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Executive Summary

This document provides an overview of economic impact assessment techniques and methodologies, particularly as they apply to Positive Energy Districts (PEDs) and their overall effect on socio-economic indicators. The first chapter outlines this intermediate deliverable, serving as a guide to understanding the objectives, logic, requirements, and limitations of various impact assessment methods, with a focus on Cost-Benefit Analysis (CBA) and Business Models (BMs) identification within the project's activities.

The second chapter outlines what is understood as CBA, focusing on the most common critiques of the methodology and the responses to those critiques. Additionally, this section provides a general overview of CBA, introducing the reader to the analyst's choices and the steps necessary to accomplish the assessment. Each step guides the reader through the analyst's decision-making process. The issue of estimating monetary values is common for both costs and benefits, but particularly poignant for the latter since they are often immaterial. The challenge of obtaining such values is particularly relevant for PED investments and interventions. Over time, the practice of economics has developed various techniques to estimate market values for goods excluded by the market system. This section will also provide a brief introduction to economic evaluation in the context of Digital Twins and PEDs.

The third section will summarise the concepts presented in the previous sections by initially providing an indicative template of CBA, with some of the most common variables to be assessed. The underlying rationale is to provide a checklist outlining the main steps to conduct a thorough CBA, including the questions that analysts should ask themselves and guidance on how to address them appropriately. Two commented examples of CBAs will complement the discussion about CBA implementation in the context of PEDs. This section aims to provide practitioners with an easy introduction to impact assessment, particularly when applied to PED projects. A ready-to-use handbook will help readers, practitioners, and local policymakers navigate challenges and support future replicability and scalability of the ExPEDite pilot.

The fourth chapter focuses on integrating Business Model concepts into the ExPEDite project, highlighting the importance of aligning business and technical development. It focuses on accelerating district energy transformation, supporting evidence-based decision-making, and enabling climate neutrality. The ExPEDite project will employ a comprehensive business modelling approach to ensure the financially sustainable implementation of Digital Twins (DTs) for Positive Energy Districts, benefiting all stakeholders. This business model approach includes an online preparatory course, onsite workshops, and a refinement stage.

The fifth chapter presents the main risks associated with PED concepts analysed in this project and their implications for economic evaluation processes and business modelling activities.

Finally, conclusions are drawn from this intermediate deliverable, and the next steps towards evaluating the Riga pilot elements are presented. A reflection on the data needed for the assessment and how to collect it will be given, together with the plan for future meetings within the project to coordinate the work of the analysts, the pilots and the data scientists supervising the data collection.

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List of definitions & abbreviations

Acronym	Meaning
BM	Business Model
BtC	Benefit-to-Cost (ratio)
CBA	Cost-Benefit Analysis
COI	Cost of Illness
CV	Contingent Valuation (stated preferences)
DaaS	Data-as-a-Service
DT	Digital Twin
EBMT	Energy Business Modelling Tool
EMS	Energy Management System
EPC	Energy Performance Contracting
ESCO	Energy Service Company
HIA	Health Impact Analysis
HP	Hedonic Prices
ICT	Information and Communication Technologies
KPI	Key Performance Indicator
MIMs	Minimum Interoperability Mechanisms
NPV	Net Present Value
NSB	Net Social Benefit
PaaS	Platform-as-a-Service
PED	Positive Energy District
PV	Present Value
ROI	Return on Investment
RPT	Revealed Preference Theory
VSL	Value of statistical life
WHO-AQG	World Health Organization’s Air Quality Guidelines
WTA	Willingness-to-Accept
WTP	Willingness-to-Pay

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1 Introduction

1.1 Purpose of the document

While it is intuitively clear how the "green" generation of electricity and, more generally, of energy is desirable, it may also be hard to pinpoint and quantify the benefits of its implementation. Relying on the CBA methodology incentivises analysts to list the benefits and costs of the adoption of different ways to generate energy. Similarly, the need to differentiate between qualitative and quantitative effects (and their respective units of measurement) prompts analysts to inquire whether they can precisely measure the impact of interest.

With the increasing popularity of Positive Energy District (PED) projects, which may be related to their ability to generate vast amounts of data and the widespread use of information and communication technology, the challenge of evaluating the consequences of these projects becomes evident. Furthermore, the diversity of objectives in PED projects, along with typically limited resources and the misalignment between the timing of impact realisation and assessment, are common challenges that contribute to the lack of standardisation in assessment methods.

Various articles in the literature reflect on the essential characteristics of impact assessment methodologies applicable to any type of PED project (Bisello et al., 2017; Brozovsky et al., 2021; Lindholm et al., 2021; Albert-Seifried et al., 2022; Binda et al., 2022; Casamassima et al., 2022; Derkenbaeva et al., 2022; Martinopoulos et al., 2024; Pan et al., 2024). Usually, the issue with the reviews is the specificity of their focus. To give further examples, Brozoswky et al. (2021) and Binda et al. (2022) focus on bibliometric analysis, while Lindholm et al. (2021) and Albert-Seifried et al. (2022) focus on PED and Casamassima et al. (2022), Derkenbaeva et al. (2022) emphasise the role of PED in sustainable urbanization in the context of participatory and interdisciplinary climate-neutral strategies.

This document will lay the foundation for future CBA analyses conducted on the Riga pilot, which is being developed through the ExPEDite project. The theoretical foundations expressed in this document will be integrated in the future with the outcomes of both the project implementation and the subsequent analyses of its impact. By the end of the project, we expect to obtain a clear guide for practitioners and workers from public and private entities, Decision-Makers, and investors to conduct an effective, albeit simplified, assessment of the pros and cons of a project implementation.

In conclusion, the guide will attempt to shed light on what economic impact assessment is and on how it is usually done. On this basis, we will then reflect on the specific challenges that will occur for the analysis of projects on energy transition and, more specifically, the implementation of PEDs. Despite the CBA being a flexible tool to conduct analyses, it also is strongly context specific. Each iteration of the analysis and each topic will generate different challenges. The analysis of energy transition and energy efficiency, particularly when paired with the implementation of a PED will need specific data and analyses.

In conclusion, the following sections will introduce the reader to, initially, general takes and concepts on CBA and then this document will specialise the explanation for conducting a CBA specifically in the case of PEDs.

1.2 Relationship with objectives and other deliverables

This Deliverable D4.3 pursues objective O3[1] of the Grant Agreement by providing a methodological basis for evaluating district development pathways through CBA, enabling evidence-based comparisons of scenarios generated by the Digital Twin. This helps inform climate neutrality strategies and supports the identification of impactful transformation actions. It also contributes to objective O4[2] by offering tools to assess the economic impact, risks, and financial viability of Digital Twin adoption and its related developments. The guidelines and examples included in D4.3 aid in developing business cases and support public authorities in evaluating PED investments, aligning with the project's goals of scalability and informed decision-making.

The Task 4.6 "Economic Impact Assessment Toolbox" is rooted in the activities performed in Task 2.1 "Requirements Co-Design and KPI definition" and in Deliverable D2.1, given the fact that what is being developed in the project will play a double role as object of the analysis and contributor to the implementation of assessment techniques both on the CBA side and on the Business Modelling activities.

The present Deliverable D4.3 will provide the elements to perform a CBA of the activities of the ExPEDite projects, with particular regard to the pathways that will be identified through the Digital Twin to predict future development of the district toward the zero-emission balance. Additionally, the Business Modelling part will involve all partners in analysing potential business models related to the individual products and services developed in the project and exploring potential market adaptations. These activities and related results will be described in detail in Deliverable D4.4 of Task T4.6. These activities are also linked to the work of Task 6.1 of "Scenario planning and training", the ExPEDite Living Lab developed in Task 6.3 and the lesson learned will contribute to Task 6.5, moreover the BM activities will provide useful elements for the activities in task T7.4 on the "Exploitation and financial sustainability" of the project.

1.3 Structure of the document

The document is structured as follows. The following section will touch upon different aspects of CBA starting from the critiques, and their answers, of this particular methodology; then, it will pass through more technical concepts needed to develop even a basic analysis and concluding with an attempt to identify metrics relevant to the analysis at hand, and a reconciliation with the DT, the topic at the core of the project.

The third section introduces the reader to a comprehensive example of CBA drawn from the literature. While not being the only possible analysis approach, it has the advantage of presenting a compact, complete, and replicable methodology. In this sense, the section concludes with some considerations on the potential application of this method to the exPEDite project.

[1] Objective O3: "*Contribute to evidence-based decision making by analysing district development pathways through the modelling suite, thus helping the district achieve climate neutrality."*
[2] Objective O4: "*Evaluate the economic impact and risks deriving from the adoption of the Digital Twin by the district, along with elaboration of business cases and analysis of the financial sustainability."*

The fourth section, instead, ties the economic considerations of the CBA to considerations on the best approach for DT implementation and the tools to choose a business model that achieves that.

Each activity of the project entails some potential risk in one form or another; the fifth section specifically addresses the risks associated with the development of Positive Energy Districts.

Finally, the sixth section will present the conclusions of the deliverable.

2 The Cost-Benefit Analysis

CBA, as described by Boardman et al. (2018), is essentially a set of techniques used to identify and categorize the positive impacts (benefits) and negative impacts (costs) of a policy. The key is to assign a monetary value to each of these impacts to calculate the overall net benefit.

The biggest challenge in CBA lies in its scope: the costs and benefits aren't just individual, rather, they're social. This means when we're assessing a policy, we need to consider social benefits and social costs to determine the Net Social Benefit (NSB). Defining the "society" under consideration and its boundaries is crucial and needs to be decided on a case-by-case basis. *Equation 1* simply states that the NSB is the difference between net social benefits (B) and net social costs (C).

Equation 1: The Net Social Benefit equation

$$NSB = B - C$$

Monetisation is crucial in CBA for two primary reasons. First, it enables assessors to assign a degree of importance to each variable, though this introduces some subjectivity. Second, it converts diverse variables, each with its own units of measurement, into a single, unified monetary unit. This standardization is vital for comparing different policy alternatives, which is central to CBA's goal of enhancing the allocative efficiency of social decision-making.

A key aspect of CBA is its inherent comparative nature. Analysts must always evaluate at least two scenarios: the status quo (or "no intervention" baseline) and the proposed intervention(s). The general rule is to accept a proposed policy if its CBA demonstrates a positive incremental change compared to the baseline scenario.

While CBA aims to maximise social gains and improve overall well-being, appearing almost foolproof, it faces two main types of critiques: one philosophical and one technical.

The philosophical critique challenges CBA's utilitarian assumptions. Utilitarianism prioritizes maximising overall welfare, often with less regard for how benefits and costs are distributed. In economics, the utilitarian welfare function, representing society's well-being, is typically expressed as the sum of all individual utilities. This raises questions about equity and fairness, as a policy could be deemed beneficial overall even if it disproportionately harms certain segments of society. *Equation 2* describes the welfare of a society (*W)* as the sum of the individual utilities (u_i) of all the people living in it.

Equation 2: The utilitarian welfare function

$$W(u) = u_1 + u_2 + u_3 + \cdots + u_n = \sum_{i=1}^{n} u_i$$

From the assessor's perspective, the problem boils down to maximising only the aggregate welfare function, *W(u)*, rather than focusing on everyone's utility. This seemingly minor difference in how the aggregate utility is computed explains why CBA often pays little mind to redistributive concerns. In theory, welfare maximisation could be achieved by handing all additional benefits to a single member of society, perhaps because they're deemed able to

make the most of it. In a nutshell, the utilitarian approach can imply a trade-off between the costs borne by certain individuals or groups and the benefits that accrue to others.

The second type of critique is more technical, largely centring on the timing of impacts, the monetisation techniques employed, and how to evaluate present versus future trade-offs. Given that the following sections will delve into the technical facets of CBA, these concerns will be touched upon indirectly and sparingly. It's worth noting that choosing unequivocally the best methodology for each technical aspect of CBA isn't straightforward.

On the other hand, the more fundamental questions regarding the validity of CBA as an assessment tool ought to be explored and addressed in greater depth before moving on to the technicalities.

2.1 Critiques of the Cost-Benefit Analysis

Following Ackerman & Heinzerling (2002) we can provide some of the harshest critiques of the practice. As previously stated, the assessor has a degree of freedom in deciding how to evaluate each of the variables, which can lead to debatable results.

A notable example of this is the assessment concluding that a country should subsidise cigarette consumption because it would ultimately save money. In fact, by eventually dying from respiratory diseases, smokers would save the state money on elder care (Viscusi, 2013). Despite the conclusion being arguably correct, albeit cynical, the key point is that the CBA is not a tool that should be blindly accepted as inherently good. It is crucial to remember that the methodology, rather than the outcome, holds greater importance in assessing the analysis. In the cited article, the main issues of CBA can be grouped into four sets:

I. Reliability of the estimation techniques.
II. Underestimation of the future.
III. Redistribution effects are disregarded.
IV. Lack of transparency.

The primary concern pertains to the trade-off between quantification and accuracy. In attempting to value something that is not “priced” by markets, the analyst is compelled to utilise techniques for the indirect assessment of its value and, in doing so, must accept a certain degree of approximation. The prime example of that kind of approximation is the Value of Statistical Life (VSL). This value is often obtained by inquiring whether individuals are willing to pay to reduce the risk of death (WTP) or how much they are willing to accept to see the same risk of death increase by a small amount (WTA). The estimated value is then derived by aggregating individual preferences regarding risk perception towards themselves, without considering how individuals value the risk to others. This approach may be unsuitable for environmental decisions, given their inherently collective nature. Furthermore, an approach that mirrors the behaviour of a customer purchasing a good (clean air, in this case) may not serve as a valid approximation of the problem of collective choice. For instance, the decision regarding how much to pay for a large public project (e.g., a highway) should consider how much other individuals involved are willing to contribute.

The second critique is that the CBA may underestimate the future, primarily in two ways: through discounting and by not adequately accounting for catastrophic and irreversible events. On one hand, the discount rate reflects individual intertemporal preferences; consequently, the choice related to the discount factor determines how much the future is

valued in relation to the present. The risk lies in postponing harms by employing a sufficiently high discount factor, thereby underestimating the damages implied by the decisions and effectively shifting present problems onto future generations. The issue of procrastinating necessary efforts to the future possibly compounds with the so-called "precautionary principle", which urges regulators to err on the side of caution and protection when risks are uncertain. When combined with a strong preference for the present (expressed through a high discount rate), this principle may encourage inaction, as it is inherently conservative.

