IANOS

SUSTAINABLE SOLUTIONS
for islands' decarbonisation

Development of LCA and LCC Tool for Transition Support

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Disclaimer

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Nomenclature/Abbreviations

ABS: Absorption chiller
AC: alternating current
AFW: animal fat waste
AP: acidification potential
APC: Air-Pollution-Control
ASHP: Air source heat pump
Bbl: produced oil barrel
BEV: battery electric vehicle
CarbFix: Carbon dioxide sequestration
CC: climate change
CCS: Carbon captured and stored
CCUS: Carbon capture use storage
CED: cumulative energy demand
CGB: Condensing gas boilers
CHP: combined heat and power
DB: dichlorobenzene
DCS-CHP: distributed concentrating solar combined heat and power
DeNOx: NOx abatement
EoL: End of life
EOR: enhanced oil recovery
FD: Fossil depletion
FE: Freshwater eutrophication
FET: Freshwater ecotoxicity
GHG: Greenhouse gas
GHP: Gas heat pump
GSHP: Ground-source heat pumps
GWP: Global Warming Potential
HHP: Hybrid heat pumps
HP: Heat pumps
HPGHP: hybrid-power gas engine heat pump
HT: Human toxicity
ICEV: internal combustion engine vehicle
KPI: Key performance indicator
LCA: Life cycle assessment
LCI: Life cycle inventory
LCOE: Levelized Cost of Electricity
LHV: Lower heating value
MD: Metal depletion
ME: Marine eutrophication
MET: Marine ecotoxicity
NGCC: natural gas combined cycle
OD: ozone depletion
ODS: Ozone-depleting substances
PB: pellet boiler
PE: person equivalent
PMF: Particulate matter formation
POF: Photochemical oxidant formation
PV: photovoltaic panel
r-SOFC: reversible solid oxide fuel cell
SOFC: solid oxide fuel cell
STC: solar thermal collector
SulFix: Hydrogen sulphide gas removal
TA: Terrestrial acidification
TET: Terrestrial ecotoxicity
WD: Water depletion
WSHP: Water-source heat pumps

Executive Summary

The present deliverable focuses on the development of an online web platform/tool for holistic lifecycle Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) calculations, called Virtual integrated platform on life cycle analysis - District (VERIFY-D). VERIFY-D performs a holistic life cycle approach considering both existing energy grid infrastructure and comparisons with planned energy grid interventions. Multiple energy grid sectors, such as the renewable energy production, the energy storage, the public infrastructures etc. can be incorporated to the life cycle analysis. At the same time communication with external software tools, through APIs offer the ability for instant communication and data exchange. The analysis results of the VERIFY-D platform offer an accurate energy intervention planning mechanism through the quantify of environmental and economic impacts and further evaluation through the operation assessment specialized on IANOS demo sites.

An environmental and financial literature review has been performed aiming at facilitating the understanding of the current situation regarding the examined technologies and their relative impacts. The literature review focuses on each technology individually; however, in the case of the IANOS project, each demo site incorporates a combination of these technologies. Hence, a suitable assessment methodology has been developed considering, the needs of both the lighthouse (LH) and fellow island (FI) of the IANOS project as described in the IANOS Use Cases (UCs).

Furthermore, the developed methodology is extended aiming at performing a scale-up approach, to examine the economies of scale of such projects. To select the appropriate scale-up methodology, a relevant literature review has been performed, highlighting and assessing existing frameworks that could potentially facilitate the scale of operation of IANOS project. In particularly the cost-to-capacity selected method, can be applied as it covers both industrial facilities, and individual pieces of industrial machinery and equipment (M&E).

Considering the data gathered from the literature review, as well as the specific needs of the IANOS project, a specific methodology approach for calculating the environmental (LCA) and financial (LCC) performance of each set of interventions is developed, on the level of geographical islands energy grid topologies. This methodology forms the core of computations of the VERIFY-D platform. The environmental impacts and associated costs, from the implementation of RES based and grid counter-congestion strategies on a district/city/island level can be computed by following the steps of this methodology. The

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VERIFY-D platform source code implementation consist of an interactive user interface (UI), smart algorithm implementation for the LCA and LCC, a robust data base for keeping secure the user data and a large data repository for collecting the demo cases monitoring data. The tool provides interactive tables and graphs in order to present life cycle analysis results in future time horizons (e.g. 25/35/45 years) and/or in real time scale (hour basis).

