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Integrated Methodology for Community-Oriented Energy Investments: Architecture, Implementation, and Assessment for the Case of Nisyros Island

Charalampos Papadopoulos [1,*], Athanasios Bachoumis [2,3], Niki Skopetou [1], Costas Mylonas [2], Nikolaos Tagkoulis [1], Petros Iliadis [1], Ioannis Mamounakis [1] and Nikolaos Nikolopoulos [1]

1 Centre for Research and Technology Hellas/Chemical Process and Energy Resources Institute (CERTH/CPERI), Egialeias 52, 15125 Marousi, Greece; n.skopetou@certh.gr (N.S.); n.tagkoulis@certh.gr (N.T.); iliadis@certh.gr (P.I.); mamounakis@certh.gr (I.M.); n.nikolopoulos@certh.gr (N.N.)
2 Ubitech Energy, Koningin Astridlaan 59b, 1780 Wemmel, Belgium; abachoumis@ubitech.eu (A.B.); kmylonas@ubitech.eu (C.M.)
3 Department of Electrical and Computer Engineering, Rio Campus, University of Patras, 26504 Patras, Greece
* Correspondence: ch.papadopoulos@certh.gr

Abstract: This paper presents an integrated methodology for decision making in smart grid investments that assesses the investment plans of stakeholders in local energy communities (LECs). Considering the energy flow exchanges of the LECs and interpreting them in terms of technical benefits and costs, this methodology indicates the most sustainable and profitable solution covering the LEC energy transition plans. A set of specialized tools capturing the energy, environmental, financial, and social impacts are integrated under a common platform called the IANOS Energy Planning and Transition (IEPT) suite. The tools evaluate a set of well-defined key performance indicators that are gathered using a cost–benefit analysis (CBA) module offering multilateral assessment. By upgrading the functionalities of specialized tools, i.e., the energy modeler INTEMA, the life cycle assessment and costing tool VERIFY, and the smart grid-oriented CBA tool, the IEPT suite evaluates the viability of different smart grid investment scenarios from a multi-dimensional perspective at the LEC level. The functionalities of the proposed suite are validated in the LEC of Nisyros island, Greece, where three smart grid-based investment scenarios of different self-consumption levels are evaluated and ranked in terms of benefits and profitability. The results highlight that for a 20-year horizon of analysis, the investment scenario where a 50% self-consumption target is achieved was more financially viable compared to the 80% and 95% scenarios, achieving values of BCR and NPV equal to EUR 2.12 and EUR 4,400,000, respectively.

Keywords: cost–benefit analysis; investment planning suite; smart grids; sustainable transition; local energy communities

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1. Introduction

Local energy communities (LECs) are entities which are constantly evolving, and can facilitate the transition towards a sustainable energy system [1]. LEC prosumers differ from other prosumers in that they are part of a collective community that actively participates in the production and consumption of energy at the local level. More specifically, they are characterized by a community-based approach which fosters collaboration on all levels between prosumers, with a strong orientation toward local RES generation. Through peer-to-peer [2] energy trading platforms or local energy markets, prosumers can sell their excess energy to other community members or purchase energy when needed. This allows for the efficient utilization of renewable energy resources and helps to balance supply and demand at the local level. To accommodate the much-needed energy transition of each LEC, targeted actions are required, evaluated from multiple perspectives that often contradict each other. However, major opportunities for environmental, economic, and social development can be created depending on the geographical characteristics, the available energy production sources, and the penetration level of innovative energy solutions.

Smart grid (SG) interventions usually involve high budgeting solutions with a significant impact on district areas, from local communities to the island and city levels. By employing SG interventions, the EU and world community strive to guide LECs on sustainable paths [3], by indicating valuable solutions and providing energy performance insights within a 25/35/45-year horizon. The integration of SG technologies has a significant impact on all three sectors regarding the electric power system (i.e., generation, transmission, and distribution). In addition, the two main stakeholders of the electricity market (namely producers and consumers) are also affected [4,5]. The level of impact is a variable of the technology type integrated into the system and the level of its integration, thus resulting in different costs and benefits for each stakeholder.

One of the most widely used tools regarding project or plan assessment is cost–benefit analysis (CBA), an economic tool for identifying, measuring, and comparing the costs and benefits of a scenario, project, investment, or program [6,7]. The application of CBA in a project requires large amounts of data, often unavailable, and therefore, most studies focus only on technology, application, or solution evaluation. CBA is a tool that aims to find out whether the benefits of a project outweigh the costs from a technical, economic, and societal perspective, thus surpassing other financial analysis tools which mostly focus only on returns to investors.

Numerous methodologies have been adopted to assess the costs and benefits of SG technologies. A comprehensive analysis of the various methods used so far to examine the economic effects and benefits is provided in [8]. Some studies focus on the computational general equilibrium (CGE) and the level of investment allocated for SG technologies [9–11], while others explore the scalability, transferability, and replicability of SG projects [12–14]. In [15], the authors use CBA to assess the efficiency of system management and planning tools for a power grid, whereas [16] employs CBA to scrutinize the effects of grid-scale electric energy storage, corroborating the findings through simulation. Similarly, [17] utilizes CBA for a virtual power plant encompassing solar photovoltaics (PV), with flow battery, heat pump, and demand management, affirming the results through simulation-based validations. The authors in [18] present an analysis by the U.S. Department of Energy estimating energy conservation gains and carbon impact reduction stemming from SG technologies. The authors in [19] conduct CBA for the implementation of a distribution management system in distribution networks as an SG solution. The authors of [15] propose a method to calculate costs and benefits related to SG reliability investments for transmission and distribution planning by evaluating reliability indices pre- and post-SG technology deployment. However, this method is exclusively centered on the financial gains produced by reliability enhancement. Others recommend the use of agent-based simulation as a replacement for equilibrium models. This agent-based simulation was subsequently translated into benefits evaluation [10,20]. Further research evaluated the costs and benefits of utilities, although from a perspective heavily centered on utility considerations [21–23]. For example, [23] undertook a regulatory impact analysis of smart meters' implementation in Brazil, specifically for low-voltage consumers. This study examined various regulatory scenarios, evaluated their respective costs and benefits, and provided preliminary conclusions laying the groundwork for a more comprehensive assessment of smart meter regulation in Brazil.

At the LEC level, the literature presents a body of research focusing on the CBA of various aspects, from solar roof energy communities and innovative energy islands to the viability and impacts of such communities. In [24], the authors propose a novel approach, using photovoltaic–green roof energy communities to uphold the European Green Deal. They carry out a probabilistic CBA to discern economically convenient scenarios. Their findings suggest that integrating green roofs with PV systems could provide substantial economic and environmental benefits. The authors of [25] contribute to the discourse by offering a life cycle CBA for battery energy storage in innovative energy islands. Their research indicates that battery energy storage systems can be a cost-effective and environmentally beneficial solution for isolated energy communities. However, they also caution that the results depend heavily on the specific characteristics of each island, including its energy demand profile and existing infrastructure. A comprehensive review of social arrangements, technical designs, and the impacts of energy communities was performed in [26]. The authors underscore the importance of aligning technical design with social arrangements to ensure the successful implementation of LECs. Importantly, this review reveals that social acceptance and active participation from community members are essential for maximizing the benefits of these communities.

Our literature survey showcases the various attempts at CBA employment in SG investments. Most of the encountered studies follow a project-based methodology, even though a software-based case-agnostic approach would enable replicability and scalability, thus unleashing the potential for techno-economical assessment of SG interventions in multi-energy systems. Furthermore, the current review renders apparent not only the scarcity of studies incorporating multi-domain performance indicators (i.e., energy, environmental, and cost), but also the simplicity of their evaluation methodology, diminishing the overall assessment reliability and emphasizing the need for a holistic LEC-oriented CBA approach.

