating costs and energy imports.

NPV remains positive across all optimal and NZED scenarios (1.4-2.0 M€), with payback times of 6- 7.5 years. The highest NPV (2.25 M€) occurs in the Baseline-District SS80 scenario although with a longer payback (10.3 years). However, beyond SS85-90, economic performance deteriorates significantly, with NPV declining and becoming negative in most setups, especially above SS95, where very high investment lead to negative IRR and payback exceeding the project lifetime. District-level setups generally achieve better economic performance than building-level ones, due to the smoother aggregated demand and more efficient use of shared resources. Retrofit setups tend to support positive NPV for slightly higher SS levels, benefiting from improved energy performance. However, the additional renovation cost limits the advantage at very high SS targets.

Table 5.7. NPV, IRR and Payback Time (PB Time) for all scenarios, taking the grid-only optimal scenario as reference.

	Baseline-District			Baseline-Building			Retrofit-District			Retrofit-Building		
	NPV (M€)	IRR	PB Time (yr)	NPV (M€)	IRR	PB Time (yr)	NPV (M€)	IRR	PB Time (yr)	NPV (M€)	IRR	PB Time (yr)
Optimal (PV - no ESS)	2.02	15%	6.2	1.83	15%	6.3	1.57	16%	6.0	1.40	15%	6.3
NZED (PV - no ESS)	1.98	13%	6.9	1.77	13%	7.1	1.53	14%	6.8	1.35	13%	7.0
Optimal	2.03	15%	6.3	1.87	14%	6.6	1.59	15%	6.3	1.46	14%	6.7
NZED	2.05	13%	7.1	1.91	12%	7.5	1.60	13%	7.1	1.48	12%	7.5
SS80	2.25	7%	10.3	2.02	6%	10.5	1.78	7%	9.9	1.57	7%	10.3
SS85	1.83	5%	11.9	1.41	3%	13.8	1.63	6%	11.0	1.42	5%	11.4
SS90	1.22	2%	16.2	-0.64	-1%	-	1.37	4%	12.4	1.13	4%	13.0
SS95	-17.39	-14%	-	-31.50	-	-	0.67	2%	17.3	0.23	1%	19.0
SS97.5	-45.55	-	-	-51.83	-	-	-1.98	-4%	-	-2.78	-5%	-
SS100	-73.71	-	-	-76.11	-	-	-16.03	-15%	-	-17.11	-16%	-

Figure 5.7 presents the cumulative cash flow curves for the selected scenarios, grouped by setup. Each graph illustrates the payback period, identified by the year in which cumulative cash flow becomes positive. For clarity, only the best-performing scenario for each objective (optimal, NZED, and SS targets) is shown, and excluding SS scenarios that do not reach payback within the 20-year lifetime.

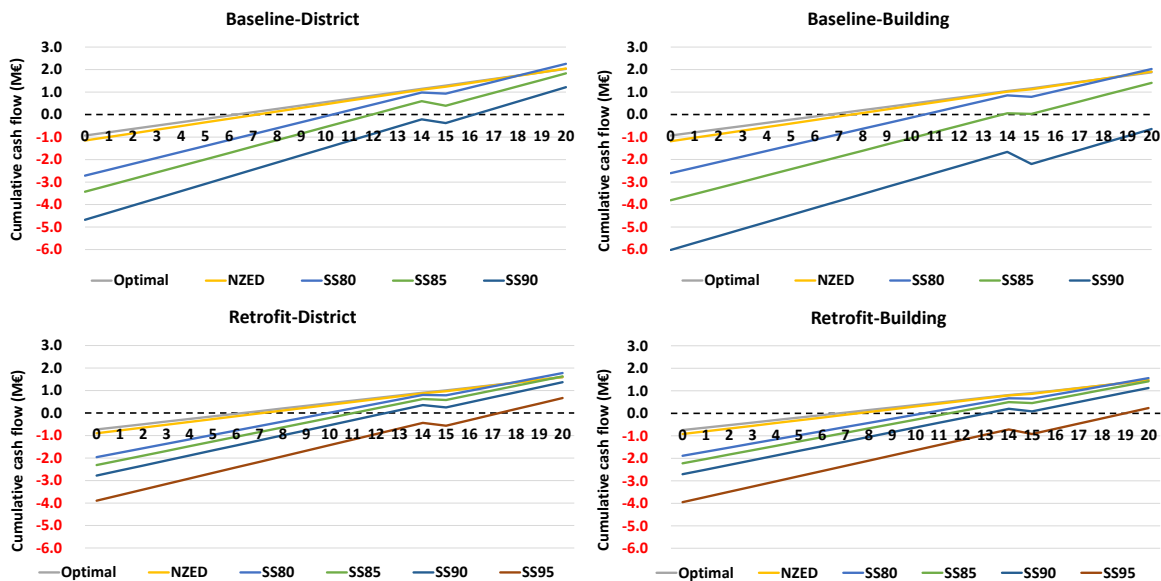


Figure 5.7. Cumulative cash flow for viable scenarios by modelling setup.

5.5.3 Sensitivity Analysis

5.5.3.1 Key economic parameters

To assess the impact of key economic parameters on the optimisation outcome, a sensitivity analysis was conducted for the cost-optimal scenario within the Baseline-District setup, which demonstrated the most consistent performance across optimisation goals. The analysis considered individual variations in the following parameters: HVAC&DHW system cost, PV cost, ESS cost, electricity retail tariff, and the injection compensation tariff. Figure 5.8 illustrates the percentage deviation in total cost from the reference scenario.

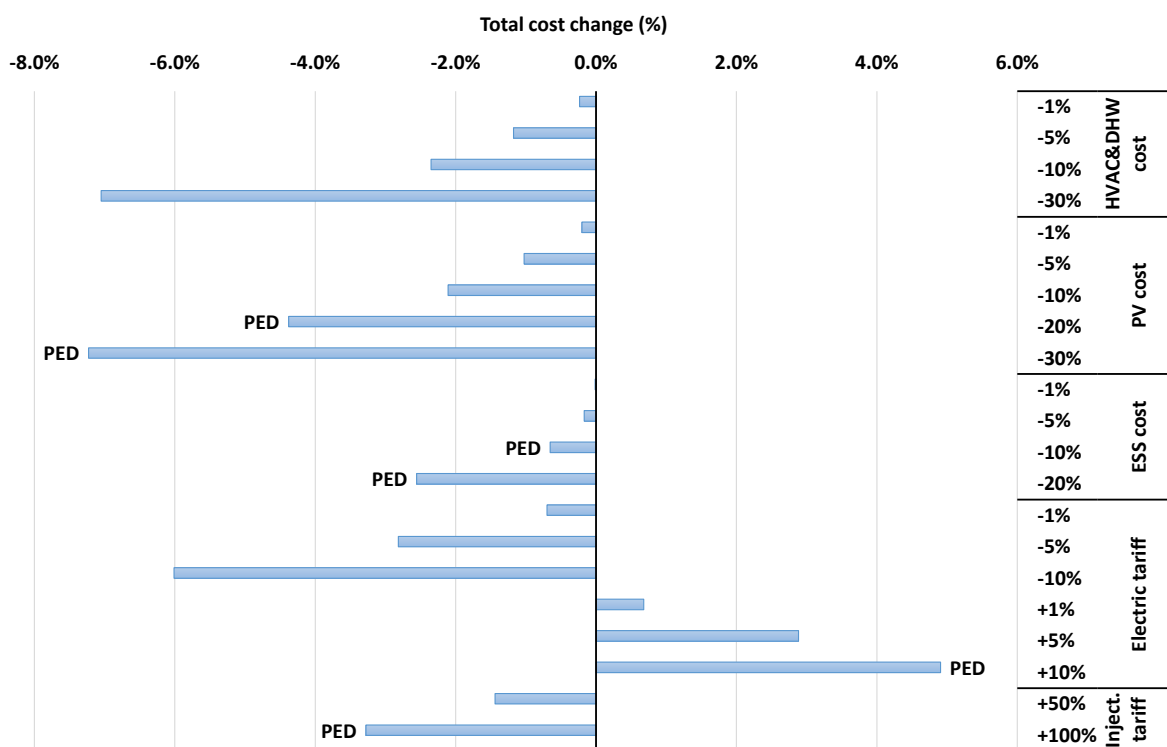


Figure 5.8. Sensitivity analysis results for the Optimal scenario in the Baseline-District setup.

The sensitivity analysis indicates that the parameters exerting the highest influence on total cost variation are reductions in HVAC&DHW and PV system costs, and variations in electricity tariffs. It is important to note that ESS system cost variations show a limited impact on total cost within this analysis, as it focuses on the optimal scenario where ESS costs are relatively lower compared to other scenarios. However, in scenarios targeting higher self-sufficiency levels, ESS represents the largest cost component, and in such cases, reductions in ESS costs would significantly improve the economic case for achieving these targets. This is further supported by the observation that even a 10% reduction in ESS cost can enable the optimal scenario to reach PED status. Interestingly, while reductions in electricity tariffs generally decrease total costs, an increase in the electricity tariff

forces the optimisation model to achieve PED status as the optimal result, albeit with higher overall costs. In this situation, investments in PV and ESS become more economically advantageous than relying on grid imports, driving the system toward greater energy autonomy. Although HVAC&DHW cost reductions influence total costs, they do not, in isolation, lead the system to PED status to the same extent as PV, ESS, and tariff factors. This suggests that while thermal energy costs are significant for overall economics, renewable generation and tariff structures are more decisive in enabling positive energy performance. In summary, the results highlight that advances in PV and storage cost reductions, coupled with supportive electricity injection compensation policies, are essential for the transition toward positive energy districts.

5.5.3.2 Isolated impact of energy demand profile aggregation in the district-level approach

To refine the interpretation about the benefits of load levelling and peak shaving effects associated with aggregation and smoothing of energy profiles of the buildings, additional simulations were run based on the district-level approach but using the same equipment efficiencies and costs as in the building-level scenarios. This allowed for an isolated assessment to accurately attribute observed gains to either technological efficiency or system-scale operational advantages. Thus, optimal and NZED scenarios achieved 3-5% lower total costs on the district-level approach for both baseline and retrofit configurations. The reductions solely in HVAC&DHW cost were 11% for baseline and 14% for retrofit, which highlights the high potential related to aggregating profiles and peak shaving in equipment dimensioning. For the optimal scenarios, PV cost, ESS cost and self-consumption rates also presented marginal improvement.

5.6 Extended analysis: EV charging demand and PV area availability

The analysis described in the previous section was extended to integrate electric mobility, a relevant component of urban energy systems that remain comparatively underexplored, as highlighted in Chapter 2. Within this context, the following analysis explores the introduction of electric vehicle (EV) charging stations and the expansion of the available PV area through carport solutions. Although the integration of electric mobility constitutes the primary motivation for this extended analysis, these elements are also examined for their potential to address the structural limitations identified in the general results of case study 1. In particular, this analysis addresses: 1) the temporal mismatch between demand and PV generation, aiming at enhancing self-consumption, reducing overall costs and facilitating the attainment of NZED; 2) the limitation of the

available PV area which led to a significant increase in total costs, driven mainly by ESS cost, for higher energy self-sufficiency targets. The objective is to evaluate the trade-offs associated with these additions in terms of cost, renewable energy integration and the ability to achieve NZED/PED.

Mobility in the context of NZED and PED has been investigated in previous studies, including the design of PED encompassing electric private vehicles and public transport use (Erba & Pagliano, 2021), coupled PV-heat pump-thermal storage-electric vehicle system for electricity prosumers in Sweden (Huang et al., 2019), and EV demand in designing a self-sufficient district (Laitinen et al., 2021) or its influence in a zero emission neighbourhood (Lausselet et al., 2021). However, none of these studies explicitly focuses on addressing the limitations identified in the present analysis.

A simplified representation of the extended system configuration is shown in Figure 5.9, including the existing buildings, grid connection, PV installations, ESS, and the newly introduced EV charging station and PV carport, together with an image of the potential real location.

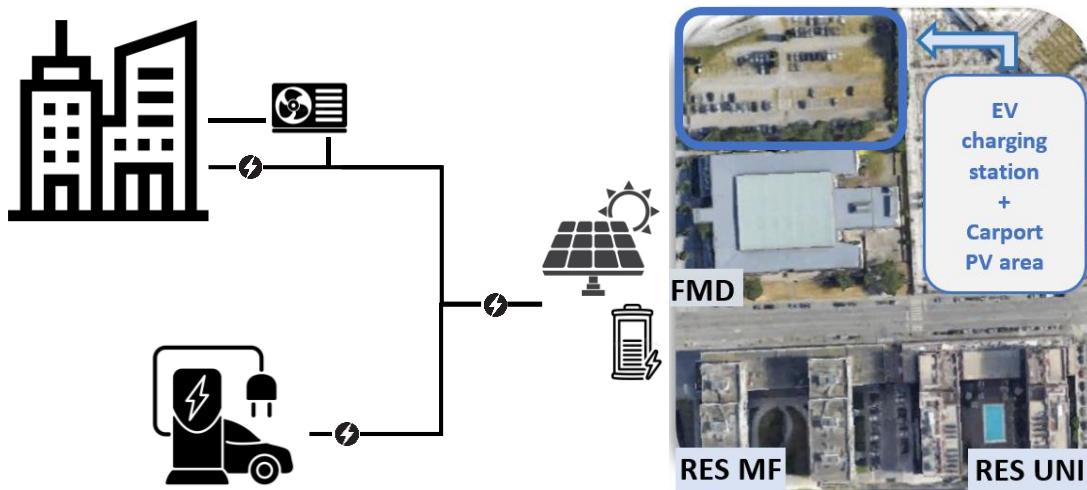


Figure 5.9. Representation of the system configuration and distribution of the project.

The application followed the same method from the previous analysis, targeting optimal, NZED and SS goals, however, focusing exclusively on the district-level approach and on the baseline setup. The alternatives considered for the district-level solutions were exactly the same from the previous analysis, both in efficiencies and costs. A new cost component is added to equation Eq. (1) related to the investment cost of the EV station based on a defined cost per charging spot.

The EV charging station is added as a new district-level demand and its operation is modelled through fixed charging profiles (kW demand per timestep), representing different temporal distributions. Two reference profiles were considered:

- Daytime (fast charging with 22 kW per spot), with higher demand between 8:00 and 18:00, reflecting charging behaviour linked to universities, offices, and commerce;

- Night-time, corresponding to residential usage (11 kW per spot) with peak demand between 18:00 and 24:00.

Profiles are scaled to the same daily and annual energy demand, allowing to isolate the effect of temporal alignment with PV generation, and are presented in Figure 5.10.

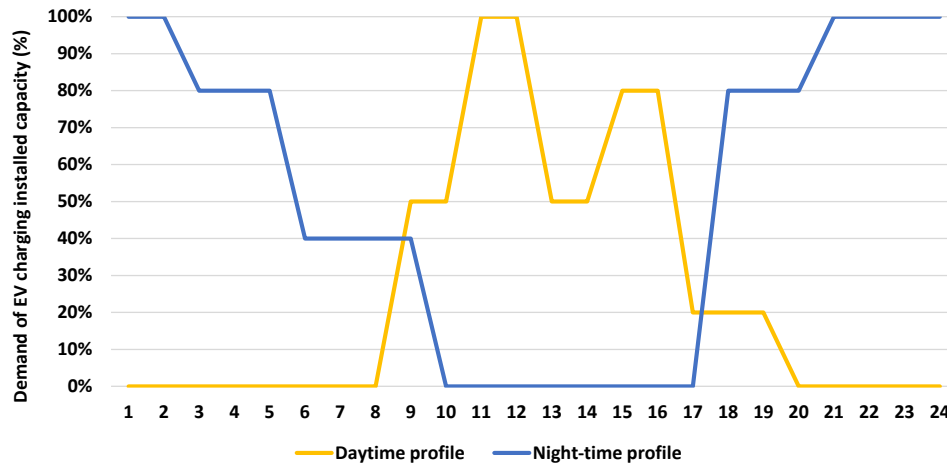


Figure 5.10. Profiles of percentual demand of EV charging: daytime vs night-time

Carport provides additional area for PV beyond rooftop availability, addressing one of the main limitations identified in the previous analysis, where PV surface area was a critical constraint to achieving higher self-sufficiency targets. A total cost of €10 000 per spot was considered for the charging station (LaMonaca & Ryan, 2022). EV charging revenues were accounted based on the cost of grid electricity, implying that EV demand does not generate additional profit. This ensures that the analysis focuses exclusively on the system-level impacts of EV charging integration and PV expansion on total cost, renewable energy share, and self-sufficiency rates. Two analyses of setup variants were structured:

- Main analysis: focusing on the influence of EV charging profiles (day vs. night) and the presence of PV carports (with vs. without). These setup variants allow a direct comparison of the effect of temporal alignment between demand and PV generation, and the impact of increasing the PV installation area.
- Scaling: exploring the effect of increasing the EV charging capacity (number of spots) and further expanding the carport PV area. These setup variants highlight how larger charging demands interact with system constraints and illustrate under which conditions the cost-optimal design shifts to NZED/PED.

Table 5.8 summarises the setup variants considered for both analyses.

Table 5.8. Setup variants considered in the analyses (D – day; N – night; CP – carport)

Setup variants		EV energy demand (MWh/yr)	Total useful energy demand (MWh/yr)	Carport PV available area (m ²)
BD		-	3 765	-
Main analysis	10-D	498 (10 spots)	4 263	-
	10-D-CP	498 (10 spots)	4 263	1 400
	10-N	498 (10 spots)	4 263	-
	10-N-CP	498 (10 spots)	4 263	1 400
Scaling	20-D-CP	996 (20 spots)	4 761	1 400
	30-D-CP	1 494 (30 spots)	5 259	1 400
	40-D-CP	1 991 (40 spots)	5 756	1 400
	30-D-CP+	1 494 (30 spots)	5 259	2 800

5.6.1 Main analysis

The analysis first focused on the setup variants designed to test the effect of EV charging profiles (daytime vs. night-time) and the addition of a PV carport. Figure 5.11 presents the variation in total cost across different optimisation scenarios.

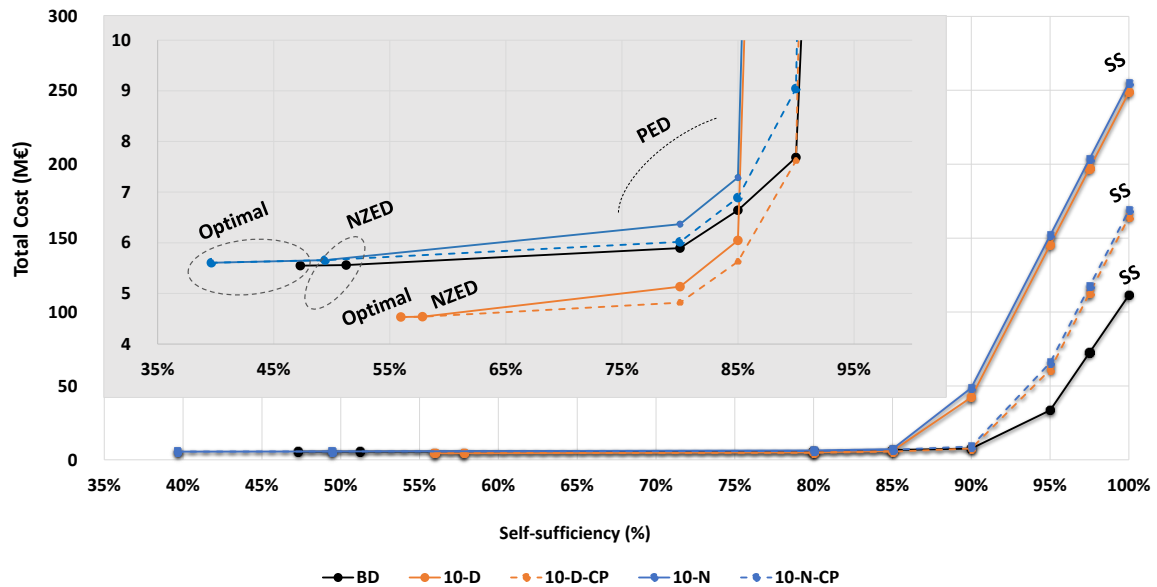


Figure 5.11. Total cost of each scenario in the setup variants (dark graph zooms into lower total cost).

Achieving NZED requires a higher cost than the cost-optimal design for all the setup variants. Daytime variants exhibit lower costs for the optimal, NZED, and low SS levels; however, above 85%

SS their total cost exceeds that of BD. Night-time variants show costs similar to BD under both optimal and NZED conditions, but with lower SS levels. This is consistent with the assumption of a selling tariff equal to the grid purchase cost: while economically neutral, the larger demand reduces the energy balance indicators despite similar PV output. Finally, the carport variants yield identical results to the non-carport ones in cost-optimal and NZED scenarios, as buildings' rooftop area was not fully used. The advantage becomes evident at high SS levels, where the additional PV surface reduces grid dependence and mitigates the need for costly storage. Figure 5.12 clarifies the differences in costs between optimal and NZED, and the percentage of net annual energy demand covered by PV in the optimal scenarios (100% would be NZED).

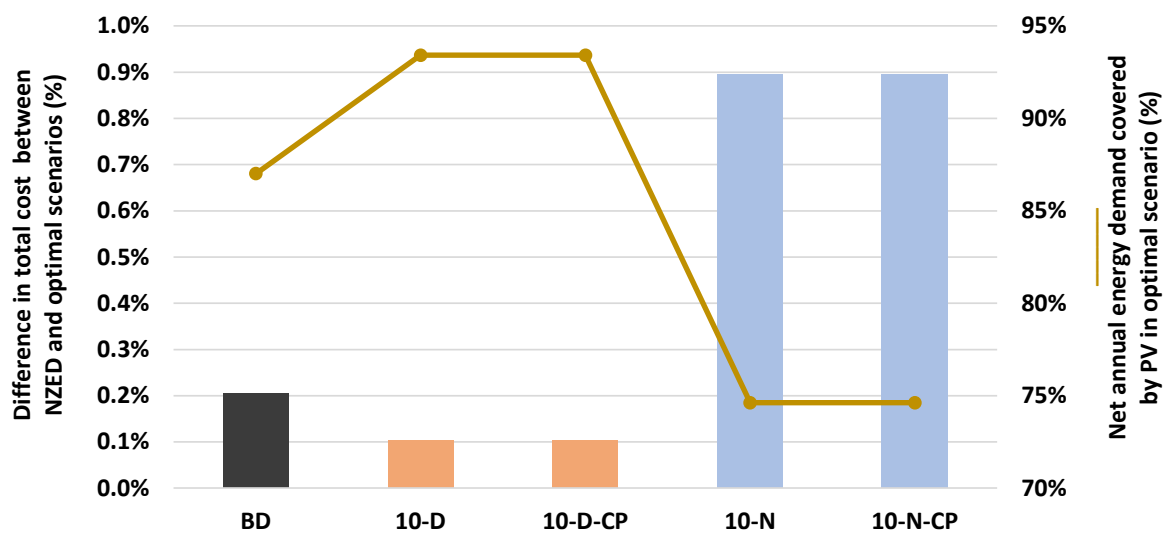


Figure 5.12. Difference in total cost (optimal vs. NZED) and energy demand vs. PV (optimal).

Results show that the daytime variants reduce the cost gap compared to BD, whereas the night-time variants increase it. Also, daytime charging favours the energy balance between demand and PV production, while night-time charging worsens it.

Key energy parameters are presented in Figure 5.13, covering the optimal and NZED scenarios, as well as selected high-SS levels, for BD and the four setup variants.

For annual final energy demand, the main difference arises between BD and all setup variants, due to the additional EV demand. This increase represents an analytical challenge and should always be considered when interpreting the results. No variation is observed between optimal and NZED scenarios, with differences only appearing at high SS levels (e.g. SS100), where the HVAC&DHW selected option changes.

For PV installed capacity, all NZED solutions require higher dimensions than the optimal. The gap is smaller for the daytime variants, reflecting better alignment between PV production and EV demand. From SS80 onwards, rooftop PV surfaces are fully saturated, with additional capacity only possible in the carport variants. For ESS nominal size, a very substantial increase is required for

NZED and high SS levels, which explains the steep rise in total costs under these conditions. The highest storage requirements occur in the night-time and no-carport variants. Regarding self-sufficiency rates, the daytime variants systematically improve SS compared to BD, whereas the night-time variants reduce it, both in optimal and NZED scenarios. Finally, for self-consumption rates, higher utilisation of PV is observed in the daytime variants, while the night-time variants show lower values. In all cases, self-consumption decreases when moving from optimal to NZED, confirming that NZED is not the cost-optimal outcome.

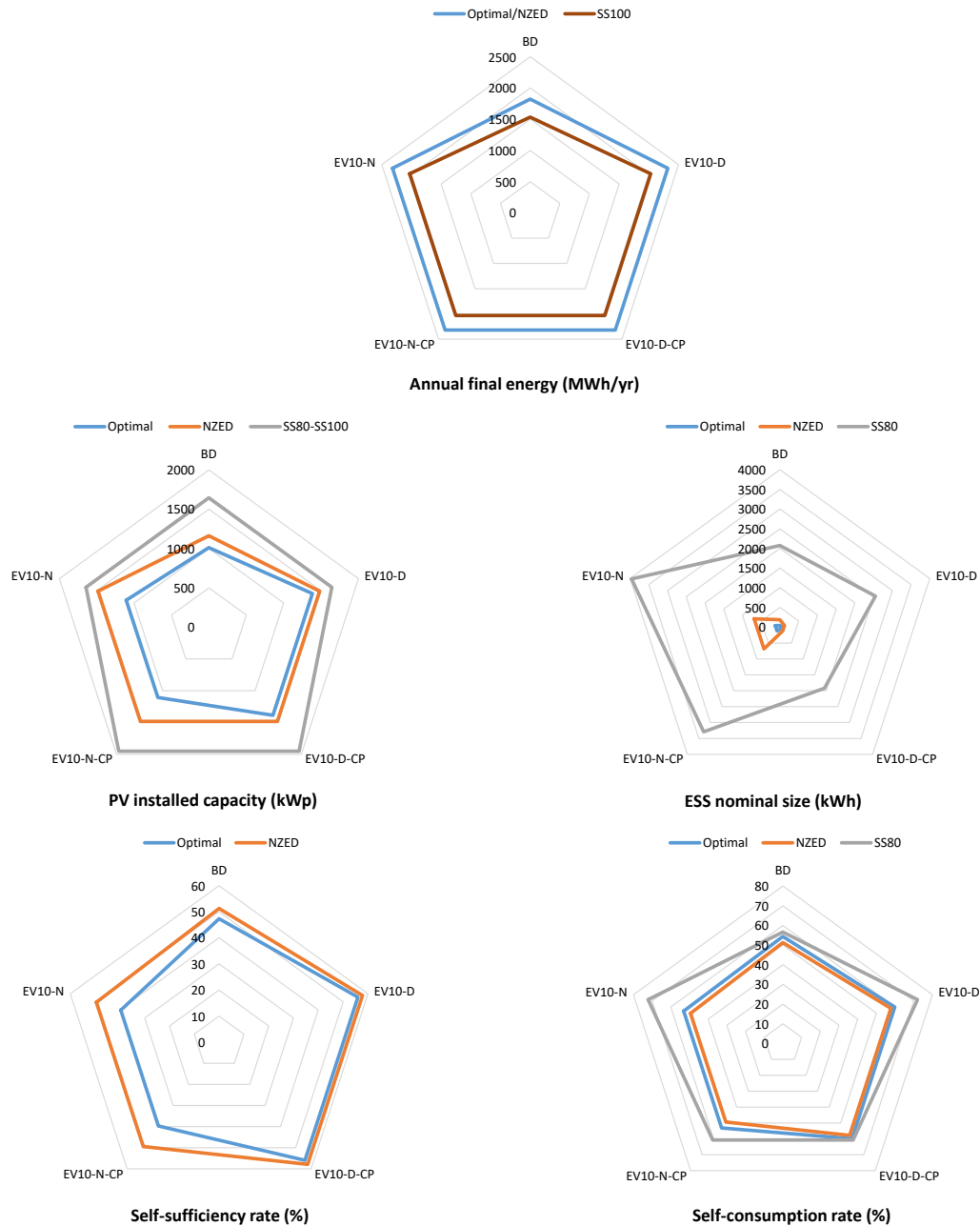


Figure 5.13. Differences on energy parameters of scenarios of the five setup variants.