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1 Introduction

1.1 Objective and Scope

The objective of Task 3.1 and Deliverable 3.1 develops a web platform (VERIFY-D) with the purpose of calculating the environmental performance and associated cost savings from the implementation of RES based and grid-counter congestion strategies. The calculations are performed at two levels:

- On a user level: single building or specific asset.
- On a community level: set of buildings or assets in the context of a district/community/island.

The developed tool examines the RES based and grid-counter congestion strategies through a lifecycle perspective. Therefore, the implementation of Life Cycle Assessment and Life Cycle Costing methodologies will provide the basis of a successful completion of the calculations. Environmental (LCA) and Economic (LCC) assessment databases and algorithms have been developed in order to assess all stages of the value chain (e.g. from production to use phase, from design to recycling strategies, etc.).

VERIFY-D as part of the IEPT tool, is responsible for two main actions. The first action is targeted at investment planning regarding the energy grid at the districts/cities/islands level. The added value is to bring consistency and complement with sustainable and energy action plans, under a common methodological approach. By creating multiple investments consisting of different innovative technologies, a proper investigation of best-fit energy infrastructures is discovered. During the second action of this platform the operational evaluation of the investment scenarios can be evaluated in terms of environmental gains and economic profits. The innovation through VERIFY-D operation is identified in the ability to provide continuous evaluation through the energy grid operation, while promoting the best practice solutions. Replication activities through the fellow islands will easily adapt the promoted solutions based on their special needs and targets.

To facilitate the further development of the platform, a comprehensive literature review was performed in terms of environmental and financial performance of all technologies planned to be integrated in IANOS Lighthouse (LH) and Fellow demo islands. Regarding the environmental literature review the environmental impacts of the various technologies were

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assessed through a lifecycle perspective. Specific emphasis is given to the overall GHG emissions, measured in gCO_2eq/kWh of electricity produced from each available technology (standard and innovative). The use of a common functional unit promotes the direct comparison of GHG emissions of each technology and provides an overview of the current situation. From an economic point of view, emphasis is given on cost categories breakdown of existing case studies. The economic literature review is considered to ensure a direct comparison of the life costs of the proposed IANOS implemented solutions with the available literature and provide a mapping of available conventional alternatives.

Moreover, an important task of Deliverable 3.1 is to provide the extensive description of the implemented tool and the proposed methodology in community/district/island level; hence selecting the proper scale-up methodology is considered as a significant step for further extended application. In order to select and implement a scale-up methodology to the online web platform, a literature review of existing scale-up methodologies is performed, examining general, and technology specific, methodological frameworks.

To achieve the overall scope of the Deliverable, the following sub-objectives have been determined:

- Perform environmental and financial literature review as a mapping process to establish the current situation, the boundaries that are selected for each study, and cost-categories considered for calculations.
- Perform a literature review regarding scale-up methodologies and select most suitable for IANOS cases.
- Utilize the knowledge from literature review to develop a methodology suitable for LCA and LCC analysis in district/city/island level.
- Develop an online web platform/tool, VERIFY-D in order to provide the software for the setup and formation of IANOS demo cases. Prepare the calculation algorithms for the environmental and financial performance computations of the IANOS solutions. Create a suitable database scheme for storing the crucial data information, necessary for the environmental and costing analysis. Develop and prepare the communication among VERIFY-D and external software tools (through APIs) in terms of communication and data information exchange.

- Enhance and incorporate data inventories of existing and/or innovative technologies under the custom material-database of VERIFY-D, in terms of CO_2 emissions and capital costs.
- Set up the overall framework, under a common monolith platform approach ready to perform the LCA and LCC analysis.