Recognizing these deficits and understanding the increasing need for versatile studies that consider both technical and social aspects, this work presents an integrated methodology for SG interventions. The proposed methodology is implemented into a web platform, hereafter called the IANOS Energy Planning and Transition (IEPT) suite. Implementation details and valuable insights are discussed. The methodology application is demonstrated for the case of Nisyros island in Greece.

2. Materials and Methods

As discussed in the Introduction, the present work follows a custom methodology that incorporates specialized software for the evaluation of technoeconomic indicators. The overall aim is to obtain valid, quantified estimations for the sustainability and profitability of the interventions under consideration, enabling the multi-perspective benefit assessment required for clean energy and SG interventions. Figure 1 presents a schematic interpretation of this approach.

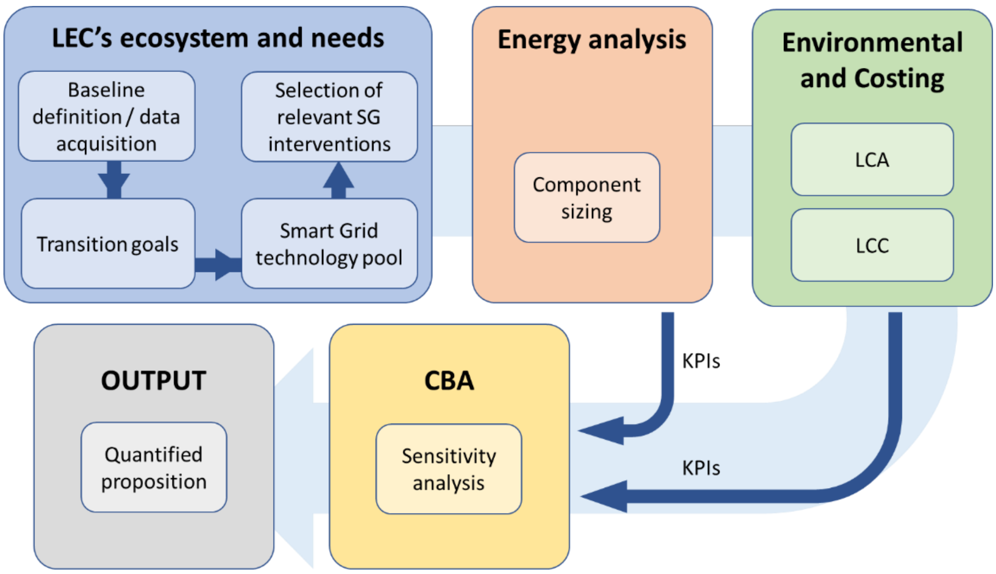


Figure 1. Smart grid interventions assessment methodology.

The first step of the methodology regards the definition of the ecosystem and the needs of the LEC. This step includes a thorough investigation of the local energy system, social aspects and the proper definition of the specific transition goals. From this process, an array of SG technologies solutions emerge, which are prime candidates for implementation in the particular environment. Additional filtering based on preliminary techno-economic indicators is applied in this pool, resulting in the final list of SG solutions being assessed. The second step involves the technical/energetic evaluation of the selected interventions. Here, depending on the specific objective, different kinds of studies can be conducted. Typically, a sizing process is required to calculate the adequate generation capacities while also taking into account economic aspects. Additional studies that may be required include power flow calculation, optimization problems, as well as transient analyses. Following the energetic evaluation, the results are propagated to the environmental and costing module. There, important metrics are evaluated regarding pollution and the economic sustainability of the overall project. The outputs from all aforementioned modules are gathered in the last step of the methodology, the CBA module. Here, the overall study scenarios are scholastically compared with each other, with the use of the calculated key performance indicators (KPIs). Finally, the result of this process is a quantified set of guidelines regarding the selected interventions.

2.1. Energy Analysis

For the energy analysis, an investment optimization problem is formulated to determine the optimal power generation schedule and capacity of the considered SG solutions (i.e., photovoltaics, wind turbines, battery storage system). This problem is well known in the literature as a multi-period optimal power flow problem. The objective function to be minimized represents the total system cost and consists of the partial costs of each asset that can supply power to the grid, i.e., generators or storage units. Each of these costs includes capital (CAPEX) and operating expenditure (OPEX) and is divided into fixed and variable costs. The standard version of the optimal power flow problem takes the following form:

$$\min_{x} f(x) \tag{1}$$

$$g(x) = 0 \tag{2}$$

$$x_{min} \leq x \leq x_{max} \tag{3}$$

where f(x) is the objective function, g(x) equality constraints represent the power balance equations, and x_{min} and x_{max} are the corresponding bounds, i.e., the generator injection limits.

To evaluate the examined scenarios over the entire investment period, the annualized capital cost of each asset is utilized in the objective function. Furthermore, to account for the stochastic nature and the variability of solar and wind power generation, the renewables.ninja (https://www.renewables.ninja/ accessed on 3 July 2023) tool is used to extract normalized power generation time-series. As a result, oversizing of the RES capacities is prevented. Once the optimization problem is addressed and the sizing of the technologies is complete, power flow simulations can be conducted. Indicative energy-related KPIs are presented in Table 1. Furthermore, the resulting generation time-series serve as the input for the ensuing environmental and costing analysis.

2.2. Environmental and Costing Analysis

In typical life cycle analysis (LCA) and life cycle costing (LCC) methodologies, products or services are evaluated independently from any possible direct or indirect interactions in their greater ecosystem. In this work, the proposed integrated LCA and LCC calculation methodology is based on a holistic life cycle approach [27] considering both the existing energy grid infrastructure and planned energy grid transition, under specific interventions at the LEC level. Following the definition of the current and planned energy scenario configurations, the LCA and LCC methodology can be initiated. This methodology includes not only the life cycle performance of assets involved in the LEC, but also the cost-effectiveness of the proposed solutions to assess intervention strategies in a combined environmental and cost level.

Table 1. Indicative energy-related KPIs.

KPIs	Description
Increased self-consumption Reduced peak load	Energy demands covered by local generation increase
Increased self-consumption Reduced peak load	Peak to mean ratio (PMR) load reduction
Decrease frequency fluctuation	Integral of difference between power generation and load time-series reduction

In order to better define and organize the analysis, the interventions are categorized into convenient sectors, based on their specific peculiarities. Considering the national long-term strategies provided by the European Commission in [28] and the needs of LECs, five sectors are selected for the LCA and LCC analysis. This classification, comprising the building, transport, energy production, energy storage and public infrastructure sectors, is deemed suitable enough to capture the multilevel energy progress towards local and national goals.

The proposed methodology is based on ISO 14040 and 14044 for the LCA and ISO 15686-5 for the LCC, ensuring the credibility and accuracy of the analysis. A set of environmental and costing KPIs are calculated by capitalizing on country specificities, meteorological data, material data, and specific user preferences divided into multiple sectors. KPIs include aspects related to primary energy (PE) and primary energy savings (PES), CO_2 emissions and savings (expressed in kg or ton $CO_{2\text{-eq}}$), self-consumption, life cycle costs, payback time, etc. The calculations are backed up by a versatile input database, containing accurate real-life measurements for variables such as temperature, emissions, electricity consumption, etc. In cases when dynamic real-life data cannot be provided, historical, literature-driven or synthetic (simulated) data can be used. Table 2 presents the most important costing and environmental KPIs, together with their respective calculation formulas.

2.3. Cost–Benefit Analysis

The proposed CBA methodology, presented in Figure 2, is based on both JRC's and ENTSO-E's methodologies [29,30]. These are comprehensive frameworks, built to assess the costs and benefits of SG interventions inserted into the electricity infrastructure from the system planning perceptive.