The compounded problem is even more significant for environmental projects, as for many programmes—such as hazardous waste clean-ups and the control of persistent toxins—the benefits are often projected far into the future, when lives are saved, rather than in the short term, when risks are merely reduced.[3]

The discounting approach illustrates once again the problem of not considering the possibility of individuals playing different roles and reducing them solely to consumers. The common rationale for discounting is the assumption that it reflects people's risk preferences, as expressed in market decisions. However, this may overlook the possibility that individuals will have different preferences when they take on different roles. One example is the tension between Americans as bank account holders and as workers. Often, Americans are considered poor savers; however, 52% of private sector workers and 82% of public sector employees participate in retirement plans (Bureau of Labor Statistics, 2023), highlighting a potentially different decision-making pattern among the same individuals when acting as citizens compared to their roles as consumers.

The third major criticism is that CBA often overlooks issues of redistribution and social inequality, effectively reinforcing them. This situation is exacerbated by the frequent reliance on stakeholders' willingness to pay (WTP) to assess benefits. As wealthier individuals typically have a greater capacity to pay—especially in environmental contexts—there is a risk of legitimising pre-existing disparities in environmental justice. Consequently, this can lead to shifting environmental burdens onto nations, communities, and individuals who possess the least resources. Lastly, the risk of CBA is its inability to deliver on the promise of more transparent decision making. CBA is a complex, resource-intensive, and expert-driven process that requires significant time and effort to implement effectively. Few communities have access to the technical expertise needed to evaluate the accuracy of the assessments made.

2.2 Answers to the critiques

Following the article by Frank (2000), it is possible to provide some answers to the arguments presented above. In any case, the first reason to attempt a CBA may be simply the fact that, by living in a world of scarcity, inevitably the resources allocated to a project cannot be used for another, and there are not enough resources to pursue every project, so that the choice is forced upon the decision-makers. Hence, the question on how to best allocate those resources lingers.

Comparing items from different categories is widely acknowledged to be quite complex. Nevertheless, many critics claim that such comparisons are fundamentally impossible. For example, if we assume two technologies exist—one clearly acceptable and the other clearly unacceptable—there must be at least one intermediate solution that is neither better nor worse than the current state in some respects. Therefore, any intermediate technology that surpasses the latter should be viewed as an improvement.

[3] Additionally, the problem of timing compounds with matters of intergenerational justice (and redistribution).

Scarcity is a fundamental aspect of human existence. To gain more of one thing, we must accept having less of another. Arguing that different values cannot be compared only complicates our understanding of challenging trade-offs. Those who reject intertemporal trade-offs argue that if we fail to implement stricter air quality standards today, respiratory illnesses will likely increase in the future. Consequently, these future illnesses should be valued similarly to those occurring today. Additionally, a comprehensive cost-benefit analysis must factor in potential advancements in medical technology. If analysts concur that future outcomes deserve equal consideration as present ones, the costs and benefits of any policy adjustment can be straightforwardly calculated on this premise.

Critics of CBA are correct that using unweighted WTP measures possibly skews the decision-making processes in favour of high-income individuals. However, rather than abandoning CBA, the unweighted WTP measures can be unapologetically employed and compensated through the welfare and tax system for both the ex-ante and ex-post harms. Low-income individuals could simply be granted the welfare and tax breaks required by distributive justice, along with additional concessions reflecting their anticipated loss from the implementation of CBA using unweighted WTP measures.

Resistance to cost-benefit analysis can arise because the costs associated with a policy change are usually much simpler to measure than the benefits, particularly in areas like environmental, health, and safety policies. (Boardman et al., 2018). Decisions on these topics tend to be driven primarily by cost considerations, resulting in a bias favouring the status quo.

The fact that benefits are more challenging to measure than costs does not present a compelling reason to abandon CBA, just as the fact that costs are easier to forecast than revenues does not offer a persuasive rationale for firms to forsake profit maximisation. In both instances, it is preferable to act on the best information available rather than to act with no information at all.

It seems there is no fundamental reason to avoid using the CBA as an assessment method. However, the methods and techniques for quantification and monetisation should be carefully considered before use, as the analyst's discretion might lead to using inappropriate methods, consequently resulting in biased recommendations.

2.3 The technical aspects

Once the limitations and rationales behind the CBA are understood, the process of conducting the analysis needs clarification. The following paragraphs outline ideal steps for performing a CBA. Section three will further examine the technical aspects of implementing these steps and the technique presented here through an example. Given that CBA may involve complex matters, it is advisable to provide guidance on the steps outlined in the handbook when approaching a CBA. It should be noted that, while generally acceptable, the following steps may need to be adjusted to fit the specific context and available resources for each situation.

Explain the purpose

The initial step in conducting a CBA is to clearly define the parameters and scope of the analysis, specifically addressing the question: "What is the rationale for considering a change in policy?"

The primary objective of a CBA is to enhance allocative efficiency, thereby increasing social welfare. The justification for undertaking a CBA is grounded in economic theory, particularly with respect to market failures. The fundamental assumption is that, in the absence of these failures, markets can effectively allocate resources to relevant projects. However, the presence of market failures can lead to inefficient allocation, which necessitates the use of alternative decision-making frameworks. Furthermore, it is essential to consider potential government-side failures, such as bureaucratic inefficiencies, when implementing policies. Therefore, a comprehensive explanation of what constitutes failure should be provided prior to initiating the analysis.

Specify the alternatives

In practice, the range of potential alternatives can be quite extensive. However, due to feasibility constraints or cognitive limitations faced by analysts and decision-makers, not all possible options for implementing a project can be evaluated. Typically, CBA focuses on comparing a limited number of projects, specifically the proposed project and the direct alternative that would be set aside if the project under consideration were to proceed. The alternative that would be displaced is referred to as the status quo policy or the continuation of existing government practices.

It's important to clarify that this does not suggest a "do nothing" approach. Rather, it indicates that the government would maintain its current practices. In some cases, the status quo policy may not represent a viable alternative. If a project would displace a specific alternative, it should be assessed against that alternative, not merely against the notion of doing nothing. For instance, if the government is considering either (1) constructing a new highway and generating alternative routes or (2) expanding the capacity of existing routes without the option to maintain the status quo, the new highway project should be compared to the expansion of the existing routes, rather than the "do nothing" alternative.

Standing – Define the affected subjects

The analyst needs to establish the critical question of standing, specifically identifying which stakeholders have the right to have their respective benefits and costs taken into account in the analysis. The concept of standing often generates contention among various parties. Generally, national governments tend to focus solely on costs and benefits that are domestic, frequently overlooking the implications that may reach beyond their borders.

Critics argue that issues with significant adverse effects on populations in other nations warrant examination from a broader global perspective. Environmental concerns exemplifying this viewpoint include, but are not limited to, global climate change, ozone layer depletion, and acid rain. In contrast, local government entities usually prioritize the assessment of benefits and costs that directly impact their constituents, often neglecting to consider the costs and benefits experienced by residents in neighbouring jurisdictions or those governed by higher levels of administration.

Identify the impact categories, order them, and measure them

This step involves the analyst identifying the impacts of the proposed alternatives, categorizing them as benefits or costs, and specifying the metric for each impact category. The term "impacts" is broadly defined to encompass both inputs (resources utilized) and outputs (primarily benefits). A comprehensive list of relevant impact categories is known as an impact

inventory. Ideally, analysts will develop an impact matrix that outlines or summarizes the effects of each policy alternative (or the effects of a single policy alternative on various groups) across each impact category.

It is crucial to incorporate the full spectrum of consequences associated with each project. However, from a practical standpoint, analysts may only consider a manageable number of relevant impacts. A key aspect of this analysis is to disregard impacts linked to sunk costs, even though defining them clearly can often be challenging. For example, the value of land designated for a new road may illustrate this point. Once the government purchases the land, the cost can be viewed as sunk (unrecoverable), yet until the road is constructed, the land may still have alternative uses, such as agriculture.

Moreover, issues related to redistribution are typically outside the scope of CBA. Taking the highway example, one might consider the potential shift in fuel demand—drivers may opt to refuel at service stations directly on the highway instead of those in the town that the new road bypasses. However, since this situation represents a zero-sum game (the money is merely redirected without significantly altering the total amount spent), this effect is generally excluded from consideration. CBA concentrates solely on the incremental impact.

From a CBA perspective, analysts are interested only in project impacts that affect the utility of individuals who have standing[4]. Impacts that do not have any positive or negative utility to human beings are not counted. Suppose, for example, the highway project would decimate the population of a particular avian species. Birds do not have standing. This impact should only be included if some humans regard it as a cost.

Another challenge in identifying impacts is the habit of documenting broadly defined effects, like “community capacity building”, “growth”, or “regional development”. These categories need to be converted into clear and measurable (and thus monetizable) indicators showing how individuals involved in the project are either better-off (e.g., improved skills, enhanced education, increased incomes) or worse-off (e.g., heightened pollution, elevated mortality rates). This is because a narrower conceptual category is easier to define and measure, facilitating monetisation.

Finally, if the chosen data is not available, such as specific metrics like the crime rate, the analyst might resort to using proxy data, which are indirect measures that can still provide useful insights. For instance, the conviction rate can serve as a surrogate for understanding crime trends. However, it is essential for the analyst to bear in mind that employing surrogate data comes with inherent limitations. Using proxies can lead to a significant loss of information because these indirect measures may not accurately reflect the underlying reality. For example, a situation may arise where the conviction rate is increasing while the actual crime rate remains stable. This discrepancy highlights the potential pitfalls of depending solely on proxy data, as it can create a skewed understanding of the situation. Analysts must therefore approach the use of surrogate data with caution, continuously seeking to validate and cross-reference their findings with direct measurements whenever possible to ensure a more comprehensive and accurate analysis.

[4] The caveat is that only human beings have the relevant knowledge and information to make rational decisions.

Project expected life and impact prediction

Nearly all public projects have impacts that extend over time. The fifth task is to forecast the impacts for each year during the discount period (the project's lifespan) for all alternatives. Specifically, the analyst must predict the incremental impacts.

An impact indicates a cause-and-effect relationship between a physical outcome of the project and the utility of individuals with standing, as previously defined. For some impacts, the expected cause-and-effect relationships are reasonably well established. For example, there is a clear causal link between motor vehicle usage and motor vehicle accidents.

However, for other impacts, the causal relationships may be less apparent. A pertinent question might be the effect of exhaust fumes from increased vehicle usage on residents' morbidity and mortality. Would this be balanced by a reduction in airplane flights? Demonstrating and estimating such cause-and-effect relationships often necessitates a comprehensive review of existing scientific and social science research. In some cases, the evidence may be inconclusive or "ambiguous," reflecting significant disagreement among experts.

In such scenarios, it is advisable to rely on existing literature to verify whether these types of relationships have been established or, at the very least, convincingly suggested elsewhere.

Monetisation

At times, it can be difficult to express certain intuitively important effects in monetary terms. In CBA, benefits are usually quantified by using WTP, which serves as a practical means to gauge the value that individuals assign to various things. Challenges with this approach arise when the market for the item in question functions poorly or doesn’t exist at all, making it difficult to assign a monetary value without any form of reference. Consequently, the economic literature contains numerous attempts to assign monetary values to items that aren’t traded in markets.

In practice, most analysts conducting CBAs rely on established figures rather than creating new ones; they often utilize best-practice "plug-in" values when available. If no individual is prepared to pay for a particular impact or to prevent it, this impact would hold zero value in a CBA. For instance, if the construction of a dam would result in the extinction of a small fish species, but no individual with standing is inclined to pay anything to conserve that species, then the potential extinction would have no cost in the CBA evaluating the dam.

It is essential to highlight that the monetary worth does not necessarily need to correspond to the present value of fish or biodiversity overall. For example, a policymaker or stakeholder might argue that even if there is no current value, the fish could have advantages down the line. If this viewpoint is considered a legitimate justification for conservation, then the cost of maintaining biodiversity can be regarded as a form of insurance for the future.

Discounting to the present

For a project with effects that span several years, we require a method to consolidate the benefits and costs that emerge in various years. In CBA, future costs and benefits are discounted in relation to present costs and benefits to derive their present values (PV).

The necessity of discounting stems from two primary factors. First, there is an opportunity cost associated with the resources allocated to a project, as they could potentially generate a positive return if invested elsewhere. Second, the general preference of individuals tends to lean towards immediate consumption rather than postponing it for the future. It's important to note that discounting is not directly related to inflation, even though inflation must be taken into account.

The calculation for discounting, is the inverse of the compounded interest operation. In fact, the proof can be derived through the following algebraic passages:

Equation 3: Compound interest for one year

$$C_t = C_{t-1} + C_{t-1}i = C_{t-1}(1+i)$$

In the previous passage, *i* denotes the yearly interest rate, and the equation simply states that the capital *C* at the year *t* is equal to the capital in the previous year (*t-1*) plus the interest computed on the same amount of capital for the same period. One can envision this computation being repeated several times, thereby generating a series of iterated computations, as in *Equation 4* for example:

Equation 4: *Expansion of the compounded interest formula*

$$C_0 = C_0$$
$$C_1 = C_0 + C_0 i = C_0(1+1)$$
$$C_2 = C_1(1+i) = C_0(1+i)(1+i) = C_0(1+i)^2$$
$$C_3 = C_2(1+i) = C_1(1+i)(1+i) = C_0(1+i)(1+i)(1+i) = C_0(1+i)^3$$

It is evident that the computation can be extended for a number *n* of years. The only constant is the value C_0 in each computation.

Equation 5: General formula of compound interest

$$\mathrm{C_n} = \mathrm{C_0}(1+\mathrm{i})^{\mathrm{n}}$$

By reversing the calculation, one can determine the value C_0 in each year, which means obtaining the PV of the capitalised amount C_n (with *n* being the year considered in the computation). In practice, it can be written as in *Equation 6*:

Equation 6: The equation for the Present Value

$$PV_n = \frac{C_n}{(1+i)^n}$$

Here, we simply stated that the Present Value at year 0 (i.e., the initial year we decide consider) is equal to the initial capital (C_0), formally: $PV_0 = C_0$. Hence, through a simple inversion of *Equation 5* we can retrieve C_0.