5.6.2 Scaling

To explore the effect of increasing charging demand, a scaling analysis was carried out with four setup variants (10-D-CP, 20-D-CP, 30-D-CP, 40-D-CP) and one case with additional PV availability (30-D-CP+). Figure 5.14 shows the percentage of available area occupied by PV and the percentage of net annual energy demand covered by PV.

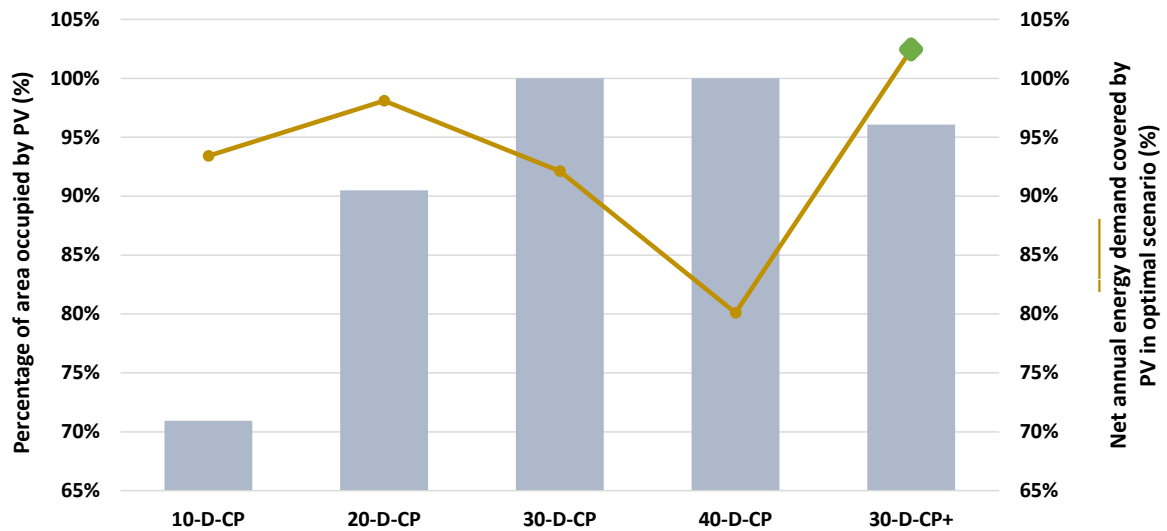


Figure 5.14. Area occupied by PV and energy demand vs. PV (optimal).

Results confirm that scaling EV demand has a non-linear effect. Compared to 10-D-CP, the 20-D-CP variant reduces the gap between PV and demand and the cost difference between optimal and NZED, but still falling short due to insufficient demand matching. With 30-D-CP, the optimal configuration still fails to reach NZED, driven by PV surface constraints. The additional surface in 30-D-CP+ unlocks the potential for greater PV installation, enabling the optimal solution to become a PED. The 40-D-CP variant not only increases the deficit in the optimal solution but also prevents NZED from being reached due to the insufficient area available. Overall, the scaling analysis demonstrates for this case that, while higher EV demand improves the match between PV production and load, additional PV availability is required to unlock PED potential.

5.7 Insights from the model application to the case study

The framework enables detailed evaluation of energy system configurations, supporting informed decisions on trade-offs between cost, performance and sustainability goals. Results show that district-level approaches are more effective in achieving high SS levels, while their advantage for cost-optimal or NZED scenarios depends on context-specific factors such as equipment costs and electricity tariffs.

Sensitivity analysis reveals that PV and ESS costs, and electricity prices are key drivers of system performance and economic viability. Notably, higher electricity tariffs promote PED by making investments in PV and ESS more attractive than relying on grid imports. Conversely, while reductions in HVAC&DHW equipment costs lower total investment, they were insufficient alone to reach PED status. Studying the economic feasibility of renewable energy integration showed that net present value (NPV) remains positive, with payback periods between 6 and 7.5 years across all optimal and NZED cases. High SS targets may not achieve payback within the 20-year analysis horizon unless supported by favourable market or policy conditions. Retrofit configurations show limited economic attractiveness under standard conditions, becoming competitive only when incentives cover around 50% of the initial investment, or when targeting high-SS levels.

EV charging analysis showed that daytime variants consistently outperformed night-time ones in terms of cost, self-sufficiency, and self-consumption, thanks to a better temporal alignment with PV production. While daytime charging and carports mitigate costs and enhance self-sufficiency, achieving NZED/PED conditions requires both higher demand during solar production periods and expanded PV capacity. These findings emphasise the critical role of spatial constraints and demand profiles in designing cost-effective, self-sustained urban energy systems.

Overall, district-scale planning offers strategic advantages for energy autonomy, while retrofit-only strategies require incentives to be economically viable. The framework provides a robust tool for urban energy planning, aligning technical and financial feasibility with long-term sustainability objectives.

While the results show that achieving high performance districts is possible through PV and ESS combination, space constraints, the daytime-limited generation profile and ESS costs constitute significant limitations. These constraints motivate the expansion of the optimisation model in the following chapter to include additional technologies and to evaluate potential pathways to overcome spatial and economic barriers.

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Chapter 6. Expanded version of the optimisation model

6.1 Expanding the dynamic optimisation model

The version of the optimisation model presented in Chapter 4 established the fundamental structure for district-level techno-economic optimisation, focusing primarily on the interaction between energy demand, PV generation, electric energy storage and grid exchanges. The application of the framework validated the first version of the model and the feasibility to achieve NZED and PED with the selected technologies. In this chapter, the model is further developed to overcome identified techno-economic constraints and to be applicable to a wider set of cases.

The major updates introduced in the advanced version of the model build directly upon the original formulation and include:

1. the integration of seasonal thermal energy storage (STES), supported by ground-source heat pumps (GSHP);
2. the implementation of wind energy as an alternative renewable generation source;
3. revisions to the objective function to incorporate the costs associated to the installation and maintenance of GSHP, STES and wind energy system;
4. revisions to the energy balance flow equations to include new technologies;
5. the update of economic indicators, regarding present value calculation and discount rates, and environmental performance indicators, embodied in greenhouse gas (GHG) emissions, with the inclusion of future projected decarbonisation factors of electric national grid.

The resulting formulation provides a more comprehensive representation of district-scale energy systems, supporting the evaluation of a wider range of strategies for achieving cost-efficient and emission-neutral performance.

The integration of the new technologies reshapes the energy balance in several ways. On the demand side, GSHP becomes an alternative to ASHP, introducing dependency on ground heat-exchange conditions, while STES adds a long-term flexibility mechanism that contrasts with the shorter-cycle behaviour of electrical storage. On the supply side, wind generation complements or competes with PV, altering the temporal distribution of renewable electricity generation. Together, these enhancements allow the model to capture the interplay between short-term and seasonal effects, leading to a more realistic evaluation of district-level energy strategies.

The expanded optimisation model preserves the original structure, allowing different technologies to be simulated depending on the configuration under analysis. This enables systematic comparison across the range of supply-side options, such as electricity from the grid, PV, wind, and optionally combine them with thermal and/or electrical storage solutions. Each cost component is included in the objective function only when the corresponding technology is selected, ensuring consistency across scenarios and comparability of the resulting solutions.

The diagram representing the structure of the expanded version of the optimisation model is presented in Figure 6.1.

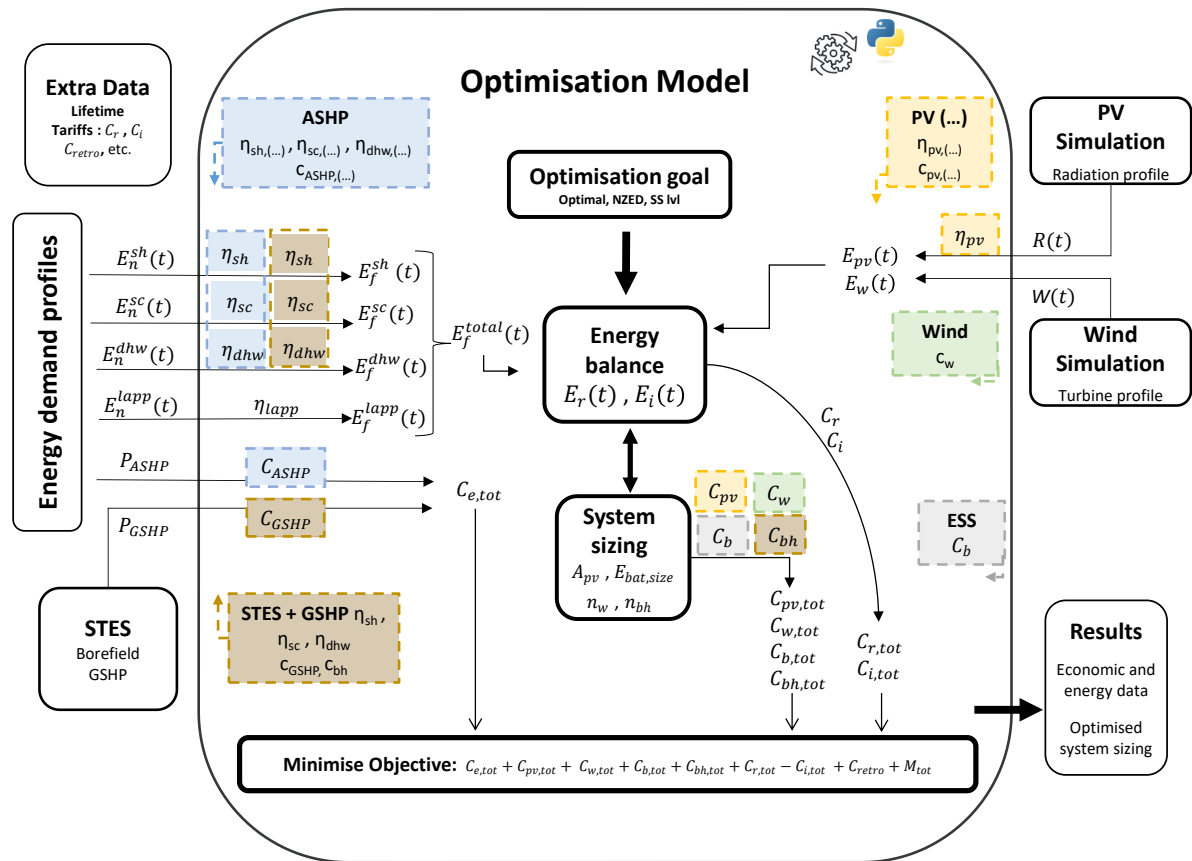


Figure 6.1. Diagram of the expanded optimisation model, with new technologies inputs and variables (STES in brown and Wind in green).

Following sections detail the incorporation of the new technologies into the model, from specific new constraints to impact on existing formulations. In brief: wind generation is integrated in a manner similar to PV, contributing as an additional renewable electricity source without significantly altering the model structure; by contrast, GSHP and STES have a more substantial influence in the model, due to the reciprocal interaction between ground temperature, GSHP performance, and the optimisation outcomes across the simulation horizon.

6.2 The new technologies included in the optimisation model

6.2.1 Seasonal Thermal Energy Storage (STES) system

Seasonal thermal energy storage (STES) technologies enable long-term shifting of thermal energy between seasons, increasing the flexibility of district heating and cooling systems and improving the utilisation of renewable resources (Guelpa & Verda, 2019). Several STES concepts exist, including aquifer thermal energy storage (ATES), pit thermal storage (PTES), water tanks and stratified reservoirs, and borehole thermal energy storage (BTES) (Sadeghi et al., 2024). These systems differ in scale, geological requirements, installation cost, and achievable temperatures, but all share the objective of capturing surplus heat when available and releasing it when demand peaks.

In the present work, the STES system is implemented through a borehole thermal energy storage (BTES) field coupled with a ground-source heat pump (GSHP). GSHP and borefield are jointly treated as components of the STES system, as their operation is interdependent: the GSHP extracts heat from or rejects heat to the borefield, while the thermal state of the ground directly affects GSHP efficiency. This distinguishes a STES-enabled GSHP system from a conventional GSHP installation, where ground extraction and rejection are typically balanced only on short timescales and where no deliberate seasonal charging is performed (Zhao et al., 2024). In contrast, STES seeks to exploit multi-month thermal storage, deliberately injecting heat into the ground in summer or early autumn, and extracting it in winter, thereby shifting energy availability across seasons.

The combination of solar thermal collector system with BTES was successfully studied in the design of net-zero energy communities, focusing in the short-term thermal energy storage (Hachem-Vermette et al., 2019). In Finland, a study combined photovoltaic-thermal system, heat pump, wind turbines and STES at building-level (Rehman et al., 2022). In South Korea, a district-level study coupled district heating system with heat pumps and multiple heat sources, including seasonal storage tank (Kim et al., 2019). This addition to the expanded optimisation model intends to evaluate the potential of borehole STES as a long-term storage solution, studying its capability to reach economic efficient net-zero balance and targeting high self-sufficiency at district-level.

The modelling of the STES behaviour is supported by the GHEtool open-source Python library, which provides ground thermal response functions, borehole resistance models, and methods for computing fluid temperatures and resulting GSHP performance (Peere & Blanke, 2022). This tool is used to generate performance profiles (COP and EER) for each borehole configuration considered in the optimisation, capturing the thermal dynamics of the ground and its impact on heat pump operation.

The implementation of STES in the present model follows a set of basic operational principles:

1. Summer ground charging: heat is injected into the ground during cooling season, both from building cooling rejection and, when beneficial, through dedicated heat-pump operation.
2. Winter ground cooling: heat is extracted from the ground during heating season to meet space heating and domestic hot water loads; no dedicated cooling of the ground is imposed during this period.
3. Enforceable annual balance: long-term thermal neutrality can be defined during simulation by constraining the annual injected energy to match annual extraction.
4. Multiple-year simulation horizon: a two-year simulation is usually run, where the first year allows the ground system to stabilise and the second year provides the performance results used in optimisation. Longer period simulation is possible, being of especial interest to analyse ground temperature drifting across time when annual balance neutrality is not enforced.

These principles guide the ground-temperature profiles, GSHP performance curves, and feasibility constraints.

6.2.1.1 STES performance modelling using GHEtool

The representation of the seasonal thermal energy storage (STES) system relies on procedures used to generate the input profiles and physical constraints that shape the interaction between the GSHP, the borefield, and the ground.

Borefield configurations are defined, as inputs to the model, being characterised by:

1. number of boreholes;
2. borehole depth;
3. borehole spacing;
4. thermal properties of the soil and grout;
5. fluid and pipe parameters.

A finite set of candidate borefield configurations are defined prior to optimisation based on the number of boreholes (e.g., 50, 100, or 200 boreholes). These discrete options allow the model to explore different borehole sizes while keeping the problem computationally tractable. Optimisation runs individually for each borefield size configuration, and all GSHP thermal constraints and performance profiles are conditioned on that choice.

GHETool computes the ground thermal response using borehole g-functions, using the *Borefield* class (Peere & Blanke, 2022). These functions characterise the temperature response of the ground to a unit heat pulse over a specified time interval.

The thermal response depends on:

- soil thermal conductivity;
- volumetric heat capacity;
- borehole geometry;
- borehole-to-borehole interactions.

The g-function curves are then used to simulate hourly ground temperature variations under a sequence of heat extraction and injection loads, using GHETool's *HourlyGeothermalLoad* (Peere & Blanke, 2022). GHETool also computes the effective borehole thermal resistance which characterises the conductive resistance between the circulating fluid and the surrounding ground. This parameter is used to relate ground temperature to the entering fluid temperature (EFT).

GHETool simulates the entering fluid temperature (EFT) over the entire time horizon, using temperature evaluation functions such as *borefield.calculate_temperatures* (Peere & Blanke, 2022).

The EFT depends on:

- heat extraction during heating season (heating and DHW);
- heat rejection during cooling season (cooling + dedicated charging);
- background undisturbed ground temperature;
- borehole thermal resistance;
- the cumulative ground temperature response from previous months.

The EFT is a key output of the STES pre-processing stage, because GSHP performance is highly sensitive to this temperature.

GHETool does not directly compute GSHP COP/EER. Therefore, this model applies a performance map that converts EFT into:

- $COP_{SH}(t)$ for space heating;
- $COP_{DHW}(t)$ for domestic hot water;
- $EER_{SC}(t)$ for space cooling;
- $EER_{charge}(t)$ for cooling season dedicated ground charging.

These performance curves are generated hourly and reflect how ground temperature degradation or seasonal recovery affects heat pump efficiency. The theoretical upper-bound efficiency for a heat pump is given by the Carnot cycle, which depends on the temperature lift between the heat source and the heat sink. Although real systems operate at a fraction of these theoretical limits, the same principle applies: GSHP COP improves when the EFT increases in heating

mode, and EER improves when the EFT decreases in cooling mode. This thermodynamic dependence motivates the use of EFT-based performance maps in the model and explains why seasonal thermal storage can enhance GSHP efficiency by controlling ground temperature evolution. These profiles are passed as time-dependent parameters to the optimisation model.

The pre-processing stage produces the hourly performance profiles that are stored and made available to the optimisation:

- Hourly $COP_{SH}(t)$;
- Hourly $COP_{DHW}(t)$;
- Hourly $EER_{SC}(t)$;
- Hourly $EER_{charge}(t)$;
- The $EFT(t)$ profile.

GSHP thermal variables are linked to the selected COP/EER profiles. ASHP and GSHP electricity consumption equations use these time-dependent values. This structure allows the GSHP performance to be represented realistically while maintaining linearity of the mixed-integer formulation. The optimisation solver then determines whether STES is selected, GSHP sizing and operation, ASHP complementary operation, and the optimal sizing of the remaining technologies (PV, wind, electric storage).

6.2.1.2 Iterative coupling between GSHP operation and STES ground response

The interaction between GSHP and the borehole STES system is inherently dynamic: GSHP operation influences ground temperature, and ground temperature in turn affects GSHP performance. A single-pass simulation would therefore not capture the mutual dependence between thermal extraction/injection and heat pump efficiency. To address this, the model adopts an iterative coupling procedure in which the hourly GSHP thermal loads from the optimisation step are fed back into GHEtool's *HourlyGeothermalLoad* engine to recompute ground temperature and associated performance profiles.

Because the optimisation determines the GSHP thermal output profiles, the resulting load pattern may differ significantly from the initial assumptions used to generate the COP/EER curves. If EFT is not updated accordingly, heat pump performance would be inconsistent with the actual thermal behaviour of the ground.

Thus, an iterative process is required to reconcile the GSHP operation from the MILP optimisation, and the ground temperature evolution computed via GHEtool:

1. Initial COP/EER profiles are pre-computed using a reference or assumed set of GSHP loads. Profiles are provided as fixed time-dependent parameters to the MILP.

2. The optimisation determines the GSHP heat extraction (SH, DHW) and heat rejection (cooling + seasonal charging) profiles.
3. Using the GSHP thermal load profiles, GHEtool recalculates the ground temperature evolution, the entering fluid temperature (EFT) and the updated COP/EER curves corresponding to the new EFT.
4. The updated EFT is compared to the EFT used in the optimisation and if the deviation is below a predefined tolerance, iteration stops. Otherwise, the updated COP/EER profiles replace the previous ones, and the MILP is solved again.

As a result, the model can identify cost-optimal solutions where borehole sizing balances investment costs and efficiency gains, seasonal charging improves COP, respecting ground conditions within operational limits. This iterative framework enables realistic coupling of long-term ground thermal dynamics with operational decision-making.

6.2.2 Wind energy modelling

Wind energy is introduced in the expanded version of the model as an optional renewable electricity source that complements PV generation. Wind power is modelled through a formulation that links hourly wind production to the number of installed turbines and the corresponding wind-speed-to-power conversion profile.

The hourly wind electricity production is given by Eq. (18).

$$E_w(t) = n_w \times W_{profile}(t) \times LT_w \quad (18)$$

Where:

$E_w(t)$ is the wind electric energy production at time step t (kWh);

n_w is the number of turbines selected by optimisation;

$W_{profile}(t)$ is the specific power output of a single turbine installed in the district under the wind conditions of time step t (kWh);

LT_w is the long-term performance correction factor that accounts for degradation, similarly to Eq. (4).

The specific power output of a single turbine is obtained from the Wind Module, being derived from the chosen wind turbine model and site-specific wind resource data. The number of turbines cannot exceed the maximum allowed capacity, which is an input of the model. Additionally, wind generation is disabled in scenarios where the system operates in grid-only mode or when wind technology is deactivated.

The pre-processing Wind Module converts meteorological wind-speed data into an electrical power profile for a selected micro- or mini-turbine.

Hourly wind speed data were retrieved at a reference height and extrapolated to the wind turbine hub height using the Hellmann power law, expressed in Eq. (19).

$$v(z) = v(z_{\text{ref}}) \left(\frac{z}{z_{\text{ref}}} \right)^{\alpha} \quad (19)$$

Where:

$v(z)$ is the wind speed at hub height z (m/s);

$v(z_{\text{ref}})$ the measured wind speed at reference height z_{ref} (m/s);

α is the Hellmann exponent, which depends on surface roughness and atmospheric stability. Typical values range from 0.10 for offshore conditions to 0.20–0.30 in urban environments (Manwell, 2009). In this work, $\alpha = 0.2$ was adopted, consistent with the urban/suburban context of the case study.

The wind speed at hub height was then converted into electrical power output using the manufacturer's power curve. The latter provides discrete pairs of wind speed and corresponding power, obtained under standardised test conditions (IEC, 2022). Intermediate values were obtained through linear interpolation between the tabulated points, following common practice in wind power modelling (Staffell & Pfenninger, 2016). This approach enables the generation of hourly wind power production profiles, $W_{\text{profile}}(t)$, that is integrated into the optimisation framework.

The resulting wind production enters the electrical energy balance directly, reducing grid imports or enabling electricity export when production exceeds demand. This formulation preserves linearity in the optimisation, allowing wind energy to be consistently evaluated alongside photovoltaic, storage, and thermal supply technologies.

6.3 Incorporating the new technologies in existing model formulations

6.3.1 Objective function – extended

The objective function minimises the total cost of the district energy system over the assumed project lifetime. Compared with the first version of the model, the updated formulation incorporates the investment cost of wind turbines, the investment cost of the borehole STES, and the investment of thermal equipment now covers both air-source and ground-source heat pumps (ASHP and GSHP). Also, an extended definition of maintenance costs reflects the inclusion of ASHP and GSHP, wind turbines, and STES infrastructure.

The updated total cost function to be minimised is expressed in Eq. (20).

$$\text{Total Cost} = C_{e,tot} + C_{pv,tot} + C_{w,tot} + C_{b,tot} + C_{bh,tot} + C_{r,tot} - C_{i,tot} + C_{\text{retro}} + M_{tot} \quad (20)$$

Where:

$C_{e,tot}$ is the total investment cost of the selected thermal equipment (ASHP + GSHP) (€);

$C_{pv,tot}$ is the total investment cost of the selected PV technology (€);

$C_{w,tot}$ is the total investment cost of the selected wind system (€);

$C_{b,tot}$ is the total investment cost of the ESS battery (€);

$C_{bh,tot}$ is the total investment cost of the borefield (€);

$C_{r,tot}$ is the total cost of electricity imported from the grid (€) in lifetime;

$C_{i,tot}$ is the total revenue from electricity injected into the grid (€) in lifetime;

C_{retro} is the retrofit cost (€);

M_{tot} is the total maintenance and battery replacement costs (€).

All the costs are for the entire assumed duration of the project/simulation.

The new or altered components of the total cost function are expressed in Eq. (20.1 – 20.4).

The $C_{e,tot}$ distinguishes between ASHP and GSHP alternatives, which can differ in investment cost and efficiency parameters.

$$C_{e,tot} = C_{ASHP} \cdot P_{ASHP} + C_{GSHP} \cdot P_{GSHP} \quad (20.1)$$

Where:

$C_{e,tot}$ is the total investment cost of the selected thermal equipment (€);

C_{ASHP} is the investment cost of the ASHP equipment (€/kW);

P_{ASHP} is the peak thermal power of ASHP (kW);

C_{GSHP} is the investment cost of the GSHP equipment (€/kW);

P_{GSHP} is the peak thermal power of GSHP (kW).

The capacity variables are defined to satisfy the heating (SH + DHW) and cooling requirements extracted from the building energy profiles. GSHP capacity is limited by the number of boreholes and ground heat-exchange limits. If GSHP is selected and sized, the model admits two relevant configurations for ASHP:

1. Complete capacity coverage (redundancy): ASHP is dimensioned to supply the full heating and cooling peak loads of the district, regardless of the GSHP coverage.
2. Residual load coverage by ASHP: when the GSHP system is installed with a capacity lower than the district peak load, the ASHP is sized to cover the remaining load.

If GSHP is not selected, due to the referred limitations or by not being cost-effective, the energy system design will be based on ASHP, renewable generation and electric storage.

The $C_{w,tot}$ depends on the number of wind turbines selected by the optimisation, and the individual cost per turbine.

$$C_{w,tot} = C_w \cdot n_w \quad (20.2)$$

Where:

$C_{w,tot}$ is the total investment cost of the selected wind system (€);

C_w is the specific investment cost per turbine (€);

n_w is the number of turbines selected by optimisation.

The $C_{bh,tot}$ depends on the number of boreholes selected by the optimisation, and the individual cost per borehole. The borefield size, based on the total number of boreholes, is selected from a predefined set of configurations, which will be detailed in subsequent subchapters.

$$C_{bh,tot} = C_{bh} \cdot n_{bh} \quad (20.3)$$

Where:

$C_{bh,tot}$ is the total investment cost of the selected borefield (€);

C_{bh} is the specific investment cost per borehole (€);

n_{bh} is the number of boreholes selected by optimisation.