The proposed 7-step methodology utilizes KPI values to measure the underlying SG solutions' planning, efficiency, environmental, economic, and reliability benefits. All these benefits are converted into monetary gains by computing the net present value (NPV) for each benefit. The NPV depicts the monetary amount of the change in the value of the energy infrastructure due to selecting and applying one or more SG interventions, according to the business objectives set by the involved stakeholders.

Table 2. Five costing and four environmental KPIs utilized in the LCA and LCC analysis.

KPIs	General Formula
Lifecycle fuel costs (kEUR)	$NPV\left(\sum_{Generators}(Annual\ fuel\ consumption\ [\mathrm{kWh}])_{Generator} * \frac{Fuel\ price\ \left[\frac{EUR}{\mathrm{kWh}}\right]}{1000}\right)$
Lifecycle income (kEUR)	$NPV\left(\sum_{Generators}(Annual\ energy\ production\ [\mathrm{kWh}])_{Generator} * \frac{Electricity\ price\ \left[\frac{EUR}{\mathrm{kWh}}\right]}{1000}\right)$
Lifecycle O&M costs (kEUR)	$NPV\left(\sum_{Generators}\frac{(\mathrm{O\&M}\ costs\ [OPEX\ in\ EUR\ ])_{Generator}}{1000}\right)$
Lifetime capital costs (kEUR)	$\sum_{Generators}\left(CAPEX\left[\frac{EUR}{\mathrm{kW}}\right] * Capacity[\mathrm{kW}]\right)_{Generator}/1000$
Lifecycle cost of (produced) energy (EUR/kWh)	$\sum_{Years}\frac{Lifetime\ capital\ Costs + Lifecycle\ Fuel\ Costs + Lifecycle\ \mathrm{O\&M}\ costs}{\sum_{Generators}(Annual\ energy\ production)_{Generator}}$
Lifetime primary energy (MWh)	$\sum_{Years}\sum_{Generators}(Annual\ fuel\ consumption\ [\mathrm{kWh}])_{Generator} * PEF +$ $(Embodied\ PE * Capacity)/1000$ where, • PEF is the primary energy factor of each type of fuel • Embodied PE is the embodied energy of the component in kWh/kW Capacity is the nominal power of the generator in kW
Lifetime CO_2 emissions (tons CO_2)	$\sum_{Years}\sum_{Generators}(Annual\ fuel\ consumption\ [\mathrm{MWh}])_{Generator} * EF\left[\frac{kgCO2}{\mathrm{kWh}}\right] +$ $(Embodied\ CO2\ emissions * Capacity\ [\mathrm{kW}])$
Annual renewable generation (GWh)	$\sum_{Generators}(Annual\ renewable\ energy\ production)_{Generator}$
Annual conventional generation (GWh)	$\sum_{Generators}(Annual\ conventional\ energy\ production)_{Generator}$

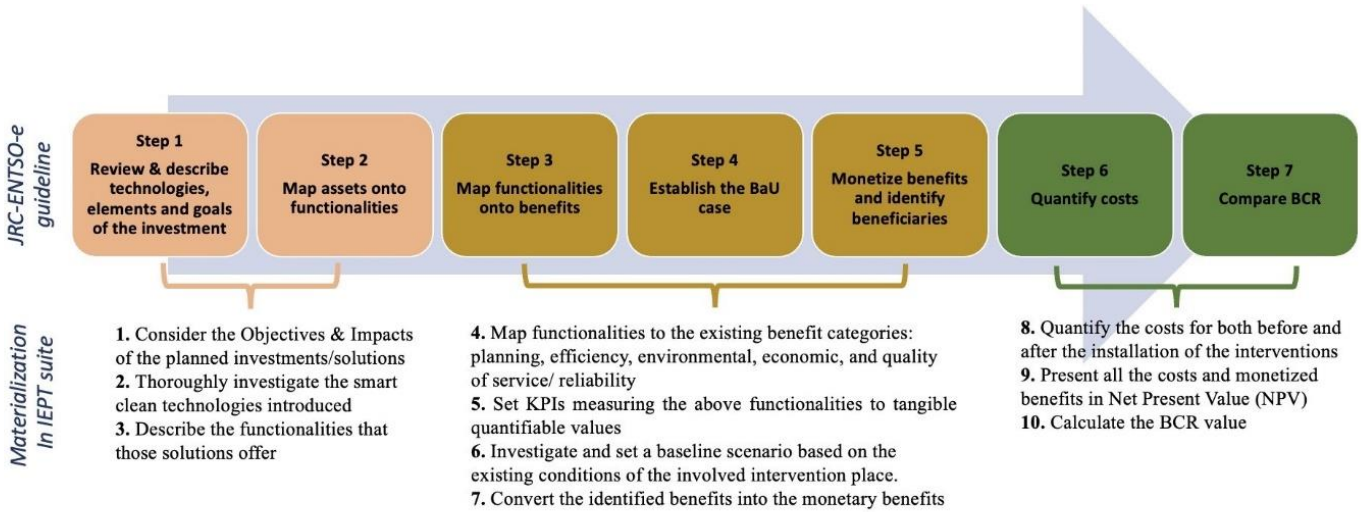


Figure 2. Methodology followed for the assessment of the investment viability.

Firstly, the Discounted Cash Flow (DCF) model is introduced. It is used to calculate the present value of future cash flows, as a result of the SG interventions for each year of the timeframe under study. The DCF model is a simple evaluation model referring to an asset that is expected to generate income in the form of cash earnings, interest, principal payment, or dividends. The DCF model can be expressed as:

$$V_o = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_n}{(1+r)^n} \quad (4)$$

where V_o is the present value of the anticipated income from the asset, $CF_{1,2,\ldots n}$ represent the income expected to be received up to n periods in the future, and r is the discount rate, which is the required rate of return per period. After each year's computation of the DCF, the NPV for each benefit is computed. An NPV > 0 showcases that the infrastructure will benefit if the new interventions are adopted. On the other hand, an NPV < 0 means that the infrastructure's value will decrease if the new interventions are implemented. The specific formula for the NPV calculation is:

$$\mathrm{NPV} = \frac{\mathrm{CF_1}}{(1+\mathrm{r})^1} + \frac{\mathrm{CF_2}}{(1+\mathrm{r})^2} + \cdots + \frac{\mathrm{CF_n}}{(1+\mathrm{r})^\mathrm{n}} - \mathrm{InInv} \quad (5)$$

where InInv is the initial investment, and the discount rate r is the internal rate of return (IRR) that determines the present value of future cash flow. A low interest rate indicates promoting the trend of development created by central banks. A high interest rate shows riskier trends. The selection of a time horizon is vital and has to be defined within each intervention's benefits and costs. The time horizon depends on the asset type of each installation, the investment scheme, and the benefits for the overall electricity infrastructure (and in the general energy infrastructure if benefits can be found in the rest of the energy carriers). To conduct the assessment between the existing business-as-usual (BaU) condition and the benefits that the planned investment provides for the buildings, communities, regions, and islands in total, the following indicator is introduced:

$$\mathrm{Benefit} - \mathrm{cost} - \mathrm{ratio(BCR)} = \frac{\mathrm{NPV(Benefits)}}{\mathrm{NPV(Costs)}} \quad (6)$$

where Benefits represents the monetized quantifiable benefits of the smart green interventions. The BCR value is the ultimate indicator of whether the SG investment is viable. Values of BCR < 1 imply that it is not worth it to continue the investment (while also increasing scalability if BCR < 1). On the other hand, if BCR = 1, it is risky to continue the investment (implying a relatively low IRR), and finally, if BCR > 1 the investment is viable with a strong potential for scalability. In cases where a benefit/residual cannot be directly converted into monetary gains (e.g., social acceptance of an SG solution), a scaler is introduced to provide an additional tool to the decision-makers by showcasing the improvements/positive impact that a specific SG intervention could make.