Lastly, the computation can be generalised for any type of amount, regardless of the nature. Future flow of benefits and costs can be actualised, i.e., represented in terms of PV, according on the year they arise, and then summed. The operation is expressed as follows in *Equation 7* and *Equation 8* for shortness:

Equation 7: The present value of Benefits

$$PV(B) = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t}$$

Equation 8: The present value of costs

$$PV(C) = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

Where B_t are the benefits and C_t are the costs while, as usual, i is the yearly interest rate, and t are the time periods (often expressed as years).

Computation of the Net Present Value

The net social benefit (NSB) can be computed as a simple difference between the PV of the future flows of benefits and the PV of future flows of costs. As indicated for Equation 1the NSB is derived from the difference between benefits and costs, with only few slight differences. Since both costs and benefits may arise in different years, all the amounts are actualised as previously discussed. Hence the NSB represents its own PV. In simpler terms, the NSB values correspond to the NPV, as follows in Equation 9:

Equation 9: The Net Social Benefit as Present Value

$$PV(NSB) = NPV = PV(B) - PV(C)$$

Where the NSB is expressed in the form of PV, which means we are computing the Net Present Value which, in turn, means that we are computing the difference between the PV of the benefits, *PV(B),* and the PV of costs, *PV(C).*

The CBA evaluation implies that the project ought to be undertaken when the NPV is greater than zero. When evaluating multiple alternative projects, the CBA assessment recommends choosing the projects with the highest NPV.

Sensitivity analysis

It is important to recognise that the present value (PV) and net present value (NPV) estimates mentioned earlier are based on certain assumptions. However, as noted in the earlier discussion, there is inherent uncertainty regarding these assumptions, both concerning the anticipated impacts and the correct monetary valuation for each impact unit.

To address these uncertainties, an analyst might perform a sensitivity analysis, which, considering just one alternative, indicates the parameter values that would shift the recommendation from “go” to “no go,” or vice versa. Analysts can also explore various scenarios using, for example, “most likely,” “optimistic,” and “pessimistic” assumptions.

The key distinction between sensitivity analysis and scenario analysis lies in the number of parameters that vary simultaneously. In sensitivity analysis, only one parameter is changed

at a time, allowing for the evaluation of the magnitude of its impact. In contrast, scenario analysis enables several parameters to vary concurrently and may even introduce additional parameters.

While sensitivity analysis aids in quantifying the influence of each component in the analysis, scenario analysis facilitates the examination of various strategies for the same situation.

Making recommendations

Consider an individual presented with two possible options, A and B, where one of them might be the current policy. Alternative A offers a greater expected NPV and lower risk (with a smaller variance) compared to alternative B. In this scenario, the analyst would undoubtedly suggest option A. Now, if alternative A has a higher expected NPV but entails greater risk than alternative B, the analyst typically operates under the assumption that society is risk-neutral and thus would recommend the option with the highest expected NPV.

Although the NPV criterion theoretically facilitates a more efficient distribution of resources, it does not guarantee the most efficient allocation, as the analyst might not have considered the optimal alternative or may have been unfeasible.

Ultimately, as this discussion underscores, analysts mainly make recommendations instead of decisions. CBA relates to how resources ought to be (or should have been) allocated; it is a normative approach. It does not purport to be a positive theory that describes how resource-allocation decisions are made in practice.

CBA does not replace the decision-making process, which is typically left to political factors. The CBA framework, through a straightforward decision rule, indicates a preferred choice, yet the decision-maker may have different preferences. In such instances, CBA merely provides an estimation of the cost associated with the preferred option (in terms of lost NPV).

2.4 Identification of relevant evaluation metrics

The identification of relevant evaluation metrics is paramount, particularly for assessing the benefits of any project.

A robust CBA requires the selection of contextually relevant evaluation metrics. These are quantifiable measures representing the significant and foreseeable impacts, both positive and negative, stemming from the project within the specific context. The primary goal is to value these metrics, ideally in monetary terms, to determine the project's overall net benefits and feasibility. A relevant metric should exhibit the following key characteristics:

- **Quantifiable**: It can be measured numerically, allowing for an objective comparison of costs and benefits.
- **Significant and Foreseeable**: It represents a substantial and reasonably predictable consequence of the PED project.
- **Valuable**: It can be assigned a value, typically monetary, to facilitate integration within the CBA framework.
- **Net Benefit-Oriented**: It contributes directly to assessing whether the PED's advantages outweigh its disadvantages over its lifecycle, considering the local economic and regulatory landscape.

The evaluation will encompass both economic and non-economic dimensions, tailored to the specific context of a university-based PED. The following metrics, aligned with available data, will be central to the analysis (see also **Table 1**):

Economic Metrics:

- Project Costs:
  - Infrastructure/technology cost
  - Cost of intervention
  - Investment in new solutions
- Energy Costs:
  - Levelized Cost of Heat (LCOH)

Environmental Metrics:

- Greenhouse Gas (GHG) Emissions:
- Reduction air pollutants

Technical Metrics:

- Energy Consumption:
- Primary energy consumption
- RES Production
- PED Energy Balance
- Fuel mix for heating buildings
- Energy savings in PED

Health Metrics

- Risk of illness from exposure to pollutants
- Cost-of-illness
- Average hospitalisation time

Demographic data:

- Studied population
- Age distribution
- Illnesses (selected) incidence

The evaluation of these metrics will employ monetary valuation techniques where feasible, alongside quantitative non-monetary assessments. Qualitative descriptions will complement the quantitative data, particularly for complex social and environmental impacts. Methodologies such as Multi-Criteria Analysis may be considered to integrate the diverse range of economic and non-economic factors in the final assessment of the project's overall value and feasibility (Squire et al., 1975; Campbell & Brown, 2003; Boardman et al., 2018).

Table 1. *List of available data relevant for analysis*

Tool	Output	Unit	
4.3	Infrastructure/technology cost	euro	Economic
4.4	Cost of intervention	euro	Economic
4.5	LCOH	euro/MWh	Economic
4.5	Investment for new solutions	euro	Economic

4.2	GHG emissions	kg CO_2-eq	Environmental
4.2	Reduction of emissions	%	Environmental
4.3	Emissions	CO_2-eq	Environmental
4.4	GHG emissions	CO_2-eq	Environmental
4.5	GHG emissions	CO_2-eq	Environmental
4.5	RES Share	RES share in total energy production	Environmental
4.2	Final energy consumption	kWh/m^2/year; MWh/year	Technical
4.2	Electricity consumption	GWh/year	Technical
4.2	Heat demand	GWh/year	Technical
4.2	Primary energy consumption	kWh/m2/year; MWh/year	Technical
4.3	Energy consumption	GJ, kWh, toe (ton of oil equivalent	Technical
4.4	Final energy consumption	kWh/m2/year; MWh/year	Technical
4.4	Electricity consumption	GWh/year	Technical
4.4	Heat demand	GWh/year	Technical
4.4	Primary energy consumption	kWh/m2/year; MWh/year	Technical
4.4	RES Production	kWh/m2/year; MWh/year	Technical
4.4	PED Energy Balance	kWh/m2/year; MWh/year	Technical
4.5	Fuel mix for heating buildings	MWh per fuel type, fuel shares	Technical
4.3	Delay	Hours, % difference from baseline	Technical/economical
4.4	Energy savings in PED	kWh/m2/year; MWh/year	Technical/economical
4.4	Reduction of emissions	%	Technical/economical
4.5	Surplus power of accumulation	kW	Technical/economical
4.5	District heating network losses	MWh or share per total produced heat	Technical/economical

One possibility is to follow the examples of literature and check how the costs and benefits (Pascal et al., 2013) are valued in projects involving the transitions from one energy source to another.

Rural China's energy transition

Specifically, in a case study of the transition from coal to electricity in rural China, the authors present several formulae to assess those aspects.

Some caution should be exerted due to the fact that the specific case considers the costs of improving the grid to accommodate the increased electricity demand of the villages involved in the study, the equipment purchase, and a subsidy. Despite this not being entirely applicable to the Riga case, it is easy to switch some of the costs considered in the study in favour of others.

Equation 10: Valuing the government costs

$$GC = (PGUI - 0)\frac{i(1+i)^n}{(1+i)^n - 1} + (EPS - 0)\frac{i(1+i)^m}{(1+m)^m - 1} + (EES - 0)$$

GC are the overall government costs sustained for the project, *PGUI* is the investment in grid rehabilitation, *EPS* is the subsidy for equipment purchase, *EES* is the electricity subsidy. In the study, the authors choose to make explicit the fact that the government cost is additive to the costs of maintaining the original situation (no-intervention), but in this particular case, the original situation does not require any public expense. Additionally, since both *PGUI* and *EPS* are one-time expenses, they choose to discount them to annual cost using the interest rate at the time (2,75%) and the useful life of the equipment. As presented in *Equation 11*, PC are the costs borne by the individuals for the transition, EPC_e and EPC_c are the purchase costs of equipment that are being discounted to annual cost. EC_e and EC_c are instead the energy costs.

Equation 11: Valuing the private costs

$$PC = (EPC_e - EPC_c)\frac{i(1+i)^m}{(1+i)^m - 1} + (EC_e - EC_c)$$

On the other hand, in *Equation 13*, *PubB* are public benefits, the subscript *i* denotes the type of air pollutant and CO_2 (i.e., sulphur dioxide SO_2, nitrogen oxides NO_x, particulate matter PM, and carbon dioxide CO_2). Q_c indicates the consumed quantity of the original energy source (coal, in the paper), E_{ci} instead is the unitary emission of pollutant *i* for electricity generation expressed in Kg/MWh. Finally, EB_i is the benefit connected to the emission reduction as expressed in yuan/Kg.

Equation 12: Valuing the public benefits

$$PubB = \sum_{i=1}^{4} (Q_c E_{ci} - Q_e E_{ei}) EB_i$$

In the *Equation 13* formula, *PB* stands for the private benefits obtained from the project, the subscript *j* indicates the three attributes of the rural households' heating process as they are identified by the authors. Those are i) daily input time, ii) indoor temperature, and iii) indoor cleanliness level. R_{cj} and R_{ej} are the levels of each attribute expressed in physical quantities for the electricity case (e) and the carbon case (c). RB_j is the monetised value of each unit of the attributes[5].

Equation 13: Valuing private benefits

$$PB = \sum_{j=1}^{3} \left(R_{cj} - R_{ej}\right) RB_j$$

[5] The authors use the *choice experiment method* to evaluate each attribute RB_j.

PED and energy efficiency in Greece

In a contribution that is relevant for the specific case of the ExPEDite project, Martinopoulos et al. (2024) explore the development of positive energy communities within Eordaia, Greece. Their investigation centres on a combined approach, analysing energy use at both the individual building level and the broader district level, with the overarching goal of achieving nearly zero energy performance. This transformation is envisioned through a combination of retrofitting existing structures, implementing district-level energy storage solutions, and integrating renewable energy technologies.

The methodological framework they employ is quite structured. It begins with a thorough collection of data pertaining to the buildings in question, followed by an assessment of their baseline energy conditions using RETScreen Expert software. An important step involves calculating the Smart Readiness Indicator (SRI), which provides insight into the buildings' capacity to utilise smart technologies for energy optimisation. The process then moves into identifying suitable renewable energy sources for the specific context and simulating the buildings' projected energy performance after the proposed retrofits are applied. To understand the broader energy dynamics, the energy requirements of the entire district are estimated, and the EnergyPLAN software is utilised for a comprehensive district energy analysis. Throughout this analysis, the authors emphasize the importance of using data-driven modelling and calculating key performance indicators (KPIs) to evaluate the effectiveness of various energy solutions. These KPIs serve as tools for urban planners and city officials, enabling them to compare different strategies and ultimately to make informed decisions to enhance energy performance.

The key performance indicators considered in the study are:

- **Energy self-supply** measures the much-proportioned district's energy needs that can be met by locally generated renewable energy.
- **Payback period:** The payback period offers an economic perspective, indicating how long it will take for the energy savings to offset the initial investment in the retrofitting measures.
- **CO_2 emission reduction:** The reduction in carbon dioxide emissions quantifies the environmental benefits of the transition, showing the decrease in GHG emissions achieved through the energy efficiency improvements.

In their detailed case study of Eordaia, the authors focus on a mixed-use neighbourhood comprising 105 buildings, along with two municipal buildings. Their analysis considers a range of energy efficiency upgrades, including enhanced insulation, the installation of photovoltaic systems, the use of LED lighting, the implementation of smart thermostats, and the application of nanotechnology coatings on windows.

While the study offers a robust methodology, the authors acknowledge certain limitations. These include a strong reliance on the availability of accurate and detailed data, potential simplifications in modelling occupant behaviour, the inherent simplifications present in energy simulation tools, the dependence on economic assumptions that can fluctuate, the need for a more nuanced analysis of dynamic grid interactions, the challenges associated with scaling the methodology to large urban areas and the potential benefit of incorporating uncertainty analysis to understand the range of possible outcomes better.

Despite these limitations, the study concludes with positive findings, emphasizing the advantages of district-level strategies over focusing solely on individual building retrofits. Their analysis reveals significant potential for reducing both carbon dioxide emissions and overall energy use, with calculated payback periods for the investments ranging from 8,7 to 9,6 years.

3 Example of Cost-Benefit Analyses

To enhance clarity for the reader and outline discussion topics for the remainder of the document, the following subsections provide an example of CBA regarding the impact of reducing air pollution on mortality and morbidity rates in Europe. The chosen example, albeit being directly drawn from a published paper, is sufficiently linear and straightforward to guide the reader through the phases of a CBA. The application to the case of pollution reduction will undoubtedly prove helpful in the next steps of the analysis when those effects are taken into consideration. The idea is to highlight, either by comparison or directly drawing from the previous section, what the difficulties and strengths of conducting this type of analysis on a PED project will be.

Pascal et al. (2013), in the context of the Aphekom[6] project, aimed at assessing the potential benefit of air pollution reduction in 25 European cities by conducting a Health Impact Analysis (HIA). The pollutants they focused on are Ozone (O_3) and Particulate Matter (PM_{10} and $PM_{2,5}$). They compare two scenarios: the first being a fixed-amount reduction of pollutants, quantified in 5 $\mu g/m^3$; the second, instead, being the full compliance to the World Health Organization's Air Quality Guidelines (WHO-AQG) limits to pollutant emissions of: 100 $\mu g/m^3$ for O_3, 20 $\mu g/m^3$ for PM_{10}, and 10 $\mu g/m^3$ for $PM_{2,5}$.