M_{tot} includes the maintenance costs for the additional components, namely the GSHP included in M_e , and the M_w representing the wind system maintenance cost.

$$M_{tot} = M_e + M_p + M_w + M_b + R_b \quad (20.4)$$

Where:

M_{tot} is the total maintenance and battery replacement costs (€);

M_e is the maintenance costs of the selected thermal equipment (€);

M_p is the maintenance costs of the selected PV technology (€);

M_w is the maintenance costs of the selected wind system (€);

M_b is the maintenance costs of the battery (€);

R_b is the battery replacement costs (€).

Maintenance cost calculation for each component was based on an annual percentage rate multiplied by the investment cost and by the simulation's lifetime or discount factor.

6.3.2 Final demand from ASHP and GSHP and thermal balance

The thermal subsystem is updated to incorporate the representation of two heat pump technologies: air source and ground source. The sizing logic depends on whether a borefield configuration is selected and on the operating mode of the ASHP, as detailed in section 6.3.1.

The first version of the model assumed fixed efficiencies for the ASHP defined by the selected equipment class. In the extended version of the model, GSHP performance varies over time according to ground temperature evolution and the selected borefield configuration. GSHP coefficients of performance for SH, SC and DHW are now pre-computed for each borefield configuration and imported into the optimisation as time-dependent profiles. An iterative processing recomputes GSHP efficiencies based on the resulting ground temperature profiles after the optimisation step. This allows the electrical consumption of the GSHP to respond dynamically to seasonal charging and extraction, improving the physical realism of the thermal-electrical coupling. The updated efficiency framework introduces additional constraints linking thermal outputs to electrical inputs and allows the model to select between technologies.

For each energy use $x \in \{sh, sc, dhw\}$ and each time step t , the useful thermal loads $E_{n,d}^x(t)$ are met by the combination of ASHP and GSHP thermal outputs, expressed in Eq. (21).

$$E_{n,d}^x(t) = Q_{ASHP}^x(t) + Q_{GSHP}^x(t) \quad (21)$$

Where:

$E_{n,d}^x(t)$ is the district useful energy demand for end-use x at time step t (kWh);

$Q_{ASHP}^x(t)$ is the useful energy demand covered by ASHP (kWh);

$Q_{GSHP}^x(t)$ is the useful energy demand covered by GSHP (kWh).

Each heat pump useful energy is limited by its nominal installed thermal capacity, ensuring that simultaneous heating modes (SH and DHW) do not exceed equipment limits.

To calculate the final energy demand $E_{f,d}^x(t)$ model follows Eq. (22).

$$E_{f,d}^x(t) = \frac{Q_{ASHP}^x(t)}{\eta_{ASHP}^x} + \frac{Q_{GSHP}^x(t)}{\eta_{GSHP}^x} \quad (22)$$

Where:

$E_{f,d}^x(t)$ is the district final energy demand for end-use x at time step t (kWh);

$\eta_{ASHP}^x(t)$ is the fixed efficiency of the ASHP equipment for each use;

$\eta_{GSHP}^x(t)$ is the efficiency of the GSHP equipment for each use, imported as time series.

This formulation captures the dynamic effects of STES charging and extraction on GSHP electrical demand.

Ground heat extraction to cover SH and DHW demand and heat rejection from SC and forced ground charging (if defined) are constrained by the borehole capacity of the selected STES configuration, as expressed in Eq. (23) and (24).

$$Q_{GSHP}^{SH}(t) + Q_{GSHP}^{DHW}(t) \leq \frac{W_{ext} n_{bh} H}{1000} \quad (23)$$

$$Q_{GSHP}^{SC}(t) + Q_{charge}(t) \leq \frac{W_{inj} n_{bh} H}{1000} \quad (24)$$

Where:

$Q_{GSHP}^{SH}(t)$ is the SH energy demand covered by GSHP (kWh);

$Q_{GSHP}^{DHW}(t)$ is the DHW energy demand covered by GSHP (kWh);

$Q_{GSHP}^{SC}(t)$ is the SC energy demand covered by GSHP (kWh);

$Q_{charge}(t)$ is the energy charged to the ground through dedicated heat pump operation (kWh);

W_{ext} is the extraction limits (W/m);

W_{inj} is the injection limits (W/m);

n_{bh} is the number of boreholes for the selected configuration;

H is the borehole length (m).

These constraints ensure physical feasibility of heat exchange with the ground. The multiple STES basic principles, e.g., forced ground energy charging, were detailed in section 6.2.1.

To maintain long-term thermal neutrality of the ground, seasonal energy balance can be active as expressed in Eq. (25).

$$\sum_{t=1}^T (Q_{GSHP}^{SC}(t) + Q_{charge}(t)) = \beta \sum_{t=1}^T (Q_{GSHP}^{SH}(t) + Q_{GSHP}^{DHW}(t)) \quad (25)$$

Where:

$Q_{GSHP}^{SH}(t)$ is the SH energy demand covered by GSHP (kWh);

$Q_{GSHP}^{DHW}(t)$ is the DHW energy demand covered by GSHP (kWh);

$Q_{GSHP}^{SC}(t)$ is the SC energy demand covered by GSHP (kWh);

$Q_{charge}(t)$ is the energy charged to the ground through dedicated heat pump operation (kWh);

β is a factor to restrict energy balance, being closer to 1 for a stricter balance restriction.

6.3.3 Energy flow constraints – extended

The updated formulation extends the supply side and modifies the balance accordingly. Wind production therefore appears as an additional renewable term, and the GSHP introduces an electrically driven thermal demand that depends on ground temperature and performance profiles bound to STES. The resulting energy balance retains the same structure as in the first version of the model but now accommodates temporal complementarities between PV and wind, as well as the influence of seasonal thermal storage.

The balance between production, consumption, imports and exports is given by Eq. (26).

$$E_{f,d}^{total}(t) = E_{pv}(t) + E_w(t) + E_r(t) - E_i(t) + E_{bat,dis}(t) - E_{bat,ch}(t) \quad (26)$$

Where:

$E_{f,d}^{\text{total}}(t)$ is the total district final electric energy demand at time step t (kWh);

$E_{pv}(t)$ is the PV electric energy production at time step t (kWh);

$E_w(t)$ is the wind electric energy production at time step t (kWh);

$E_r(t)$ is the electric energy drawn from the grid at time step t (kWh);

$E_i(t)$ is the electric energy injected into the grid at time step t (kWh);

$E_{bat,dis}(t)$ is the energy discharged from the battery at time step t (kWh);

$E_{bat,ch}(t)$ is the energy used to charge the battery at time step t (kWh);

Electricity can only be injected if there is renewable production available: $E_i(t) \leq E_{pv}(t) + E_w(t)$, and grid import must be non-negative: $E_r(t) \geq 0$. GSHP electrical consumption is embedded within $E_{f,d}^{\text{total}}(t)$.

6.3.4 Net zero balance and additional equations updated

This constraint now ensures that the total annual final energy demand matches the total annual renewable energy production, from PV and wind, as expressed in Eq. (27).

$$\sum_{t=1}^T E_{f,d}(t) = \sum_{t=1}^T (E_{pv}(t) + E_w(t)) \quad (27)$$

Where:

$E_{f,d}^{\text{total}}(t)$ is the total district final electric energy demand at time step t (kWh);

$E_{pv}(t)$ is the PV electric energy production at time step t (kWh);

$E_w(t)$ is the wind electric energy production at time step t (kWh);

T is the total number of time steps (t).

Also, the annual renewable energy for self-consumption, $E_{ren,self}$ is updated to Eq. (28).

$$E_{ren,self} = E_{pv,annual} + E_{w,annual} + E_{bat,level}(T) - E_{bat,level}(1) - E_{i,annual} - L_{bat,annual} \quad (28)$$

Where:

$E_{pv,annual}$ is the total annual PV production (kWh);

$E_{w,annual}$ is the total annual wind production (kWh);

$E_{bat,level}(T)$ is the battery level at the final time step $t = T$ (kWh);

$E_{bat,level}(1)$ is the battery level at time step $t = 1$ (kWh);

$E_{i,annual}$ is the total injected energy to the grid (kWh);

$L_{bat,annual}(t)$ is the annual battery energy loss (kWh);

T is the total number of time steps (t).

6.4 Economic and environmental performance

6.4.1 Present value

Annual electricity expenditure and maintenance costs must be projected over the analysis period to obtain the corresponding lifetime contribution to the objective function. In the first version of the model, lifetime costs were computed assuming a constant-cost approach, whereby annual values were simply multiplied by the project lifetime. To increase economic realism and align the model with standard life-cycle cost (LCC) practices, the updated formulation introduces a discount factor that converts recurring annual payments into their present value equivalent (Mearig & Morris, 2024).

To aggregate a constant annual cost over the project lifetime years, the model applies a discount factor, DF , defined in Eq. (29) (Ozbay & Parker, 2003).

$$DF = \sum_{t=1}^{L_t} \frac{1}{(1+r)^t} \quad (29)$$

Where:

r is the real discount rate;

L_t is the project's lifetime [years].

This expression enables recurring annual quantities to be directly compared with upfront capital expenditures. Accordingly, the life cycle cost associated with any annual recurring component is computed, as in Eq. (30) (Ozbay & Parker, 2003).

$$C_{LCC} = C_{annual} \times DF \quad (30)$$

Where:

C_{LCC} is the life cycle cost of a given component (€);

C_{annual} is the annual cost of a given component (€);

DF is the discount factor.

Therefore, DF replaced L_t in equations such as Eq. (1.4) and Eq. (1.5), and in the maintenance cost calculations. The real discount rate can incorporate the combined effect of inflation, interest rates, and expected price evolution (Mearig & Morris, 2024). Optionally, different real discount rates may be applied to electricity expenditures and maintenance to reflect distinct price drivers or sector expectations.

6.4.2 GHG emissions with decarbonisation factor

The extended model greenhouse gas (GHG) emissions accounting evolves over time to reflect expected decarbonisation of the national electricity grid system.

An initial emission factor, EF_0 (kgCO₂e/kWh) is assigned to the base year, and a constant annual decarbonisation rate d is applied. The emission factor in year y is given by Eq. (31).

$$EF(y) = EF_0(1 - d)^y \quad (31)$$

This produces a declining series over the project lifetime, which enables the optimisation to account for the progressively lower carbon intensity of imported electricity, making the model consistent with long-term climate and energy policies.

The GHG accounting framework supports two evaluation modes:

- Net balance: both imported and exported electricity are considered, allowing renewable generation to offset grid emissions;
- Imports-only: emissions are attributed solely to electricity drawn from the grid.

The resulting emissions profile can be aggregated annually or over the full lifetime to support environmental comparisons across optimisation scenarios.

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Chapter 7. Case study 2: urban district in Lisbon

7.1 Description of case study 2

A second case study was selected to apply the expanded version of the analysis and optimisation model. The selected district is located in the metropolitan area of Lisbon, Portugal, and is based on a real case of a project currently under development and aiming at high-energy performance and low emissions. The district comprises a mix of multi-family and single-family residential buildings, and mixed-use buildings including offices and retail spaces. The complexity of the district, characterised by multiple uses and heterogeneous demand profiles, together with its planned district-level approach and the potential integration of shared energy technologies, makes it particularly well suited to test the expanded optimisation framework. The case study includes a total of 28 buildings, serving residential, service and office functions. As the development is still in the design phase, the application of the model relies on the information currently available. For design features that are not yet fully defined, high-performance assumptions were adopted in line with the objectives of the project and the targeted sustainability standards. The geographical distribution of the district's buildings is illustrated in Figure 7.1.



Figure 7.1. Map of the selected district in Lisbon, Portugal (QGIS).

The energy system concept being studied for the district is based on a combination of air-source and ground-source heat pumps, photovoltaic generation, and a borehole seasonal thermal

energy storage (STES) system. The main objective of this case study is to simulate alternative configurations in terms of system organisation and technology selection using the expanded version of the optimisation model, as described in Chapter 6. The planned energy system is the basis of the present study but alternative solutions and technologies (e.g. wind) were tested.

Using CEA, energy demand was simulated considering the physical characterisation, energy use and profiles of the buildings. The simulation used a typical meteorological area (TMY) weather file in EnergyPlus Weather File (EPW) format from the Portuguese SCE database (DGEG, 2025). Figure 7.2 illustrates the selected buildings in CEA.



Figure 7.2. Representation of the buildings composing the selected district in the CEA software.

Geometric characteristics were based on available data, e.g.: height, number of floors, floor area, windows-to-wall ratio, etc. The constructive characteristics of the buildings were estimated from specific data selected for each building, made available by the project developer. Nonetheless, being the project under development at the time of the present analysis, some options may differ from the final construction solution.

The district was divided in four groups of buildings, based on location and characteristics. The following tables describe the characteristics assumed for each building considered in this case-study, including physical dimensions, construction details, internal loads and indoor comfort. Similar to case study 1, thermal bridges were accounted as a thermal transmittance factor of 1.6 for opaque envelope and of 1.1 for glazing surfaces, with heating being considered available from October to April, and cooling from May to September. The air ventilation rate was estimated so that, when combined with natural air infiltration, the total air change rate would reach 0.6 air changes per hour (ACH) for all buildings under assessment. Hourly schedules for occupancy, appliances, lighting, heating, cooling and hot water used for each building took into consideration the respective use-types. End-use energy schedules are presented by building use-type in Annex G.

Figure 7.3 and Table 7.1 describe and summarise data for Group A buildings.

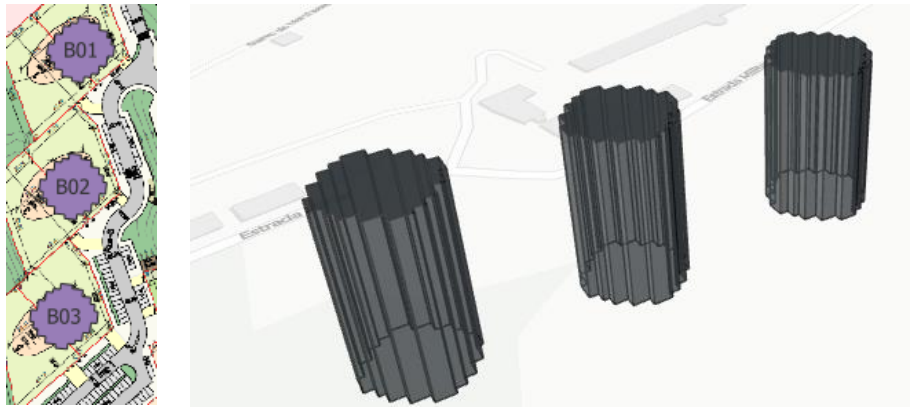


Figure 7.3. Group A buildings (representation in QGIS and CEA softwares, respectively).

Table 7.1. Characteristics of buildings in Group A.

	B01	B02	B03
Floors above ground	15	16	17
Floors below ground	2	2	2
Height above ground (m)	54	57	60
Gross floor area (GFA) (m ²)	13 038	14 093	14 855
Useful floor area (UFA) (m ²)	9 778	10 648	11 298
Rooftop area (m ²)	777	793	792
Window to wall ratio – North	0.5	0.5	0.5
Window to wall ratio – East	0.5	0.5	0.5
Window to wall ratio - South	0.5	0.5	0.5
Window to wall ratio - West	0.5	0.5	0.5
Roof	100 mm XPS U-value = 0.14 W/m ² K		
Walls	Wooden walls with 100 mm mineral wool U-value = 0.35 W/m ² K		
Windows	U-value = 1.7 W/m ² K ; g-value = 0.30		
USE	100% Multi Residential		
Occupancy (m ² /p)	35		
Appliances (W/m ²)	5		
Artificial lighting (W/m ²)	2.5		
Daily hot water consumption (ldp)	60		
Cooling Setpoint temp. (°C)	24		
Setback point temp. (°C)	30		
Heating Setpoint temp. (°C)	20		
Setback point temp. (°C)	17		
Min. outdoor air ventilation rate for Air Quality (l/s/p)	8.8		

Figure 7.4 and Table 7.2 describe and summarise data for Group B buildings.



Figure 7.4. Group B buildings (representation in QGIS and CEA softwares, respectively).

Table 7.2. Characteristics of buildings in Group B.

Group B	B08	B09	B10	B12	B13.1	B13.2
Floors above ground	4	4	4	4	4	4
Floors below ground	1	1	1	1	1	1
Height above ground (m)	14	14	14	14	14	14
Gross floor area (GFA) (m ²)	9 395	2 910	6 438	6 408	3 417	6 301
Useful floor area (UFA) (m ²)	6 389	1 979	4 378	4 357	2 324	4 285
Rooftop area (m ²)	1 871	582	1 288	1 282	683	1 260
Window to wall ratio – North	0.5	0.5	0.5	0.5	0.5	0.5
Window to wall ratio – East	0.5	0.5	0.5	0.5	0.5	0.5
Window to wall ratio - South	0.5	0.5	0.5	0.5	0.5	0.5
Window to wall ratio - West	0.5	0.5	0.5	0.5	0.5	0.5
Roof	100 mm XPS U-value = 0.14 W/m ² K					
Walls	Wooden walls with 100 mm mineral wool U-value = 0.35 W/m ² K					
Windows	U-value = 1.7 W/m ² K ; g-value = 0.30					
USE	100% Multi Residential					
Occupancy (m ² /p)	35					
Appliances (W/m ²)	5					
Artificial lighting (W/m ²)	2.5					
Daily hot water consumption (ldp)	60					
Cooling Setpoint temp. (°C)	24					
Setback point temp. (°C)	30					
Heating Setpoint temp. (°C)	20					
Setback point temp. (°C)	17					
Min. outdoor air ventilation rate for Air Quality (l/s/p)	8.8					

Figure 7.5 and Table 7.3 describe and summarise data for Group C buildings.

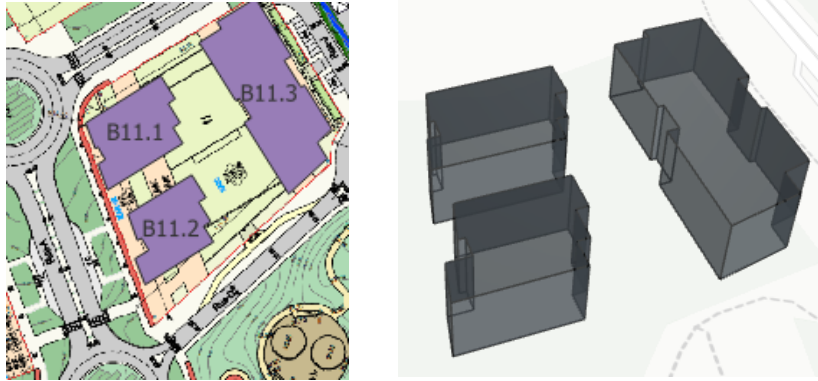


Figure 7.5. Group C buildings (representation in QGIS and CEA softwares, respectively).

Table 7.3. Characteristics of buildings in Group C.

	B11.1	B11.2	B11.3
Floors above ground	5	5	5
Floors below ground	4	4	4
Height above ground (m)	23	23	23
Gross floor area (GFA) (m ²)	12 189	10 585	23 336
Useful floor area (UFA) (m ²)	5 756	4 999	11 020
Rooftop area (m ²)	1 342	1 176	2 564
Window to wall ratio – North	0.5	0.5	0.5
Window to wall ratio – East	0.5	0.5	0.5
Window to wall ratio - South	0.5	0.5	0.5
Window to wall ratio - West	0.5	0.5	0.5
Roof	80 mm XPS U-value = 0.2 W/m ² K		
Walls	Wooden walls with 40 mm mineral wool U-value = 0.41 W/m ² K		
Windows	U-value = 1.7 W/m ² K ; g-value = 0.30		
USE	80% Office and 20% Retail		
Occupancy (m ² /p)	18 (0.8 x 20 + 0.2 x 8)		
Appliances (W/m ²)	8		
Artificial lighting (W/m ²)	2.5		
Daily hot water consumption (ldp)	2.3 (0.8 x 2.5 + 0.2 x 2)		
Cooling Setpoint temp. (°C)	24		
Setback point temp. (°C)	30		
Heating Setpoint temp. (°C)	20		
Setback point temp. (°C)	17		
Min. outdoor air ventilation rate for Air Quality (l/s/p)	3.9		

Figure 7.6 and Table 7.4 describe and summarise data for Group D buildings.

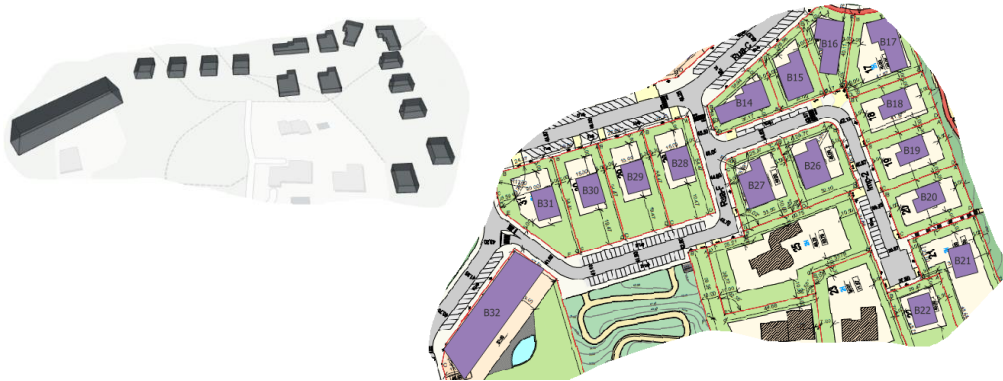


Figure 7.6. Group D buildings (representation in QGIS and CEA softwares, respectively).

Table 7.4. Characteristics of buildings in Group D.

	B14/ 16/17	B15/ 26/ 27	B18/ 19/20	B21/22/ 28/29/ 30/ 31	B32
Floors above ground	1	1	2	2	4 (avg)
Floors below ground	0	0	0	0	1
Height above ground (m)	4	4	7	7	14
Gross floor area (GFA) (m ²)	347	314	370	402	6 445
Useful floor area (UFA) (m ²)	295	267	314	342	4 382
Rooftop area (m ²)	342	314	181	201	1 289
Window to wall ratio – North	0.5	0.5	0.5	0.5	0.5
Window to wall ratio – East	0.5	0.5	0.5	0.5	0.5
Window to wall ratio - South	0.5	0.5	0.5	0.5	0.5
Window to wall ratio - West	0.5	0.5	0.5	0.5	0.5
Roof	100 mm XPS U-value = 0.14 W/m ² K				
Walls	Wooden walls with 100 mm mineral wool U-value = 0.35 W/m ² K				
Windows	U-value = 1.7 W/m ² K ; g-value = 0.30				
USE	100% Single Residential				100% MR
Occupancy (m ² /p)	48				35
Appliances (W/m ²)	5				
Artificial lighting (W/m ²)	2.5				
Daily hot water consumption (ldp)	60				
Cooling Setpoint temp. (°C)	24				
Setback point temp. (°C)	30				
Heating Setpoint temp. (°C)	20				
Setback point temp. (°C)	17				
Min. outdoor air ventilation rate for Air Quality (l/s/p)	12				8.8

7.2 Energy demand results

The district's energy demand results obtained from CEA are presented in Table 7.5. Results are presented both for the individual buildings and the district as whole, by end-use and total demand, and expressed per gross floor area (GFA) and useful floor area (UFA). Space heating (SH), space cooling (SC) and domestic hot water (DHW) energy demand ensures comfort conditions. Electric energy demand relates to electricity demand for lighting, appliances and ventilation.

Table 7.5. Annual energy demand results. SH, SC and DHW are expressed in thermal energy / useful energy.

by GFA/UFA	Electric energy (kWh/m ² /yr)		SH (kWh/m ² /yr)		SC (kWh/m ² /yr)		DHW (kWh/m ² /yr)		Total energy demand (kWh/m ² /yr)	
	GFA	UFA	GFA	UFA	GFA	UFA	GFA	UFA	GFA	UFA
1 – B01	10.7	14.2	23.7	31.6	15.4	20.5	19.7	26.3	69.4	92.6
2 – B02	10.7	14.1	23.4	31.0	15.3	20.3	19.7	26.1	69.2	91.5
3 – B03	10.7	14.0	23.0	30.3	15.2	20.0	19.7	25.9	68.6	90.2
4 – B08	10.1	14.9	15.8	23.3	12.8	18.9	18.1	26.7	56.9	83.7
5 – B09	10.3	15.2	22.2	32.7	13.5	19.8	19.0	27.9	65.0	95.6
6 – B10	10.3	15.1	19.5	28.7	13.3	19.5	18.3	26.9	61.3	90.2
7 – B11.1	16.4	34.6	10.2	21.6	6.6	14.0	1.7	3.7	34.9	73.9
8 – B11.2	16.4	34.7	10.5	22.3	6.7	14.2	1.8	3.8	35.4	74.9
9 – B11.3	16.4	34.7	8.7	18.4	6.9	14.5	1.6	3.5	33.6	71.1
10 – B12	10.2	15.0	19.4	28.6	13.1	19.2	18.6	27.3	61.3	90.2
11 – B13.1	10.2	15.1	21.4	31.4	13.2	19.4	18.5	27.3	63.4	93.2
12 – B13.2	10.2	15.1	19.9	29.3	13.2	19.4	18.4	27.0	61.7	90.7
13 – B14	11.0	12.9	44.6	52.5	18.6	21.9	19.5	22.9	93.7	110.3
14 – B15	11.0	12.9	45.4	53.4	18.5	21.8	18.7	22.0	93.5	110.0
15 – B16	11.0	12.9	45.5	53.5	18.7	22.0	19.7	23.2	94.9	111.6
16 – B17	11.0	12.9	45.3	53.3	18.7	21.9	19.5	23.0	94.5	111.1
17 – B18	10.7	12.6	43.0	50.6	16.2	19.1	23.5	27.6	93.4	109.9
18 – B19	10.7	12.6	43.0	50.6	16.2	19.1	23.5	27.6	93.4	109.9
19 – B20	10.7	12.6	42.8	50.3	16.2	19.0	23.5	27.6	93.2	109.6
20 – B21	10.7	12.6	41.6	49.0	16.4	19.3	24.6	28.9	93.3	109.8
21 – B22	10.7	12.6	41.6	48.9	16.4	19.3	24.6	28.9	93.2	109.7
22 – B26	10.9	12.9	44.8	52.8	18.6	21.9	18.7	22.0	93.1	109.5
23 – B27	10.9	12.8	44.2	52.0	18.7	22.0	18.7	22.0	92.4	108.8
24 – B28	10.7	12.6	41.4	48.7	16.4	19.3	24.6	28.9	93.0	109.4
25 – B29	10.8	12.7	41.9	49.3	16.5	19.4	24.6	28.9	93.7	110.3
26 – B30	10.7	12.6	41.6	49.0	16.4	19.3	24.6	28.9	93.4	109.9
27 – B31	10.8	12.7	41.7	49.1	16.4	19.3	24.6	28.9	93.5	110.0
28 – B32	10.2	15.0	18.8	27.7	13.0	19.1	18.2	26.7	60.1	88.4
District	12.4	19.5	18.0	28.3	11.7	18.4	13.2	20.7	55.4	86.9

Several factors should be considered when interpreting the annual energy demand values. The relatively high space heating demand observed in some buildings is largely explained by high window-to-wall ratios, which increase transmission losses. Space cooling demand is also significant across the district, reflecting both the climatic conditions of the Lisbon metropolitan area and the associated cooling needs of residential and mixed-use buildings. High domestic hot water demand contributes substantially to total energy consumption, as a daily hot water use of 60 L per person was assumed, following project's requirements.