3. Implementation

The described methodology is implemented in the context of the IANOS project [31] into a web-based software application entitled IEPT suite. To achieve the set requirements, three distinct software modules are integrated under the wider IEPT umbrella platform, namely INTEMA, VERIFY, and ECCOBEA, for the energetic, environmental and cost–benefit analyses, respectively. In this section, the suite architecture and its intrinsic components are thoroughly presented.

3.1. Architecture

A system design approach is employed to conceptualize IEPT's architecture, depicting the fundamental characteristics, while demonstrating the means to fulfill individual requirements. The methodology adopted for the design of the suite is based on the decentralized approach of the "Viewpoints and Perspectives" framework and the ISO/IEC/IEEE 42010:2011 [32,33]. According to this framework, an architecture description may be organized in different perspectives using viewpoints, thus providing a mechanism for the separation of concerns among the stakeholders (viewpoints), while at the same time providing the description of the whole system that is fundamental to the notion of architecture (framework). The "Overview-Context" and "Functional" viewpoints are selected to present the suite architecture in the present work.

The "Overview-Context" viewpoint seeks to provide a high-level view of the IEPT suite and present its scope, responsibilities, and interfaces with its environment, i.e., people, systems, and external components. The IEPT suite acts as an integrating solution for existing and future modules and provides interfaces to stakeholders to conduct planning and funding processes for smart interventions. Figure 3 illustrates the IEPT suite context overview, which encapsulates the following elements:

- Integration of the intrinsic components developed by different providers;
- Access to data from the different data providers of a particular test case;
- Access to analysis data from the different components and data flow coordination among them;
- Provision of fine-grained analytics and metrics to the in volved stakeholders.

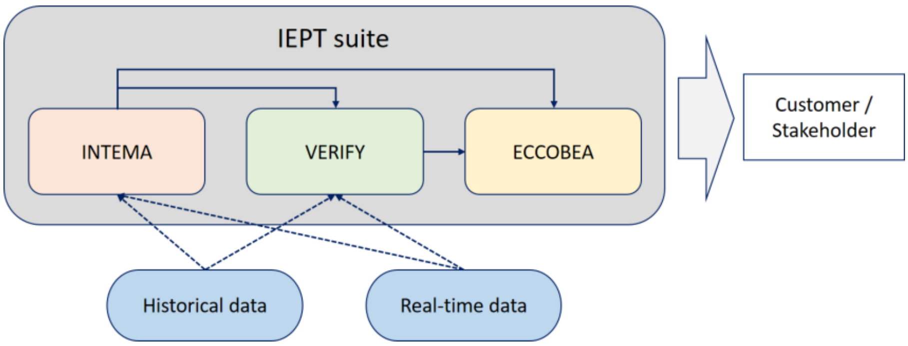


Figure 3. The IEPT suite context view.

The Functional viewpoint describes the system's functional elements, their responsibilities, interfaces, and primary interactions. The microservice architectural paradigm is applied to the design of the solution [34]. According to this paradigm, a collection of lightweight, loosely coupled services are utilized, each one offering a single business capability. These services are INTEMA, VERIFY, and the ECCOBEA component. This type of architecture offers great independence in the scalability of the solution and the development of the various components, as well as the capability of decentralized governance (implementation decisions) offering a relevant autonomy for each component. These microservices are containerized in Dockers, simplifying their delivery and management [35]. The containerization process provides individual microservices with their own isolated workload environments, making them independently deployable and scalable. Figure 4 illustrates the main elements of the design in a unified modelling language (UML) diagram.

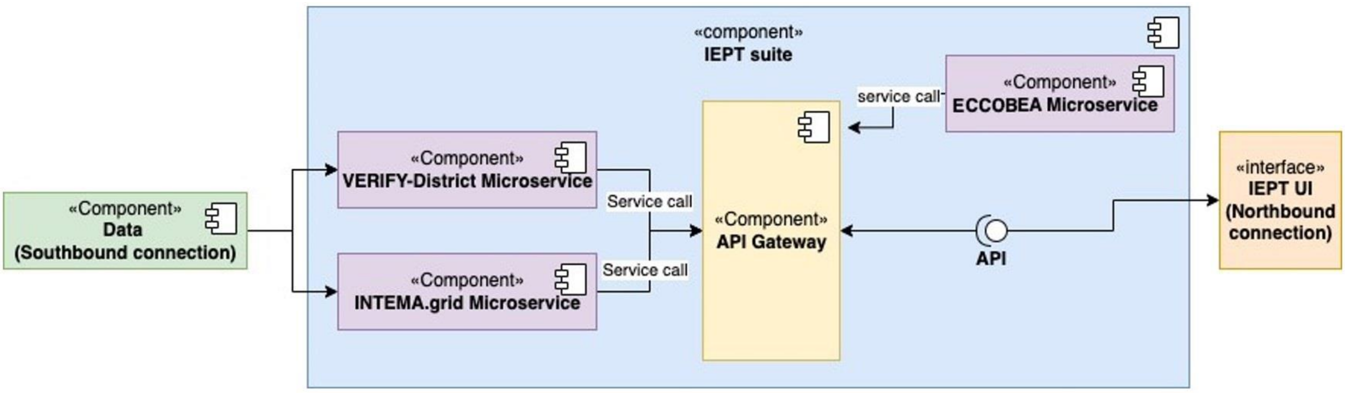


Figure 4. Component diagram of the IEPT suite.

3.2. Components

3.2.1. Energy Analysis: INTEMA

In order to address the energy analysis, the use of the INTEMA tool is adopted. The Integrated Energy Management (INTEMA) tool facilitates simulation modules aiming to help engineers address challenges regarding achieving a sustainable energy transition, covering both building and district spatial scales. The INTEMA.building submodule performs dynamic in-time simulations for the thermal behavior of the buildings coupled with active energy [36]. INTEMA.grid, on the other hand, offers the capacity to facilitate studies on an expanded scale, thereby aiding the development and maintenance of detailed models pertaining to a wide range of systems, from small energy communities and microgrids to more intricate transmission and distribution systems.

While there are a plethora of energy systems analysis applications, each one is aimed at solving a specific problem, failing to provide a holistic energetic assessment. Although the freeware EnergyPlan [37] tool is a popular option for steady-state hourly optimization, it does not consider interactions between energy demand and supply. The energy system tool LEAP [38] is a scenario-based modeling tool restricted to only medium- to long-term assessment horizons. The PLEXOS [39] tool, on the contrary, supports hourly and even intra-hourly simulations, but mainly refers to market operations with limited technical model representations. Conversely, simulation software that can support multiple aspects for both technical and economic evaluation, such as Simulink/Simscape, suffers from closed-source code and expensive proprietary licenses.

INTEMA's dynamic simulation module takes advantage of the open source Modelica language's capabilities [40], which enable modelers to study and modify the underlying component equations, in contrast with similar commercial tools. Another significant advantage lies in simulating the synergy among various assets of multiple energy vectors (i.e., electricity, heating, cooling and storage). It mainly includes white-box models along with custom grey-box implementations for cases of high data availability and a critical accuracy requirements. In addition to dynamic simulations, INTEMA offers a set of custom-made ancillary tools developed in Python. These have been integrated to support specific grid-related tasks such as AC power flow, optimal power flow, optimal dispatch, load leveling, investment optimization, etc. This tool is provided through a user-friendly web-based user interface along with a RESTful API that enables automation and interoperability with similar applications.

In the context of the IEPT platform, a subset of specific energy-related performance indicators have been defined as the output of INTEMA. These include calculation of the RES energy production, energy savings, RES-produced self-consumption, storage capacity of the energy grid per total island energy consumption, reduction in the energy curtailment of RES and distributed energy resources (DERs), reduction in peak load, and load covered by the external grid. Along with the aforementioned KPIs that are forwarded to the rest of the tools, INTEMA also outputs time-series data regarding grid operation that are utilized by VERIFY to evaluate the environmental impact of the energy generation sector. These time-series provide performance information, but are not limited to power plant dispatch, RES generation, and level of battery utilization.