1.2 Relation to other activities

The VERIFY-D tool, that has been developed in the context of this deliverable, is part of the IANOS Energy Planning and Transition decision support toolset (IEPT), which is developed in Task 3.3. As part of the IEPT suite of tools, the VERIFY-D platform is responsible for assessing the economic and environment benefits of the IANOS interventions through the calculations of relevant KPIs, as defined during Task 2.3. The VERIFY-D tool will exchange data with the power system modelling and simulation tools of the IEPT (INTEMA.grid and ESSIM) that provide necessary information for the LCA/LCC analyses through data timeseries (e.g. power consumption, production, etc). Eventually, the VERIFY-D tool will be utilized in Task 7.2 “Environmental Impact Assessment” to perform LCA and LCC analyses of the IANOS UCs utilizing this time monitoring data from the LH islands, as measured in Tasks 5.4 and 6.4 (Use case operation, optimization and performance monitoring).

1.3 Structure of the deliverable

The document is structured as follows:

- Chapter 1 contains the introductory section for the definition of the objectives and the work of this document.
- Chapter 2 presents a comprehensive literature review regarding the environmental and financial performance of the technologies under consideration.
- Chapter 3 illustrates a literature review of the available Scale-up methodologies based on different technologies, with the purpose of selecting a proper one for the IANOS planned interventions.
- Chapter 4 describes the development of the LCA and LCC platform.
- Chapter 5 presents the overall conclusions of the current deliverable.

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2 Review analysis regarding various IANOS related energy technologies

2.1 Review of the lifecycle environmental impact

A comprehensive literature review was carried out, to examine relevant case studies assessing the environmental impacts of the various technologies both existing or planned to be installed in the IANOS project. The reviewed case studies examine the environmental impacts from a lifecycle perspective, with the implementation of Life Cycle Assessment methodology. An overview of previously examined cases (studies retrieved from the open literature), is presented on **Table 1**, alongside their scope, functional unit of the study and Life Cycle Assessment (LCA) system boundaries.

Table 1 *Case Studies*

Case study	Goal Description	Functional Unit of the study	LCA System Boundaries
[1]	Assess and compare the environmental impacts of a condensing gas boiler and a hybrid heat pump for an existing semi-detached house in the UK	Generating 252,000 kWh of space heat over 20 years	• Production • Use • Transport • Raw materials transportation • Heating devices transportation • End-of-life devices and materials of heating systems transportation • End-of-life phases of heating system
[2]	Estimate the life-cycle greenhouse gas of onshore and offshore wind turbines with the nominal capacity of 2 MW for 20-year lifetime	1 MJ electricity generated at the wind power plants with the selected turbines	• Manufacturing of foundation, tower, nacelle, rotor, transmission grid • Transportation • Installation • Operation • Maintenance • Dismantling and disposal
[3]	Investigate the cradle-to-gate environmental impacts of a geothermal power plant that uses	Common functional unit for electricity and heat production: 1	• Electricity production • Construction • Power plant building • Mechanical equipment

	flashing technology to produce 1 kWh of electricity and 1 kWh of heat from a high temperature geothermal resource	kWh for operational time of 30 years	• Transport - Operation - Maintenance • Heat production • Construction • Heat station buildings Mechanical equipment • Transport – Operation - Maintenance • Multifunctional processes • Steam collection & reinjection • Transport of extracted geothermal wells • Disposal of the extracted geothermal fluid • Use of geothermal fluid • Drilling of make-up wells
[4]	Calculate the carbon footprint associated with a residential electricity supply system based on photovoltaic roof tiles, and compare with a photovoltaic panel-based system	The functional unit of the study, to which all inputs and outputs of the system are related, is the installation of a 0.52kWp solar photovoltaic system to supply a typical house from the Brazilian National Housing Program	• Raw material extraction • Manufacture - Transportation – Installation of PV system to site • Operation/use • End-of-life disposal is NOT included
[5]	Calculate CO2 emissions and energy consumption in wind farm construction and operation	1 kWh for operational time of 25 years	• Raw material and resources extraction • Production of components • Transportation of equipment and prefabricated turbine sections • Excavation and compaction • End of the operational design life of the wind park
[6]	Develop an energy generation system that utilizes a renewable energy source (concentrating solar combined heat and	Common functional unit for electricity and heat production: 1 kWh	• Raw material extraction • Manufacturing of components • Installation • Operation phase • Maintenance