Differences between GFA and UFA are observed for certain buildings due to the presence of extensive underground parking levels, as in the cases of buildings B11.1, B11.2, and B11.3. These three buildings are of mixed-use, combining office and retail functions, and exhibit markedly lower energy demand during weekends, which further explains their reduced annual energy demand per unit area.

Figure 7.7 illustrates the annual useful energy demand by end-use of the district.

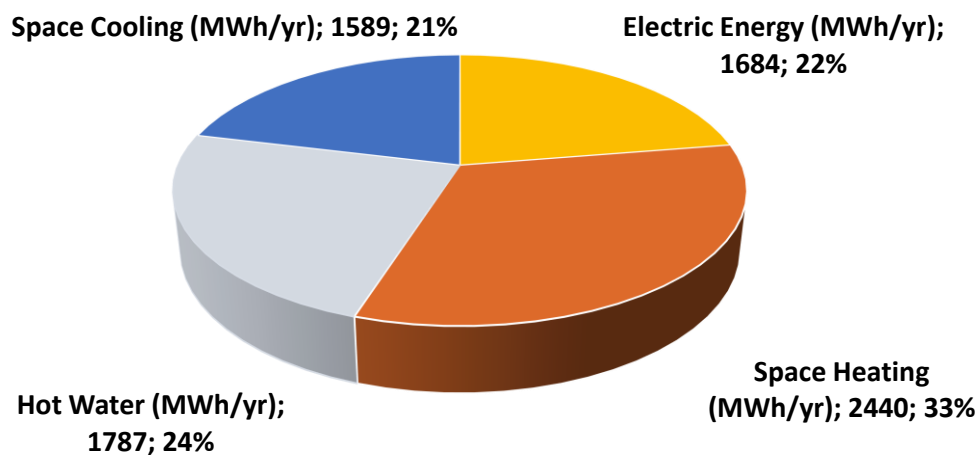


Figure 7.7. Useful energy demand of the district by end-use.

7.3 Selected technologies for HVAC&DHW, electricity generation and storage

The application of the expanded version of the optimisation model encompasses a broad set of energy technologies. Data for both district-level and building-level HVAC&DHW solutions, as well as PV, wind, ESS and STES technologies, were compiled. The dataset includes both equipment and installation costs and is primarily based on commercially available solutions.

The resulting technology database is summarised in Table 7.6. Costs and efficiencies of district-level HVAC&DHW solutions are strongly influenced by system typology, inlet and outlet temperature levels, energy sources, and network characteristics, including piping length, substations, and associated distribution losses. In some configurations, district-level systems can benefit from heat recovery through simultaneous heating and cooling, which may lead to efficiency gains of up to 30%. However, in the present case study, space heating and space cooling demands occur predominantly in distinct periods, and such synergies were therefore not considered.

For the GSHP district-level solution, system efficiencies are calculated endogenously within the model and depend on the hourly entering fluid temperature profiles obtained from the borefield. This solution is only applicable at the district scale. In contrast, ASHP efficiencies are assumed constant and were estimated based on representative values reported in the literature.

Table 7.6. HVAC&DHW systems efficiencies and costs.

HVAC&DHW		District-level ¹		Building-level ²	
		Efficiency	Cost (€/kW)	Efficiency	Cost (€/kW)
ASHP	SCOP	5.0		5.9	
	SEER	7.5	1 200	9.5	1 676
	COP DHW	3.5		3.9	
GSHP	Efficiencies are calculated by the model at an hourly timestep		1 200	Not applicable	

¹ literature review on centralised solutions (Buffa et al., 2019; EC, JRC et al., 2017; Ivančić et al., 2021; Mazhar et al., 2018; Vilén et al., 2023; Wirtz et al., 2020)

² (Bosch, 2017; Daikin, 2023)

The selected data for PV, wind, ESS and STES systems were based on commercially available solutions and include both equipment and installation costs. For PV systems, the maximum installable capacity was constrained by the available rooftop area of each building, with different shares of usable area considered across the district. A south-facing orientation with a fixed tilt angle

of 15°, without solar tracking, was assumed for all PV installations, together with an inverter efficiency of 90%.

ESS performance was characterised by a round-trip efficiency of 95% and a maximum C-rate of 0.5C. For wind generation, the estimated investment cost includes a 10 kW turbine and both turbine structure and installation. An inverter efficiency of 90% was assumed. The full set of cost assumptions adopted for PV, wind, ESS and STES technologies is summarised in Table 7.7.

Table 7.7. PV, Wind, ESS and STES efficiencies and costs.

Technology	Efficiency	Cost
PV ¹	0.23	895 €/kWp or 196 €/m ²
Wind ²	-	30 000 € / turbine
ESS ³	0.95 (round-trip)	600 €/kWh
STES	-	10 000 € / borehole

¹ Real application examples and PV module market survey (*Europe-Solarstore*, 2025)

² Wind turbines market survey (Flexpro-industry, 2025)

³(EC, DG ENER et al., 2023; *Europe-Solarstore*, 2025; Minuto et al., 2021)

The degradation of components was accounted for HVAC&DHW equipment, PV system and wind turbines are mainly affected in their efficiency parameters, with an estimated 0.25% yearly efficiency degradation (Lee et al., 2022) for HVAC&DHW, and a 0.55% yearly efficiency degradation for PV and wind turbines (*Europe-Solarstore*, 2025). ESS is affected with 2% yearly degradation of battery storage capacity (EC, DG ENER et al., 2023). Similarly, yearly maintenance costs were estimated for each component, with an average of 1% of investment cost for all components. For ESS system, a maximum lifetime of 15 years was estimated for a normal operation in standard conditions (including degradation losses) (EC, DG ENER et al., 2023), therefore battery replacement was considered for larger simulation lifetimes. Electric energy cost of 0.17€/kWh was based on average electricity prices in the Portuguese energy market in 2024 (Eurostat, 2025). A value of compensation / income for electricity injection in the grid was conservatively estimated at 0.01€/kWh. The total lifetime of simulation, i.e., the time horizon to consider for the optimisation was set at 20 years.

Characterising STES system entails not only the total cost associated with borehole drilling and installation, but also a detailed representation of ground and borefield properties. Input data for the STES modelling were based on real case examples and recommendations from GHETool, and

include parameters related to borehole geometry, spacing, ground thermal properties, and operational limits. The full set of parameters adopted for the borefield simulation is summarised in Table 7.8.

Table 7.8. STES simulation input parameters.

Input parameters	Values (unit)
Undisturbed ground temperature	16.5 °C (Lisbon)
Ground conductivity	2.3 W/mK
Volumetric heat capacity	1.6e6 J/m ³ K
Thermal resistance	0.07 mK/W
Number of boreholes	10, 25, 50, 100, 200
Borehole depth	150.0 m
Borehole spacing	7.0 m
Borehole radius	0.075 m
Borehole buried depth to top	2 m
Minimum temperature	-2.0 °C
Maximum temperature	27.0 °C
Heating extraction capacity	65 W/m
Cooling injection capacity	110 W/m
Heating temperature	35.0 °C
DHW temperature	50.0 °C
Cooling temperature	7.0 °C

The operation of the STES system follows a set of predefined principles. During the summer period, the ground is charged with heat through both the rejection of excess heat from building cooling and, when advantageous, dedicated heat pump operation. In winter, the system operates in heat extraction mode to supply space heating and domestic hot water, without dedicated ground cooling operation. An annual thermal balance is enforced, such that the amount of heat injected into the ground over the year matches the extracted heat. The STES behaviour is simulated over a two-year horizon, where the first year serves as an initialisation period to stabilise ground temperatures, and the second year is used for performance assessment. Heat extraction is assumed to begin at the onset of the heating season and, once the stored thermal energy is fully depleted, the system operates as a conventional GSHP.

7.4 Simulation

The optimisation model was implemented in Python using the PuLP modelling framework (Mitchell et al., 2011) and executed on an Intel core i5 with 16 GB RAM. The optimisation was solved using the Gurobi solver (Gurobi Optimization, LCC, 2024).

The simulations evaluated combinations of the previously described HVAC&DHW systems, energy generation technologies and storage solutions. For each configuration, system capacities were optimally dimensioned to meet predefined economic and energy performance targets. These targets include the cost-optimal solution (minimum total cost), NZED (lowest total cost to achieve net zero energy), and self-sufficiency (SS) targets between 80% and 100%. Self-sufficiency, as defined in Chapter 4, is the share of annual final energy covered by self-consumed renewable energy.

The analysis was structured in multiple stages to test different system configurations and boundary conditions. First, a comparison was performed between district-level and building-level approaches. The “District” approach represents a fully centralised energy system encompassing all the buildings of the district, while the “Building” approach assumes individual systems at the building scale. An intermediate configuration, referred to as “Clusters”, was also analysed. In this case, buildings from Groups A, B and C formed three sub-districts, each served by its own district-level ASHP system and shared electricity generation and storage system. Each building from the fourth group (Group D) was supplied by building-level ASHP systems and individual generation and storage systems. This intermediate configuration reflects a more plausible implementation option for the project, under the current Portuguese regulatory constraints, which limits private energy networks from crossing public roads. For this first comparative analysis, only ASHP-based solutions were considered for HVAC&DHW, and only PV and ESS technologies were allowed for electricity generation and storage.

Subsequent analyses focus exclusively on the district-level approach, progressively expanding the technology alternatives. The second analysis introduces the STES system coupled with GSHP operation, while the third analysis incorporates wind generation. The simulations set concludes with a sensitivity analysis, in which the best performing scenarios for the Optimal, NZED, and SS targets, considering all studied technologies simultaneously, are evaluated under variations in technology costs, energy tariffs, and building energy demand assumptions related to design and operation.

When different combinations of technologies are compared, each setup is named according to the technologies made available to the optimisation model, regardless of whether they are ultimately selected (e.g., “District PV+ESS” or “District PV+ESS+STES”).

7.5 Results and discussion

7.5.1 Building-level vs district-level comparison with combination of PV and ESS

This section presents the results of the optimisation scenarios considering PV generation combined with ESS. The analysis compares building-level, partial district (Clusters) and full district-level approaches, highlighting how different degrees of system aggregation influence system sizing, energy performance and costs.

Table 7.9 summarises the energy and economic results obtained for the three main optimisation goals (optimal, NZED and 100% SS) between the three different approaches.

Table 7.9. Energy and economic results for the main optimisation goals for all approaches.

Scenario	Building	Clusters	District		
	Optimal	Optimal	Optimal	NZED	SS100
Total cost (M€)	13.5	12.0	11.3	11.4	350.0
CAPEX (M€)	7.2	5.9	5.3	5.7	242.0
HVAC&DHW (M€)	5.9	4.4	3.8	3.8	3.8
PV (M€)	1.4	1.5	1.4	1.8	2.5
ESS (M€)	0.01	0.02	0	0.03	236.0
OPEX (M€)	6.3	6.1	6.0	5.7	107.3
Grid energy use (M€)	4.8	4.96	5.0	4.6	-0.2
Maintenance (M€)	1.4	1.2	1.1	1.1	107.5
Final energy (GWh/yr)	2.8	2.9	2.9	2.9	2.9
PV production (GWh/yr)	2.2	2.4	2.3	2.9	4.0
Self-consumption (GWh/yr)	1.3	1.4	1.4	1.5	2.9
Exported (GWh/yr)	0.9	1.1	0.9	1.4	1.0
Imported (GWh/yr)	1.5	1.5	1.5	1.4	0.0
Self-sufficiency rate (%)	47	48	48	51	100
Self-consumption rate (%)	59	57	60	51	73
Carbon emissions (tCO ₂ e/yr)	157	163	163	153	0
System sizing					
Heating capacity (MW)	3.5	3.5	3.2	3.2	3.2
Cooling capacity (MW)	1.8	1.8	1.8	1.8	1.8
PV capacity (MWp)	1.5	1.7	1.6	2.0	2.8
ESS nominal size (MWh)	0.015	0.03	0	0.05	393.4

Based on the results summarised in the table, the analysis of the cost-optimal scenarios shows that increasing the degree of system centralisation leads to reductions in both CAPEX and OPEX, resulting in a lower total cost. The reduction in CAPEX is primarily driven by lower HVAC&DHW investment costs, consequent from reduced installed heating and cooling capacities at the district scale. At the same time, final energy demand increases in centralised approaches, reflecting the higher efficiencies of the building-level HVAC&DHW solutions selected in decentralised setups compared to the district-level alternative.

The district-level results further enable a comparison between the cost-optimal (Optimal), NZED, and SS scenarios. While the Optimal district-level design does not achieve net-zero energy status, transitioning to an NZED configuration requires only a marginal increase in total cost, below 1%. This difference lies well within the uncertainty range associated with both methods and data inputs considered. Moving from the Optimal to the NZED scenario involves higher investment costs and reduced operational costs, as additional generation and storage capacity is installed to offset grid imports. In contrast, achieving high self-sufficiency levels leads to a substantial increase in total cost, largely driven by the need for significantly higher energy storage capacities.

In this case study, the Optimal centralised solution exhibits higher GHG emissions than the Optimal building-level scenario due to increased reliance on grid electricity. However, the district-level NZED scenario presents both a lower total cost and GHG emissions than the Optimal building-level solution.

Figure 7.8 and Figure 7.9 illustrate the main differences across the analysed scenarios in energy flows and cost components, respectively.

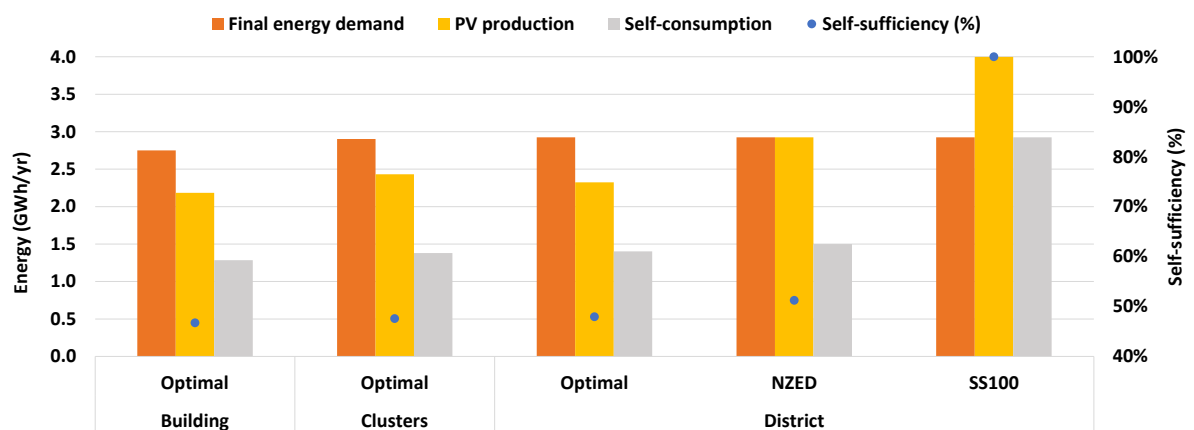


Figure 7.8. Annual energy results for the main scenarios (optimal, NZED and SS100).

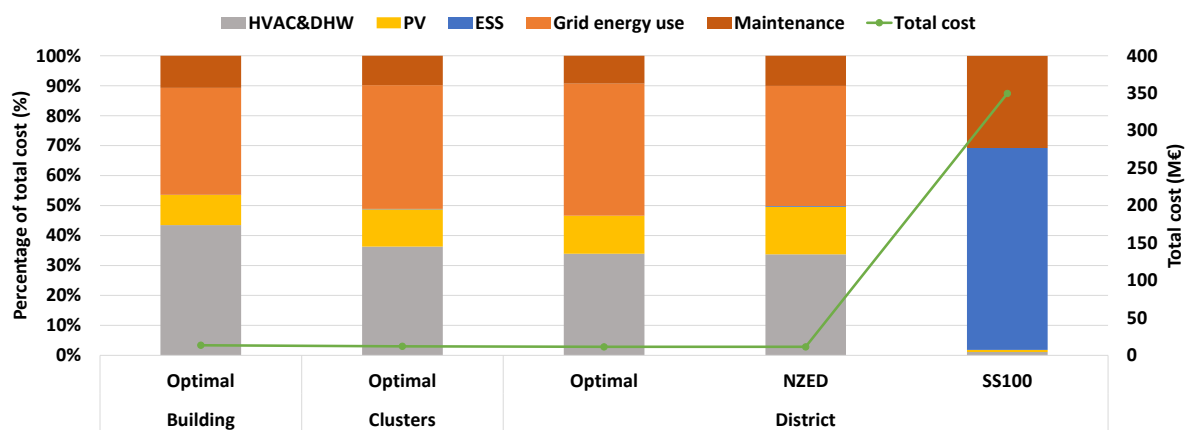


Figure 7.9. Cost split across lifetime horizon for the main scenarios (optimal, NZED and SS100).

The building-level approach does not allow the district to achieve a net-zero energy status when considering all buildings collectively. In particular, buildings B01, B02, and B03 do not have sufficient rooftop area to install enough PV capacity to fully cover their annual electricity demand. The remaining buildings are able to reach net-zero energy status individually, with systems optimally designed to meet their respective energy needs. It would be possible to individually oversize the PV systems of buildings with surplus rooftop availability in order to offset the residual energy demand of B01, B02, and B03. However, this approach falls outside the scope of the present analysis, which aims to contrast two distinct paradigms: a district-level approach, in which the total energy demand of all buildings is centrally balanced by an optimised shared system, and a building-level approach, in which each building relies exclusively on its own optimally designed decentralised system. The percentage of available rooftop area was estimated based on the project blueprints and may differ from the final district design. Areas dedicated to terraces and leisure functions were excluded, and spacing between PV modules was considered. For buildings B01, B02, and B03, the entire rooftop area was assumed to be available for PV installation, as these buildings do not include leisure areas. This assumption highlights the physical limitation of rooftop PV in these cases and illustrates that, even assuming the extreme scenario of using all rooftop area, a full annual energy coverage cannot be achieved at building-level.

Achieving full self-sufficiency (SS100) is a particularly challenging target due to physical limitations in available PV area, which must be compensated by substantially increasing electrical energy storage capacity, as explicit in Table 7.9. This leads to a significant rise in investment costs, driving the total system cost to several times that of the Optimal or NZED scenarios. Larger buildings benefit more from a district-level approach, as some of them are unable to reach SS100 individually, or can only do so at a prohibitively high cost, e.g. up to 20 times higher than the Optimal scenario. By contrast, smaller buildings, represented in this case study by single-family buildings, are able to

achieve SS100 with a more moderate cost increase, on the order of twice the cost of the Optimal scenario.

Table 7.10 summarised the total available area for PV in each building's rooftop and the percentages of area covered for the different studied scenarios.

Table 7.10. Area available and covered by PV for the studied scenarios.

Building or Group	Percentage of rooftop area available for PV	Maximum area available for PV (m ²)	Optimal		Net-zero	Self-sufficient
			Occupied area (%)	Energy goal	Occupied area (%)	Occupied area (%)
1 – B01	100%	777	77%	Nearly-zero	Net-zero and Self-sufficient not possible due to limited area for PV	
2 – B02	100%	793	81%	Nearly-zero		
3 – B03	100%	792	85%	Nearly-zero		
4 – B08	50%	936	40%	Nearly-zero	60%	100%
5 – B09	50%	291	44%	Nearly-zero	65%	100%
6 – B10	50%	644	42%	Nearly-zero	63%	100%
7 – B11.1	95%	1275	69%	Positive energy	58%	100%
8 – B11.2	75%	882	88%	Positive energy	73%	100%
9 – B11.3	50%	1282	100%	Nearly-zero	Net-zero and SS not possible	
10 – B12	50%	641	42%	Nearly-zero	63%	100%
11 – B13.1	50%	342	43%	Nearly-zero	64%	100%
12 – B13.2	50%	630	42%	Nearly-zero	63%	100%
13 – B14	75%	256	7%	Nearly-zero	11%	59%
14 – B15	75%	236	7%	Nearly-zero	11%	58%
15 – B16	75%	256	7%	Nearly-zero	11%	59%
16 – B17	75%	256	7%	Nearly-zero	11%	59%
17 – B18	75%	136	15%	Nearly-zero	22%	100%
18 – B19	75%	136	15%	Nearly-zero	22%	100%
19 – B20	75%	136	15%	Nearly-zero	22%	100%
20 – B21	75%	151	15%	Nearly-zero	22%	100%
21 – B22	75%	151	15%	Nearly-zero	22%	100%
22 – B26	75%	236	7%	Nearly-zero	11%	58%
23 – B27	75%	236	7%	Nearly-zero	11%	58%
24 – B28	75%	151	15%	Nearly-zero	22%	100%
25 – B29	75%	151	15%	Nearly-zero	22%	100%
26 – B30	75%	151	15%	Nearly-zero	22%	100%
27 – B31	75%	151	15%	Nearly-zero	22%	100%
28 – B32	40%	516	52%	Nearly-zero	77%	100%
Building	65%	12590	55%	Nearly-zero	Net-zero and SS not possible	
Group A	100%	2 363	88%	Nearly-zero	Net-zero and SS not possible	
Group B	50%	3 483	45%	Nearly-zero	67%	100%
Group C	68%	3 439	100%	Positive energy	83%	100%
Individual buildings from 13 to 28						
Clusters	65%	12 590	61%	Nearly-zero	Net-zero and SS not possible	
District	65%	12590	58%	Nearly-zero	73%	100%

7.5.2 Integration of Seasonal Thermal Energy Storage (STES) at district-level

In this section, a set of scenarios integrating seasonal thermal energy storage (STES) was analysed and compared to the previous section district-level results. The scenarios differ exclusively in the size of the borefield, expressed by the number of boreholes. The district baseline case corresponds to a setup without boreholes (case *Bh 0*), similar to the District setup from the previous section, while the STES scenarios consider an increasing borefield size, i.e., number of boreholes (cases *Bh 10*, *Bh 25*, *Bh 50*, *Bh 100*, and *Bh 200*). This range of borefield sizes allows the assessment of different levels of STES dimensioning in support of the PV and ESS technologies already included in the district-level analysis.

As described in Chapter 6, the borehole STES system is defined by the introduction of a discrete number of boreholes, which directly determines the borefield investment cost. The borefield enables thermal exchange between the ground, acting as a seasonal storage medium, and the GSHP system. GSHP operation and capacity are constrained by borefield size and ground thermal limits, which in turn affect the achievable thermal contribution of the STES system.

Two alternative sizing strategies for the combined ASHP and GSHP systems can be evaluated in the model: GSHP capacity partially replaces ASHP capacity, as long as the total HVAC&DHW demand is met; or ASHP capacity is dimensioned to fully cover peak thermal demand regardless of GSHP sizing, resulting in duplicated capacity. Under the adopted cost and performance assumptions, the optimisation results indicate that the latter strategy does not provide economic benefits. When ASHP capacity is already sufficient to meet peak demand, the additional investment in GSHP and STES is not offset by the potential efficiency gains achieved during favourable periods.

Consequently, only results in which ASHP and GSHP operate as complementary technologies, i.e., such that the sum of their peak capacities covers the total district thermal demand, are presented and discussed. While system redundancy could be justified in practice for reliability reasons, this would require the introduction of additional investment and maintenance costs associated with duplicated HVAC&DHW capacity. Given that the integration of STES already leads to higher total costs in most cases, primarily driven by borefield investment, such duplication would further accentuate the cost increase and is therefore not considered in the present analysis.

The main impacts of STES integration on total cost, self-sufficiency, and self-consumption rates throughout borefield size are illustrated in Figure 7.10, Figure 7.11 and Figure 7.12 for the Optimal, NZED, and self-sufficiency scenarios, respectively. The graphs present total system cost, PV and ESS investment costs, and OPEX, including energy costs and maintenance, enabling comparisons both across energy performance targets and across borefield sizes. As HVAC&DHW costs remain constant across these scenarios, given that ASHP and GSHP are assumed to have the

same specific cost per unit of thermal power, the total HVAC&DHW investment (3.8 M€) is not shown explicitly. Instead, the figures report the relative share of ASHP and GSHP capacity within the combined HVAC&DHW system.

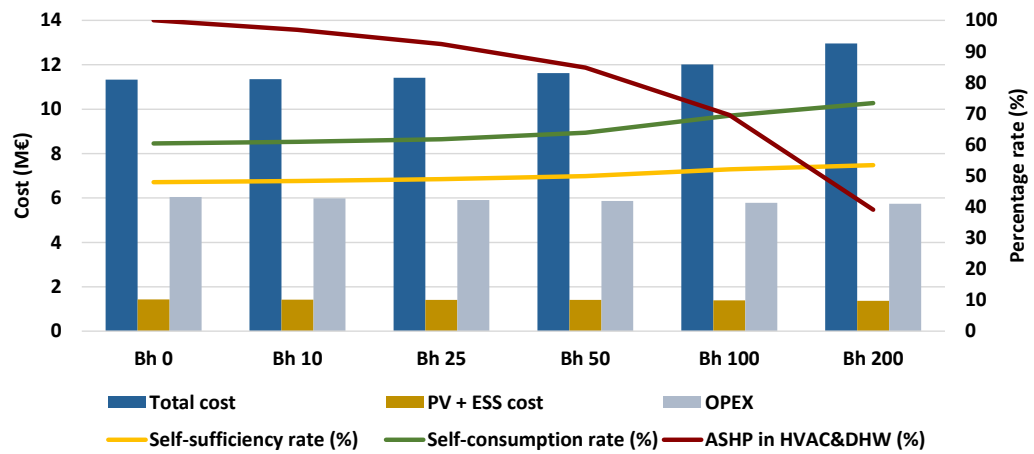


Figure 7.10. Impacts of borefield size in energy and cost parameters for the Optimal scenario.

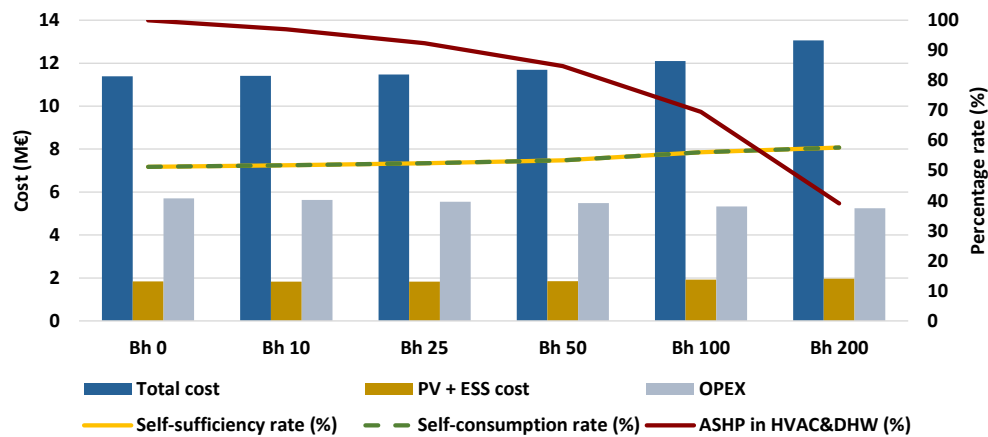


Figure 7.11. Impacts of borefield size in energy and cost parameters for the NZED scenario.