3.2.2. Environmental and Costs: VERIFY

For the environmental and cost analysis, the VERIFY tool is employed. VERIFY-D is a web-based platform that provides a holistic methodology and evaluation for the LCA and LCC analysis in district-level energy systems. The platform provides an extensive analysis that overcomes simple inventory level computations, by also assessing the energy flows during the use phase of the project in terms of environmental and cost impacts.

Available LCA tools vary in their features, data requirements, cost, and user-friendliness, while some require specialized expertise to use compared to others. SimaPro v9.5 [41] is a widely used LCA software tool that allows for comprehensive life cycle assessment of various energy systems, while providing a range of features for modeling and analyzing of the environmental impacts of energy systems across their life cycle stages. GaBi [42] is another popular LCA software tool that offers modules specifically designed for assessing the environmental impacts of energy systems, focusing on life cycle inventory data, impact assessment methods, and modeling capabilities for conducting detailed energy system LCAs. The above list is not exhaustive, and there are other LCA software tools available as well (e.g., OpenLCA [43], eTool [44]). The choice of software tool depends on the specific requirements of the energy system being assessed, the level of detail needed, and the available data and resources

VERIFY stands out from other LCA software due to its custom methodology that involves multi-domain LCA in a 'sector coupling' manner, thus providing a complete approach toward integrating energy supply with the main sectors on the demand side. The main sector division, through VERIFY, considers the impacts of (1) private and public buildings, (2) transportation infrastructure elements, (3) the produced energy by RES and non-RES technologies, (4) energy storage systems, and (5) public infrastructure energy-related elements. Another significant advantage of this tool regards the combination of static LCA–LCC analyses with the dynamic use phase of system components set during the specified lifetime. While other pieces of software in the sector pay little to no attention to the use phase of a project, VERIFY is capable of accurately representing this important step utilizing time-series operation data.

Input data (either real-time, near real-time, or synthetic) from multiple external sources or tools (specifically for the synthetic type of data) are supported through custom API implementation. VERIFY is based on open source libraries, frameworks, and databases (e.g., Python, Ruby on rails, PostgreSQL, etc.), eliminating the dependence on closed-source tools. The output extracted from VERIFY can be divided into environmental and cost indicators presented through a graphical user interface to the end-users. Environmental performance indicators include the reduction in greenhouse gas emissions and fossil fuel consumption. Economic performance indicators include total investments, operational and replacement expenses by the end of the analysis life time, while the annual costs and revenues are also available for the purposes of a more detailed results examination.

3.2.3. Investment Viability: ECCOBEA

CBA is an essential tool for evaluating SG investment from a techno-economic standpoint. Its value lies not just in the provided outcome, i.e., in evaluating whether an investment is financially viable, but also in how it requires one to define and quantify the expected costs and benefits. This analytical approach is often more informative than the result itself, offering the various involved stakeholders a pathway towards integrating green solutions in their business-as-usual (BaU) operations.

The ECCOBEA module was also developed as a web application. The backend implements all of the required functionality described in Section 2.3, while a user interface presents the results of the CBA methodology. The integration with the rest of the tools is implemented via RESTful APIs. All of the KPIs received from the other modules and the results of the CBA are stored in a database to be accessible by the user for future reference. A snapshot of the at-a-glance page with the different results can be seen in Figure 5.

While other CBA methodologies and applications are extensively presented in the Introduction, to the author's knowledge, a specific software module has yet to be developed that is able to conduct a CBA for LEC-oriented SG investments. This is mainly because developing a module for automated CBA requires much effort to render it use case-agnostic, since costs, benefits, and baseline scenarios and assumptions are scenario-dependent.

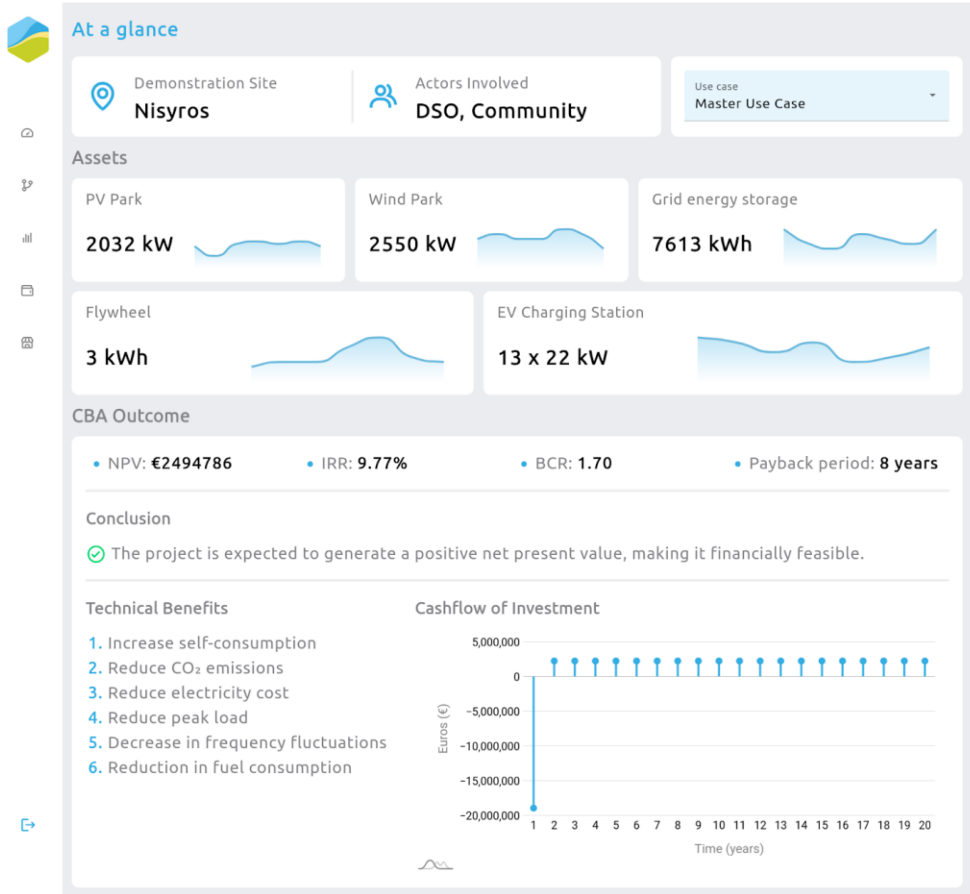


Figure 5. The "at-a-glance" page of the IEPT dashboard with the results of the CBA module.

4. Case Study

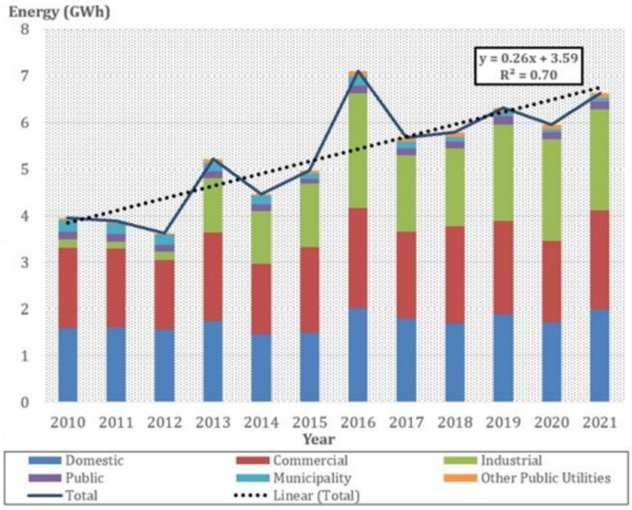
The aim of this section is to showcase the proposed energy investment methodology by applying the IEPT tool to Nisyros island, Greece. For this purpose, the overall case description of the as-of-today status of operation of the island is initially provided, representing the reference scenario (baseline). Then, the under-consideration scenario-based investment plan is defined.