	power) while working towards mitigation of global climate destabilization		• Decommissioning
[7]	To quantify the environmental burden associated to the production of 1 kW unit of a reversible Solid Oxide Fuel Cell (r-SOFC) with hydrogen storage and its BoP and to compare it with an analogue system, where the cell is fed by reforming of natural gas	1 MJ of energy produced and self-consumed by the system	• Manufacturing of the SOFC stack • Manufacturing of the BoP • Manufacturing of thermal storage system, including electric resistance • Maintenance of the SOFC cogeneration system • Operation • In the case of reversible fuel cell, the hydrogen storage was also inventoried • End-of-life scenarios are NOT accounted
[8]	Assess the environmental performances of MSW incineration in France, considering the whole incineration sector currently in function	The thermal treatment of 1 tonne of Municipal Solid Waste in France	• Incineration direct emissions to air and water • Production of auxiliary products and reagents • Management of bottom ashes, and APC residues • Energy recovery as heat and electricity and consumption • Material recovery
[9]	Analyze the generation of electric energy from animal fat waste (AFW), coming from the rendering process of animal by-products, under an environmental perspective, comparing it to the electricity production by conventional routes	1 MWh of electric energy produced	• Transport • Pre-treatment/cooking (included in the rendering process) • Purification and electricity production (cogeneration) of slaughterhouse residues
[10]	Estimation of GHG emissions arising from a carbon capture use	CCUS: the electricity dispatched from the NGCC power plant to	• Natural gas extraction and supply • Power generation in a combined cycle plant (NGCC)

	storage (CCUS) case with a natural gas combined cycle (NGCC) power plant and GWP impact, by using LCA methodology	the distribution grid measured in kWh CCUS: the primary energy produced measured in oil barrels (bbl)	• CO2 emissions capture and supply • Enhanced oil recovery (EOR)
[11]	To develop a life cycle model enabling the calculation of the impact on climate change of an hourly changing electricity mix (nuclear energy, natural gas, municipal waste treatment, blast furnace gas and hard coal)	The production of 1 kWh delivered to the grid in 2011	• Full supply chain of conventional fossil fuels (coal, oil and natural gas) • Transport to collect and deliver the fuel to the treatment plant • Production of the electricity • Land transformation and occupation, use of material • Construction of the power plant • Maintenance of power plants • Decommissioning of power plants
[12]	To evaluate the environmental impacts of mini-hydropower plants via an LCA perspective and to provide the environmental information from cradle to gate of electricity production from existing mini-hydropower plants	1 MWh electricity production from a mini-hydropower plant with a lifespan of 50 years in Thailand	• Preparation before construction • Transportation of materials to construct the plant Construction of mini-hydropower plant • Operation – Maintenance -Demolition - Transportation of materials from demolition of the mini-hydropower plants (including recyclable materials transported to recycling facilities by truck)
[13]	The environmental impacts related to potential future energy systems with high shares of wind power were evaluated using LCA, focusing on cycling emissions (due to part-load operation and start-ups) from dispatchable generators	The functional unit of the study was "fulfilling the electricity demand in Ireland in 2025", corresponding to 41 TWh	• Fuel provision (from the extraction of fuel to the gate of the plant) • Plant operation (direct stack emissions) • Infrastructure (commissioning and decommissioning)

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[14]	To assess the potential environmental impacts that are associated with the production of electricity from geothermal power plants for 40 years lifetime	1 kWh of net electricity produced	• Commissioning phase • Drilling of production and injection wells • Well-pad & pipelines construction • Power plants building • Operation • Production of sulfuric acid • Maintenance • Substitution of selenium-based sorbent; of plastic parts (drift eliminator, fan) of metals components of various technical parts • Lubricant oil refilling • Decommissioning • Closing of the wells with cement • End of life • Treatment and disposal of drilling mud and of the spent sorbent from AMIS maintenance, of exhaust oil from equipment maintenance activity
[15]	To precisely estimate the climate change impact of electricity and heat production from existing and future geothermal power plants throughout its 25-year lifetime.	kWhel and kWhth	• Exploration • Well development • Transportation • Construction, operation, and disposal • Mobility of personnel • End of life • Transportations of the used equipment to the intended waste treatment plant (landfill or recycling)
[16]	Evaluate the impacts of the electricity produced by four different grid-tied 3 kW PV systems. Thermal energy converted to hot water needs and consequently the equivalent avoided electricity consumption	PV systems 1 kWh of produced electricity over 30 years of operational lifetime Solar Thermal saving of 1 kWh electricity for hot water production	PV systems • Extraction of raw materials for the PV & for the BoS components • Processing of PV components • Production of PV systems • Transportation – Installation - Disposal Solar thermal systems • Production • Transportation – Installation