The authors found that chronic exposure to $PM_{2.5}$ caused the most significant health burden across 25 cities. Meeting the WHO's 10 $\mu g/m^3$ annual guideline could add up to 22 months to life expectancy at age 30 (city-dependent), resulting in a delay of approximately 19,000 deaths. This would yield a yearly monetary gain of €31 billion, encompassing health savings, reduced absenteeism, and intangible benefits such as improved well-being and quality of life.

3.1 Methods

The overall study comprised of 25 cities scattered across 12 European countries drawing data from 2004 to 2006 to meet the requirements for data availability in all the cities. The aim was to standardise data, as much as possible, from countries that, for several reasons, do not completely share standards on data collection and could potentially have started the collection campaigns in different periods.

The data choices primarily regarded the study area, defined in each city following shared criteria, pollutant levels (as said before, O_3, PM_{10} and $PM_{2.5}$), health endpoints, the health consequences linked to the exposure to each pollutant as shown by the literature, mortality and hospitalisations clearly linked to pollutants. The data have subsequently been standardised across cities (e.g., to account for the missing collection of data on $PM_{2.5}$ using data on PM_{10} and a conversion factor).

Health impacts quantification

For short-term exposure to PM_{10} and O_3, the health impact is computed using the following *Equation 14*. Implicitly, the equation assumes that the effect is due to a reduction on pollutant concentration, everything else being equal.

[6] http://aphekom.org/web/aphekom.org/home

Equation 14: Variation in health outcomes as number of deaths and hospitalisations

$$\Delta y = y_0\left(1 - e^{-\beta \Delta x}\right)$$

Δy	the decrease in health outcome is associated with the decrease in pollutant concentrations, in terms of the annual number of deaths or hospitalisations.
y_0	is the baseline health outcome, in annual number of deaths or hospitalizations.
β	is the coefficient of the concentration response function (CRF).
Δx	is the decrease in the pollutant concentration in each scenario, in μg/m^3.

The long-term exposure to $PM_{2.5}$ is, instead, computed using the life table methodology, which is the total number of deaths in the age group starting at age n and covering m years.

Equation 15: Number of deaths for each age cohort

$$D_{n,m}^{impacted} = D_{n,x}\, e^{\beta \Delta x}$$

Where is stated that the number of deaths of each cohort (n) in the subsequent m years is the original mortality rate $D_{n,x}$ modified by $e^{\beta \Delta x}$ which is the same metric stated above that states the variation in the incidence of an illness (β) when the varying the concentration of a pollutant x.

They applied the function to a 5-year age group starting at age 30 using the same β for all age groups. The results are expressed in terms of the number of postponed deaths and gains in life expectancy at the age of 30.

3.2 Economic analysis and results

The value of any benefit must be retrieved from consumers' preferences. Usually, any evaluation method belongs either to stated preferences (Contingent Valuation) or to revealed preferences methodologies

Economists employ various methods to understand consumer behaviour and assign value, particularly to non-market goods. Two prominent approaches are Contingent Valuation (CV) and Revealed Preference Theory (RPT), both rooted in the concept of utility.

CV is a survey-based technique for valuing non-market resources like environmental preservation or pollution impacts. Unlike market-priced goods, a beautiful view, for instance, provides utility without a direct price. CV addresses this by asking individuals their willingness to pay (WTP) for, or willingness to accept (WTA) compensation for the loss of, such features. Often called a "stated preference" model, CV directly queries individuals about their hypothetical choices (Pascal et al., 2013).

Conversely, Revealed Preference Theory, pioneered by Paul Anthony Samuelson in 1938, infers consumer preferences directly from their actual purchasing habits. RPT arose as a pragmatic response to earlier consumer demand models, which relied on unobservable utility functions. By observing real choices, RPT aimed to empirically ground demand theory, distinguishing itself from direct preference measurement methods like stated preference surveys.

In essence, while CV asks people about their hypothetical choices to state their preferences, RPT observes their real-world actions to reveal them. Both methods contribute to a comprehensive understanding of how individuals value goods and services, even when conventional market prices are absent.

In this sense, for mortality assessment, Pascal et al. (2013) they decided to rely on the mortality valuation study conducted by the Institute for Energy Economics and the Rational Use of Energy (IER) in the context of the NewExt project (2001 – 2003) aiming at improving the estimation of the VSL (see subsection *2.1*). Within the report, the authors identified a High value (mean) of € 2.220.000 and Low value (median) of € 1.090.000, and by taking the average of the two they obtained the reference value for their subsequent analysis of € 1.645.000 (Friedrich RF et al., 2004). The values are in range of the VSL used for other studies (Gephart et al., 2006; Bickel et al., 2006; Chanel & Luchini, 2008).

For hospitalisation assessment, the Cost of Illness was used (COI) and, for each country, figures on average hospitalisation length, average daily hospitalisation costs, and total hospitalisation costs are reported in **Table 2**. Those are further imputed to either circulatory or respiratory system illnesses.

COI represents the monetary value of resources either spent or forfeited as a consequence of a health problem. From a broad societal perspective, this concept encompasses the multifaceted economic repercussions that an illness inflicts upon individuals, communities, regions, and indeed, an entire nation. Such studies are deemed vital evaluation techniques within healthcare, as they quantify the economic burden of various diseases, thereby assisting decision-makers in formulating and prioritising health policies and interventions. Ultimately, COI estimations provide crucial insights into the costs associated with mortality, morbidity, disability, and other characteristics pertinent to a given disease.

The costs associated with illness are typically stratified into three principal categories:

Firstly, direct costs refer to those incurred by the health system, society, and directly by the patient and their family. This category encompasses medical care expenditures for diagnosis, treatment, and rehabilitation, including hospitalisation, medication, and emergency transport. Beyond the healthcare sector, direct costs also include non-refunded payments for hospital stays, medical consultations, and drugs, as well as transportation costs for patients and their families for health visits or to visit hospitalised relatives. Furthermore, modifications to the home necessitated by the illness and the costs associated with providing informal care at home are also included.

Secondly, indirect costs primarily relate to productivity losses experienced by individuals, families, society, or employers due to morbidity and mortality. These losses can stem from the illness itself, premature death, side effects of treatment, or simply the time dedicated to receiving medical care. Not only do these affect the patient's own earning potential, but they can also impact family members who may reduce or cease employment to care for the ill individual. In the tragic event of premature death, the indirect cost specifically quantifies the loss of potential wages and associated benefits.

Intangible costs are conceptualised as the burden of pain and suffering. However, these are seldom quantified in COI studies due to inherent measurement difficulties and ongoing controversies surrounding their valuation.

Table 2. *Average length of stay, average cost per day and total hospitalisation cost per patient. (Pascal et al., 2013)*

Country	Average length of stay in days in 2005		Average cost per day (€ 2005)		Total costs related to hospitalisation (€ 2005)	
	Circulatory system	Respiratory system	Hosp. all causes	Work loss	Circulatory system	Respiratory system
Austria	8,2	6,6	319	83	3977	3201
Belgium	9,2	8,8	351	98	5032	4814
France	7,1	7,1	366	83	3777	3777
Greece	7,0	5,0	389	48	3395	2425
Hungary	7,4	6,5	59	18	703	618
Ireland	10,5	6,9	349	81	5366	3526
Italy	7,7	8,0	379	62	3873	4024
Romania	8,5	7,4	57	6	587	511
Slovenia	8,6	7,3	240	34	2649	2248
Spain	8,5	7,4	321	55	3664	3189
Sweden	6	5,2	427	92	3666	3177
United Kingdom	11,4	8,0	581	116	9268	6504
Mean	**8,5**	**7,4**	**373**	**73**	**4411**	**3840**

Results from the example

Since most of the data entail a degree of uncertainty (e.g., the health outcomes from pollution exposure) the following computations will internalise that uncertainty. For that reason, the authors reported the confidence intervals in many of the tables and explicitly stated the expected variability of other factors (e.g., the magnitude of benefits) to clearly show when those figures were estimated and how much those could potentially vary.

Table 3 and **Table 4** report the estimated benefits averaged among the 25 studied cities, for reduce mortality and morbidity, respectively. By considering the column of the medium values (i.e., central estimates) for both tables, it is possible to observe how, generally, the higher benefits are associated with the reduction in mortality. In **Table 3**, the ozone reduction could be potentially responsible for a benefit of € 521.000.000. Since $PM_{2.5}$ have more severe health effects, it is reasonable to expect any improvement on that regard to be more substantial. In fact, decreasing $PM_{2.5}$ by 5 μg/m³ could have a benefit of € 14 500 000 000 circa while complying with WHO-AQG (i.e., reducing $PM_{2.5}$ by 10 μg/m³) would benefit for € 31 116 000 000 circa. While morbidity-reduction benefits are lower, they may still overall result sizeable.

In short, the highest negative health impact is due to the chronic exposure to $PM_{2.5}$. Complying with the WHO-AQG would, potentially, increase the life expectancy at 30 years of age by 22 months. That translates to 19 000 postponed death each year. The associated benefit (see **Table 3**) is in the order of € 31 billion yearly. By considering this together with the reduction of PM_{10} on morbidity rates, we could achieve additional potential benefits of € 11 982 million for respiratory hospitalisations and further € 6 867 million for cardiovascular hospitalizations.

Finally, since these are annual benefits and are expected to repeat over time, those can be discounted following *Equation 7*:

$$PV(B) = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t}$$

Table 3. *Total annual monetary valuations of the long-term mortality impact of reducing ozone and $PM_{2.5}$ in the 25 cities (Low, Central and High monetary estimates of mean, upper 95% CI and lower 95% CI number of cases. Costs rounded to the nearest € million.).(Pascal et al., 2013)*

	Mortality	Associated benefits, Low estimates € million [95% CI]	Associated benefits, Central estimates € million [95% CI]	Associated benefits, High estimates € million [95% CI]
Long-term impacts of decreasing ozone by 5 µg/m³	Respiratory mortality	315 [83:514]	521 [137:851]	1 157 [304:1890]
Long-term impacts of complying with the WHO AQG of 10 µg /m³ for $PM_{2.5}$	Total mortality >30 years old	20 493 [7 190:35 353]	31 116 [10 918:53 678]	41 738 [14 645: 72,003]
	Cardiovascular mortality >30 years old	16 366 [11 479:19 724]	24 850 [17 429:29 947]	33 333 [23 379:40 171]
Long-term impacts of decreasing $PM_{2.5}$ by 5 µg/m³	Total mortality >30 years old	9 549 [3277:16,909]	14 499 [4 975:25 674]	19 449 [6 673:34 439]
	Cardiovascular mortality >30 years old	6 975 [4 780:8 547]	10 590 [7 257:12 977]	14 206 [9 735:17 407]

Table 4. *Total annual monetary valuations of the morbidity impact of reducing ozone and PM_{10} in the 22 cities (Low, Central and High monetary estimates of mean, upper 95% CI and lower 95% CI number of cases. Costs rounded to the nearest € thousand.). (Pascal et al., 2013).*

	Hospitalization	Associated benefits, Low estimates € thousands [95% CI]	Associated benefits, Central estimates € thousands [95% CI]	Associated benefits, High estimates € thousands [95% CI]

Short term impacts of complying with the WHO-AQG of 100 µg/m³ for ozone	Respiratory hospitalizations 15-64 years old	61 [0:486]	91 [0:729]	121 [0:972]
	Respiratory hospitalizations >64 years old	327 [0:464]	491 [0:695]	655 [0:927]
Short-term impacts of decreasing ozone by 5 µg/m³	Respiratory hospitalizations 15–64 years old	137 [0:1 779]	206 [0:2 669]	275 [0:3 559]
	Respiratory hospitalizations >64 years old	837 [0:1 768]	1 256 [0:2 651]	1 675 [0:3 535]
Short-term impacts of complying with the WHO AQG of 20 µg /m³ for PM_{10}	Respiratory hospitalizations	7 987 [4 338:11 486]	11 982 [6 573:17 403]	15 976 [8 764:23 203]
	Cardiovascular hospitalizations	4 578 [2 299:6 832]	6 867 [3 449:10 249]	9 156 [4 599:13 665]
Short-term impacts of decreasing PM_{10} by 5 µg/m³	Respiratory hospitalizations	4 795 [2 618:6 999]	7 194 [3 927:10 499]	9 591 [5 237:13 999]
	Cardiovascular hospitalizations	2 659 [1 332:3 982]	3 990 [1 999:5 973]	5 319 [2 665:7 963]

3.3 General considerations on the possible applications of this methodology in ExPEDite

The methodology presented in this section can prove extremely useful for the scope of the ExPEDite project. Since it comprises of several areas of intervention, e.g., improving buildings' energy efficiency, increasing the share of RES energy generation, and improve traffic flows in and out of Ķīpsala island, we suggest translating the effects (impacts) into pollutant reductions and assessing the potential health benefits associated with these kinds of interventions.

Reducing traffic congestion has a direct impact on air pollution. The issue then becomes estimating how a localised congestion reduction will impact the overall city pollution levels. It is entirely possible that sensors may not detect the air quality improvement if they are not located in proximity of the affected area. This is especially true when considering the relatively short period available for the project to collect data.

In the same vein, the improved buildings' energy efficiency can indirectly affect the pollution emission by simply reducing their energy demand. Similarly to the traffic case, the limited time available may prove a hindrance in collecting data for a sufficiently long time to conclude.

In this sense, the CBA's most relevant contribution will be of providing the methodological tools to perform the estimation in the future, once enough data will be available to draw conclusive results.

Finally, on the topic of the DT, we expect the time constraints to affect the direct evaluation of this aspect of the project as well. While we do not expect to be able to draw definitive conclusions on the DT effectiveness as a decision-making complementary tool, we reasonably expect it to be relevant in the future once it will be fully implemented. In this sense, we expect its main strength to be the creation of alternative scenarios. In this context, we suggest implementing the CBA methodology in the DT and allow it to use the CBA results as a way to rank the alternatives for example by using the Benefit-to-Cost (BtC) ratio together with other indicators.