4.1. Nisyros Island Reference Scenario

Nisyros is a small (41.6 km^2) Greek island in the Aegean Sea, part of the Dodecanese group of islands, with approximately 1100 inhabitants. During the tourist season, the population undergoes an almost two-fold surge, consequently leading to increased energy demands. Nisyros is located in an area of exceedingly high solar irradiation, while the wind potential is amongst the highest in the country. Infrastructure-wise, Nisyros belongs to the Kos–Kalymnos non-interconnected electric power system operating at 50 Hz, which is responsible for the electricity supply of nine islands in total (Figure 6a).

For the purposes of the baseline case definition, details regarding the island topology and network characteristics, as well as information about the autonomous Kos–Kalymnos network, are required. All data were obtained with the help of Nisyros municipality and through sufficient literature research. The energy production time-series of the year 2018 (non-disclosable source—personal communication) for the islands of Kos and Kalymnos and the load time-series of the island for the year 2020 (Municipality of Nisyros) were considered. The simulations were implemented assuming that no significant changes regarding the time-series would appear throughout these 2 years. Additionally, in the scope of the investment scenarios and the consideration of photovoltaic and wind turbine installations, the optimization tool utilized weather data from the Photovoltaic Geographical Information System (PVGIS) provided by the EU [45].

(**a**)



(**b**)

Figure 6. (**a**) Kos–Kalymnos transmission network; (**b**) pattern for the progression of the load allocated to domestic, commercial, industrial, public, and municipal sectors.

The load of Nisyros is primarily covered by the thermal power stations in Kos and Kalymnos (total installed capacity of 106 MW_e and 14.8 MW_e, respectively). In addition, 4 wind parks (15.2 MW_e), 92 PV installations (8.78 MW_e), and a small hybrid station (0.4 MW_e of wind turbine, solar panel, and storage) contribute to the energy production of the Kos–Kalymnos system, with an annual penetration ranging between 10 and 20%. Nisyros does not currently have any power generation system in operation. An old oil-fired (diesel) generation group of 1 MW_e installed on the island is currently in cold lay-up and serves as a backup source in emergencies (in case of a local blackout during the busy summer months).

Nisyros' internal electricity transmission and distribution grid consists of the main medium-voltage (MV) line at 22 kV, which departs from Kos and runs through the island communities, where a series of local transformers downgrade the voltage level to 400 V for home and commercial usage. Another MV transmission line runs from the island's capital (Mandraki) directly to the south of the island, which connects to submarine cables that power Tilos island, the southernmost end of the grid.

The annual energy consumption of the island used to be approximately 4 GWh_e up until 2013, with the bulk demand stemming from the domestic and commercial sectors (Figure 6b). Since then, there has been a significant increase in the island's energy demand, to which the installed desalination units contribute over 1 GWh_e on an annual basis. The current demand stands at 6.5 GWh_e.

The extended nature and complexity of the grid affect the quality of supply, often resulting in instability (voltage/frequency fluctuations) and even blackouts, leading to a wide range of social impacts, such as population insecurity, health issues, and economic growth in the area [46].

4.2. Technology Interventions Selection and Energy Targets

Having described the energy infrastructure, profile, and needs of the island of Nisyros, a set of interventions are selected for this study. Nisyros aims to increase energy self-consumption levels by boosting the energy efficiency and RES penetration on one hand, while on the other ensuring the decarbonization of its energy grid, through electrification. In this frame, both conventional and innovative technologies were considered for application, whose combined implementation would maximize the objectives of the Nisyros municipality.

As part of this study, a number of available options from a technology perspective (related with solar, wind, hydroelectric and geothermal energy) are assessed, which could represent viable solutions for the Nisyros study case. However, among those examined, several technologies were not suited to the island's specific energy profile needs and characteristics (e.g., no potential for a hydroelectric plant, due to a lack of major water streams or reservoirs), and thus were considered out of scope. Furthermore, certain technologies could not be considered due to technical (e.g., geothermal activities in a highly sulfuric environment such as Nisyros island are accompanied by unpleasant fumes) and financial limitations (e.g., exceeding the allocated budget) or were in contrast with Nisyros municipality's internal planning and goals (e.g., digester or hydrolyzer). Therefore, only solar and wind energy solutions are considered for installation on Nisyros.

Finally, after the conclusion of the literature and market review and various feasibility studies, the technologies chosen to increase local RES production and self-consumption capabilities are both conventional, including PV plants of BENQ (327 W_p per panel), Vestas v52 Wind Turbines (850 kW), and innovative, including the biobased saline batteries from SUWOTEC (50 kW/120 kWh) and the EFACEC Electric Mobility vehicle-to-grid (V2G) EV chargers (22 kW each) [47].

To estimate the potential benefits of the proposed intervention, three scenarios are defined and studied regarding the size and the capacity of each selected technology. In all scenarios, system topology and assets' capacities are subject to optimization in order to ensure that a pre-defined self-consumption target value is reached. The first scenario entitled "high-RES" regards a target for local self-consumption of 50% and refers to an implementation horizon by 2030. The second and third scenarios, called "very-high RES", represent a more optimistic and long-term target, in which the local generation and self-consumption reach the values of 80% and 95%, respectively, by the year 2050.

5. Results and Discussion

5.1. IEPT Results

In order to identify the optimal capacities for the PV, wind turbines, and battery storage system, an iterative optimization problem was defined and solved for the local grid of Nisyros, as was described earlier. However, regarding the V2G EV chargers, a multi-aspect (social, economic, grid stability, etc.) analysis was conducted to calculate the number of chargers. A fleet of 100 EVs was assumed for a total population of 1000 inhabitants, according to projections regarding the mobility sector electrification. Taking into consideration the IEA directive regarding the maximum number of simultaneously operating EV chargers, which calls for a ratio of chargers to EVs equal to 1:10 [48], the total number of chargers was set to 10. The dimensioning of the assets was carried out for the worst-case scenario (peak demand date, 1.8 MW_e), which occurred on 13 August 2022. The complete results regarding the asset sizing in the Nisyros island case are presented in Table 3.

Table 3. Total installed capacity of the proposed investment under three distinct scenarios based on the achieved percentage of self-consumption.

Technology	Scenario 1	Scenario 2	Scenario 3
	50% Local Self-Consumption	80% Local Self-Consumption	95% Local Self-Consumption
PV plant	50%	80%	95%
Wind park	602 kW	1030 kW	2032 kW
Grid battery	850 kW	1700 kW	2550 kW
EV chargers	10 × 22 kW	10 × 22 kW	10 × 22 kW

With the dimensioning results from INTEMA now available, VERIFY was used to quantify the environmental and economic aspects of the interventions under study. In order to complete the quantification of the relevant KPIs, a number of assumptions were necessary:

- Simulations: Annual power flow simulations were conducted with an hourly resolution.
- Oil-fired power plant: It is assumed that the oil-fired plant on Kos island is the sole responsible for Nisyros' energy transmission. However, only the percentile of the emissions that correspond to the amount of energy that Nisyros absorbs is considered in the calculations (1 kWh production from an oil-fired power plant is assumed to correspond to approximately 0.65 $kgCO_2$/kWh [42,43]). The price of produced electricity is assumed to be 0.15 EUR/kW [44].
- Grid: In the baseline scenario, the load is covered by a mix of RES and oil-fired power plants from the neighboring interconnected islands. There are three transformers of 500 kVA serving the island of Nisyros. Each transformer is 15 years old, with a remaining service life of 10 years under current operating conditions.
- EVs: The vehicle-required energy is assumed to be the same for EVs and conventional vehicles, and the relevant power is produced from an oil-fired power plant.
- Since the local RES production increases, the losses caused by the energy imported from the transmission grid decrease.