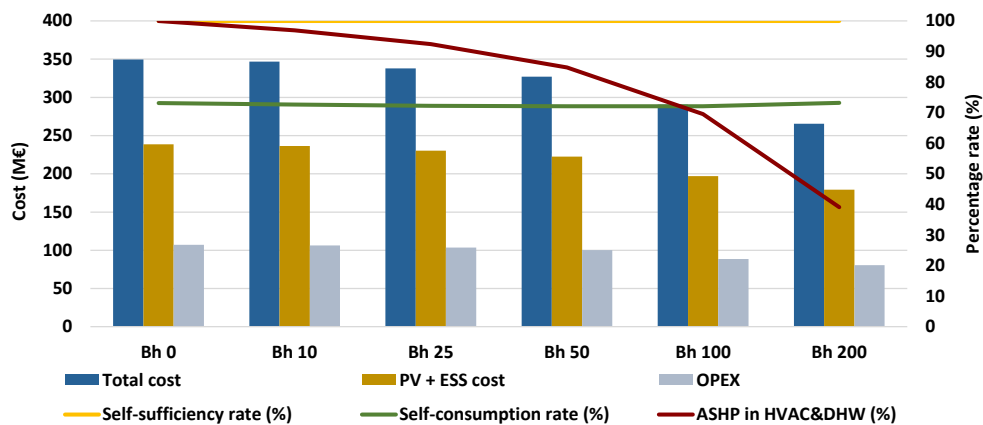


Figure 7.12. Impacts of borefield size in energy and cost parameters for the SS scenario.

For the Optimal scenario, results show that total system cost increases with larger borefield sizes. Although PV and ESS investment and OPEX are slightly reduced as borefield size increases, these savings are insufficient to compensate for the additional cost of the borefield. At the same time, both self-sufficiency and self-consumption rates improve with increasing borefield size, reflecting the enhanced ability of STES to shift thermal energy seasonally and reduce reliance on electric heating during peak periods.

For the NZED scenarios, total system cost also increases with larger borefield sizes. While OPEX is slightly reduced due to improved thermal efficiencies and reduced grid electricity use, both PV and ESS investment costs increase to support the higher self-sufficiency levels enabled by STES. As a result, the additional borefield investment is not compensated. Although self-sufficiency and self-consumption rates increase with borefield size, these gains lead to higher total costs under NZED conditions.

In contrast, for high self-sufficiency targets, the role of STES becomes more favourable. At elevated SS levels, the borefield investment associated with larger borefields is partially or fully compensated by substantial reductions in PV capacity, ESS sizing and OPEX, once more reflecting ability of seasonal thermal storage to shift energy across seasons and reduce reliance on PV and ESS solutions that would otherwise be required to achieve high SS levels.

Table 7.11 summarises the energy and economic results obtained for the three main optimisation goals (optimal, NZED and 100% self-sufficiency - SS100) for the combination of PV, ESS and STES. The aggregated results confirm that, under the assumptions adopted in this study, STES provides economic advantages only when targeting high levels of self-sufficiency. For the Optimal and NZED scenarios, the smallest borefield configuration yields the lowest total cost, while larger borefields result in increasing investment without sufficient operational savings. Although STES consistently reduces OPEX and increases self-consumption rates, the high upfront cost associated with borehole installation is only offset when SS targets are sufficiently ambitious. In the SS100 scenario, the optimisation selects a larger share of GSHP capacity relative to ASHP, highlighting the relevance of these systems when aiming for full self-sufficiency.

Table 7.11. Energy and economic results for the three main optimisation goals for all setups.

Scenario	District PV+ESS			District PV+ESS+STES		
	Optimal	NZED	SS100	Optimal	NZED	SS100
Selected borefield case	Bh 0	Bh 0	Bh 0	Bh 10	Bh 10	Bh 200
Total cost (M€)	11.33	11.40	350.0	11.34	11.41	266.0
CAPEX (M€)	5.3	5.7	242.0	5.4	5.8	185.0
HVAC&DHW (M€)	3.8	3.8	3.8	3.8	3.8	3.8
PV (M€)	1.4	1.8	2.5	1.4	1.8	2.5
ESS (M€)	0	0.03	236.0	0	0.04	176.7
Borefield (M€)	-	-	-	0.1	0.1	2.0
OPEX (M€)	6.0	5.7	107.3	5.9	5.6	80.6
Grid energy use (M€)	5.0	4.6	-0.2	4.9	4.5	-0.2
Maintenance (M€)	1.1	1.1	107.5	1.1	1.1	80.8
Final energy (GWh/yr)	2.9	2.9	2.9	2.9	2.9	2.9
PV production (GWh/yr)	2.3	2.9	4.0	2.3	2.9	4.0
Self-consumption (GWh/yr)	1.4	1.5	2.9	1.4	1.5	2.9
Exported (GWh/yr)	0.9	1.4	1.0	0.9	1.4	1.0
Imported (GWh/yr)	1.5	1.4	0.0	1.5	1.4	0.0
Self-sufficiency rate (%)	48	51	100	48	52	100
Self-consumption rate (%)	60	51	73	61	52	73
Carbon emissions (tCO ₂ e/yr)	163	153	0	161	150	0
System sizing						
Heating capacity (MW)	3.2	3.2	3.2	3.2	3.2	3.2
Cooling capacity (MW)	1.8	1.8	1.8	1.8	1.8	1.8
GSHP capacity (%)	0	0	0	3	3	61
ASHP capacity (%)	100	100	100	97	97	39
PV capacity (MWp)	1.6	2.0	2.8	1.6	2.0	2.8
ESS nominal size (MWh)	0	0.05	393.4	0	0.05	294.5
Number of boreholes	0	0	0	10	10	200

Figure 7.13 further compares total system cost across scenarios with increasing SS targets. The district configuration based exclusively on PV and ESS exhibits the lowest total cost for both the Optimal and NZED objectives, consistent with the results discussed previously. However, between the 85% and 90% self-sufficiency levels, STES becomes cost efficient across all tested borefield sizes. While STES scenarios exhibit higher total costs under Optimal and NZED objectives, they consistently achieve higher self-sufficiency levels than setups relying exclusively on PV and ESS. Notably, at the 85% SS target, the second lowest cost solution is no longer the smallest borefield (Bh 10), but already the Bh 25 configuration, indicating that moderate STES sizing becomes advantageous as self-sufficiency requirements increase.

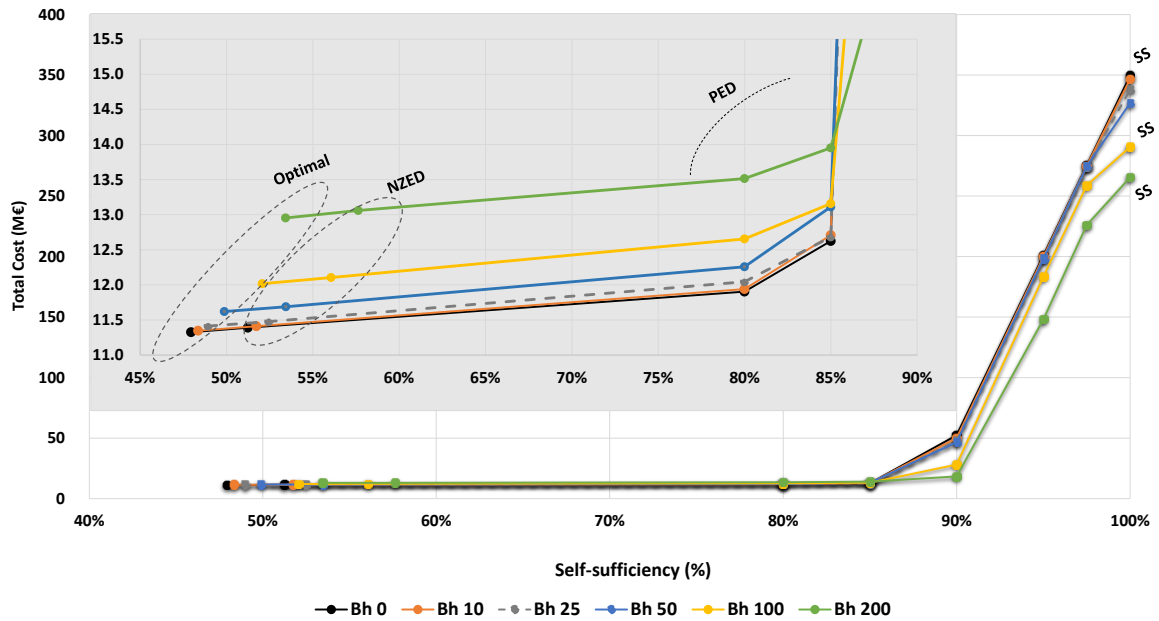


Figure 7.13. Variation of total cost with the level of self-sufficiency for each borefield size (dark graph zooms into lower total cost).

In order to illustrate how borefields influence the efficiencies of GSHP, the following graphs were selected for the Optimal design of District Bh 200. Figure 7.14 describes the evolution of Fluid Temperature in the borehole during the year. Similarly, Figure 7.15, Figure 7.16 and Figure 7.17 describe the effect of the temperature on space heating COP, domestic hot water COP and space cooling EER, respectively.

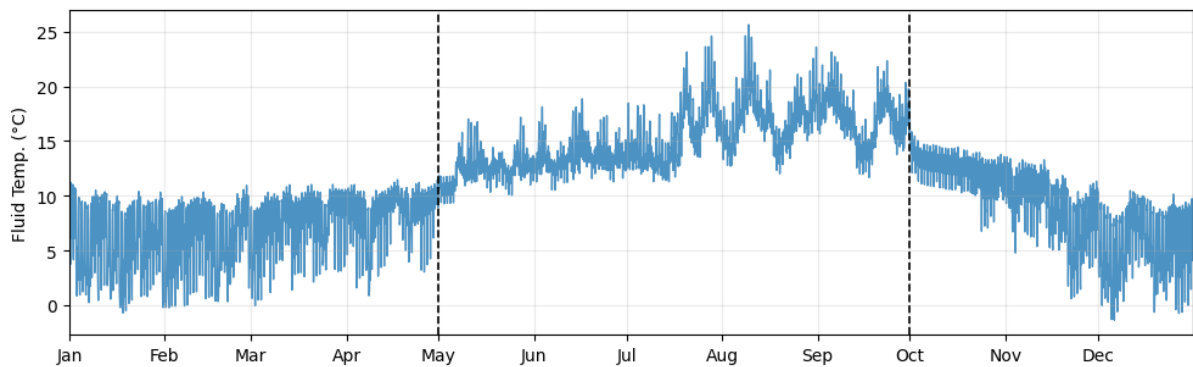


Figure 7.14. Variation of entering fluid temperature across the year (case bh 200).

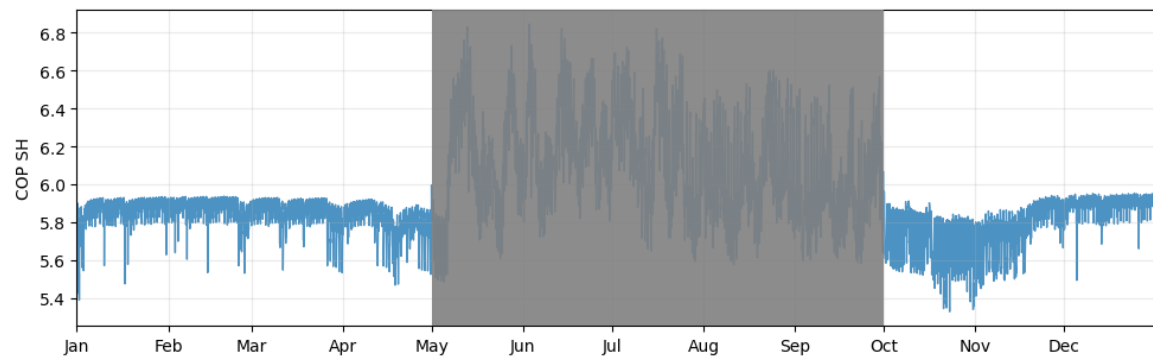


Figure 7.15. Variation of space heating COP across the year (case Bh 200).

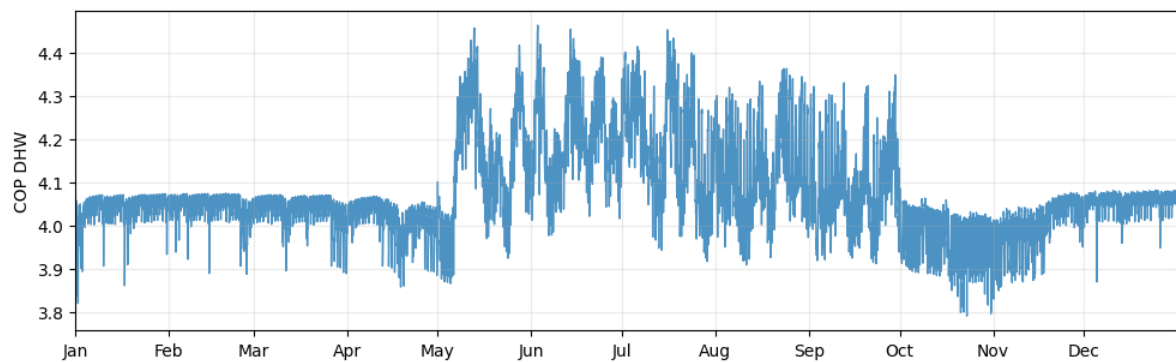


Figure 7.16. Variation of domestic hot water COP across the year (case Bh 200).

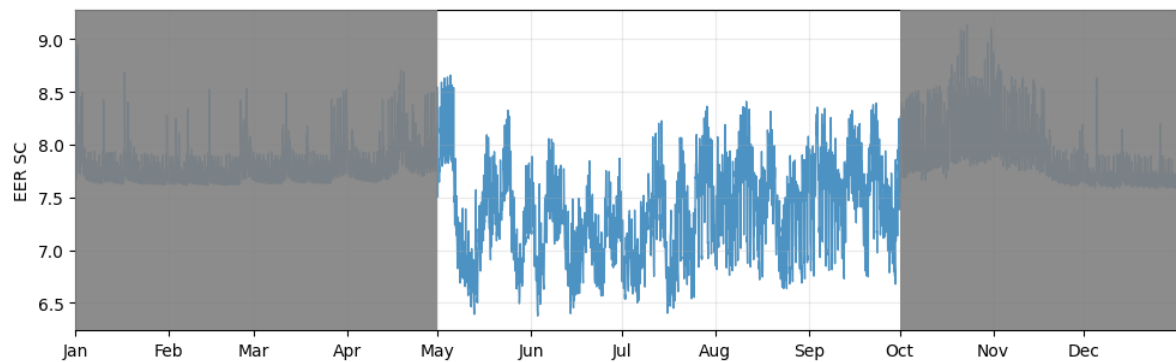


Figure 7.17. Variation of space cooling EER across the year (case Bh 200).

The set of figures illustrates an example of the annual evolution of entering fluid temperature (EFT) and the corresponding GSHP performance indicators, namely COP and EER. These results highlight the dynamic interaction between borefield thermal behaviour and GSHP efficiency throughout the year. During the cooling season, the GSHP operates in heat rejection mode, injecting heat into the ground and progressively increasing both ground and fluid temperatures. As

a consequence, the efficiency of cooling operation decreases over time, reflected by a gradual reduction in the EER as the temperature of the heat sink rises.

Conversely, during the heating season, heat is extracted from the ground to supply space heating and domestic hot water. This extraction leads to a reduction in ground and fluid temperatures, which in turn reduces the COP of the GSHP as the temperature lift required for heating increases. The seasonal evolution of EFT, COP, and EER therefore illustrates how borefield charging and discharging directly influence heat pump performance and underscores the importance of properly sizing and operating the STES system to maintain favourable operating temperatures over the year.

7.5.3 Integration of wind generation at district-level

The inclusion of wind generation in this analysis is explored as a theoretical extension. Wind technology is not currently envisaged for implementation in the real project, and several real-world constraints would likely hinder its deployment, including limited unobstructed areas, noise restrictions, visual and landscape impacts, licensing requirements and broader aesthetic considerations. Nonetheless, given the riverfront location of the district and the sloping terrain, the installation of a limited number of small-scale wind turbines could be conceptually envisaged. From a modelling perspective, wind generation represents an alternative renewable electricity source with a less static profile and potentially complementary to PV. A market survey was conducted to identify representative investment costs and power curves for small-scale wind turbines. Based on these data, a unitary production profile per turbine of 10 kW was derived, with an estimated annual electricity generation of approximately 18.8 MWh per turbine, simulated using historical wind speed data for the project location. This production level corresponds to roughly 25% of the rated annual energy output achievable under high average wind speed conditions, reflecting the moderate wind resource at the site. Investment costs, including equipment and installation, were found to range between 25 000€ and 35 000€ per turbine. For the optimisation runs, an average cost value was adopted to facilitate direct comparison between district setup based on PV and ESS alone and those incorporating PV, ESS, and wind generation. As wind investment cost strongly influences the optimal number of turbines selected by the model, this parameter is further explored in the sensitivity analysis. To limit spatial conflicts and turbine-turbine and turbine-building interactions, the total number of wind turbines was capped at 50 units. This constraint corresponds to an average gross land availability of approximately 4 000 m² per turbine across the project area, ensuring conservative assumptions regarding spacing and local impacts.

Table 7.12 summarises the main energy performance and cost related results across scenarios, allowing the comparison between District PV + ESS and District PV+ESS+W setups.

Table 7.12. Energy and economic results in the multiple scenarios for each setup.

	Scenario	Optimal	NZED	SS80	SS85	SS90	SS95	SS97.5	SS100
Total cost (€)	District PV+ESS	11.3	11.4	11.9	12.6	52.4	201.0	275.3	349.7
	District PV+ESS+W	11.3	11.3	11.7	12.1	12.8	21.0	88.4	162.7
CAPEX (€)	District PV+ESS	5.3	5.7	8.1	9.0	36.7	139.5	191.0	242.4
	District PV+ESS+W	5.7	6.2	8.1	8.8	9.8	15.8	62.4	113.8
OPEX (€)	District PV+ESS	6.0	5.7	3.8	3.7	15.7	61.5	84.4	107.3
	District PV+ESS+W	5.6	5.1	3.6	3.3	3.0	5.2	26.0	48.9
PV installed capacity (kWp)	District PV+ESS	1 602	2 017	2 757	2 757	2 757	2 757	2 757	2 757
	District PV+ESS+W	1 440	1 695	2 063	2 459	2 757	2 757	2 757	2 757
Number of turbines	District PV+ESS	0	0	0	0	0	0	0	0
	District PV+ESS+W	20	27	41	40	50	50	50	50
ESS nominal size (MWh/yr)	District PV+ESS	0	0.05	3	4	51	222	308	393
	District PV+ESS+W	0.04	0.15	2	3	3	13	91	177
PV production (GWh/yr)	District PV+ESS	2.3	2.9	4.0	4.0	4.0	4.0	4.0	4.0
	District PV+ESS+W	2.1	2.5	3.0	3.6	4.0	4.0	4.0	4.0
Wind production (GWh/yr)	District PV+ESS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	District PV+ESS+W	0.4	0.5	0.7	0.7	0.9	0.9	0.9	0.9
Self-sufficiency rate (%)	District PV+ESS	48	51	80	85	90	95	97	100
	District PV+ESS+W	54	59	80	85	90	95	97	100
Self-consumption rate (%)	District PV+ESS	60	51	59	62	66	69	71	73
	District PV+ESS+W	65	59	63	58	54	57	58	60

Including wind generation leads to a slight reduction in total system cost for both the Optimal and NZED scenarios. Although total CAPEX increases due to the additional investment in wind turbines, this effect is compensated by a reduction in OPEX, driven by lower grid electricity imports. Moreover, wind production also reduces the system's dependence on PV generation and, consequently, on available rooftop area. This effect delays the saturation of PV area constraints, which are only reached at the 90% self-sufficiency level, as illustrated in Figure 7.18.

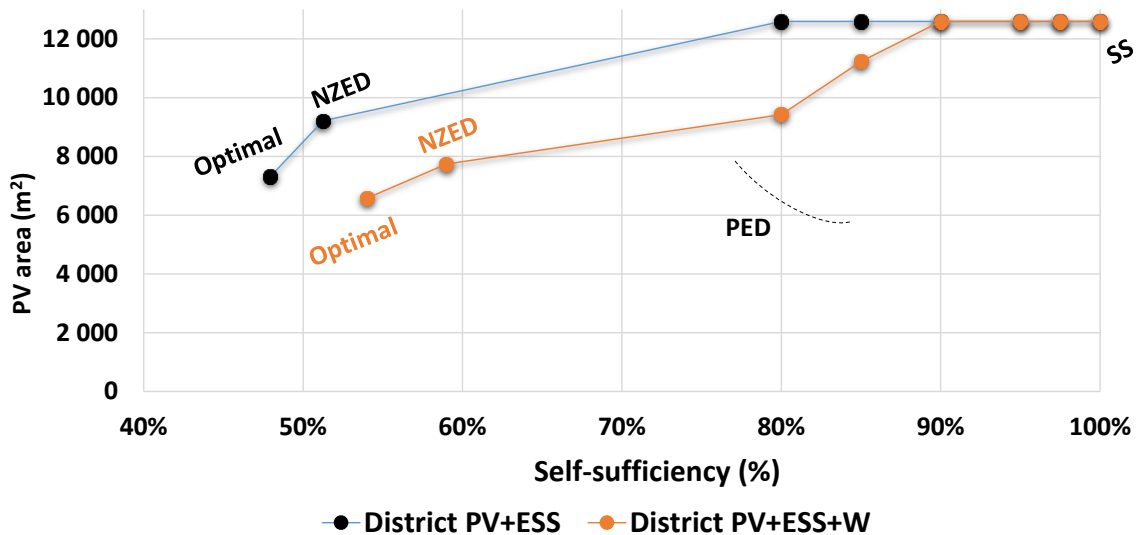


Figure 7.18. PV area covered for the scenarios in each setup.

By partially substituting PV generation, wind allows the system to achieve higher self-sufficiency levels without immediately requiring further increases in PV capacity. Self-sufficiency and self-consumption rates are therefore improved for both the Optimal and NZED configurations.

Figure 7.19 compares the evolution of total system cost across increasing self-sufficiency targets for the District PV+ESS and District PV+ESS+Wind setups. While the impact of wind on total cost is relatively limited for the Optimal and NZED objectives, its contribution becomes more pronounced above the 85% self-sufficiency threshold. In this range, wind generation emerges as a cost-effective alternative to further increases in electrical storage capacity, which would otherwise be required in PV-only scenarios.

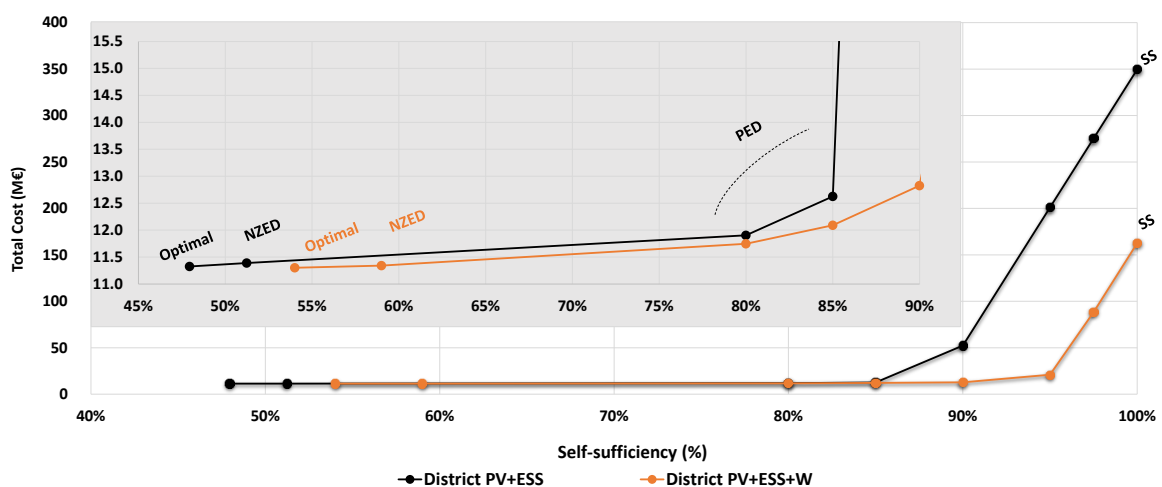


Figure 7.19. Variation of total cost with the level of self-sufficiency for each setup (dark graph zooms into lower total cost).

7.5.4 Sensitivity analysis

The sensitivity analysis builds upon the best performing setups identified for the Optimal, NZED, and SS goals, considering the full set of available technologies, presented in Table 7.13. For the Optimal and NZED targets, the reference setup corresponds to the District PV+ESS+W scenarios. In contrast, the SS100 scenario represents a distinct outcome, achieved through the combined deployment of PV, ESS, wind generation and STES.

These reference scenarios are used as the starting point to assess how variations in key techno-economic parameters influence system design, total cost, and energy performance.

Table 7.13. Energy and economic results for the three main optimisation goals considering all technologies.

Scenario	District PV+ ESS+W+STES		
	Optimal	NZED	SS100
Selected borefield	Bh 0	Bh 0	Bh 200
Total cost (M€)	11.3	11.3	104.2
CAPEX (M€)	5.7	6.2	74.1
HVAC&DHW (M€)	3.8	3.8	3.8
PV (M€)	1.3	1.5	2.5
Wind (M€)	0.6	0.8	1.5
ESS (M€)	0.02	0.09	64.3
Borefield (M€)	0	0	2.0
OPEX (M€)	5.6	5.1	30.1
Grid energy use (M€)	4.4	3.8	-0.4
Maintenance (M€)	1.2	1.3	30.5
Final energy (GWh/yr)	2.9	2.9	2.9
PV production (GWh/yr)	2.1	2.5	4.0
Wind Production (GWh/yr)	0.4	0.5	0.9
Self-consumption (GWh/yr)	1.6	1.7	2.9
Exported (GWh/yr)	0.9	1.2	2.0
Imported (GWh/yr)	1.3	1.2	0.0
Self-sufficiency rate (%)	54	59	100
Self-consumption rate (%)	65	59	59
Carbon emissions (tCO ₂ e/yr)	144	128	0
System sizing			
Heating capacity (MW)	3.2	3.2	3.2
Cooling capacity (MW)	1.8	1.8	1.8
GSHP capacity (%)	0	0	61
ASHP capacity (%)	100	100	39
PV capacity (MWp)	1.4	1.7	2.8
Number of turbines	20	27	50
ESS nominal size (MWh)	0.04	0.15	107.2
Number of boreholes	0	0	200

7.5.4.1 Costs and tariffs

As the cost-optimal configuration does not achieve NZED or PED status under baseline assumptions, the Optimal scenario is used as the reference case for the sensitivity analysis on technology costs and energy tariffs. The analysis aims at evaluating how variations in specific cost parameters affect total system cost, and assessing whether such variations enable the cost-optimal design to transition toward NZED or PED performance. The results of this analysis are illustrated in Figure 7.20. In the figure, the “PED” indication marks that the optimal scenario reaches positive energy status as a consequence of the selected cost variation.