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	from two types of commercial solar thermal systems.	over 20 years of operational lifetime	• Disposal
[17]	To estimate the impact of energy supply infrastructures and supply chains, on CO2 emissions and energy use, regarding conventional and electric vehicles	Two stages were implemented during LCA. The first used an intermediate unit that states CO2 and MJ per unit of energy and a second stage takes into account the unit CO2 and MJ per unit of km, to enable comparison between LCA stages.	• Primary fuel handling infrastructure • Transport system of end fuel • Distribution facilities
[18]	To reduce the uncertainties in assessments of the environmental impacts from real-world battery production, by reporting the cradle-to-gate emissions of a battery electric vehicle (BEV), based on primary data for large scale production and battery design	1 kWh of battery energy capacity & 1 kg battery to compare GHG emissions across studies	• Materials production, cell and component • Manufacturing • Battery pack assembly • Transportation
[19]	To analyze the environmental impacts of nuclear, wind and hydro power plants	1 kWh of electricity produced	Nuclear power plant • Mining uranium • Milling • Refining • Conversion • Fuel fabrication • Construction – operation – decommissioning - waste of nuclear power plant Hydropower plant • Extraction of raw materials

			• Manufacture of turbine and generator • Production of construction materials • Facility construction • Production of auxiliary materials • Operation - Decommissioning Wind power plant • Production of auxiliary materials
[20]	Evaluate the cumulative energy demand (CED) and scaling effects by applying a cradle-to-gate life cycle assessment to systems such as: solar thermal collector (STC), photovoltaic panel (PV), combined heat and power (CHP), ground-source heat pumps (GSHP), air source heat pump (ASHP), absorption chiller (ABS), pellet boiler (PB), hot water storage	STC: 1 m2 PV: 1 m2 CHP: 160 kWel & 360 kWth GSHP: 10.25 kWth ASHP: 10.25 kWth ABS: 100 kW PB: 12 kWth Hot water storage: 2000l	• Raw material extraction (cradle) • Raw material processing • Transportation of processed materials to manufacturing site • Production of components • Assembly of the system • Transportation to market (gate)

All selected case studies were examined in terms of their respective environmental impacts, with specific focus to GHG emissions (gCO_2/kWh of produced electricity). The use of a common functional unit for the GHG emissions facilitate the comparison of each technology, despite their overall technical and technological differences. **Figure 1** depicts the comparative values of GHG emissions per kWh for the energy technologies in the presented case studies.

The results from the case studies under examination, show that geothermal and mini-hydro produced energy has the lowest GHG emissions with less than 50 gCO_2/kWh of produced electricity, while solid oxide fuel cells has the highest emissions with more than 700 g CO_2/kWh. Additional information regarding each selected case study, and their respective scope, are presented in **Annex 1**.