4 Business Model Strategic Approach for DT Implementation

Following the steps of a CBA, this chapter introduces the business modelling activities and related concepts in energy efficiency projects and the key elements that characterize sustainable BMs. The ExPEDite project is characterised by the use of Digital Twin technologies and their specificities will guide the choice of evaluation items that are to be assessed through the lens of business model analysis.

4.1 The strategic approach of business model to Digital Twins implementation

The implementation of DT technology in urban environments represents a significant paradigm shift in how we approach energy management and urban planning. A strategic business model approach is essential to ensure the successful implementation and long-term sustainability of DT solutions, particularly for Positive Energy Districts.

When implementing DT for energy management, organisations must first articulate a clear value proposition. The primary value of the DT lies in its ability to provide real-time monitoring, visualisation, and analysis of energy flows at the district level. This enables evidence-based decision-making for urban planners and stakeholders, ultimately leading to more efficient energy use and reduced carbon emissions. Each stakeholder must understand how the Digital Twin addresses their specific needs and challenges, whether by reducing operational costs for building owners, improving policy effectiveness for city authorities, or enhancing service delivery for energy providers.

Stakeholder engagement forms the second pillar of a successful DT implementation strategy. This requires identifying and involving all relevant actors, including city authorities, energy providers, building owners, technology providers, and citizens. The strategic approach must include mechanisms for continuous dialogue with these stakeholders throughout the implementation process, ensuring that their needs and concerns are addressed. This engagement also helps foster the trust necessary for data-sharing and the adoption of new technologies.

In addition to the interactions with the actors, resource requirements must be carefully assessed as part of the strategic approach. Implementing a Digital Twin requires significant technical infrastructure (sensors, networks, computing resources), data collection capabilities, specialised expertise, and financial resources. Organisations must realistically evaluate their capacity to provide these resources and identify potential gaps. The strategy should also include plans for building necessary capabilities through recruitment, training, partnerships, or external services.

For sustainable implementation, the business model must include clearly defined revenue streams and cost structure. This involves identifying who will pay for the development, implementation, and ongoing operation of the Digital Twin, as well as through which mechanisms. Options may include public funding for initial development, service fees from building owners or managers, subscription models for data access, or value-sharing arrangements based on energy savings. The cost structure must account for both initial implementation costs and long-term operational expenses.

Given this long-term perspective, risk management represents another essential element of the strategic approach. Digital Twin implementations face various risks, including technical failures, data security breaches, stakeholder resistance, and regulatory changes. A comprehensive risk assessment should identify potential risks, their likelihood and impact, and mitigation strategies. This ensures that the implementation remains resilient in the face of challenges and can adapt to changing circumstances.

Within the ExPEDite project, the strategic business model approach focuses on creating a sustainable framework for implementing the district's Digital Twin, aligning with the project's core objectives. The ExPEDite approach emphasises interoperability and scalability through its modular, open architecture, which supports integration with existing systems and allows for expansion across different districts and cities. This technical foundation supports a business model that can grow incrementally, allowing organisations to start with targeted applications and expand as they demonstrate value.

The ExPEDite business model also recognises the diverse needs of stakeholders in the energy ecosystem and aims to create value for each group through tailored features and applications. By mapping stakeholder needs against Digital Twin capabilities, the project ensures that the implementation delivers tangible benefits to all participants, strengthening their commitment to the initiative.

A key element of the ExPEDite business model strategy is the emphasis on public-private partnerships. The model leverages collaborations between public entities (city authorities) and private organizations (technology providers, energy companies) to pool resources and share risks. This approach recognizes that neither sector alone possesses all the capabilities and resources necessary for successful implementation, and that cooperation creates opportunities for innovation and efficiency.

Knowledge transfer and replicability form another cornerstone of the ExPEDite approach. The project prioritizes the development of reusable patterns, guidelines, and training materials to facilitate knowledge sharing and enable replication in other European cities. This not only extends the impact of the project but also creates potential for economies of scale as solutions are adapted and deployed in multiple locations.

Beyond the project's duration, the business model considers how the Digital Twin can continue to operate sustainably through appropriate revenue mechanisms and governance structures. This long-term perspective acknowledges that while initial funding may come from project sources, sustainable operation requires ongoing value creation and resource allocation. The governance approach defines roles, responsibilities, and decision-making processes that will ensure the Digital Twin continues to serve stakeholder needs over time.

By adopting this comprehensive strategic business model approach, the ExPEDite project aims to ensure that the implemented Digital Twin not only meets technical objectives but also establishes a foundation for long-term operation and widespread adoption across European cities pursuing climate neutrality goals.

Figure 1 illustrates the layered framework of the strategic business model approach for implementing Digital Twins. At the core is the Digital Twin platform itself, surrounded by concentric layers representing Value Creation, Resources, Governance, and Sustainability. Each layer contains key elements that must be addressed to ensure successful implementation,

and shows how these elements interact to support the Digital Twin and guide its implementation in the ExPEDite project.

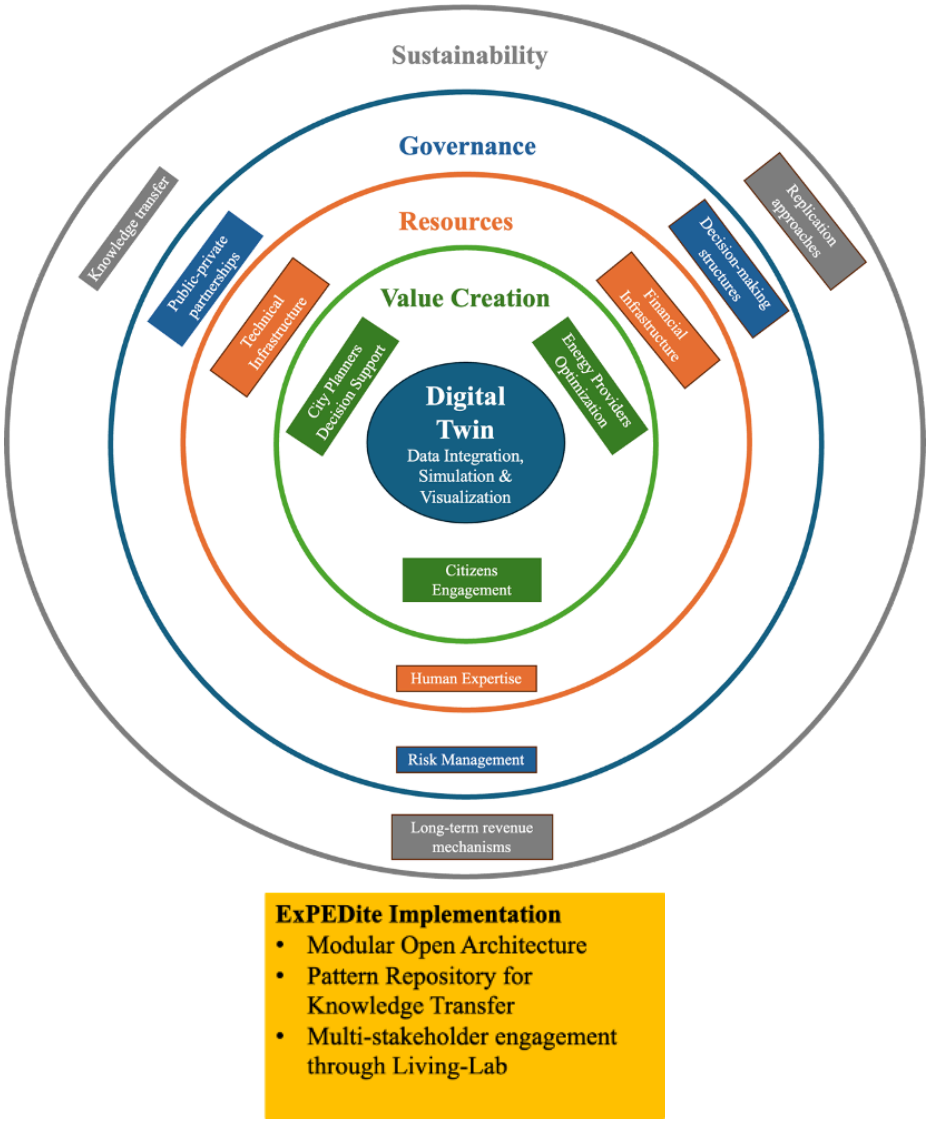

Figure 1. Strategic Business Model Approach for Digital Twin Implementation in ExPEDite

4.2 Identification of Business Models for Energy Efficiency Projects

Energy efficiency projects have traditionally employed several established business models that provide valuable insights for Digital Twin implementations. Understanding these models helps identify appropriate approaches for financing and sustaining Digital Twin solutions in urban energy contexts.

The equipment sales model represents the most straightforward approach, where vendors sell energy-efficient technologies directly to end-users. This model emphasizes long-term energy savings to offset initial investments but often struggles with adoption due to high upfront costs and uncertainty about actual returns. Public institutions with constrained capital budgets find this model particularly challenging, as they may be unable to make the necessary initial investments despite potential long-term benefits.

Energy Performance Contracting (EPC) addresses these limitations by restructuring the financial relationship between service providers and clients. Under this model, providers implement energy efficiency measures and receive payment based on verified energy savings. This approach effectively aligns incentives, as both parties benefit when energy savings are maximised. The service provider assumes performance risk, which reduces adoption barriers but necessitates robust measurement and verification protocols to ensure fair compensation.

Taking this concept further, the Energy Service Company (ESCO) model delivers comprehensive energy solutions encompassing analysis, equipment, installation, maintenance, and often financing, with payment linked to performance outcomes. ESCOs provide turnkey solutions that minimize client involvement and risk, making this approach particularly effective for complex, multi-technology implementations similar to Digital Twins. However, the model requires significant expertise and financial capacity from service providers, limiting the number of organizations that can effectively operate as ESCOs.

Utility-driven programs offer another traditional approach, where energy utilities incentivize efficiency through rebates, direct installation services, or other customer programs. These initiatives leverage existing utility-customer relationships and can achieve considerable scale. However, their effectiveness may be constrained by regulatory frameworks and utility business models that sometimes create disincentives for reduced energy consumption.

The emergence of digital technologies has enabled new business models particularly relevant to Digital Twin implementations. Data-as-a-Service (DaaS) creates value by providing access to energy data and analytics generated by Digital Twins to support decision-making and optimization. This model generates recurring revenue through subscription or usage-based pricing, with value increasing alongside data volume and quality. As more data is collected and analysed, the insights become more valuable, creating a self-reinforcing cycle of implementation and value creation.

Platform-as-a-Service (PaaS) expands this concept by positioning the Digital Twin as a platform where third-party developers can create and deploy specialized applications addressing specific energy management needs. This creates an ecosystem of solutions that enhances the core platform's value while distributing development costs across multiple participants. The platform owner benefits from network effects as additional users and developers join, while users gain access to an expanding range of tailored applications.

Optimization-as-a-Service focuses on delivering ongoing energy optimization using the Digital Twin's simulation and prediction capabilities. This approach ties revenue directly to value creation through energy savings or performance improvements. While similar to traditional ESCO models, digital capabilities enhance optimization potential and enable continuous improvement. The ongoing nature of optimization creates long-term client relationships and provides revenue stability, though it requires maintaining technological advantages to remain competitive.

Smart City Partnership Models recognize the multi-stakeholder nature of urban energy systems by establishing collaborative frameworks where various participants (city authorities, technology providers, energy companies, citizens) share resources, risks, and benefits. While more complex to establish and manage, these partnerships can create resilient implementations with broad stakeholder support. They are particularly suitable for Digital Twin projects that span organizational boundaries and require coordination across multiple systems and actors.

The ExPEDite project evaluates these models to identify the most appropriate approaches for implementing Digital Twins in Positive Energy Districts. The project recognizes that different contexts may require different business models or hybrid approaches depending on local conditions, existing infrastructure, and stakeholder preferences. By understanding each model's strengths and limitations, ExPEDite can develop implementation strategies that are financially sustainable while providing clear value to all stakeholders.

For Digital Twin implementation in urban energy contexts, a hybrid model combining elements of platform services, optimization services, and multi-stakeholder partnerships appears most promising. This approach acknowledges that no single entity possesses all the resources and capabilities necessary for successful implementation, and that value creation occurs across multiple dimensions and stakeholder groups.

Table 5. *Comparison of Business Models for Energy Efficiency and Digital Twin Implementation*

Business Model	Key Characteristics	Value Proposition	Applicability to Digital Twins
Traditional Business Models			
Equipment Sales	Direct sale of energy-efficient technologies to end-users	Long-term energy saving offset initial investment	**Pros:** simple transaction model **Cons:** high upfront cost limit adoption, and limited relationship
Energy Performance Contracting (EPC)	Service providers implement measures and receive payment based on verified energy savings	Aligned incentives through performance-based payment	**Pros**: Risk shifted from client to provider; Reduces adoption barriers **Cons**: Requires robust measurement protocols
Energy Service Company (ESCO)	Comprehensive solutions including analysis, equipment, installation,	Turnkey solution minimizing client involvement and risk	**Pros**: Well-suited for complex implementations;

	maintenance, and often financing		Comprehensive service approach **Cons**: Requires significant provider expertise and capacity
Utility-Driven Programs	Energy utilities incentivize efficiency through rebates, direct installation, or other programs	Leverages existing utility-customer relationships	**Pros**: Can achieve considerable scale **Cons**: Constrained by regulatory frameworks; Potential disincentives for reduced consumption
Digital Business Models			
Data-as-a-Service (DaaS)	Providing access to energy data and analytics generated by Digital Twins	Supports decision-making and optimization through data insights	**Pros**: Recurring revenue through subscription; Value increases with data volume and quality **Cons**: Requires data privacy and security measures
Platform-as-a-Service (PaaS)	Digital Twin serves as platform for third-party applications addressing specific needs	Ecosystem of solutions enhancing core platform value	**Pros**: Benefits from network effects; Distributes development costs **Cons**: Complex ecosystem management
Optimization-as-a-Service	Ongoing energy optimization using Digital Twin simulation and prediction capabilities	Revenue tied directly to value creation through energy savings	**Pros**: Creates long-term client relationships; Enhanced by digital capabilities **Cons**: Requires maintaining technological advantage
Smart City Partnership Models	Collaborative frameworks where stakeholders share resources, risks, and benefits	Addresses multi-stakeholder nature of urban energy systems	**Pros**: Creates resilient implementations with broad support; Suitable for cross-boundary projects **Cons**: Complex to establish and manage
Hybrid Approach	Combines elements of platform services, optimization services, and multi-stakeholder partnerships	Acknowledges diverse stakeholder needs and distributed resources/capabilities	**Pros**: Adaptable to different contexts; Creates value across multiple dimensions; Supports long-term sustainability

Table 5 provides a comparative overview of traditional and digital business models for energy efficiency projects, highlighting their key characteristics, value propositions, and specific applicability to Digital Twin implementations. The ExPEDite hybrid approach combines strengths from multiple models to address the complex requirements of Digital Twin implementation in urban energy contexts.