Finally, a comprehensive CBA is conducted to assess the viability of the investment opportunities for the LEC of Nisyros, in accordance with national energy efficiency mandates, the island decarbonization plan, and the Fit-for-55 directive; the policy goals are the main drivers behind the proposed investment plan (Table 3). The functionalities that each technology provides are explored: local green energy production (both PV and wind farm), efficiency in day-to-day grid operation (grid battery), improvement in electricity market functioning (PV, wind park, grid storage), increase in the municipality and citizens' welfare (all investment technologies), and establishment of green transportation (EV chargers). These functionalities are mapped onto benefits, as depicted in Table 4.

Table 4. Mapping investment stack functionalities onto benefits.

	Local Green Energy Production	Ensuring Efficiency in Day-to-Day Grid Operation	Better Market Functioning	Increasing Consumer's Prosperity	Ensuring Green Transportation
Increased self-consumption	X		X		
Reduced CO_2 emissions	X				
Reduced electricity costs	X		X		
Reduced peak load	X				
Reduced transportation costs				X	
Improved air quality in the community				X	X
Reduced transmission losses		X			
Deferred capacity investments		X			
Increased social benefits in the local community				X	X

Each benefit is then coupled with the relevant calculations of the INTEMA and VERIFY (Table 5), quantifying the CBA for the three distinct scenarios in this way. Of the eight quantified benefits, only two directly translate into financial gains, i.e., reduced electricity and transportation costs. Table 6 contains the approach for translating the non-directly monetized benefits, i.e., reduced CO_2 emissions, into financial gains that are used as the input into step 5 of the CBA methodology (Figure 2).

Table 5. Benefits quantification per year in the three different self-consumption scenarios.

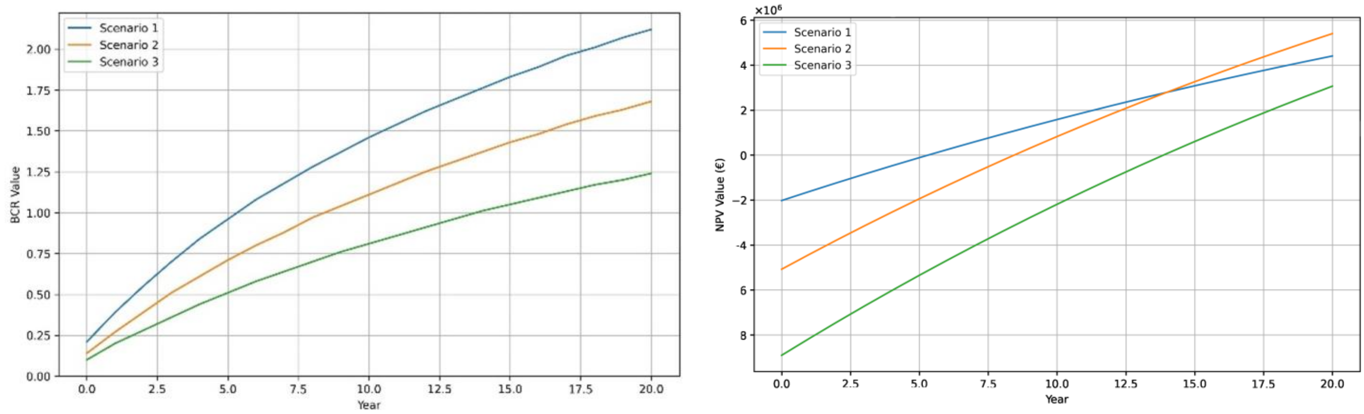
Benefit	Metric	Self-Consumption Scenario 50%	80%	95%
Increased self-consumption	The increase in Nisyros' self-consumption due to the installation of a wind park and PV.	3345 MWh (PV 12.9% Wind 36.3%)	5415 MWh (PV 16.5% Wind 63.2%)	6462 MWh (PV 16% Wind 79%)
Reduced CO_2 emissions	The difference between the reduction in operational CO_2 emissions due to the production of energy from RES and the emissions emitted during the production phase of the newly installed component infrastructure.	3050 tCO_2	4185 tCO_2	5025 tCO_2
Reduced electricity emissions	Reduction in electricity costs for the municipality of Nisyros and its citizens due to an increase in self-consumption due to RES.	3345 MWh × 150 EUR /MWh = 501,750 EUR	5415 MWh × 150 EUR /MWh = 812,250 EUR	6462 MWh × 150 EUR /MWh = 969,000 EUR
Reduced peak load	Peak to mean ratio (PMR) load reduction	0%	−2.20%	−3.12%
Reduced transportation costs	Reduction in transportation costs for the municipality of Nisyros due to the replacement of diesel vehicles with EVs.	12,970.9 EUR	15,548.7 EUR	16,851.8 EUR
Improved air quality in community	Reduction in CO_2 emissions in the municipality of Nisyros due to the replacement of diesel vehicles with EVs	10.3 tCO_2	21.5 tCO_2	27.1 tCO_2
Reduced transmission losses	Reduction in transmission losses on the underwater transmission cable coming from the thermal stations of Kos and Kalymnos.	−19.24%	−53.70%	−86.19%
Increased self-consumption	The increase in Nisyros' self-consumption due to the installation of a wind park and PV.	3345 MWh (PV 12.9% Wind 36.3%)	5415 MWh (PV 16.5% Wind 63.2%)	6462 MWh (PV 16% Wind 79%)
Reduced CO_2 emissions	The difference between the reduction in operational CO_2 emissions due to the production of energy from RES and the emissions emitted during the production phase of the newly installed component infrastructure.	3050 tCO_2	4185 tCO_2	5025 tCO_2

Table 6. Mapping of non-direct monetized benefits to economic gains.

Benefit	Direct or Indirect Monetary Gains	Self-Consumption Scenario		
		50%	80%	95%
Reduced CO_2 emissions	Contribution of the municipality to reducing the country's total carbon emission by linking it to the social cost of carbon (SCC). SCC for Greece is calculated as the five scenarios average of [49], combining the socio-economic, climate, and impact data—that is, the marginal damages from CO_2 emissions—for an average of the possible scenarios for sustainable development using exogenous and endogenous discounting factors.	3060.3 tCO_2 × 0.56 EUR /tCO_2 = 1713.758 EUR	4206.5 tCO_2 × 0.56 EUR /tCO_2 = 2355.64 EUR	5052.1 tCO_2 × 0.56 EUR /tCO_2 = 2829.176 EUR

For the CBA, a 20-year period was considered, equal to the shortest lifetime of the proposed technologies (i.e., EV chargers). For that period, the NPVs for both costs and benefits are calculated. The weighted average cost of capital (WACC) represents the discount rate that should be used to conduct a discounted cash flow analysis of a given SG investment. The reason for this is that the discount rate represents the opportunity cost of obtaining something in the future relative to obtaining something today. Since the WACC represents the average return for an energy project (the average is weighted across both debt and equity investors), it is denoted as a kind of average opportunity cost for investment in a project. For the CBA analysis, a WACC value equal to 7% was considered, which is a reasonable assumption consulting the historical trend of WACC in RES investments in Greece [50]. In addition, a fixed growth rate of 2% is considered for the annual operational costs of the different technologies.