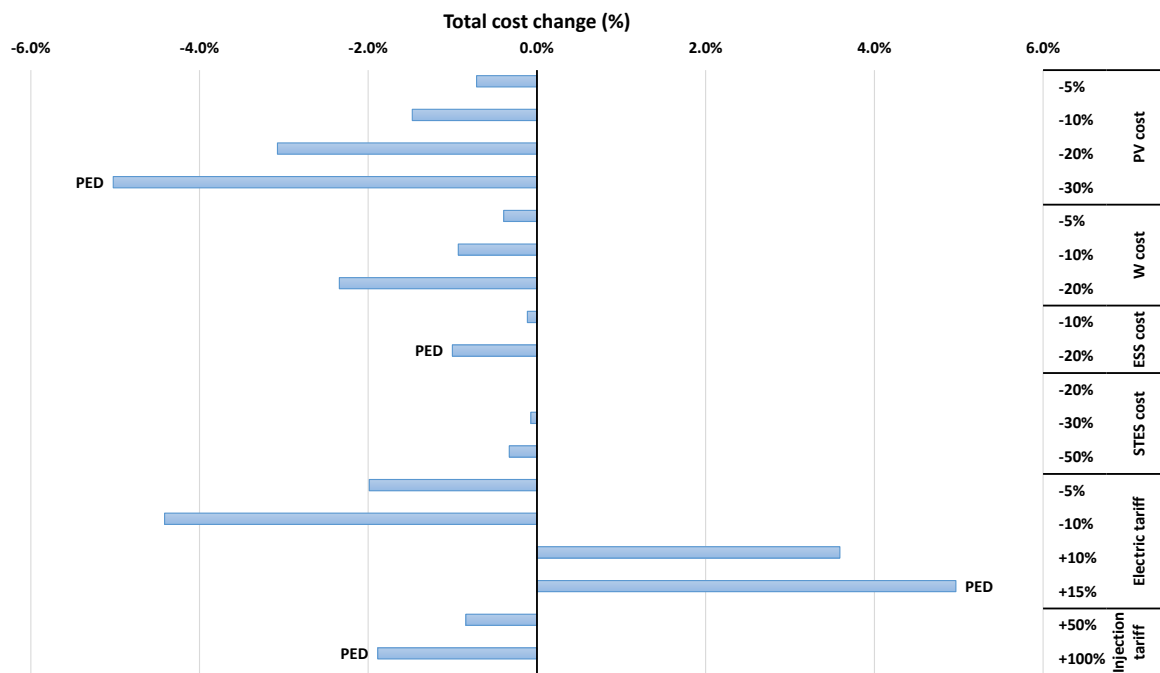


Figure 7.20. Sensitivity analysis on costs and tariffs for the optimal scenario.

A reduction in PV investment cost leads to a direct decrease in total system cost and strongly incentivises additional PV installation. When PV costs are reduced by approximately 30%, the optimal scenario reaches PED status. At the same time, lower PV costs reduce the attractiveness of wind generation, which is partially displaced in the optimal solution. Reducing wind investment cost alone is not sufficient to achieve NZED or PED performance. Even with a 20% reduction in wind costs, the maximum allowable number of turbines is reached, and additional wind capacity would be required to fully offset district energy demand. This indicates that spatial and policy constraints, rather than cost alone, limit the contribution of wind in this case study. Lower ESS costs also lead to a reduction in total system cost but tend to disincentivise wind deployment, as increased storage capacity allows higher utilisation of PV generation without relying on complementary production sources. Reducing STES investment costs does not significantly promote higher levels of renewable

electricity generation. While lower borefield costs make STES more attractive and lead to the selection of larger borefield configurations, their impact on total system cost and renewable penetration remains limited under the examined conditions. Variations in electricity tariffs have a pronounced effect on system design. Reducing electricity prices decreases total system cost but does not encourage the optimal solution to evolve toward NZED or PED targets. Conversely, increasing electricity tariffs raises total system cost but incentivises higher levels of on-site generation, particularly PV and wind, thereby promoting NZED or PED performance. Finally, increasing the compensation for electricity injection into the grid tends to disincentivise wind generation while encouraging PV deployment, as PV systems benefit more directly from export remuneration under the assumed market conditions.

7.5.4.2 Energy demand alternatives

Variations on building design and operational conditions were simulated to assess their impact on energy demand and total system cost. Given that the district is a new development, alternatives on the window-to-wall ratio were studied, differing from the assumed 0.5 based on information provided. Two alternative configurations were tested, reducing the ratio to 0.4 and 0.3, in order to evaluate the sensitivity of system performance to changes in building envelope design.

In addition, two alternative scenarios with more relaxed indoor comfort conditions were analysed by adjusting heating and cooling setpoint temperatures. These scenarios represent plausible operational or design choices aimed at reducing energy demand while maintaining acceptable comfort levels. All four intervention scenarios were evaluated independently and not cumulatively. The impact in energy demand is summarised in Table 7.14.

Table 7.14. Energy demand results from building design and operation alternatives.

		Electric energy (MWh/yr)	SH (MWh/yr)	DHW (MWh/yr)	SC (MWh/yr)	Total energy demand (MWh/yr)	Percentual difference in total demand
District base scenario		1 684	2 440	1 787	1 589	7 501	-
Window-to-wall ratio	0.4	1 681	2 257	1 787	1 619	7 344	-2.1%
	0.3	1 677	2 072	1 787	1 610	7 146	-4.7%
SH/SC setpoint temperatures (°C)	19/25	1 659	1 938	1 788	1 415	6 800	-9.3%
	18/26	1 648	1 481	1 789	1 314	6 232	-16.9%

These alternatives were simulated and shown a relevant impact in the total cost as presented in Figure 7.21.

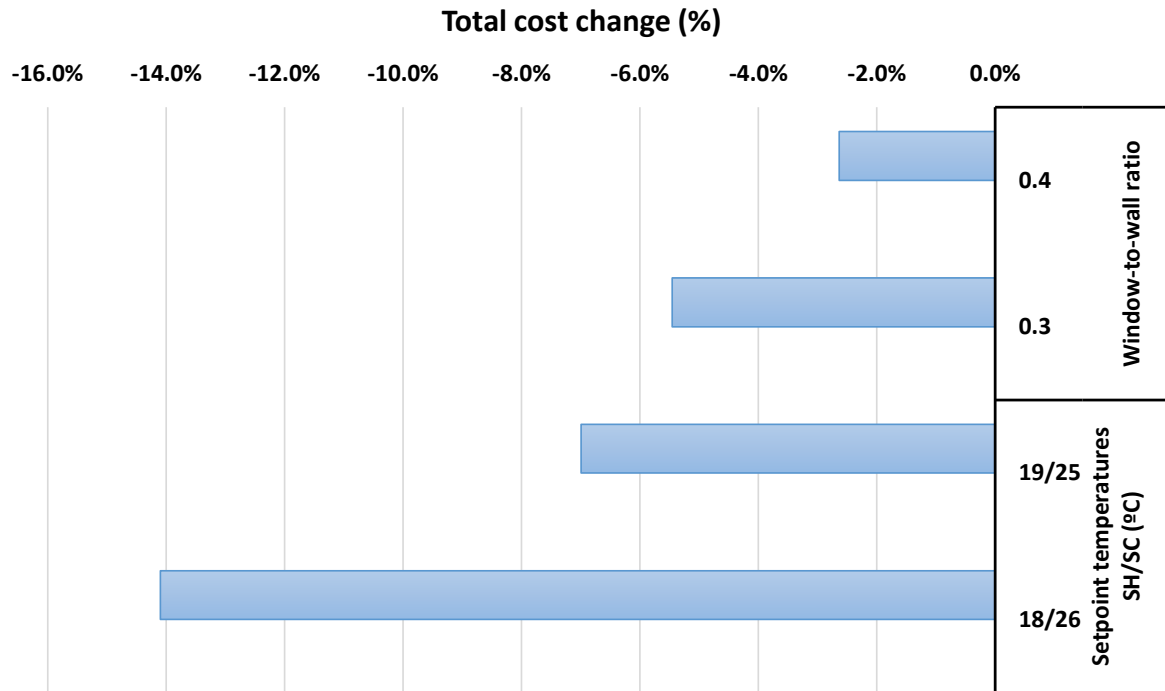


Figure 7.21. Sensitivity analysis results for the optimal scenario.

Unlike variations in energy prices or technology costs, which directly affect the economic competitiveness of on-site generation and storage and may enable the system to reach net-zero or positive energy targets, changes in energy demand primarily influence total system cost. While the demand-reduction measures lead to noticeable cost savings, they do not alter the ability of the optimal system design to achieve net-zero or positive energy status under the conditions examined.

7.5.4.3 Discount rate

In the development of the optimisation framework, the discount rate was explicitly implemented as an optional parameter, allowing lifetime costs to be evaluated under different financial perspectives. Nevertheless, in the analysis presented throughout this chapter, a zero-discount rate was adopted. This choice was deliberate and aimed at minimising confounding effects associated with long-term macroeconomic assumptions, such as future electricity price trajectories, inflation or regulatory changes. Given that real price increases may partially offset the effect of temporal discounting, and that such dynamics are inherently uncertain over the considered time horizon, adopting a zero-discount rate enabled a clearer assessment of the techno-economic feasibility of NZED, PED, and self-sufficient configurations without additional financial bias.

Despite this baseline assumption, the discount rate remains a key parameter in the economic evaluation of energy systems, as it directly affects the trade-off between CAPEX and OPEX. For this reason, a sensitivity analysis was conducted to explicitly assess the influence of the discount rate on the optimisation results. The analysis focuses on the resulting NZED scenario and considers different discount rate values applied to electricity-related costs and maintenance expenditures.

Changes in the cost-optimal technological configuration resulting from variations in the discount rate are summarised in Table 7.15, highlighting potential shifts in the selected generation and storage technologies.

Table 7.15. Influence of discount rate in systems sizing.

Discount rate	0%/yr	2%/yr	4%/yr
PV area (m ²)	7 738	9 210	9 210
EES capacity (kWh)	151	0	0
Number of wind turbines	27	0	0

The corresponding economic implications are detailed through a separate cost breakdown graph, in Figure 7.22, reporting CAPEX and discounted OPEX values for each discount rate scenario.

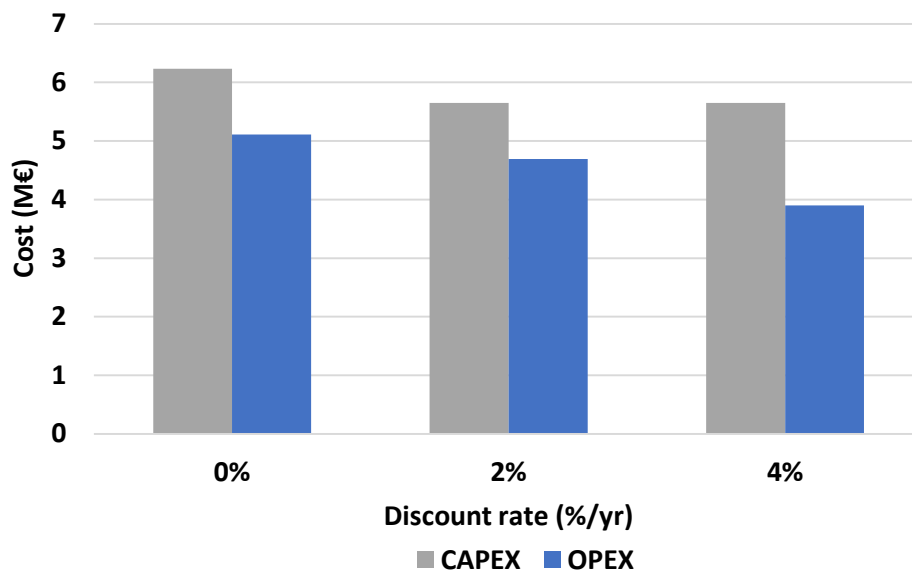


Figure 7.22. Influence of discount rate alternatives in CAPEX and OPEX.

Introducing a positive discount rate leads to a threshold effect. A first transition occurs between 0% and 2%, where technologies with higher upfront investment and long payback periods (wind and electrical storage) are replaced by PV. Beyond this point, increasing the discount rate does not alter the optimal system configuration, but only reduces the present value of operational costs.

7.5.4.4 GHG emissions

In the previous analyses, reported annual GHG emissions were calculated using a fixed, current grid emission factor. The reference emission factor was set to 0.107 kgCO₂/kWh, the corresponding 2023 Portuguese electricity grid (APA, 2025). For the present analysis a comparison was performed between the reference emissions value, assuming no grid decarbonisation, and scenarios incorporating annual grid decarbonisation rates, over the 20-year project lifetime. Annual decarbonisation rates of 2%, 4%, and 6% were tested to reflect a range of plausible future trajectories. These values are informed by historical trends, as the Portuguese electricity grid experienced an average decarbonisation rate of approximately 5% per year between 2011 and 2023, allowing both conservative and optimistic projections to be explored (APA, 2025). These rates are also aligned with the Portuguese grid decarbonisation rates targeted in the long-term strategy for carbon neutrality, aiming at a 90% decarbonisation between 2005 and 2050 (RNC2050, 2019).

For this comparison, the conservative approach followed before was kept, which accounted for carbon emissions based exclusively on electricity imported from the grid, without accounting for potential offsets associated with renewable electricity injected into the grid. Under a net emissions accounting perspective, any NZED configuration would therefore result in net-zero operational carbon emissions.

Figure 7.23 presents the resulting lifetime GHG emissions over the 20-year project lifetime for the analysed scenarios.

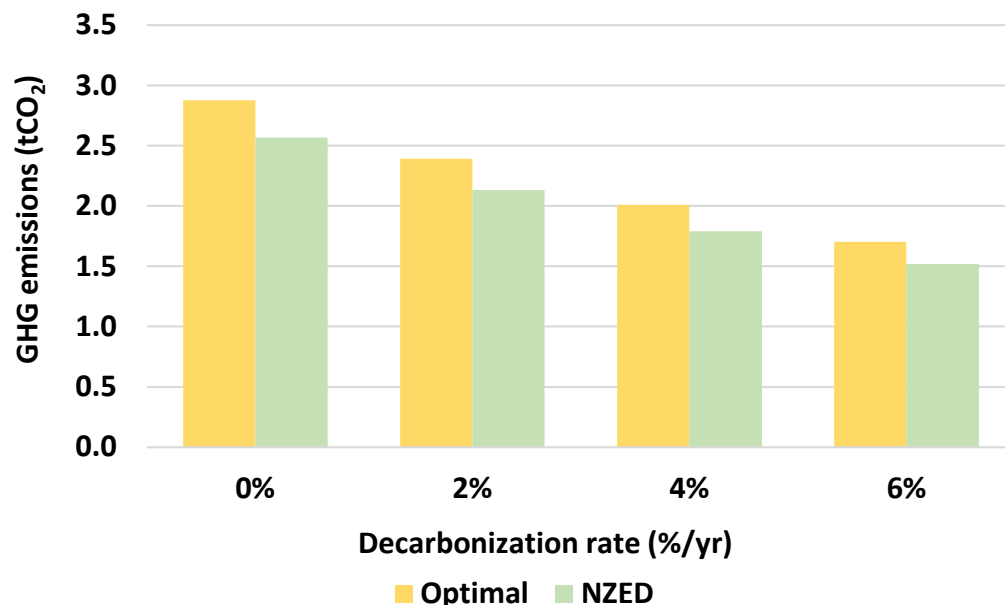


Figure 7.23. Influence on project lifetime carbon emissions of decarbonisation rates.

7.6 Insights from the expanded model application to the case study

The increased scale of the district and the technology diversity applied to this case study through the expanded optimisation model demonstrated how system scale, technology aggregation and performance targets shape the techno-economic outcomes of district energy design.

Aiming cost-optimal and NZED targets is primarily driven by PV generation combined with ESS. Centralisation at the district scale reduces both investment and operational costs through capacity aggregation, even with building-level HVAC&DHW systems presenting higher efficiency and, therefore, lower grid electricity use. Similar to case study 1 application, the results show that achieving NZED status at the district level requires only marginal additional investment relative to the Optimal solution, making net-zero energy performance economically attainable under realistic assumptions. However, the pursuit of very high self-sufficiency levels reveals clear structural limitations of electricity-only strategies. Physical constraints on rooftop PV area and the rapidly increasing cost of electrical storage make SS targets above 85-90% increasingly expensive. In this context, the integration of STES coupled with GSHP becomes advantageous. Although STES entails high upfront costs, these are progressively compensated at high self-sufficiency levels through reduced reliance on PV, ESS, and grid electricity, demonstrating that thermal storage plays a critical role when temporal mismatches between energy supply and demand extend beyond daily timescales.

Wind generation, while not envisaged for real-world implementation in the studied project, illustrates the flexibility of the modelling framework and highlights the value of complementary renewable production profiles. Even under conservative assumptions, wind contributes to reducing total cost and improving self-sufficiency, particularly at intermediate and high SS targets, by partially substituting additional electrical storage. Nevertheless, spatial and regulatory constraints may limit its contribution, emphasising that technology feasibility cannot be assessed on cost alone.

The sensitivity analyses further indicate that economic drivers such as electricity tariffs and PV costs have a stronger influence on the transition toward NZED and PED than moderate demand-side design adjustments. However, the latter show stronger ability to reduce total cost.

Finally, lifetime GHG emissions analysis and discount rates evaluation further validate results and highlight the developed modelling framework application.

Chapter 8. Conclusions

8.1 Main findings and applications

The aim of this work was to develop a modelling framework to assist the design of cost-efficient Net-zero and Positive Energy Districts.

This challenge was addressed by: 1) developing a systematic literature review of current approaches used to design NZED and PED; 2) performing a meta-analysis of district-level solutions reported in the literature, through the systematic classification of implemented measures, the analysis of their impacts and the identification of relevant indicators; 3) designing a comprehensive framework centred on a newly developed optimisation model and its application to a theoretical case study; 4) expanding the optimisation model and analysis, to incorporate a broader set of technologies, operational functions and performance indicators, followed by its application to a large and real case study.

The modelling framework, the key output of this work, combines detailed energy demand modelling with technology characterisation and cost assessment within a linear optimisation model that selects and sizes energy systems under multiple constraints. The literature review revealed that existing studies primarily focus on demonstrating the efficacy of solutions to achieve energy performance targets, while comparatively less attention is given to cost-efficient oriented design approaches. To address this gap, this work proposes a framework with a clear emphasis on cost-optimal design, while enabling the integration of multiple energy technologies to meet performance targets, namely net-zero and positive energy balance, as well as energy self-sufficiency. The flexibility of the model to enable the design of the energy systems under multiple constraints and technological choices composes a significant distinction. The assessment of modelling choices and the technology selection were informed by a wide range of sources and examples, including the results of the literature review and meta-analysis of district-level solutions, while maintaining a consistent focus on the development of a novel and integrated framework.

This work demonstrates that the proposed approach is flexible and capable of being applied to a variety of cases. The key findings are summarised below.

Current NZED and PED design practices remain conceptually fragmented and predominantly supply-focused, reinforcing the need for integrated techno-economic frameworks capable of consistently comparing district energy solutions under common definitions and performance criteria, as concluded in Chapter 2. This work contributed to a more structured analysis that

improves comparability across studies and supports more coherent district design practices. The thorough analysis of district-scale case studies contributes to greater clarity in both research and practice. By standardising terminology and spatial boundaries, it facilitates more consistent benchmarking across projects and supports more transparent communication among urban planners, energy engineers and regulatory agencies. This clarity is also essential for developing regulatory definitions of NZED and PED districts and foster policy implementation.

The proposed framework integrates operational energy modelling based on a mathematical representation of each considered technologies, combined with a time step-based energy balance and a comprehensive cost assessment covering investment, maintenance and operational costs over a defined lifetime. The framework is highly adaptable, enabling the simultaneous energy demand assessment of multiple buildings with different geometries and use profiles, while allowing the evaluation of a wide range of energy technologies under varying cost assumptions and physical location constraints. As a result, the framework is not case-specific and can be applied to different district configuration, scales and conditions.

The results of applying the modelling framework to two case studies (Chapters 5 and 7) indicate that district-level approaches outperform building-level solutions in terms of economic efficiency of HVAC&DHW system sizing, renewable energy integration and potential to achieve higher self-sufficiency. The coordinated system design enables lower installed HVAC&DHW capacities, as well as a smaller and more efficient use of generation and storage systems, leading to lower total costs. It should be noted that the results obtained from the application of the framework are based on two Portuguese case studies. The promising outcomes on the advantages of coordinated centralised design and the feasibility of net-zero and positive energy scenarios suggest that the Portuguese context may be favourable to this approach. Nonetheless, it is important to consider that the results are highly dependent on location-specific conditions and the findings may not be directly transferable to other contexts.

Moreover, results from case studies have also shown that NZED/PED scenarios nearly match the cost-optimal scenarios in the long term, hinting that decarbonisation at the district-level can be economically attractive. Nevertheless, the feasibility of NZED and PED is strongly conditional on local economic conditions, particularly electricity tariffs, technology costs and spatial constraints. Lower investment costs for generation and storage were shown to enable positive energy balance as the cost-optimal solution, in both cases studies. Temporal alignment between demand and renewable generation is decisive, with demand profiles, including those related to electric mobility, playing a role in improving self-consumption, reducing energy storage needs and lowering total costs, as illustrated in Chapter 5. Spatial constraints, especially limited PV installation area, can sometimes represent a structural barrier to achieving NZED and PED performance in urban

contexts, highlighting the importance of alternative deployment options such as carports and alternative generation sources, such as wind. In addition, and as clearly exemplified in case study 2, the area available for PV in some of the individual buildings' rooftops was not sufficient to enable annual net-zero balance at building-level, highlighting the district-level approach as key to achieve urban energy neutrality. Energy demand reduction measures implemented at building design stage, as tested in case study 2, demonstrated better economic performance than renovation measures in case study 1, while both approaches improved the feasibility of achieving NZED and PED.

Furthermore, both case studies have shown that, while NZED/PED scenarios nearly match the cost-optimal scenarios on long-term, self-sufficiency levels above 85% (share of annual demand covered by self-consumed renewable energy) require highly favourable conditions or policy support. Very high self-sufficiency levels entail disproportionately high costs, leading to oversized generation and storage installations, resulting in systems that seldom achieve payback within a 20-year horizon. Under this conditions, complementary renewable sources and seasonal storage technologies become relevant at high self-sufficiency levels, as wind generation and seasonal thermal energy storage can reduce reliance on electrical storage and mitigate cost escalation.

The obtained results also provide relevant insights for policy makers on the implications of different decisions regarding urban planning and energy and climate policy decisions.

First, the results highlight the importance of local features, as electricity tariffs, technologies costs, available rooftop and carport areas and thermal demand profiles on the feasibility of achieving NZED or PED conditions. Policymakers can exploit these insights to design targeted incentives, particularly for retrofitting and energy storage adoption, and to prioritise districts where structural conditions favour higher self-sufficiency and faster payback.

Secondly, from a broader system perspective, the research demonstrates how district-scale coordination enables economic benefits that individual buildings cannot achieve. This has implications for the design of municipal and national decarbonisation plans, where collective solutions, such as district heating, shared storage, coordinated EV charging and PV deployment, can significantly reduce infrastructure duplication and unlock higher renewable integration. In the context of increasing integration of renewable energy sources and decentralised storage, the proliferation of multiple individual building-level systems poses challenges for the central electricity grid, whereas the adoption of closed district-level systems can facilitate renewables integration by limiting grid interaction points and improving system-level control.

Therefore, the findings of this thesis carry several potential implications for the planning, design and governance of future carbon neutral districts. The methodological contributions,

combined with insights from the literature review and optimisation results, provide a coherent evidence base to support both practitioners and policymakers in shaping urban energy transitions.

Overall, the results position district-level design as a rational pathway for urban decarbonisation, capable of balancing technical feasibility, economic efficiency and long-term sustainability.

Furthermore, the framework developed in this thesis demonstrates its practical value as a decision-support tool. The model was set to assess trade-offs between cost, performance and self-sufficiency under different conditions. Its modular structure enables adaptation to diverse district types and technology solutions. Importantly, the integration of EV charging and PV carports shows the model's capacity to address emerging mobility interactions, providing a platform to plan district-level infrastructure that supports both renewable integration and electrified mobility.

By combining methodological innovation with actionable insights, this thesis contributes to building the knowledge base required for designing cost-effective, resilient and carbon-neutral urban districts.

8.2 Limitations

The scope and methodological choices adopted in this thesis necessarily have associated limitations that define the boundaries of the research.

First, most of the analysis is made at hourly level. While this captures the dominant dynamics of energy demand, PV production and storage behaviour, it does not fully represent power quality issues, real-time grid constraints, or transient equipment behaviour. The model therefore provides a basis for strategic planning but is not intended for detailed electrical engineering or operational control studies.

Second, the modelling approach assumes well-defined demand and generation profiles. This enables a clear comparison of solutions but abstracts from uncertainties such as weather variability, behavioural changes or market-driven fluctuations in prices. As a consequence, the results should not be interpreted as precise forecasts of operational outcomes, as these uncertainties may affect technology utilisation and costs and may vary on a year-to-year basis.

Third, while the methodology is of general application regardless of geographical boundaries, some data is bounded to European or Portuguese context, particularly regarding climate, building stock characteristics, regulatory frameworks and costs. The application to Portuguese case studies limits the comparison of results to regions with substantially different climatic conditions, energy mixes, or infrastructure maturity. Adaptation to non-European contexts would require recalibration

of cost parameters, emission factors and building envelope assumptions – which the model easily allow.

Fourth, life-cycle environmental impacts, embodied energy in materials and circularity aspects were not directly integrated into the optimisation framework. Although discussed conceptually, the model remains focused on operational energy and economic performance. As a result, the assessment does not capture potential trade-offs between upfront environmental impacts and long-term operational benefits. Technologies or design options may be favoured by the optimisation, even if their life-cycle environmental performance is less advantageous.

Fifth, geographical or territorial constraints affecting the installation or adoption of selected technologies were not explicitly considered in the modelling framework, nor were factors such as visual impacts, noise restrictions or licensing requirements.

Together, these limitations delineate the intended use of the framework: strategic, techno-economic comparison of district-level energy solutions. Recognising these boundaries helps guide interpretation of the results and highlights opportunities for further refinement and expansion in future research.

8.3 Future research

Building upon the contributions and limitations of this thesis, several avenues for future research emerge that could strengthen methodological capabilities, broaden applicability, and deepen the understanding of district-scale energy transitions.