4.3 Key Elements of Sustainable Business Models

Successful digital business models for Digital Twins must integrate both digital capabilities and sustainability principles to ensure long-term viability and impact. These models extend beyond traditional financial considerations to address technological, environmental, social, and governance dimensions that collectively determine implementation success.

The digital component of these business models starts with robust data collection and management infrastructure. Digital Twins rely on comprehensive data gathering from diverse sources including sensors, building management systems, energy meters, weather stations, and user inputs. This data must be processed, validated, stored, and protected according to relevant regulations such as GDPR. The increasing volume and variety of data in urban environments makes sophisticated data management increasingly critical, with particular attention required for data quality, security, and privacy.

Interoperability represents another essential digital element, enabling the Digital Twin to connect with existing systems and platforms across organizational boundaries. Following standards and protocols such as the Minimum Interoperability Mechanisms (MIMs) adopted in the ExPEDite project ensures that Digital Twins can leverage existing investments and avoid creating isolated solutions. This approach reduces implementation costs and increases the potential value of the Digital Twin by enabling it to access and process data from diverse sources. Interoperability also supports future scalability and integration of new capabilities as technologies evolve.

User interfaces and experience design determine how effectively different stakeholders can interact with the Digital Twin. Intuitive interfaces tailored to different user groups enable each stakeholder to access information and functionality relevant to their specific needs. Technical experts may require detailed dashboards with comprehensive analytical capabilities, while city planners might need planning tools with visualization of alternative scenarios, and citizens may prefer simplified visualizations that communicate key information accessibly. The user experience design must balance complexity with usability to ensure adoption by all stakeholder groups.

Analytics and intelligence capabilities transform raw data into actionable insights through a combination of modelling, simulation, prediction, and optimization. These capabilities form the core value proposition of the Digital Twin, enabling stakeholders to make better decisions, optimize operations, and identify new opportunities. Advanced techniques such as machine learning and artificial intelligence can enhance these capabilities by identifying patterns, predicting future conditions, and recommending actions. The business model must articulate how these capabilities create specific value for each stakeholder group.

Technological scalability ensures that the Digital Twin can grow and adapt as requirements evolve. This includes horizontal scalability to accommodate increasing data volumes and user numbers, and vertical scalability to incorporate new functionality and use

cases. Cloud-based architectures often provide this scalability while minimizing upfront infrastructure investments, but require careful consideration of data sovereignty, security, and long-term costs. The business model should specify how scalability will be managed and funded over time.

On the sustainability side, environmental impact assessment must be explicitly incorporated into the business model. This includes quantifying how the Digital Twin contributes to environmental goals such as carbon reduction, resource efficiency, and climate resilience. The model should articulate specific metrics for measuring environmental impact and mechanisms for verifying and reporting these benefits. This environmental dimension is particularly important for Digital Twins supporting Positive Energy Districts, where environmental performance is a primary objective.

Economic viability requires clear mechanisms for value creation and capture that ensure financial sustainability beyond initial implementation. This includes identifying who will pay for the Digital Twin's development, operation, and maintenance, and through what mechanisms. Options range from public funding and grants to service fees, subscriptions, performance-based payments, and shared savings arrangements. The business model must ensure that revenue streams are sufficient to cover both capital and operational expenditures over the Digital Twin's lifecycle.

Social inclusion considerations ensure that the Digital Twin's benefits are accessible to all community members, avoiding digital divides or disproportionate impacts. This includes designing interfaces and services that are accessible to users with different abilities, languages, and technical proficiency. It also involves ensuring that decision-making processes incorporate diverse perspectives and that benefits are equitably distributed across the community. The business model should specify how these social dimensions will be addressed and measured.

Governance structures provide frameworks for decision-making, accountability, and ongoing management of the Digital Twin. This includes defining roles and responsibilities for different stakeholders, establishing processes for resolving conflicts, and creating mechanisms for community input and oversight. Effective governance is particularly important for Digital Twins spanning organizational boundaries or involving public-private partnerships. The business model should articulate the governance approach and how it will evolve over time.

Adaptability ensures that the business model can evolve as technologies, regulations, and stakeholder needs change. This involves establishing feedback mechanisms to understand changing requirements, regular review processes to evaluate performance, and flexible structures that can accommodate new participants or use cases. The business model should specify how adaptability will be maintained and how decisions about future directions will be made.

The ExPEDite approach to Digital Twin business models carefully balances these digital and sustainability elements to create a comprehensive framework that addresses technical, environmental, economic, social, and governance dimensions. This holistic approach recognizes that successful implementation requires attention to all these dimensions, with different contexts potentially requiring different emphases or approaches (see *Figure 2*).

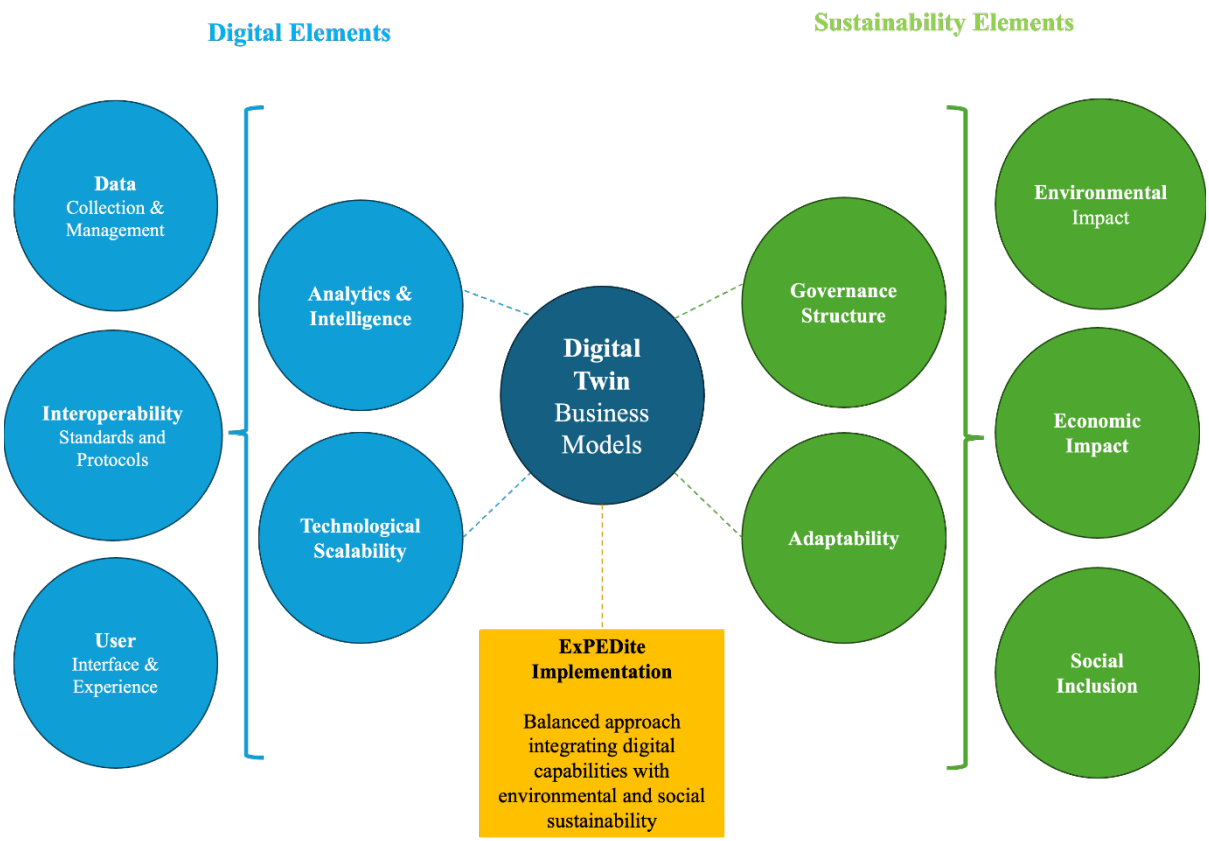

Figure 2. Key Elements of Digital and Sustainable Business Models for Digital Twins

4.4 Integration of Business Model Concepts in the ExPEDite Project

The ExPEDite project integrates business model concepts throughout its approach to Digital Twin implementation, ensuring that technical developments align with sustainable business practices. This integration helps create a foundation for long-term viability and widespread adoption beyond the initial project scope.

At the strategic level, ExPEDite's business model concepts are tightly aligned with the project's core objectives of accelerating district energy transformation, supporting evidence-based decision making, and enabling climate neutrality. The business model addresses how the Digital Twin creates value for different stakeholders, mobilizes necessary resources, establishes appropriate governance structures, and ensures long-term sustainability. This comprehensive approach recognizes that technical excellence alone is insufficient for successful implementation; the Digital Twin must also establish a viable operational model that serves stakeholder needs.

The project's approach to data framework development emphasizes the creation of a standardized framework that consolidates district-level energy data streams, following open standards and Minimum Interoperability Mechanisms (MIMs). This technical design choice supports the business model by enabling data sharing across organizational boundaries, reducing integration costs, and allowing for future expansion. By establishing common data models and interfaces, ExPEDite creates the foundation for an ecosystem of compatible applications and services that can enhance the Digital Twin's value over time.

The suite of modelling and simulation tools developed within ExPEDite creates value through its ability to analyse and optimize energy-related performance across multiple dimensions. These tools enable stakeholders to visualize alternative scenarios, understand complex interactions between different systems, and identify optimal intervention points. The business model articulates how these capabilities translate into specific benefits for different stakeholders, such as reduced energy costs for building operators, improved planning processes for urban authorities, and enhanced service delivery for energy providers.

Evidence-based decision-making forms a core value proposition within the ExPEDite business model. The Digital Twin's analysis capabilities enable better-informed decisions by providing comprehensive data, advanced analytics, and visualization of complex scenarios. This addresses a key challenge for urban energy planning, where decisions often rely on incomplete information or simplified models. By demonstrating how the Digital Twin improves decision quality and outcomes, the business model establishes a clear rationale for investment and adoption.

Economic impact assessment is explicitly incorporated into the ExPEDite approach through comprehensive evaluation of costs, benefits, and risks associated with Digital Twin implementation. This includes direct financial impacts such as implementation and operating costs, energy savings, and improved asset utilization, as well as broader economic impacts like job creation and increased property values. By quantifying these impacts, the project addresses concerns about return on investment and provides a foundation for financial planning and resource allocation.

The stakeholder engagement approach within ExPEDite recognizes the diverse needs and capabilities of different participants in the urban energy ecosystem. The business model explicitly addresses how various stakeholders, from city authorities to citizens, can engage with and benefit from the Digital Twin. This includes tailored interfaces for different user groups, dedicated engagement processes, and mechanisms for incorporating stakeholder feedback into ongoing development. This approach helps build the stakeholder support necessary for successful implementation and sustainable operation.

Implementation in the Riga pilot provides a concrete application of business model concepts in a real-world context. The pilot tests and validates value propositions for different stakeholders, assesses resource requirements and constraints, and establishes governance structures for collaborative decision-making. This practical experience provides valuable insights that refine the business model and identify potential challenges or opportunities not apparent in theoretical analysis. The pilot also creates a reference implementation that demonstrates the Digital Twin's feasibility and benefits to potential adopters.

A distinctive element of the ExPEDite business model integration is the pattern repository approach. The project codifies successful implementation patterns, including business model elements, into a structured repository with machine-readable metadata about application preconditions and measured KPIs. This enhances knowledge transfer and reusability, allowing other cities to adapt proven approaches to their specific contexts. The repository includes patterns specific to business model elements, such as stakeholder engagement approaches, revenue mechanisms, and governance structures, providing practical guidance for implementation.

Beyond the immediate project, ExPEDite's business model approach extends to developing a broader ecosystem around Digital Twin implementation. This includes

community building through engagement with the Mission Cities Platform and other stakeholders, contribution to standardization efforts around Minimum Interoperability Mechanisms, development of capabilities through training and knowledge sharing, and establishment of innovation networks connecting technology providers, research institutions, and city authorities. These ecosystem development activities create a foundation for continued innovation and adoption beyond the project's duration.

The ExPEDite business model approach specifically addresses the transition from project implementation to long-term operation. This includes identifying sustainable funding mechanisms, establishing appropriate governance structures, and ensuring knowledge transfer to operational teams. By planning for this transition from the outset, the project increases the likelihood that the Digital Twin will continue to provide value after the initial implementation phase, avoiding the common pitfall of promising pilots that fail to achieve sustained operation.

The integration of business model concepts into the ExPEDite project demonstrates the importance of considering business dimensions alongside technical development. This integrated approach increases the likelihood of successful implementation and sustainable operation, creating a foundation for widespread adoption of Digital Twin solutions for Positive Energy Districts across European cities.

4.5 Business Model Workshop application guidelines

The ExPEDite project will adopt a comprehensive business modelling approach to ensure that the Digital Twin implementation for Positive Energy Districts can be financially sustainable and create value for all stakeholders. This approach consists of two main components: an online preparatory course and onsite workshops, followed by a refinement stage.