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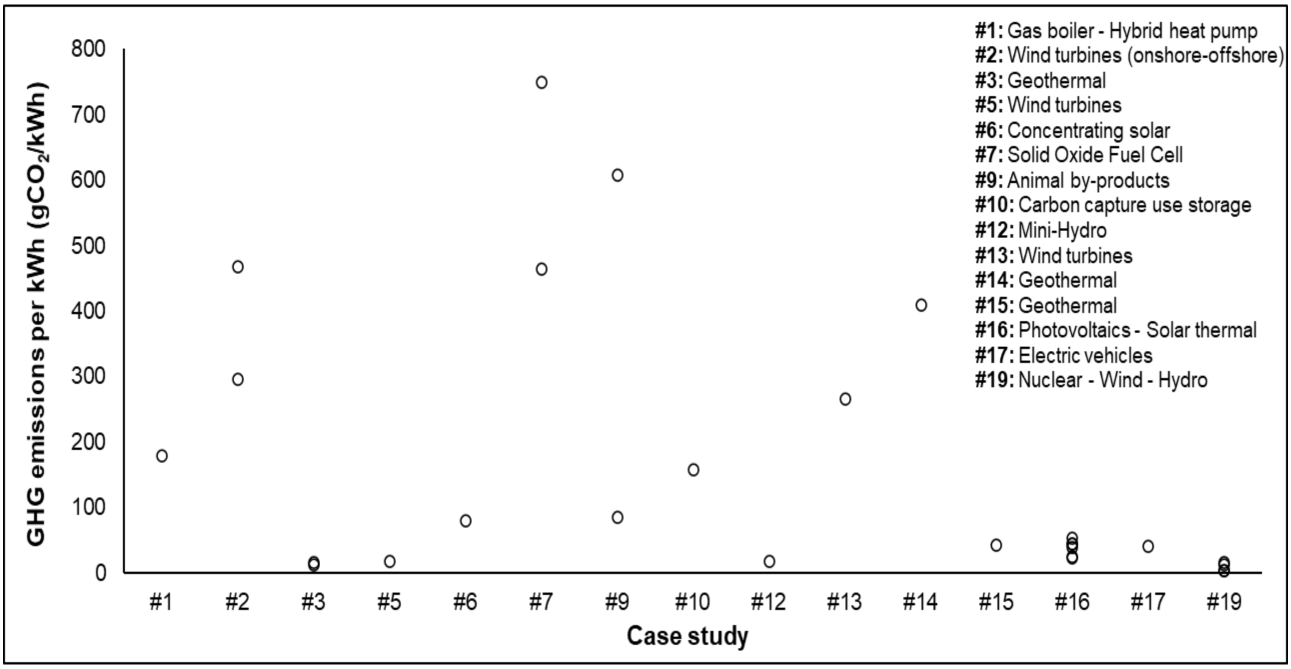

Figure 1 *GHG emissions of each examined case study for different technologies (in g CO2/kWh)*

2.2 Review of the lifecycle economic impact

A comprehensive review of the economic information related to the assets that exist or will be installed in the context of the IANOS project during the demonstration campaigns is presented on **Table 2**. Each column of the table provides the following information:

- **Technology:** The specific type of technology for each asset.
- **Source:** The source used to retrieve the information. This includes academic work conducted in the last 6 years, technical reports from projects, and commercial brochures.
- **Linked Demo Site:** The IANOS demonstration site that contains the particular type of asset: AML stands for AMELAND and TER for TERCEIRA.
- **Capacity:** The capacity of the asset for which the below values are given.
- **CAPEX:** The Capital Expenditures of the asset installation. Those are funds used to acquire, upgrade the assets.
- **OPEX:** The Operational Expenditures of the asset. Those are the ongoing costs for operating a particular asset after its installation.

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- **LCOE:** The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime.
- **IRR:** The internal rate of return (IRR) is a metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis.
- **Economic Lifespan:** The expected period of time during which an asset will be useful to its owner without limitation by the lease term, over which the economic benefits embodied in the asset are expected to be consumed by the entity.

***Table 2**: Economic information for the IANOS assets per technology type and capacity.*

Technology	Source	Linked Demo Site[1]	Capacity (MW)	CAPEX (€/kW)2	OPEX (€/KW/yr)	LCOE (€/KWh)3	IRR	Lifespan
Solar Parks	[21]	AML	1kWp[4]	853 (fixed) 988 (1-axis: V or I) 1235 (2-axis)	9 (fixed) 13 (1-axis: V or I) 19 (2-axis)	0.075 (fixed) 0.070 (inclined & vertical) 0.088 (2-axis)	5.56	25
Wind Parks	[22]	TER	2.6- MW wind turbines	1282	38	0.033	6.32	25
			6.1- MW offshore Wind Turbine	3641	111	0.075	5.29	25
			6.1- MW Floating Offshore Wind Turbine	4758	116	0.118	5.29	25
			20 – kW Residential Wind Turbine	5068	31	0.142	5.6	25
			100-kW Commercial Wind Turbine	3840	31	0.092	5.6	25
Geothermal plants	[23]	TER	100MWe	3080	73	0.085	13	30