A first suggestion is the integration of uncertainty into the optimisation framework. The current deterministic approach provides a strong foundation for comparative analysis but does not capture the variability inherent in real-world energy systems. Incorporating stochastic weather datasets, probabilistic demand models or price volatility scenarios would enable the assessment of system robustness and provide even more realistic investment decisions under uncertainty.

Second, expanding the modelling of mobility integration presents a major opportunity. The analysis performed in the case study 1 demonstrated the relevance of considering EV charging in the design of district solutions. Future research should explore bidirectional vehicle-to-building (V2B) and vehicle-to-grid (V2G) interactions, seasonal variations in mobility patterns, and infrastructure constraints within low-voltage distribution networks. These developments would provide a more complete understanding of how electrified mobility can contribute to flexibility, storage and demand-side management at the district scale.

A third direction relates to the extension of the framework to include life-cycle environmental impacts. Integrating embodied carbon, material circularity, and end-of-life

considerations into the optimisation model would align district planning more closely with comprehensive sustainability goals. This is particularly relevant for retrofit strategies, where material impacts may be substantial in relation to operational savings.

Additionally, the increasing digitalisation of energy systems could justify integrating demand-response strategies, smart-building controls and dynamic tariff mechanisms into future versions of the model. Such enhancements would allow assessment of flexibility services and provide insights into how behavioural and automation-based interventions influence district performance.

Finally, empirical validation through real-life demonstration projects are needed. Applying the framework to monitored districts and comparing results with measured data would help refine assumptions, validate model accuracy and strengthen its credibility for practical deployment.

Collectively, these research directions would extend the capabilities of the proposed framework and contribute to the broader effort of designing resilient, cost-efficient and fully decarbonised energy districts.

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Annex A. Literature review complementary data

(Chapter 2)

The list of 87 papers identified in the literature search as describing or including the characterisation of a case study is compiled in Table A. 1.

Table A. 1. Results of the literature search describing a case study.

Publications	
(Allende & Stephan, 2022)	(Andresen et al., 2022)
(Aparisi-Cerdá et al., 2022)	(Bruck, Casamassima, et al., 2022)
(Bruck, Díaz Ruano, et al., 2022b)	(Castillo-Calzadilla et al., 2022)
(Chacón et al., 2022)	(Fatima et al., 2022)
(HosseiniHaghighi et al., 2022)	(Kazmi et al., 2022)
(Ligardo-Herrera et al., 2022)	(Mihailova et al., 2022)
(M. Li et al., 2022)	(Oreskovic & Gupta, 2022)
(Rose et al., 2022)	(Revesz et al., 2022)
(Sibilla & Abanda, 2022)	(Volpe et al., 2022)
(Alpagut et al., 2021)	(Ascione et al., 2021b)
(Bambara et al., 2021)	(Boeri et al., 2021)
(Bruck et al., 2021)	(Erba & Pagliano, 2021)
(Fatima et al., 2021)	(Ferrante & Villani, 2021)
(Fichera et al., 2021)	(Franzoi et al., 2021)
(García-Fuentes et al., 2021)	(Gouveia et al., 2021)
(Haneef et al., 2021)	(He et al., 2021)
(Iturriaga et al., 2021)	(Janzadeh & Zandieh, 2021)
(Jędrzejuk & Chwieduk, 2021)	(Laitinen et al., 2021)
(Lausset et al., 2021)	(Maturo et al., 2021)
(Nematchoua, Nishimwe, et al., 2021)	(Neumannová, 2021)
(Neumann et al., 2021)	(Pinel et al., 2021)
(Saarloos & Quinn, 2021)	(Samadzadegan et al., 2021)
(Uspenskaia et al., 2021)	(Wills et al., 2021)
(Aparicio-Gonzalez et al., 2020)	(Aste et al., 2020)
(Blumberga et al., 2020)	(Bisello, 2020)
(Boccalatte et al., 2020)	(Byrne et al., 2020)
(Cortés et al., 2020)	(De Torre Minguella et al., 2020)
(Hirvonen & Kosonen, 2020)	(Isaac et al., 2020)
(Lausset et al., 2020)	(Maas et al., 2020)
(Mutani & Todeschi, 2020)	(Natanian & Auer, 2020)
(Nematchoua, 2020)	(Pinel, 2020)
(Piselli et al., 2020)	(Shaw-Williams et al., 2020)
(Sougkakias et al., 2020)	(Sugár et al., 2020)
(Verbruggen et al., 2020)	(Aelenei et al., 2019)
(Birge & Berger, 2019)	(Hachem-Vermette et al., 2019)
(Huang et al., 2019)	(Rehman et al., 2019)
(Kim et al., 2019)	(Mittal et al., 2019)
(Ramos et al., 2019)	(Sözer & Sözen, 2019)
(Ş. Kılış & Kılış, 2019)	(Becchio et al., 2018)
(Bucking & Dermardiros, 2018)	(B. Kılış & Kılış, 2018)
(García-Fuentes et al., 2018)	(Hachem-Vermette et al., 2018)
(Natanian & Auer, 2018)	(Pinna et al., 2018)
(Sameti & Haghighat, 2018)	(Tucci et al., 2018)
(van den Dobbela et al., 2018)	

A complete description of useful energy (UE) and final energy (FE) values is presented in Table A. 2. For many cases the values could be retrieved directly from the original documents, even if some required dividing by the area, for better comparability. These numbers are shown in regular format. On the other hand, for some cases it was necessary to perform conversions between useful and final energy, using stated or inferred efficiencies of the mechanical systems. The values obtained in this way are presented in italic.

Table A. 2. Energy demand values (UE: Useful Energy; FE: Final Energy).

Publication	Ref.	Energy Uses	UE (kWh/m ² /yr)	FE (kWh/m ² /yr)	Comments
(Volpe et al., 2022)	1	Total	-	71,5	SH and DHW FE demand estimated, considering stated biomass boiler efficiency of 0.93.
		SH, DHW	37,1	39,9	
		Electricity	31,6	31,6	
(Neumann et al., 2021)	2	Total	-	60,9	FE demand available in the source document.
		SH	-	30,6	
		SC	-	1,2	
		DHW	-	12,8	
		Electricity	-	16,3	
(Erba & Pagliano, 2021)	3	Total	-	39,6	Both UE and FE demand were presented. Total FE demand value was calculated.
		SH	16,6	6,1	
		SC	7	2,6	
		DHW	12	4,4	
		Electricity	26,5	26,5	
(Janzadeh & Zandieh, 2021)	4	Total	-	68,2	FE demand presented. Total FE demand value was calculated.
		SH	-	26,6	
		SC	-	5,1	
		DHW	-	7	
		Electricity	-	29,5	
(Kim et al., 2019)	5	Total	-	35,2	Based on Case 3-1 ("best system configuration"), SC was covered by heat pump (stated COP of 5.27), and SH and DHW by heat pump and solar thermal (balanced with 75% and 25% of UE demand, respectively).
		SH	25,7	10,1	
		SC	7,9	1,5	
		DHW	12,8	5,0	
		Electricity	18,6	18,6	
(Mavrigiannaki et al., 2021)	6	Total	-	39,5	Total FE demand presented.
(Laitinen et al., 2021)	7	Total	-	63,7	Heat pump with a COP of 3 covered SH and DHW. SC was covered by free cooling.
		SH	28,2	9,4	
		SC	4,9	0	
		DHW	28,2	9,4	
		Electricity	44,9	44,9	
(Huang et al., 2019)	8	Total	-	98	FE demand presented. Total FE demand value was calculated.
		SH	91,3	56,2	
		SC	0	0	
		DHW	18,6	11,4	
		Electricity	30,4	30,4	

Publication	Ref.	Energy Uses	UE (kWh/m ² /yr)	FE (kWh/m ² /yr)	Comments
(Pinel et al., 2021)	9	Total	-	148,6	SH was converted based on an average between: CHP (efficiency of 0,83 to 0,98), boiler (efficiency of 1) and heat pump (COP of 3,5). For SC, heat pump (COP of 5) was considered.
		SH	62,5	40,8	
		SC	0	0	
		DHW	11,2	2,2	
		Electricity	105,5	105,5	
(Lausset et al., 2021)	10	Total	80,1	85,0	Based on a stated district heating efficiency of 0,9.
		SH, SC, DHW	44,2	49,1	
		Electricity	35,9	35,9	
(Lausset et al., 2019)	11	Total	71,2	75,3	Based on a stated district heating efficiency of 0,9.
		SH, SC	12,3	13,7	
		DHW	23,5	26,1	
		Electricity	35,5	35,5	
(He et al., 2021)	12	Total	-	21,9	FE demand presented.
		SH	-	3,9	
(Ascione et al., 2021b)	13	Total	-	46,3	Total primary energy of 90,3 kWh/m ² y (no PV impact) was converted to FE, assuming indicated factor of 1,95. SH and SC conversion based on indicated heat pump COP of 4,5 for heating and 4,0 for cooling.
		SH	6	1,3	
		SC	32,7	8,2	
(Aste et al., 2020)	14	Total	76,2	25,9	For SC, stated EER of 7 was used. For SH, conversion was based on the combination of heat pump and CHP in winter (38% and 62%, respectively). For DHW different COP per season were stated in paper.
		SH	15,2	10,5	
		SC	37,0	5,2	
		DHW	18,0	4,0	
		Electricity	6,1	6,1	

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Annex B. Meta-analysis complementary data

(Chapter 3)

The complete quantitative analysis of the measures is presented in Table B. 1, with the number of times each measure is presented within the 32 case studies and how many case studies included each measure in its analysis. The distribution of measures by the scope of intervention categories is included, with the respective quantification. The most frequent measures were highlighted in the table.

Table B. 1. Quantification of measures identified and analysed in the papers.

Scope of Intervention Categories	Measures	Quantity of measures	Quantity of case studies
Building Envelope (BE)		29 (18%)	12 (38%)
BE-1	Envelope (external walls)	12 (7%)	11 (34%)
BE-2	Envelope (internal walls/floor)	2 (1%)	1 (3%)
BE-3	Envelope (rooftop)	5 (3%)	5 (16%)
BE-4	Green roofs	2 (1%)	2 (6%)
BE-5	Windows refurbishment	8 (5%)	8 (25%)
Building Design (BD)		2(1%)	2 (6%)
BD-1	Shading systems	2 (1%)	2 (6%)
Appliances and Lighting (AL)		5 (3%)	3 (9%)
AL-1	Efficient lighting system	3 (2%)	3 (9%)
AL-2	Efficient appliances	2 (1%)	1 (3%)
Heating, Ventilation, and Air Conditioned, Domestic Hot Water (HVAC&DHW)		49 (30%)	24 (75%)
HVAC&DHW-1	Cooling system	4 (3%)	3 (9%)
HVAC&DHW-2	Heat exchanger system	1 (1%)	1 (3%)
HVAC&DHW-3	Heat recovery system	2 (1%)	2 (6%)
HVAC&DHW-4	Biomass boiler	3 (2%)	3 (9%)
HVAC&DHW-5	Efficient boiler	7 (4%)	6 (19%)
HVAC&DHW-6	District heating system	13 (8%)	13 (41%)
HVAC&DHW-7	Heat pump (SH, SC and DHW)	19 (12%)	17 (53%)
Energy Supply (ES)		51 (31%)	29 (91%)
ES-1	CHP/CCHP	8 (5%)	7 (22%)
ES-2	Photovoltaic Thermal Units (PVT)	1 (1%)	1 (3%)
ES-3	Photovoltaic system	25 (15%)	25 (78%)
ES-4	Solar thermal system	9 (6%)	9 (28%)
ES-5	Wind energy micro system	5 (3%)	4 (13%)
ES-6	Hydrogen production by electrolyzer	1 (1%)	1 (3%)
ES-7	Geothermal energy system	2 (1%)	2 (6%)
Energy Storage (EST)		17 (10%)	16 (50%)
EST-1	Electric battery system	7 (4%)	7 (22%)
EST-2	Thermal energy storage	9 (6%)	9 (28%)
EST-3	Hydrogen storage	1 (1%)	1 (3%)
Energy Management and Control Systems (EMCS)		2 (1%)	2 (6%)
EMCS-1	Energy management system	2 (1%)	2 (6%)

Scope of Intervention Categories	Measures	Quantity of measures	Quantity of case studies
Waste Management (WM)		1 (1%)	1 (3%)
WM-1	Recycling incentives	1 (1%)	1 (3%)
Carbon sequestration (CS)		1 (1%)	1 (3%)
CS-1	Urban forestry	1 (1%)	1 (3%)
Public Space (PS)		1 (1%)	1 (3%)
PS-1	Efficient public lighting system	1 (1%)	1 (3%)
Transport (T)		6 (4%)	5 (16%)
T-1	Electric vehicles	1 (1%)	1 (3%)
T-2	Electric vehicles charging station	2 (1%)	2 (6%)
T-3	Soft modes of transport incentive	1 (1%)	1 (3%)
T-4	Public Transport Incentive	2 (1%)	2 (6%)

In Table B. 2, the percentage of measures, by scope of intervention categories, evaluated in each of the impact categories is presented, allowing to identify the most frequent assessed impact categories by category of measures. The analysis of the present results must consider the aggregated impact evaluation of measures in some case studies, as in some cases the evaluation was made by total result or by combination of measures.

Table B. 2. Percentage of measures evaluated by impact category.

Scope of Intervention Categories	Energy Performance	Renewable Energy Share	Economic Cost	Carbon Emissions	Life Cycle Impacts
BE	93%	14%	55%	48%	28%
BD	All	None	None	50%	None
AL	All	20%	60%	40%	None
HVAC&DHW	78%	24%	69%	63%	16%
ES	76%	20%	61%	57%	10%
EST	82%	41%	59%	65%	6%
EMCS	50%	50%	50%	None	None
WM	All	None	None	All	None
CS	All	None	None	All	None
PS	All	None	All	All	None
T	83%	None	33%	83%	17%

The detailed data to achieve the graphical representation of occurrence of measures, individually or combined with others, in scenarios of solutions with high impact and total scenarios is presented in Table B. 3.

Table B. 3. Data collected and calculated for occurrence of measures analysis.

Measures	Occurrences in total (A)	Share in total measures (B)	Occurrences in impact > 50% (C)	Share in measures with impact > 50% (D)	Ratio D/B
BE-1	34	5%	9	5%	1.0
BE-2	4	1%	3	2%	2.7
BE-3	25	4%	2	1%	0.3
BE-4	4	1%	4	2%	3.6
BE-5	20	3%	4	2%	0.7
BD-1	5	1%	4	2%	2.9
AL-1	17	3%	2	1%	0.4
AL-2	9	1%	1	1%	0.4
HVAC&DHW-1	9	1%	1	1%	0.4
HVAC&DHW-2	0	0%	0	0%	0.0
HVAC&DHW-3	12	2%	6	3%	1.8
HVAC&DHW-4	12	2%	5	3%	1.5
HVAC&DHW-5	14	2%	3	2%	0.8
HVAC&DHW-6	73	12%	25	15%	1.2
HVAC&DHW-7	84	13%	21	12%	0.9
ES-1	20	3%	4	2%	0.7
ES-2	8	1%	3	2%	1.4
ES-3	127	20%	33	19%	0.9
ES-4	31	5%	8	5%	0.9
ES-5	4	1%	0	0%	0.0
ES-6	1	0%	1	1%	3.6
ES-7	5	1%	0	0%	0.0
EST-1	43	7%	17	10%	1.4
EST-2	37	6%	12	7%	1.2
EST-3	1	0%	1	1%	3.6
EMCS-1	2	0%	0	0%	0.0
WM-1	1	0%	0	0%	0.0
CS-1	1	0%	0	0%	0.0
PS-1	0	0%	0	0%	0.0
T-1	1	0%	0	0%	0.0
T-2	17	3%	3	2%	0.6
T-3	0	0%	0	0%	0.0
T-4	6	1%	0	0%	0.0

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Annex C. Criteria for selecting CEA (Chapter 4)

From the several bottom-up physics-based UBEM models, a selection of six tools was made based in applicability, availability and with relevant projects and active support, presented in Table C. 1. Each tool was designed for different purposes, although all presenting general applicability and similar workflows.

Table C. 1. Bottom-up physics based UBEM models selected to analysis (available features are marked in green).

		CitySim	SimStadt	umi	CityBES	CEA	URBANopt
Year		2009	2013	2013	2015	2016	2016
Developer, Country		EPFL, Switzerland	University of Stuttgart, Germany	MIT, USA	LBLN Berkeley, USA	ETH Zurich, Switzerland, and Singapore	NREL, USA
URL		https://www.epfl.ch/labs/leso/transfer/software/citysim/	https://simstadt.hft-stuttgart.de/getting-started/install-software/	https://web.mit.edu/sustainabledesignlab/projects/umi/index.html	https://citybes.lbl.gov/	https://www.cityenergyanalyst.com/	https://www.nrel.gov/buildings/urbanopt.html
Status and availability		Free	Free	Free, needs Rhino 8 licence	Research free	Free, open source	Free, open source
Computing platform		Personal computer	Personal computer	Personal computer	Web-based	Personal computer	High-performance computer
Approach		Reduced order resistance-capacitance (RC)	Reduced order resistance-capacitance (RC)	Multi-zone dynamic thermal simulation	Multi-zone dynamic thermal simulation	Reduced order resistance-capacitance (RC)	Multi-zone dynamic thermal simulation
Data input	Urban climatology modelling (CFD, radiation)			Radiance software	Radiance software		Radiance software
	Building stock characterisation (location, GIS)						
	GIS data format	CityGML	GIS and CityGML	GIS and IDF	CityGML, GeoJSON and IDF	GIS and CityGML	GeoJSON, Open Street Maps (osm.), IDF
	Individual building characterisation (archetypes, geometry)						
	Non-residential building						
	Archetypes based on	Intended use					
		Construction year					
		Building typology					
	Default characteristics included						
	Characterisation includes	Envelope					
		Systems					
		Energy use					
	Occupant behaviour	Deterministic					
		Stochastic					
	Mobility characterisation (in building use)						

		CitySim	SimStadt	umi	CityBES	CEA	URBANopt
Calculation method - core algorithm/engine		CitySim solver	ISO 13 790	EnergyPlus + Rhinoceros 3D	EnergyPlus + OpenStudio	ISO 13 790 adapted	EnergyPlus + OpenStudio
Calibration or validation		Only electrical appliances	Unspecified	Unspecified	Automated calibration based on logic and pattern-fitting criteria	Hourly result validated	Unspecified
Data output	Daylight						
	Building energy demand uses	Heating					
		Cooling					
		Domestic hot water					
		Appliances					
		Lighting					
		Ventilation					
		Electricity					
	Energy generation modelling	PV					
		Wind					
		Solar thermal					
		CHP					
		HP					
		GSHP					
		Storage					
		Chiller					
	District heating						
	District cooling						
	Electrical network						
Transport energy demand modelling		MatSIM					
Output evaluation	Scenarios						
	Benchmarking						
	Cost-benefit						
	LCA						
	Food						
Optimisation analysis							
Output minimum timescale		hourly	monthly/yearly	hourly	hourly	hourly	hourly
Output spacial resolution	Single building						
	Group of buildings						
Reference		(Robinson et al., 2009)	(Nouvel et al., 2015)	(Reinhart et al., 2013)	(Hong et al., 2016)	(Fonseca et al., 2016)	(Kontar et al., 2020)

Annex D. Photovoltaic production simulation module (Chapter 4)

The PV simulation module relies on the Python library *pvlib* to calculate energy production over time, using the climate data for the system's location and the PV system specifications (Anderson et al., 2023). The model follows a logical sequence, outlined in the following steps.

The initial inputs of the PV production simulation model include:

- Location: latitude, longitude, and altitude.
- Photovoltaic system configuration: number of solar panels, tilt angle, and azimuth.
- Photovoltaic panel parameters: nominal power, module area, efficiency, operating temperature, and temperature coefficient.
- Inverter parameters: inverter efficiency.

A weather file is used to retrieve hourly weather data for a 1-year period based on the specified location. The selected weather file location should be the closest to the system's location. Meteorological data includes: air temperature, wind speed, diffuse radiation (DHI), direct normal irradiance (DNI), global horizontal irradiance (GHI).

Using the *pvlib* library, the solar position (zenith, azimuth) is calculated for the specified time period and location. The relative and absolute airmass is determined based on altitude and atmospheric pressure.

If applicable, a solar tracker can be defined using *pvlib.tracking.singleaxis*, which adjusts the panel angle to optimise radiation capture (Anderson & Mikofski, 2020; Lorenzo et al., 2011). A maximum angle is defined for PV systems with solar tracking, and panel tilt and azimuth are adjusted at each time step. For stationary PV systems, a maximum angle of zero is defined.

The *pvlib.irradiance.get_total_irradiance* function is used to compute the total irradiance on the panel plane (POA), yielding direct, diffuse, and global irradiance components (Anderson et al., 2023). These components calculations are based on the panels tilt and azimuth, solar position, DHI, DNI and GHI.

The total POA irradiance, I_{total} , incident on a tilted surface, is calculated by summing three components: beam (direct), sky diffuse, and ground-reflected irradiance, as expressed in Eq. (D.1). This decomposition enables accurate modelling of solar energy capture on PV modules under different sky conditions and surface orientations (Anderson et al., 2023).

$$I_{\text{total}} = I_{\text{beam}} + I_{\text{sky diffuse}} + I_{\text{ground}} \quad (\text{D.1})$$

Where:

I_{beam} : Beam irradiance on the plane-of-array (POA), determined using the angle of incidence (AOI);

$I_{\text{sky diffuse}}$: Diffuse irradiance from the sky, modelled using various diffuse models;

I_{ground} : Ground-reflected irradiance, computed based on albedo and global horizontal irradiance (GHI).

`pvlib.irradiance.get_total_irradiance` uses `pvlib.irradiance.get_sky_diffuse`, `pvlib.irradiance.get_ground_diffuse`, and `pvlib.irradiance.poa_components` methods to compute these components (Anderson et al., 2023).

The angle of incidence (AOI) is calculated internally using panel and solar geometry. The sky diffuse model can be selected from several options, such as Isotropic (default), Hay-Davies, Perez, Klucher, Reindl, King, Perez-Driesse. POA diffuse irradiance represents the sum of diffuse irradiance from the sky and ground-reflected irradiance.

The cell temperature is estimated using the SAPM (Sandia Array Performance Model) via `pvlib.temperature.sapm_cell`, accounting for incident irradiance, ambient temperature, and wind speed. The Sandia Array Performance Model (SAPM) estimates the module back surface temperature T_m using an exponential function of irradiance and wind speed, as illustrated in Eq. (D.2). This model captures the influence of ambient temperature and convective heat loss from the module surface, with parameters tuned to specific mounting configurations (King et al., 2004).

$$T_m = I_{\text{total}} \cdot \exp(a + b \cdot WS) + T_a \quad (\text{D.2})$$

Where:

T_m : Module back surface temperature (°C);

I_{total} : Plane of array irradiance (W/m²);

T_a : Ambient air temperature (°C);

WS : Wind speed (m/s);

a, b : Empirical coefficients related to module and mounting type (unitless).

Coefficients a and b are experimentally derived and represent the effect of mounting structure on convective heat transfer. SAPM provides predefined parameter sets for various representative module types and installation conditions (e.g., open rack, insulated back, roof mount) (King et al., 2004). Examples of the coefficients are illustrated in Table D. 1.

Table D. 1. PV mounting effect structure on convective heat transfer parameters.

Module	Mounting	a	b	ΔT (°C)
glass/glass	open rack	-3.47	-0.0594	3
glass/glass	close roof	-2.98	-0.0471	1
glass/polymer	open rack	-3.56	-0.075	3
glass/polymer	insulated back	-2.81	-0.0455	0

The angle of incidence (AOI) is calculated using *pvlib.irradiance.aoi*, considering panel tilt, panel azimuth, and solar position (tilt and azimuth).

The effective irradiance absorbed by the modules is then determined using *pvlib.pvsystem.sapm_effective_irradiance*, which accounts for reflection losses and solar spectrum effects (King et al., 2004), as expressed in Eq. (D.3).

$$G_{\text{eff}}(t) = f_1(AM_a) \cdot (I_{\text{beam}} \cdot f_2(\text{AOI}) + f_d \cdot I_{\text{diffuse}}) \quad (\text{D.3})$$

Where:

$G_{\text{eff}}(t)$: Effective irradiance on the plane of array (W/m²);

AM_a : Absolute air mass (unitless);

f_1 : Empirical correction factor (4th-degree polynomial of air mass);

I_{beam} : Beam (direct) irradiance on the plane of array (W/m²);

AOI: Angle of incidence between the sun and the panel normal (°);

f_2 : Empirical correction factor (5th-degree polynomial of AOI);

I_{diffuse} : Diffuse irradiance on the plane of array (W/m²);

f_d : Fraction of diffuse irradiance not reflected away (unitless, usually ≈ 1).

The DC power is calculated using *pvlib.pvsystem.pvwatts_dc*, considering the effective irradiance and cell temperature (Dobos, 2014).

The AC power is obtained by multiplying the DC power by the inverter efficiency. The hourly energy production is calculated by scaling the result by the total solar panel area. The sequence of calculations is demonstrated in Eq. (D.4-D.6).

$$E_{\text{pv,dc}}(t) = \eta_{\text{pv}} \cdot G_{\text{eff}}(t) \cdot [1 + \gamma \cdot (T_{\text{cell}}(t) - 25)] \cdot A_{\text{pv}} \quad (\text{D.4})$$

$$E_{\text{pv}}(t) = E_{\text{pv,dc}}(t) \cdot \eta_{\text{inv}} \quad (\text{D.5})$$

$$E_{\text{pv}}(t) = \eta_{\text{pv}} \cdot R(t) \cdot A_{\text{pv}} \cdot \eta_{\text{inv}} \quad (\text{D.6})$$

Where:

$G_{\text{eff}}(t)$: Effective irradiance at time t (W/m²);

$T_{\text{cell}}(t)$: PV cell temperature at time t ($^{\circ}\text{C}$);
 η_{pv} : Reference PV efficiency at STC (25°C);
 γ : Temperature coefficient ($1/^{\circ}\text{C}$);
 A_{pv} : PV system area (m^2);
 η_{inv} : Inverter efficiency (DC to AC conversion);
 $E_{\text{pv,dc}}(t)$: DC power output at time t (kWh);
 $E_{\text{pv}}(t)$: AC power output at time t (kWh);
 $R(t)$: Adjusted irradiance profile at time t (W/m^2).

The DC Power function, Eq. (D.7), was adapted to be included in the optimisation model through an adjusted irradiance profile, $R(t)$. Considering that efficiency and area are variables to be optimised in the model, $R(t)$ accounts for the effective irradiance and the influence of cell temperature on the efficiency of the solar module.

$$R(t) = G_{\text{eff}}(t) \cdot [1 + \gamma \cdot (T_{\text{cell}}(t) - 25)] \quad (\text{D.7})$$

Annex E. Selected design variables alternatives

(Chapter 4)

8.3.1 Energy demand variables for energy demand calculation

Buildings heating and cooling energy needs are influenced by many factors, e.g., location, size, built structure, occupancy, etc. Alternatives were compiled to support the selection of design solutions for each design variable.