Online course

The ExPEDite online course is designed to establish a common understanding of Digital Twin concepts and business modelling approaches among project participants before engaging in collaborative workshops. The course will be provided through the Energy Business Modelling Tool (EBMT) (see *Figure 3*) platform and will consist of six units:

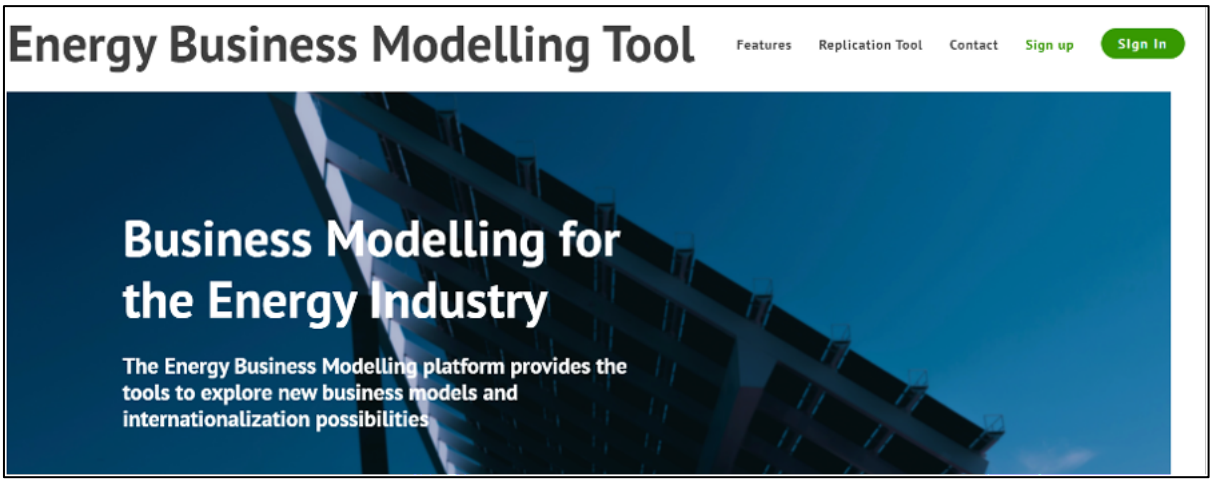

Figure 3. Energy Business Modelling Tool (https://energy.venturely.io)

- **Unit 1: Introduction to Digital Twins for Positive Energy Districts**

This unit introduces the fundamental concepts of Digital Twins in the context of urban energy systems. It covers the definition, components, and functionality of Digital Twins, their role in monitoring, analysing, and optimising energy flows, and their potential applications in Positive Energy Districts.

- **Unit 2: Technical Architecture and Implementation Considerations**

This unit explores the technical aspects of Digital Twin implementation, including data collection frameworks, modelling approaches, integration with existing systems, and cybersecurity considerations. It provides a foundation for understanding the technical requirements and constraints that influence the development of business models.

- **Unit 3: Emerging Trends in Energy and Digital Technologies**

This unit examines current and emerging trends in the energy sector and digital technologies, with a focus on how these trends affect the development and adoption of Digital Twin solutions. It introduces key market drivers, regulatory developments, and technological innovations that create opportunities for Digital Twin applications.

- **Unit 4: Market Research and Customer Discovery**

This unit introduces primary market research methodologies and guides participants through the process, techniques, and tools that support learning more about potential customers and the problems they seek to solve. It emphasises the importance of evidence-based customer discovery in developing successful business models.

- **Unit 5: Stakeholders and Value Creation in Complex Ecosystems**

This unit explains the stakeholder perspective and methods for mapping and analysing stakeholder ecosystems in urban energy contexts. It provides frameworks for identifying stakeholder needs, concerns, and contributions, as well as approaches for ensuring that solutions create value for all involved parties.

- **Unit 6: Business Model Development and Value Capture**

This unit introduces the purpose and components of business models, providing a practical approach to building sustainable business models for Digital Twin solutions. It covers revenue mechanisms, resource requirements, partnership structures, and governance approaches that support ongoing operation and development.

Onsite workshops

The ExPEDite business model workshops will be conducted over one and a half days, during the next plenary meeting in Bilbao. During this workshop, the UCP team will guide participants through a structured process to develop viable business models for at least three key outcomes: the Mobile App, the Digital Twin, and the Living Lab. The workshops will consist of six sequential activities:

1. **Solution introduction**

This initial activity establishes a shared understanding among participants regarding the specific solution being addressed (Mobile App, Digital Twin, or Living Lab). Participants will discuss the solution's objectives, functionality, target users, and potential limitations or barriers to implementation, such as regulatory, engagement, or economic issues.

2. **Stakeholder intentions**

Participants will identify and analyse the various stakeholders involved in or affected by the solution's development and implementation. The activity defines the stakeholder ecosystem, aligns strategic intentions, and initiates discussions on commercialisation roles and responsibilities.

3. **Market size & segmentation**

This activity will focus on identifying the primary paying customer segment for the solution. Participants will analyse different market segments' problems, restrictions, and potential sizes to target the most attractive market segment for each solution (Mobile App, Digital Twin, or Living Lab).

4. **Solution description**

Participants will apply the solutions by summarising them across various dimensions, including the target customer, end-users, enabling technology, and involved stakeholders. This creates a clear articulation of how the solution addresses specific needs.

5. **Business model design**

Building on the previous activities, participants will structure the elements into a comprehensive business model. Using a specialised canvas (though the Energy Business Modelling Tool - EBMT), they will outline their customers, the partners needed, the resources they must provide, the key activities they must continuously perform for the solution to succeed, they will assess the cost structures and will come up with potential revenue streams.

6. **Business model presentations**

In the final activity, participants will briefly present their developed business models to receive feedback from other workshop participants. This collaborative review process focuses on sharing insights, gathering feedback, and enhancing understanding of potential improvement areas through common insights.

Follow-up and refinement

Following the workshops, the UCP will review all the activities done during the workshop. Feedback will be provided to partners to reflect on the results and refine the business models if needed. This stage is mainly focused on achieving coherence between business model elements and ensuring alignment with the overall project objectives. The refined business models will be documented and shared through the ExPEDite knowledge repository to support replication in other contexts.

Business Modelling Tool

To support this process, ExPEDite will utilise the Energy Business Modelling Tool (EBMT), which provides resources and functionalities specifically tailored for energy-related business model development. The tool includes:

1. **Business Model Database**: a library of business model patterns relevant to Digital Twin implementations in urban energy contexts, providing inspiration and reference points for business model development.
2. **Step-by-Step Guidance**: a structured process guiding users through the business model development journey, from initial ideation to detailed planning.
3. **AI Assistance**: intelligent agents that help users identify potential competitors, enhance sustainability aspects, and explore integration opportunities relevant to their specific implementation context.
4. **Internationalization Brain:** partners will be able to test the replicability of their business models in different country contexts.

Through this comprehensive approach to business model development, ExPEDite aims to ensure that at least the three key solutions developed in the project – Mobile App, Digital Twin, and Living Lab – can be effectively implemented and sustained in real-world contexts, creating lasting value for urban communities in their transition to climate neutrality.

5 Risk Analysis Approach

Defining, characterising, and implementing PEDs is essential for advancing urban decarbonisation and the energy transition. For example, in response to its inclusion in the EU's "100 Climate-Neutral and Smart Cities by 2030" initiative, Riga has committed to ambitious climate goals, formalised in the SECAP 2022–2030 and the Riga Climate City Contract. The city aims to reduce CO_2 emissions by 70% from 1990 levels and by 30% from 2019 levels, primarily through the transformation of its energy system. Currently, electricity production is led by natural gas cogeneration, with renewables like solar PV contributing minimally. Heating is largely centralised (56%) and reliant on natural gas, though efforts are underway to shift toward biomass and digitalised, low-temperature networks. Decentralised systems will phase out fossil fuels after 2025, further increasing the use of renewables. By 2030, Riga aims to increase its combined renewable energy production by over 1,000 GWh per year and reduce CO_2 emissions by ~181,000 tons. These developments underscore the need for a comprehensive risk assessment to guide the complex, multi-sectoral transition toward PEDs, as exemplified by the ExPEDite project.

5.1 Identification of Key Risks in PED Development

The implementation of PED faces a diverse array of risks and barriers across technical, governance, economic, environmental, and social domains. Drawing on a review of recent studies, this analysis synthesises the eight core risk categories that must be addressed to achieve successful PED implementation. Some prominent and potential challenges have been identified, and in the following paragraphs, a detailed breakdown of each of the eight key risk areas is provided, and finally summarised in Table 6:

Governance and Policy

PEDs often span multiple institutional boundaries—energy, urban planning, transport, housing—and therefore suffer from fragmented governance. This fragmentation leads to ambiguous responsibilities, a lack of harmonised definitions, and inconsistent regulatory support across EU member states. As Lindholm et al. (2021) emphasise, the absence of a shared PED definition complicates standardisation efforts across Europe. Yang et al. (2025) further emphasise the importance of clear institutional roles, particularly when energy systems must be coordinated at both local and regional levels. Additionally, Kozlowska et al. (2024) and Krangsås et al. (2021) highlight legal ambiguities in surplus energy management and the emergence of energy communities as regulatory grey areas.

A consistent challenge across all sources is the lack of standardised PED definitions, legal frameworks, and multi-level governance structures. Fragmented responsibilities between local, regional, and national authorities lead to inefficient policy alignment and hinder long-term planning. Furthermore, regulatory frameworks are often not adapted to district-level energy production and surplus trading, reducing institutional support for PED initiatives.

The realisation of a PED necessitates the integration of advanced energy infrastructures and dynamic interconnections among key components of the urban system (such as power generation units, mobility and energy networks, buildings, and storage systems). Additionally, the institutional design of energy communities, including clearly defined roles, regulatory

responsibilities, and legal frameworks, continues to evolve. Meanwhile, stakeholder engagement and commitment cannot be assumed and must be actively addressed.

Financial and Business Models

PEDs require significant upfront investments in renewable energy infrastructure, digital systems, and retrofitting, with lengthy payback periods and uncertain returns on investment (ROI). Conventional funding tools often fail to accommodate district-scale returns or non-monetary value creation. Derkenbaeva et al. (2022) argue that PEDs face "mainstreaming lock-ins," where innovative districts don't align with current financing flows. Sassenou et al. (2024) also warn that operating cost risks—particularly in managing thermal and electrical systems simultaneously—are often underestimated. Martinopoulos et al. (2024) reveal that investors rarely use district-level LCOE metrics, and Yang et al. (2025) add that uncertainty in market revenue from excess energy hinders long-term financial planning. PEDs require substantial upfront investment in infrastructure and technology, often exceeding the risk appetite of private investors. The identification of business models for PEDs that can accommodate mixed-use developments and flexible ownership structures is an open challenge. Financial risks are also compounded by insufficient access to blended funding mechanisms and uncertainty around return on investment, particularly when energy savings are shared among multiple stakeholders.

Beyond the inherent technical complexities of enabling real-time energy exchange and coordination, there are emerging challenges related to governance structures and business models that remain inadequately tackled. Critical issues such as the capital and operational costs of innovative energy management systems, the optimisation between thermal and electrical energy flows, demand response strategies like peak shaving, and the paradigm shift from delivering energy to ensuring user-centric outcomes like thermal comfort, all present unresolved questions.

Technological integration

A major technical hurdle lies in integrating multiple energy carriers (electricity, heating, cooling), storage systems, and digital platforms. Kozlowska et al. (2024) note that PEDs often lack robust interoperability between building systems, grids, and mobility services. Yang et al. (2025) emphasise that technology adoption must account for context-specific factors such as local climate and grid resilience. Sassenou et al. (2024) highlight mismatches in temporal energy availability and user demand, and Derkenbaeva et al. (2022) underline the lack of modular, scalable technology packages that can serve diverse urban typologies.

The technical complexity of PEDs goes beyond individual building retrofits. Intermittent renewable energy sources (solar, wind) challenge energy balancing, while smart grid and energy management systems (EMS) are not yet mature or universally deployable. The need to integrate mobility, storage, heating/cooling, and Information and Communication Technologies (ICT) systems further increase technical uncertainty and risk.

Given the diverse challenges associated with PED implementation (including site-related climatic conditions and varying energy demand requirements), a universal technological solution is neither feasible nor effective. Instead, PED design must adopt a context-sensitive approach that strategically integrates a broad array of available technologies to maximise annual renewable energy production. Equally important is the identification of cross-sectoral synergies among stakeholders and the proactive integration of PEDs with

existing urban energy infrastructures such as district heating networks, electrical grids, and gas distribution systems (to name the principal and most present ones). Recognising and managing the interconnections among these multi-energy networks is important for accurately quantifying the environmental and economic performance of smart districts. Such an integrated systems perspective will surely improve the overall value of PEDs.

Social acceptance and equity

While PEDs are technological and planning innovations, their social legitimacy is equally vital. Krangsås et al. (2021) stress the importance of co-creation to involve citizens, especially in early design stages. However, Derkenbaeva et al. (2022) warn that socio-technical lock-ins may exclude vulnerable groups from participation and benefits. Kozlowska et al. (2024) report low engagement from key stakeholders such as real estate developers and residents, and Lindholm et al. (2021) advocate for strong participatory mechanisms to avoid "technocratic energy transitions" that ignore social equity. These findings reveal that without equitable participation and distribution of benefits, PEDs may reproduce or deepen existing social inequalities.

Stakeholder engagement is widely acknowledged as a critical challenge (and obstacle) to the successful planning and implementation of PEDs initiatives. This complexity stems from the diverse range of actors involved, including local authorities responsible for urban planning and governance, energy service providers, real estate developers, local businesses, and residents (regular citizens). These stakeholders often have limited preliminary collaboration, and their divergent interests and levels of influence can further complicate coordination efforts.

As the structural and operational complexity of PEDs increases, effective stakeholder management becomes increasingly essential. A comprehensive understanding and mapping of the stakeholder landscape, along with strategies for its systematic and inclusive management, can significantly enhance the odds of project success. In this context, the concept of co-creation has gained relevance. This bottom-up approach, which actively involves all relevant stakeholders, offers a promising pathway for fostering ownership, trust, and context-specific solutions in the development of PEDs.

Spatial and contextual constraints

PED feasibility is highly location sensitive. Historic centres, low-density suburbs, and regions with poor solar irradiance may struggle to meet energy positivity targets. Derkenbaeva et al. (2022) caution that PED solutions often assume optimal conditions, which limits their replicability. Yang et al. (2025) underscore the lack of adaptive planning tools that can align technological solutions with urban morphology and socio-spatial dynamics. Kozlowska et al. (2024) reinforce this view by identifying urban density and orientation as key predictors of PED performance. Martinopoulos et al. (2024) further show that heat demand variability in colder climates is a persistent design barrier.