For the benefits, the choice of the discount rate involves balancing intergenerational equity and the time value of money. A lower discount rate gives more weight to future benefits and costs, prioritizing long-term considerations and sustainability. In contrast, a higher discount rate emphasizes present value and shorter-term gains. Determining an appropriate social discount rate is subjective and can vary across jurisdictions and contexts. Different countries and organizations may adopt different approaches. Therefore, the present analysis considers a discount rate equal to 3%, which is in the lower bound range of the discount rates used in energy system modelling in the EU [51]. Based on the investment costs and benefits presented in the previous subsection, the CBA module analyzed the three scenarios. The results are shown in Figure 7.



(**a**) (**b**)

Figure 7. (**a**) BCR evolution through the CBA period for the 3 scenarios; (**b**) NPV evolution through the CBA period for the 3 scenarios.

The first scenario provided the highest BCR equal to 2.12, indicating that the estimated benefits are more than double the costs. The NPV was found to be EUR ~4,400,000, suggesting a positive value and hence a profitable investment. From the annual trend analysis, it was observed that the project break-even point in terms of cumulative benefits and costs (BCR equals 1) is around year 5 (Figure 7a). After this point, the BCR consistently increases, reflecting growing benefits relative to costs. In terms of NPV, the project becomes profitable (NPV becomes positive) the same year (Figure 7b), and the NPV continues to increase for the rest of the project period.

In the second scenario, the BCR was found to be 1.68 (Figure 7a), which, while lower than Scenario 1, still indicates that the benefits outweigh the costs by a significant margin. The NPV for this scenario was the highest among the three, amounting to EUR ~5,400,000, showcasing the highest profitability in terms of present values. The project break-even point in terms of cumulative benefits and costs is around year 10 (Figure 7b). This is also reflected in terms of NPV. While this scenario has a lower BCR, it yields a higher overall NPV due to a higher flow of net benefits in the later years of the project.

The third scenario presented the lowest BCR of 1.24 (Figure 7a), suggesting that the benefits are still higher than costs but by a smaller margin compared to the other two scenarios. The NPV for this scenario was EUR 3,000,000, the lowest among the three scenarios. The break-even point in terms of BCR and NPV for this scenario is around the 14th year (Figure 7b). This reflects a longer payback period and lower profitability compared to the other scenarios.

In summary, all three scenarios indicate a profitable project over a 20-year period, with benefits exceeding costs. However, the degree of profitability and the time taken to break even vary significantly between the scenarios. Scenario 1 provides the highest BCR, while

Scenario 2 yields the highest NPV. Scenario 3, while profitable, lags behind the other two regarding both NPV and BCR.

5.2. Sensitivity Analysis

The sensitivity analysis measures the impact of different discount rates on costs and benefits during the 20-year period of the CBA. It provides a break-even value which provides the discount rate at which the CBA NPV equals zero. In this study, it was conducted for various discount rates ranging from 7% to 13% to assess the robustness of the project's profitability under the three scenarios. The results of the sensitivity analysis are shown in Figure 8.

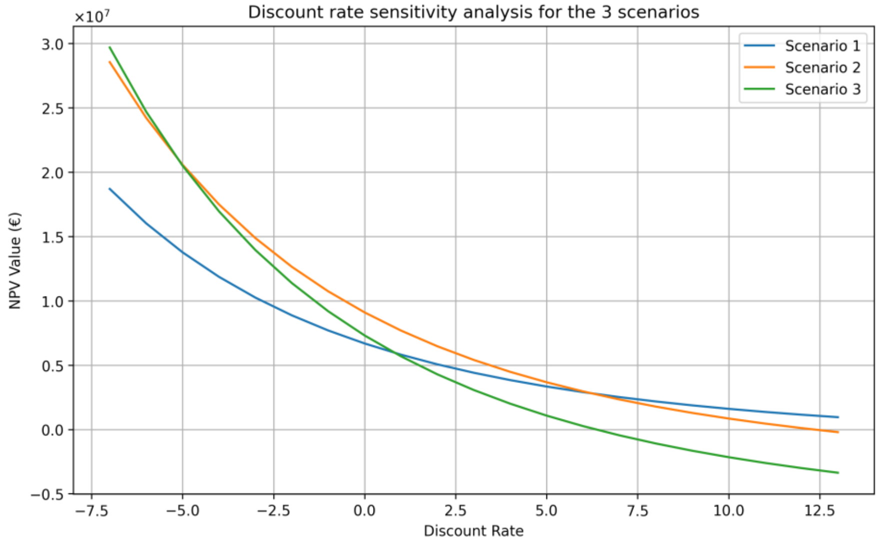


Figure 8. Discount rate sensitivity analysis for the 3 scenarios.

The NPV of the first scenario demonstrates a consistent decline as the discount rate increases from −7% to 13%. At lower discount rates (−7% to 0%), the NPV remains significantly high, reflecting a large NPV of future benefits when those benefits are heavily weighted. At a 0% discount rate, the NPV is EUR ~6,700,000. As the discount rate increases, the NPV decreases, reflecting the lower present value of future benefits. At the standard discount rate of 3%, the NPV is EUR ~4,400,000. Beyond a discount rate of 8%, the NPV becomes negative, suggesting that the project would not be profitable if the discount rate is 8% or more.

Similar to Scenario 1, the NPV in Scenario 2 decreases with increasing discount rates. The NPV remains high for negative to low positive discount rates, peaking at EUR ~28,500,000 at a −7% discount rate. At a 0% discount rate, the NPV is approximately EUR ~9,100,00. At the standard discount rate of 3%, the NPV is EUR ~5,400,000. However, the project remains profitable until a discount rate of 12%, beyond which the NPV becomes negative.

The NPV pattern in Scenario 3 also showcases a consistent decline as the discount rate increases. The NPV is extremely high at lower discount rates, peaking at EUR ~29,700,000 at a −7% discount rate. At a 0% discount rate, the NPV is about EUR ~7,300,000. At the standard discount rate of 3%, the NPV is EUR ~3,000,000. The project becomes unprofitable when the discount rate exceeds 9%.

In summary, all three scenarios demonstrate that the project's profitability is sensitive to the discount rate applied. While the project appears highly profitable at lower discount rates, the profitability decreases as the discount rate increases. This suggests that the project may not yield a positive return if future benefits are heavily discounted.

6. Conclusions

This paper presented a systematic methodology for the multidimensional assessment of energy interventions. This methodology was implemented into the IEPT suite utilizing specialized software tools. The overall goal is oriented toward energy planning evaluation, including economic, environmental, and technical dimensions. Through the specific use case of Nisyros island, the applicability and effectiveness of the IEPT suite in supporting decision-making processes for LECs have been demonstrated. The suite's capabilities to model, analyze, and optimize energy systems have been showcased, providing valuable insights into the feasibility and potential benefits of different energy planning scenarios.

The IEPT suite's performance results provide promising results, indicating its reliability and accuracy in assessing the viability of multidimensional SG investment planning. The suite's integration with INTEMA.grid and VERIFY-D tools facilitated the quantification and evaluation of KPIs, enabling a comprehensive assessment of the LEC's viability, economic efficiency, and environmental impact. For the 20-year horizon of analysis, investment scenario 1 was the most financially viable (BCR equal to 2.12), followed by scenarios 2 (BCR equal to 1.68) and 3 (BCR equal to 1.24). Overall, the IEPT suite showcased a robust framework for decision-makers, energy planners, and stakeholders to analyze and optimize energy systems in LECs. Its functionalities contribute to informed decision-making, promoting sustainable and efficient energy solutions that align with the goals of decarbonization, energy transition and LEC empowerment in the EU.

Future research and development can focus on further enhancing the functionalities of the IEPT suite, addressing emerging challenges, by including more novel SG technologies while incorporating multi-energy grids. Furthermore, the extension of the analysis horizon to 30 or 40 years would return useful results, especially when considering the replacement cost of the installations. The transition to a more sustainable and resilient energy future for LECs can be better supported by continuously improving and refining the suite.

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