8.3.1.1 Roof, walls and floors thermal characteristics

Roof, walls, and floors thermal parameters include thermal transmittance (U-value), solar absorption (α -value), emissivity of external surface, and reflectance in the red spectrum.

Thermal insulation alternatives include Passive House reference values, EU legal minimum values for new buildings, and the Portuguese SCE guidelines, being presented in Table E. 1., considering a typical brick wall installation.

Table E. 1. Thermal insulation reference U-values for walls and roofs, and respective costs.

Insulation thickness	U-value (W/m ² .C) ¹	Costs (€/m ²) ¹
30 mm	0.80	
40 mm	0.58	From
60 mm	0.47	35 (lower insulation)
80 mm	0.36	to
120 mm	0.2	55 (higher insulation)

¹(ADENE, 2021; BPIE, 2023; IEA, 2013; ISO 13790, 2007; PHI, 2018), complemented with market survey

Cost estimations include insulation materials and installation works, which can highly vary. For internal walls and floors, reference values of U=2.4 W/m².C and U=0.62 W/m².C, respectively, were suggested (ADENE, 2021). CEA databases suggest emissivity of 0.9 and reflectance of 0.4 (Fonseca et al., 2016). Solar absorption reference values were compiled in Table E. 2 (ADENE, 2021).

Table E. 2. Solar absorption values based on surface colours.

Surface colours	α -value ¹
Light: white, creme, yellow, orange, light red	0.4
Medium: dark red, light green, light blue and light gray	0.5
Dark: brown, dark green, dark blue, dark gray	0.8
¹ (ADENE, 2021)	

8.3.1.2 Tightness: air renewal by infiltration and ventilation

The hourly air renewal rate (Rph) is a crucial parameter to ensure indoor air quality in buildings. According to Portuguese standards and guidelines, new buildings must have a minimum air renewal rate of 0.5 renewals per hour (Portaria n.º 138-I, 2021). Also, a minimum of 0.6 renewals per hour (Rph) is indicated during cooling season (ADENE, 2021). Thus, the combination of natural infiltration (Rph_infiltration) and ventilation (Rph_ventilation) should guarantee a minimum of 0.6 Rph for any level of building tightness.

Natural infiltration (Rph_infiltration) can be converted to infiltration at a pressure of 50 Pa (Rph_n50), as required by CEA, following a standard conversion expressed in Eq. (E.1) (Stafford & Johnston, 2017).

$$Rph_{n50} \approx 20 \times Rph_{infiltration} \quad (E.1)$$

The required ventilation rate should be then calculated per occupant, based on the internal volume occupied by each person in the building, following Eq. (E.2). The volume is based on the occupancy area defined in the internal loads' parameters and the floor's height.

$$V \text{ (L/s)} = \frac{Rph_{ventilation} \times Volume}{3600} \times 1000 \quad (E.2)$$

8.3.1.3 Glazing and shading

Table E. 3 presents a selection of glazing alternatives, adapted from Raimundo et al. (2021), and covers a range of available windows, from less efficient to highly efficient solutions (Raimundo et al., 2021).

Table E. 3. Alternative glazing solutions, adapted from ADENE (2021) and Raimundo et al. (2021).

Windows type	U-value (W/m ² .C)	g-value	Price (€/m ²)
G: Aluminium frame without thermal cut and with double glass (colourless + air + colourless)	3.788	0.753	118
F: Aluminium frame with thermal cut (or PVC or wood) and double glass (colourless + air + colourless)	3.053	0.707	125
E: Aluminium frame with thermal cut (or PVC or wood) and double glazed (coloured + air + colourless) or (colourless with reflective film + air + colourless) or (colourless reflective + air + colourless)	2.407	0.642	172
D: Aluminium frame with thermal cut (or PVC or wood) and double glass (coloured reflective + argon + colourless “thermal”)	1.994	0.424	196
C: Aluminium frame with thermal cut (or PVC or wood) and triple glass (coloured reflective + argon + colourless “thermal” + argon + colourless)	1.225	0.396	241
B: Two independent windows per span, e.g., two of type E, or one of F and one of D, or one of G and one of C	0.554	0.384	334
A: Two independent windows per span, e.g., one of type D and one of type C	0.477	0.103	423
(ADENE, 2021; Raimundo et al., 2021)			

Additional considerations were taken:

- G-values include an angular selectivity correction factor (Fw) of 0,9 in any period without shading device, as suggested in SCE procedures (ADENE, 2021);
- U-values and g-values consider only window parameters, excluding shading;
- Emissivity of external surface of glazing was fixed at 0.89 (Fonseca et al., 2016);
- The window frame fraction coefficient (m² frame/m²window) is estimated to be about 0.3 for metal frames and 0.35 for PVC or wood frames, although other values may apply (ADENE, 2021);
- Shading coefficients (Rf_sh) for different shading devices can be selected from (ADENE, 2021).

8.3.1.4 Internal loads

Selected data on internal loads is summarised in Table E. 4, covering occupancy density and heat and moisture per person, as well as daily water consumption. This data was compiled from information retrieved from multiple sources, including ISO 13790:2007, CEA and Portuguese SCE guidelines.

Table E. 4. Internal loads related data by building use.

Building use	Occupancy density (m²/p)	Peak sensible heat load of people (W/p)	Moisture released by occupancy at peak conditions (g/h/p)	Peak specific daily hot water consumption (l/d/p)	Peak specific fresh water consumption (includes cold and hot water) (l/d/p)
Residential	35	70	60	40	123
University	10	70	80	2	30
Office	20	80	60	2.5	22.5
Retail	8	80	80	2	30

(ADENE, 2021; Fonseca et al., 2016; ISO 13790, 2007)

8.3.2 Energy system variables for optimisation model

A selection of systems to cover the heating and cooling energy needs of buildings was compiled, based on an extended search on technologically up-to-date solutions. This selection prioritised renewable energy-based solutions, and included alternatives at building-level and at district-level. For renewable energy supply and storage, a selection of systems and case studies allowed to compile a well-supported set of alternatives.

8.3.2.1 Decentralised HVAC&DHW solutions (ASHP)

Two sets of solutions were studied for decentralised HVAC&DHW equipment:

1. air-to-water heat pump equipped to cover all HVAC and DHW energy needs;
2. the combination of air-to-air heat pump, for space heating and cooling, with air-to-water heat pump or electric water heater, for domestic hot water.

A collection of examples focused on the Portuguese market, e.g., from Daikin, Ariston, Bosch catalogues, which included equipment with different efficiency labels to cover the existing range of options. Output power in thermal energy, SCOP, SEER and DHW COP values were compiled. In few

cases, an EER to SEER conversion was estimated based on similar equipment data. Specific cost, in €/kW, was calculated by dividing equipment cost by the average of heating and cooling output thermal powers.

Table E. 5 include examples of the set 1 solutions, divided in two levels of SCOP class.

Table E. 5. Solutions for set 1) air-to-water heat pump (SH, SC, DHW).

Solutions by heating efficiency class		Total cost (€)	Output power (kW)	S. cost (€/kW)	SCOP	SEER	DHW COP
A+++	Average	11 425	8.5	1 517	4.6	4.5	3.3
	Max. Sp. Cost	15 410	9.5	1 802	5.1	3.9	3.5
	Max. SCOP / SEER	16 840	11.5	1 607	5.1	4.2	3.4
	Max. SEER	5 252	6.3	1 654	4.8	5.3	3.2
A++ / A+ / A	Average	7 120	9.7	799	3.9	3.6	2.9
	Min. Sp. Cost/ SCOP/ SEER/ DHW COP	8 880	14.5	610	3.7	3.5	2.7

(Ariston, 2024; Daikin, 2017, 2023).

Similarly, a list of examples was selected for set 2. In this case, the combination of the different technologies is described in Table E. 6 and the data is detailed in Table E. 7. Specific cost calculation was based on the sum of the total cost divided by the total output power, which considers the average between cooling power and the total heating power. Total heating power is calculated by adding heating output powers from space heating and DHW equipment.

Table E. 6. Selected alternatives to combined solutions for set 2).

Space heating and cooling	Domestic hot water
1. Air-to-air heat pump with SCOP classes of A+++ / A++ 1.1. Average values 1.2. Max Sp. Cost, Max. SCOP and Max. SEER	Air-to-water heat pump for DHW with higher COP
2. Air-to-air heat pump with SCOP classes of A+ / A 2.1. Average values 2.2. Min. Sp. Cost	Air-to-water heat pump for DHW with lower COP
3. Air-to-air heat pump with SCOP classes of A+ / A 3.1. Average values 3.2. Min. Sp. Cost 3.3. Min. SCOP followed by Min. SEER	Electric water heater average

Table E. 7. Combined solutions for set 2) (SH, SC, DHW).

Selection	Class SCOP	Total Cost (€)	Output power (kW)	S. Cost (€/kW)	SCOP	SEER	DHW COP
1.1	A+++ / A++	4 640	4.4	1 058	4.9	8.2	3.9
1.2		5 198	3.7	1 397	5.9	9.5	3.9
2.1	A+ / A	4 047	6.0	678	4.1	6.5	2.6
2.2		3 467	8.0	436	4.0	6.1	2.6
3.1	A+ / A	1 917	5.6	344	4.1	6.5	0.38
3.2		1 337	7.6	177	4.0	6.1	0.38
3.3		2 562	8.1	318	3.8	5.2	0.38

(Ariston, 2024; Bosch, 2017, 2023; Daikin, 2017, 2023; Mitsubishi Electric, 2025).

In general, air-to-water heat pumps tend to be more expensive than air-to-air systems, with installation costs following a similar trend (EC, JRC, 2023a). The proportion of installation cost relative to equipment cost ranges from a minimum of 20% for smaller systems (around 5 kW) to as much as 50% for larger systems (approximately 9 kW) (EC, JRC, 2023b).

8.3.2.2 Centralised HVAC&DHW solutions

District heating networks are typically classified into five generations, being the earliest the first-generation systems, which appeared in the late 19th century and relied on steam for heat distribution. Over the years, district heating technology has advanced significantly, with most modern systems now belonging to either the third or fourth generation (Wirtz et al., 2020). Third-generation district heating relies on pressurised hot water, typically around 100°C, to transport heat efficiently, however mainly due to significant energy losses, fourth-generation district heating networks (4GDH) have been developed with reduced supply temperatures of approximately 70°C. The lower temperature not only minimises distribution losses but also facilitates the integration of renewable heat sources, such as solar thermal energy, geothermal energy, and industrial waste heat, making these systems more adaptable to contemporary sustainability goals (Wirtz et al., 2020). The latest innovation in district energy systems is the fifth-generation district heating and cooling (5GDHC) networks, which operate at ultra-low temperatures, enabling a bidirectional exchange of thermal energy. A key advantage of 5GDHC is its ability to transfer excess heat from buildings with cooling demand to those requiring heating, thereby increasing overall energy efficiency and reducing reliance on external energy sources (Buffa et al., 2019).

Both the 4GDH and the 5GDHC networks are suitable to be applied in the optimisation model, considering that both heating and cooling needs are fulfilled. The choice of a heating and cooling

system for a district depends on several factors, including project scale, building thermal demand, the need and availability for renewable energy integration, energy efficiency, and economic feasibility of infrastructure.

Considering the goals of the present work, the identification of alternatives focused in heat-pump based networks. The working principles of large heat pumps for DHC is similar to building-level ones, with heat source, evaporator, compressor, condenser and lamination valve (EC, JRC, 2023a). The readiness level of DHC heat pump is parallel to smaller heat pump, for supply temperatures of less than 90°C (EC, JRC, 2023a). Nonetheless, large heat pumps are associated to an increased degree of complexity. In EU, the DHC sector is increasingly adopting heat pumps as network temperature are lowered in the latest generation DHC. The expected increase of large capacity heat pumps in DHC, by more than 80% by 2030, will drive the share of heat pumps to rise to more than 25% by 2050 (EC, JRC, 2023a). Integration of new sources as geothermal, solar thermal, and waste heat from sewage, metros, data centres, supermarkets or public buildings is favoured by the lower temperatures network (EC, JRC, 2023a). In Portugal, the only DHC system exists in Lisbon (Parque das Nações district) is supplied by natural gas boilers (ENGIE, 2018).

Contrary to the decentralised solutions, a list of selected alternatives is not presented, due to the complexity of the systems and different options available. Available sources suggest solutions with different efficiencies and costs. Efficiency values are greatly dependent on the energy source and the input and output temperature differences. Also, district level solutions efficiencies and costs are highly influenced by the systems typology and the dimensions of the network. This supports a more thorough and complete characterisation of technical solutions, alternative network designs and systems.

The projected detailed costs for the installation of large-scale heating and cooling systems in EU is presented in Table E. 8, featuring European Commission reference values.

Table E. 8. Heat pump-based DHC predicted reference values from European Commission.

	Heat Pump		Substation		DH network piping*	
	2020	2030	2020	2030	2020	2030
Nominal investment (€/kWth) and (€/rm)*	500 - 1000	600	85 - 150	98	300 - 800	500
Equipment (%)	50%	50%	30%	30%	33%	33%
Installation (%)	50%	50%	70%	70%	67%	67%
O&M (%CAPEX/yr)	>0.45%	>0.45%	0.51%	0.51%	1%	1%
Lifetime (yrs.)	15 - 30	25	20	20	25 - 40	35
(EC, JRC et al., 2017)						

Literature on heat pump-based DHC and DH cases illustrates the significant range of costs, thermal power, and heating and cooling efficiencies. The typology of systems varies from industrial, 4GDH and 5GDHC and with different heat sources /sinks. An overview is presented in Table E. 9.

Table E. 9. Heat pump-based DHC and DH solutions from cases studies.

Typology	CAPEX (€/kW)	OPEX (% CAPEX/y)	Heating		Cooling		Reference
			SCOP COP	Max Power (MW)	SEER EER	Max Power (kW)	
Multiple cases 5GDHC	-	-	2.5 - 6	0.1 - 10	6.9 - 12.1	2 - 5.5	(Buffa et al., 2019)
5GDHC	350	1%	5.1	-	6	-	(Wirtz et al., 2020)
Multiple cases 4GDH	660 – 1 100	0.9 - 1.5%	-	-	-	-	(Mazhar et al., 2018)
Multiple cases 4GDH	600 - 700	<1%	3.5	4 - 12	-	-	(Vilén et al., 2023)
DHC	800 – 1 100	1%	4.95	-	4.5	-	(Ivančić et al., 2021)
Multiple cases Industrial HP	-	-	0.5 - 7.7	0.1 - 12	-	-	(IEA, 2023)
Multiple cases Industrial HP	-	-	3.3 - 4.7	0.1 - 50	2.7 - 5.8	2 - 40	(EHPA, 2020)

8.3.2.3 Photovoltaic systems

Photovoltaic (PV) systems are composed by the PV module, inverters, racking and electrical wiring. Total cost includes equipment, installation, and soft/administrative costs. Soft costs are deemed to add up to 25% of total cost (Lugo-Laguna et al., 2021). Based on real market budgets, a fixed cost of 645 €/kWp was calculated for installation, soft costs and auxiliary equipment, e.g. inverters, connections, and a 30° tilted structure. PV modules were selected based on different typical efficiencies available (*Europe-Solarstore*, 2025). The alternatives are presented in Table E. 10.

Table E. 10. Photovoltaic alternative solutions.

Efficiency (%)	Output power (kWp)	Cost PV (€/kWp)	Cost PV (€/m ²)	Fixed costs (€/kWp)	Fixed costs (€/m ²)	Total cost (€/kWp)	Total cost (€/m ²)
23	0.6	250	58			895	196
21	0.55	182	39	645	138	827	176
18	0.464	151	27			796	165

Real application examples and PV module market survey (*Europe-Solarstore*, 2025; U.S. DOE, 2023)

PV module costs depend on the efficiency and size, accounting for less than 30% of total cost, which is aligned with a study from the U.S. Department of Energy suggesting that module cost accounts up to 25% (U.S. DOE, 2023). Inverters' energy conversion efficiency is about 95% in standard conditions (Micheli et al., 2024).

8.3.2.4 Electric energy storage

From market survey on electric energy storage (ESS), a CAPEX range between 593 and 714 €/kWh, round-trip efficiencies between 0.9 and 0.95, and charging rates of 0.5 of maximum capacity per hour (*Europe-Solarstore*, 2025). Examples from literature suggest a CAPEX of 600€/kWh and OPEX of 2% of CAPEX per year, for a battery of 30 kWh of reference size, 2 hours of charge/discharge time and a 0.9 efficiency value (Minuto et al., 2021). A European Commission study on the state of art at the end of 2021 indicates CAPEX values from 345 €/kWh for large scale lithium-ion batteries, to 675 €/kWh for sodium-based batteries, as well as 1000 €/kWh to lithium-ion batteries at home-scale. OPEX values of 0.5-1.5% of CAPEX per year were estimated, and round-trip efficiencies of 85% to 95% (the higher efficiency for lithium-ion batteries) were identified (EC, DG ENER et al., 2023).

From the data collected, reference ranges for an ESS solution were identified in Table E. 11.

Table E. 11. Reference values for ESS solution.

CAPEX (€/kWh)	OPEX (% of CAPEX per year)	Round-trip efficiency	Charging rate	Loss rate (%/yr)
600 - 700	1 - 2	0.9 - 0.95	0.5	1 - 3%

(EC, DG ENER et al., 2023; *Europe-Solarstore*, 2025; Minuto et al., 2021)

8.3.2.5 Yearly degradation

Yearly degradation values with adequate maintenance are presented in Table E. 12.

Table E. 12. Reference values for yearly degradation.

Equipment	Yearly degradation	Reference
Decentralised HVAC&DHW system	- 0.25% efficiency	(Lee et al., 2022)
Centralised HVAC&DHW system	- 0.25% efficiency	(Lee et al., 2022)
PV system	- 0.55% efficiency	(Europe-Solarstore, 2025)
EES system	- 2% capacity	(EC, DG ENER et al., 2023)

8.3.2.6 Yearly maintenance costs

Yearly maintenance costs for the multiple technologies were summarised in Table E. 13. In general, a cost of 1% of CAPEX per year is applicable for the entire system. Replacement of heating and cooling systems, and PV is usually suggested for equipment older than 25 years. For EES system, a maximum lifetime of 15 years was estimated for a normal operation in standard conditions (EC, DG ENER et al., 2023).

Table E. 13. Reference values for maintenance costs.

Equipment	Yearly maintenance costs (% of CAPEX per year)	Reference
Decentralised HVAC&DHW	1%	(Ju et al., 2025)
Centralised HVAC&DHW	1% for HP station 0.5% for substation	(Ju et al., 2025)
PV	1%	(Lugo-Laguna et al., 2021)
EES	1%	(EC, DG ENER et al., 2023)

Annex F. Case study 1 end-use schedules

(Chapter 5)

Table F. 1 and Figure F. 1 illustrate the schedules by building and by end-use.

Table F. 1 Monthly weighting factor applied on energy use schedules definition.

Weighting factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
FMD	0.7	0.8	0.8	0.8	0.8	0.7	0.7	0.5	0.8	0.8	0.8	0.7
RES MF	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
RES UNI	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.71

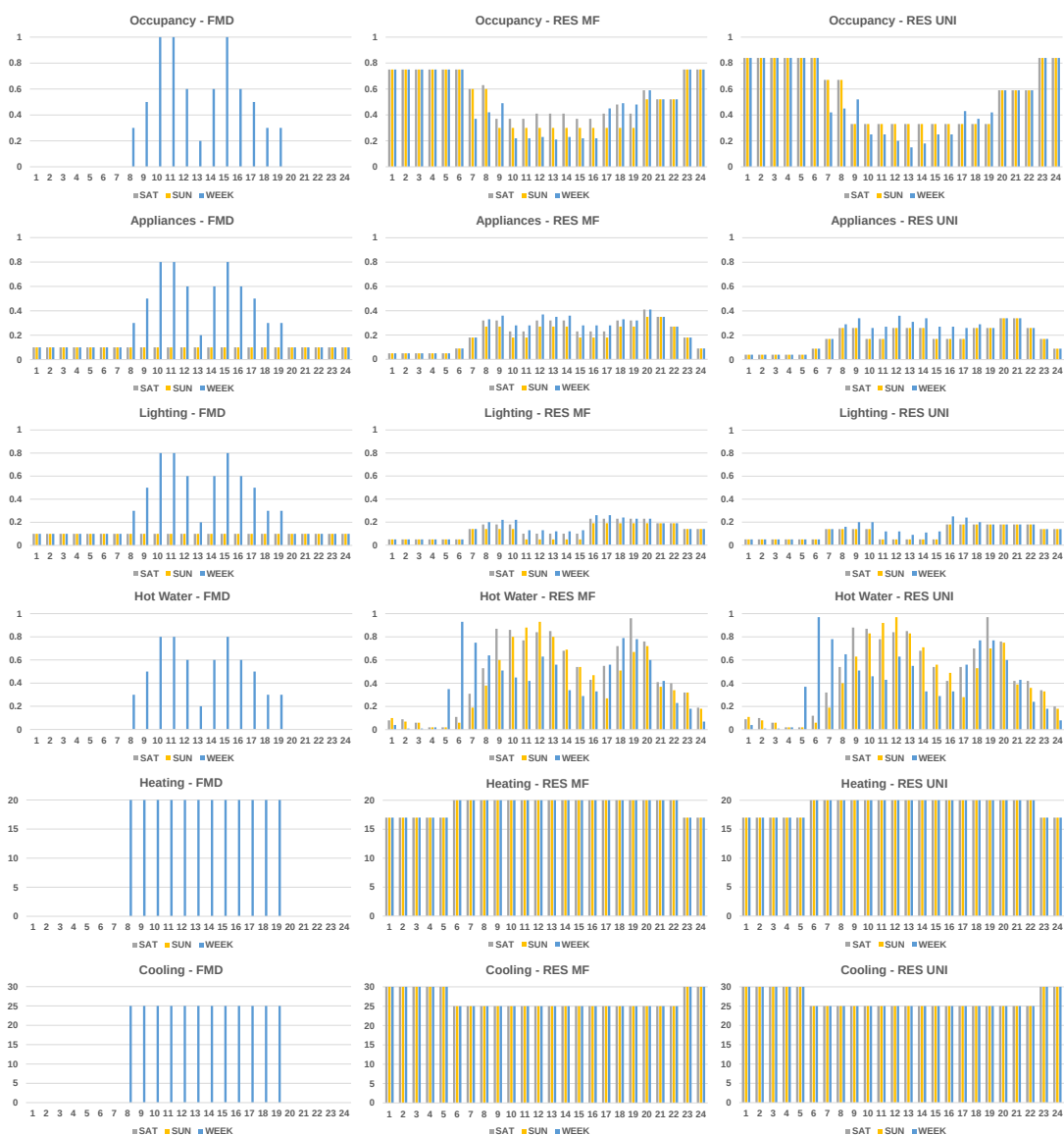


Figure F. 1. Schedules for each energy end-use by building.

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Annex G. Case study 2 end-use schedules

(Chapter 7)

Table G. 1 and Figure G. 1 present the schedules by building use-type and by energy end-use.

Table G. 1. Monthly weighting factor applied on energy use schedules.

Weighting factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Residential	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Office	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8
Retail	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

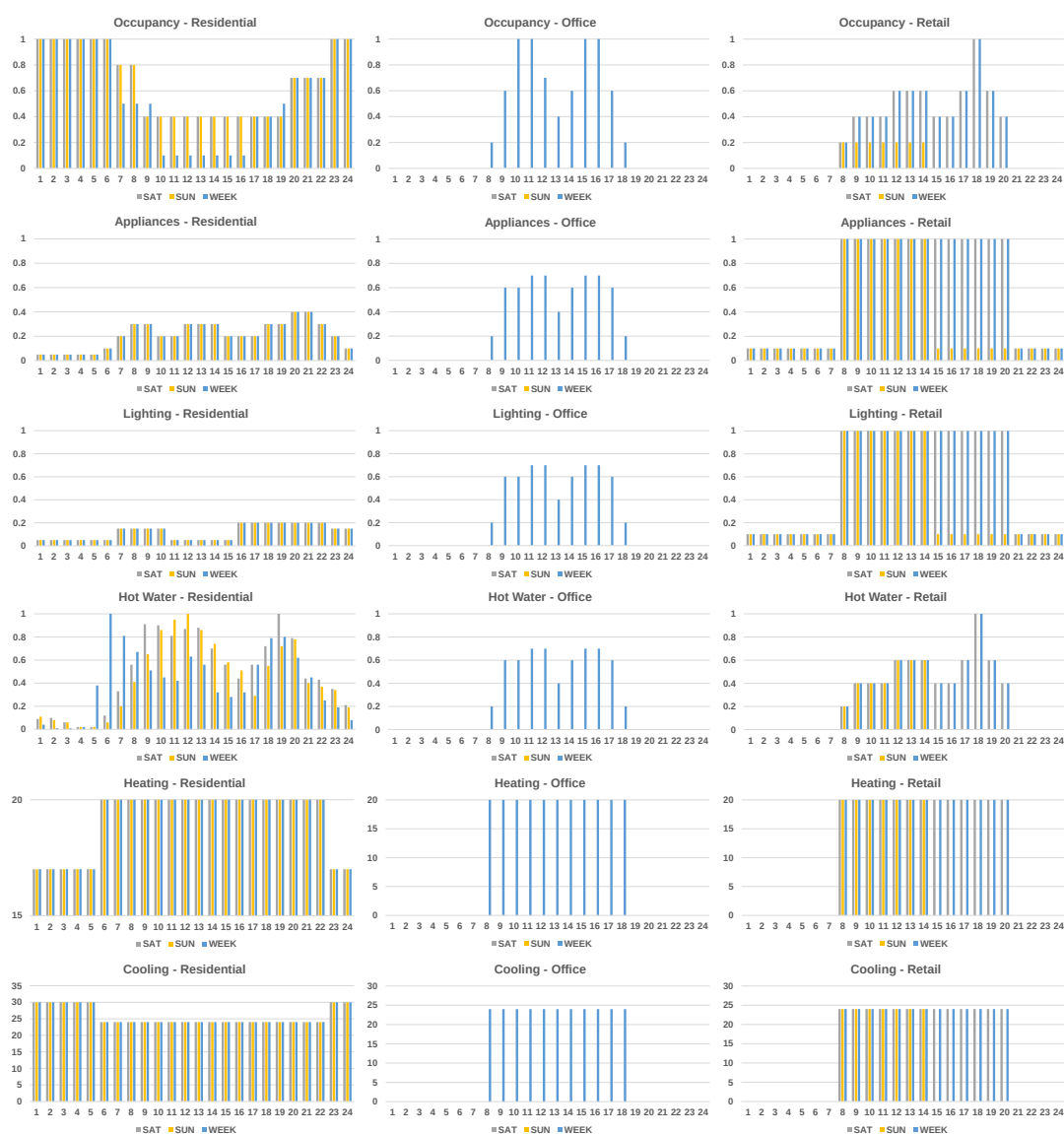


Figure G. 1. Schedules for each energy end-use by building use-type.