[1] *TER: Terceira, AML: Ameland*

[2] *Some original values where in USD. Converted to Euro with the exchange rate of 2019: 1USD equal to 0.8931 EUR.*

[3] *Some original values where in AUSD. Converted to Euro with the exchange rate of 2020: 1AUSD equal to 0.604 EUR.*

[4] *Size can be measured by the concept of installed peak power. This concept is defined by the European Commission Joint Research Centre as: "the power that the manufacturer declares that the PV array can produce under standard test conditions, which are a constant 1000 W of solar irradiation per square meter in the plane of the array, at an array temperature of 25 ºC". Since the main goal of this study is a cost comparison between different production technologies, a standard value of 1 kWp is considered.*

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Hydro Plants	[24]	TER	1kW	4500	3% - 7% of CAPEX	0.09	9	30
CHP Plants	[25]	AML	5kW (electrical) 15kW (thermal)	6800	994	0.324	1.53	30
Oil fuel Plants	[24]	TER	1kW	1170	2% - 4% of CAPEX	0.39	9.43	30
Tidal Kites[5]	[26]	AML	0.3 – 10 (1st stage) 0.5-28 (2nd stage) 3-90 (commercial)	4518 -12934 (1st stage) 3809 – 7707 (second stage) – 3189 – 4961 (commercial stage)	141 – 1027 (1st stage) 133 - 469 (2nd stage) 79 – 354 (commercial)	0.186 – 0.416 (2nd stage) 0.122 – 0.248 (commercial)		
Incineration Plants	[27]	TER		2.2 m€[6] 4.5 m€	12m€/year	0.55	5.5	30
BESS	[28]	TER	10MWh	13338	6.9	0.61	8.5	25
Flywheel	[28]	TER	1 MWh	90275	5	0.59	8.5	25
Electric Water heater[7]	[29]	TER		810 – 1050 (€/m²)	0.008 (€/m²)	0.14 – 0.18	3	25
Buidling Integrated PVs	[30]	AML	3.1 MWh/ m² (lifetime)	473 (€/m²)	65 (€/m²)	0.10 – 0.16	3	30

[5] *The first stage refers to the first project that the technology deployed. The second corresponds to the project before the commercialization of the product.*

[6] *The amount considers the entire plants cost and not per kW output.*

[7] *Data retrieved from https://www.solarthermalworld.org/news/iea-shc-levelised-cost-heat-and-calculations-behind-it and concern a single-family house*

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Gas electric hybrid heat pumps	[31]	AML	5kW	1183	68	0.11		15

A detailed cost – breakdown, based on Table 2 for the construction and operation taken from the literature review for: 1) solar energy production technologies, 2) wind energy production technology, 3) geothermal power plant, 4) hydropower power plant, 5) CHP power plant, 6) oil fuel power plant, 7) tidal kite technology, 8) battery incineration plant, 9) battery storage systems, 10) flywheel systems, 11) fuel cell technology, 12) hybrid transformers, 13) water heaters, 14) hybrid heat pumps;   is presented in **Annex 7.2**.

Adaptation to VERIFY-D list of technologies database

All the aforementioned case studies provide useful and important information considering the economic parameters, that are necessary for the costing analysis. The purpose of this extensive literature review is to gather data to build a comprehensive technologies database, that will be utilized from the developed tool for the needs of the LCC analysis.

Specifically, the values of the CAPEX, OPEX and the economic lifespan are directly fed into the list of technologies database of VERIFY-D. Additionally LCOE and the IRR values are utilized during the verification procedure, and they are not included permanent into the database. The overall objective is to expand the existing list of technologies costing information (CAPEX, OPEX, maintenance) with conventional and innovative IANOS technologies from: 1) literature review, 2) market research and 3) through project technology partners. When possible, more than one scales of capacity – under the same technology (e.g., wind turbines of 10, 100, 500 kW) needs to be incorporated. Appropriate scale up/down factors will be dynamically applied for each of the examined/offered technology through VERIFY-D platform.