Modelling and assessment gaps

In recent years, a growing body of literature has addressed energy modelling, analysis, and performance optimisation at the district level. Nevertheless, significant challenges persist in accurately representing the innovative and heterogeneous elements characteristic of PEDs. These challenges adversely impact model reliability and hamper the ability to perform

meaningful comparisons across studies. PEDs require dynamic, multi-scale models to evaluate interactions across buildings, energy systems, mobility, and users. Yet current modelling tools remain fragmented. Kozlowska et al. (2024) demonstrate that input variability (e.g., occupancy patterns, weather data) yields inconsistent results. Sassenou et al. (2024) identify the absence of unified district modelling frameworks as a significant barrier to comparative benchmarking. Martinopoulos et al. (2024) emphasise the computational burden of modelling energy flows at the district level, especially when integrating real-time data. Yang et al. (2025) argue that without robust data governance, these models fail to inform actionable planning decisions for PED.

Unlike models developed for individual buildings, district-scale simulations must account for multiple interactions and a broader range of inputs, often resulting in reduced predictive accuracy. This reduction is mainly due to the increased difficulty in modelling dynamic variables such as occupant behaviour, microclimatic variations, and the aggregated complexity of diverse building typologies. Additional uncertainties arise from various sources, including input and meteorological data quality, geometrical representations, energy system configurations, mobility integration, user interactions, and the consistency of modelling processes.

The absence of standardised frameworks for incorporating these diverse elements often leads to inconsistencies and limits the comparability of results. Moreover, managing the extensive data sets generated at the district level necessitates the development of robust data management strategies, far exceeding the requirements typical of a single-building analysis model.

Environmental impact and KPI standardisation

Although energy positivity is the primary goal, PEDs often neglect broader environmental performance indicators. Lindholm et al. (2021) critique the narrow focus on energy balance, which may obscure impacts on biodiversity, land use, or lifecycle emissions. Yang et al. (2025) point to the absence of harmonised KPI frameworks for PED evaluation. Derkenbaeva et al. (2022) emphasise the difficulty in assessing long-term climate resilience or seasonal variations. Kozlowska et al. (2024) add that system boundaries for emissions accounting are inconsistently defined across projects. A unified and transparent metric set is necessary to effectively track and compare environmental outcomes.

A narrow focus on achieving net-positive energy balance may neglect broader sustainability goals such as biodiversity, ecosystem impact, or resource use. Seasonal mismatches between energy supply and demand also undermine real-world performance. PEDs need to be assessed not just for energy, but for their resilience to climate extremes and systems-level impacts.

Environmental impact assessment at the district scale represents a fundamental requirement for advancing urban sustainability. Contemporary studies have employed a range of methodologies to evaluate environmental performance at this level, differing significantly in the definition of system boundaries and the selection of environmental KPIs. Nevertheless, the lack of a harmonised, methodologically thorough, and reproducible framework for assessing the environmental impacts of PEDs - applicable to a variety of assessment scopes and indicator sets - remains a critical gap in the current research and practice.

Systems design and integration complexity

PEDs are inherently systemic. Effective implementation requires the concurrent alignment of energy, spatial, social, and economic subsystems. Kozlowska et al. (2024) argue that current design approaches are too siloed, failing to account for trade-offs across domains. Sassenou et al. (2024) show that fragmented planning leads to suboptimal performance or costly redesigns. Derkenbaeva et al. (2022) recommend early integration of life-cycle thinking and cross-sectoral planning. Yang et al. (2025) advocate for flexible, adaptive PED design tools that respond to future uncertainties and multiple stakeholder priorities.

Designing an effective and sustainable PED requires a comprehensive, systems-oriented approach that integrates technological, environmental, and socio-economic dimensions. Currently existing assessment frameworks for PEDs typically rely on discrete sets of economic, energy, and environmental indicators, often analysed in isolation without capturing their interconnections.

However, to meet PED objectives within a context characterised by overlapping and interrelated domains, it is essential to adopt an integrated evaluation strategy that also accounts for social dynamics, life cycle impacts, and active stakeholder participation (social inclusiveness in short). This multidimensional complexity necessitates a holistic design paradigm capable of addressing a spectrum of (often) competing objectives. Such an approach should be embedded from the earliest stages of the planning and design process to ensure coherence and adaptability, thereby avoiding costly or painful redesigns in later phases. A forward-looking, integrative methodology is therefore critical to navigating the interconnected challenges and trade-offs inherent in PED development.

***Table 6**. Summary of risk areas*

#	Risk Areas	Key Issues / Risks
1	*Governance & Policy*	Lack of unified PED definitions and legal standards; policy fragmentation between city and national levels
2	*Financial & Business Models*	High upfront capital costs; absence of viable district-level business models; poor access to funding instruments
3	*Technological Integration*	Intermittency of renewables; immature smart grid/EMS technologies; complexity in retrofitting existing urban fabric
4	*Social Acceptance & Equity*	Low citizen engagement or awareness; risk of energy injustice; inequitable access to PED benefits
5	*Spatial & Contextual Constraints*	Geographic variability in resource potential; urban morphology challenges; lack of site-adaptive planning tools
6	*Modelling & Assessment Gaps*	Lack of harmonized PED assessment metrics; inconsistent integration of diverse inputs and outputs in models
7	*Environmental & Systemic Risks*	Mismatch of energy production and consumption; climate adaptation and resilience risks; biodiversity impacts
8	*Environmental Impact & KPI Standardization*	Lack of standardized environmental KPIs and life-cycle metrics; fragmented methodologies for performance tracking
9	*Systems Design & Integration Complexity*	Need for holistic PED design integrating environment, economy, social inclusion, and technology from inception

6 Conclusion and Next Steps

The evaluation and implementation of PEDs have underscored the importance of multidimensional strategies that integrate technological, environmental, and socio-economic factors. Stakeholder engagement remains a cornerstone for success, necessitating co-creative approaches that build trust and foster collaboration across diverse actors. Similarly, the adoption of integrated systems for design and sustainability proves critical for addressing overlapping objectives and ensuring adaptability throughout PED development.

Looking ahead, efforts must concentrate on refining practical frameworks that align PED objectives with real-world conditions. This includes advancing methodologies for quantifying cross-sector interactions, optimising renewable energy integration, and enhancing stakeholder mapping techniques. At the same time, leveraging existing urban infrastructures will be pivotal in maximising environmental and economic benefits while mitigating technological challenges.

CBA may contribute towards the objective of aligning aspirations and context by supporting the policymakers' decision-making process. By itself, the CBA is already a tool to support decision-making, albeit imperfect, and often considered insufficient in isolation. It could be advisable to integrate CBA and other decision support tools. Given the limitations of the CBA methodology (e.g., the lack of redistribution considerations), CBA and other tools and analyses have the potential to complement each other, despite the absence of a clear rule for weighting information from disparate sources.

Future deliverables, particularly Deliverable 4.4, aim to delve deeper into these aspects, providing actionable insights and robust guidelines for implementing PED. By consolidating interdisciplinary expertise, these next steps will strengthen decision-making processes and contribute to the scalability of the PED initiative, reflecting on the best way to implement the DT within the analyses and decision-making process.

References

Ackerman, F., & Heinzerling, L. (2002). Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection. *University of Pennsylvania Law Review*, *150*(5), 1553. https://doi.org/10.2307/3312947

Albert-Seifried, V., Murauskaite, L., Massa, G., Aelenei, L., Baer, D., Krangsås, S. G., Alpagut, B., Mutule, A., Pokorny, N., & Vandevyvere, H. (2022). Definitions of Positive Energy Districts: A Review of the Status Quo and Challenges. In J. R. Littlewood, R. J. Howlett, & L. C. Jain (Eds.), *Sustainability in Energy and Buildings 2021* (Vol. 263, pp. 493–506). Springer Nature Singapore. https://doi.org/10.1007/978-981-16-6269-0_41

Bickel, P., Friedrich, R., Burgess, A., Fagiani, P., Hunt, A., Jong, G. D., Laird, J., Lieb, C., Lindberg, G., Mackie, P., Navrud, S., Odgaard, T., Ricci, A., Shires, J., & Tavasszy, L. (2006). *HEATCO developing harmonized European approaches for transport costing and project assessment—Deliverable d5: Proposal for harmonized guidelines.* 1–149.

Binda, T., Bottero, M., & Bisello, A. (2022). Evaluating Positive Energy Districts: A Literature Review. In F. Calabrò, L. Della Spina, & M. J. Piñeira Mantiñán (Eds.), *New Metropolitan Perspectives* (Vol. 482, pp. 1762–1770). Springer International Publishing. https://doi.org/10.1007/978-3-031-06825-6_170

Bisello, A., Grilli, G., Balest, J., Stellin, G., & Ciolli, M. (2017). Co-benefits of Smart and Sustainable Energy District Projects: An Overview of Economic Assessment Methodologies. In A. Bisello, D. Vettorato, R. Stephens, & P. Elisei (Eds.), *Smart and Sustainable Planning for Cities and Regions* (pp. 127–164). Springer International Publishing. https://doi.org/10.1007/978-3-319-44899-2_9

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2018). *Cost-Benefit Analysis: Concepts and Practice* (5th ed.). Cambridge University Press. https://doi.org/10.1017/9781108235594

Brozovsky, J., Gustavsen, A., & Gaitani, N. (2021). Zero emission neighbourhoods and positive energy districts – A state-of-the-art review. *Sustainable Cities and Society*, *72*, 103013. https://doi.org/10.1016/j.scs.2021.103013

Bureau of Labor Statistics. (2023, February 1). *Retirement plans for workers in private industry and state and local government in 2022*. Bureau of Labor Statistics. https://www.bls.gov/opub/ted/2023/retirement-plans-for-workers-in-private-industry-and-state-and-local-government-in-2022.htm

Campbell, H. F., & Brown, R. P. C. (2003). *Benefit-Cost Analysis: Financial and Economic Appraisal using Spreadsheets*. Cambridge University Press.

Casamassima, L., Bottecchia, L., Bruck, A., Kranzl, L., & Haas, R. (2022). Economic, social, and environmental aspects of Positive Energy Districts—A review. *WIREs Energy and Environment*, *11*(6), e452. https://doi.org/10.1002/wene.452

Chanel, O., & Luchini, S. (2008). *Monetary Values for Air Pollution Risk of Death: A Contingent Valuation Survey*. 1–28.

Derkenbaeva, E., Halleck Vega, S., Hofstede, G. J., & Van Leeuwen, E. (2022). Positive energy districts: Mainstreaming energy transition in urban areas. *Renewable and Sustainable Energy Reviews*, *153*, 111782. https://doi.org/10.1016/j.rser.2021.111782

Frank, R. H. (2000). Why Is Cost-Benefit Analysis so Controversial? *The Journal of Legal Studies*, *29*(S2), 913–930. https://doi.org/10.1086/468099

Friedrich RF, Rabi A, Hirschberg S, Desaigues B, Markandya A, & Nocker La. (2004). *New Elements for the Assessment of External Costs from Energy Technologies Final report to the European Commission.* (pp. 1–333). Institute for Energy Economics and the Rational Use of Energy.

Gephart, L., Lewis, J., Roberts, P., Salter, E., & White, L. (2006). Analysis of the CAFE cost benefit analysis. *Air Pollution*, *4*. https://www.concawe.eu/wp-content/uploads/rpt064-2006-01564-01-e.pdf

Kozlowska, A., Guarino, F., Volpe, R., Bisello, A., Gabaldòn, A., Rezaei, A., Albert-Seifried, V., Alpagut, B., Vandevyvere, H., Reda, F., Tumminia, G., Ranjbar, S., Rincione, R., Cellura, S., Eicker, U., Zamini, S., Balsategui, S. D. D. G., Haase, M., & Di Pilla, L. (2024). Positive Energy Districts: Fundamentals, Assessment Methodologies, Modeling and Research Gaps. *Energies*, *17*(17), 4425. https://doi.org/10.3390/en17174425

Krangsås, S. G., Steemers, K., Konstantinou, T., Soutullo, S., Liu, M., Giancola, E., Prebreza, B., Ashrafian, T., Murauskaitė, L., & Maas, N. (2021). Positive Energy Districts: Identifying Challenges and Interdependencies. *Sustainability*, *13*(19), Article 19. https://doi.org/10.3390/su131910551

Lindholm, O., Rehman, H. U., & Reda, F. (2021). Positioning Positive Energy Districts in European Cities. *Buildings*, *11*(1), 19. https://doi.org/10.3390/buildings11010019

Martinopoulos, G., Tsimpoukis, A., Sougkakis, V., Dallas, P., Angelakoglou, K., Giourka, P., & Nikolopoulos, N. (2024). A Comprehensive Approach to Nearly Zero Energy Buildings and Districts: Analysis of a Region Undergoing Energy Transition. *Energies*,

17(22), Article 22. https://doi.org/10.3390/en17225581

Pan, Y., Jiang, L., & Wang, H. (2024). Cost–Benefit Analysis of the China's Household Coal-to-Electricity Transition: A Case Study on the Beijing Mentougou Area. *Energies*, *17*(23), Article 23. https://doi.org/10.3390/en17235933

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., Henschel, S., Meister, K., Haluza, D., Martin-Olmedo, P., & Medina, S. (2013). Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project. *Science of The Total Environment*, *449*, 390–400. https://doi.org/10.1016/j.scitotenv.2013.01.077

Sassenou, L.-N., Olivieri, L., & Olivieri, F. (2024). Challenges for positive energy districts deployment: A systematic review. *Renewable and Sustainable Energy Reviews*, *191*, 114152. https://doi.org/10.1016/j.rser.2023.114152

Squire, L., Tak, H. G. van der, & Bank, W. (1975). *Economic Analysis of Projects*. World Bank Publications.

Viscusi, K. (2013). Using data from the Census of Fatal Occupational Injuries to estimate the "value of a statistical life". *Monthly Labor Review*. https://doi.org/10.21916/mlr.2013.35

Yang, K., Zou, R., Zhang, W., Zeng, X., Li, Z., & Guo, J. (2025). Comprehensive review of Positive Energy Districts: Multidimensional analysis of energy, economic, social, and environmental aspects. *Renewable and Sustainable Energy Reviews*, *217*, 115740. https://doi.org/10.1016/j.rser.2025.115740