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3 Scale-up methodologies investigation and selection

3.1 Cost-to-capacity method

In the early stages of any project, cost estimates are vital to support its economic viability and to help further design and scale-up. The cost-to-capacity method is an effective tool to perform required cost estimates and can be applied to both overall industrial facilities, and individual pieces of industrial machinery and equipment (M&E) and thus has been chosen to be applied to the overall computation and evaluation approach. The fundamental concept behind the cost-to-capacity method is that the costs of facilities (or pieces of M&E) of similar technology but with different sizes vary nonlinearly. More specifically, cost is a function of size raised to an exponent or scale factor. *Eq. 1* represents the general expression for the application of the method, where SC is the unknown cost of the facility with scaled capacity SQ, RC is the known reference cost of the facility with known reference capacity RQ and x is the scale exponent of that specific technology. [1]

$$\frac{SC}{RC} = \left(\frac{SQ}{RQ}\right)^{x} \qquad \textit{Eq. 1}$$

To obtain meaningful results, the technology of the facility or M&E for which the cost is being estimated must be the same as, or very similar to, that with known historical costs. The scale factor should also be specifically applicable to the range of sizes for the specific technology of facility being analysed. In addition, when the locations of the two equipment are different, a locational cost adjustment factor due to factors that include but are not limited to regional differences in skilled labour rates (union vs. non-union), material costs, equipment costs, and general site condition costs (rural vs. urban), need to be accounted for. In 1950 C.H. Chilton identified a common scale factor for chemical facilities of approximately 0.6, reason for which the method is also known as “six-tenths rule”. This value of 0.6 is a result of an averaging process, and it is also used in cases with limited or complex data [35]. Since then, many other sources have derived scale factors for specific technologies. The work made in 2019 by the U.S. National Energy Technology Laboratory (NTEL) [36] defines a standard basis for scaling costs, with specific emphasis on scaling exponents, of frequently used pieces of equipment in energy systems. Even if not addressing renewable energy systems, the work can be still useful in the IANOS context for some general equipment. It provides exponents for various plant types, together with the range of applicability and the specific equation. The scaling equation proposed is ***Eq. 2*** (more general in respect to *Eq. 1*), where RC is the reference cost and RP the reference parameter for the equipment (capacity, size, volume etc.)

$$\frac{SC}{RC} = \left(\frac{SP}{RP}\right)^{x} \qquad \textit{Eq. 2}$$

The scaling exponents proposed in systems analysis work are logarithmically derived from previously obtained vendor supplied cost quotes using Eq. 3. This equation could be implemented to determine scaling coefficients for IANOS technologies, when they are not available in literature.

$$x = \frac{\ln\left(\frac{RC1}{RC2}\right)}{\ln\left(\frac{RP1}{RP2}\right)} \qquad \text{Eq. 3}$$

The tables with the x coefficients for a lot of energy systems can be directly accessed from the primary source. It has been considered useful for IANOS as the RES system envisage a digestor and a waste-to-energy plant, that may have many parts in common.

A similar approach to cost-to-capacity one is the use of Power scaling laws. For example, Caduff et al. [37] developed power scaling laws in the form $y = ax^{b}$ for commonly used energy conversion equipments, such as boilers, engines and generators which can be of interest for IANOS. Starting from experimental datasets, they found scaling factors and constants a, e, b to relate the power of the equipment to mass, fuel consumption and cost, respectively. The parameters are reported in ***Table 3***.

Table 3: Exponent b and intercept a, for the parameters Mass M (kg), Fuel Consumption Q (kWh/h) and Costs C (US$) versus Power P (kW) using Ordinary Least Squares (OLS). n: Number of observations; R2: coefficient of determination; SE: standard error; CI: Confidence interval. [37]

Product	**OLS**		**n**	**R^2**	**SE**
	b (95% CI)	a (95% CI)			

M = a*Pb					
gasoline engine	0.77 (0.71-0.83)	0.73 (0.66-0.79)	43	0.94	0.08
diesel engine	0.64 (0.61-0.68)	1.36 (1.29-1.43)	89	0.95	0.05
marine engine	1.23 (1.14-1.33)	0.19 (-0.19-0.57)	35	0.95	0.10
generator	0.68 (0.63-0.72)	1.89 (1.82-1.96)	60	0.94	0.10
steam boiler	0.87 (0.84-0.90)	0.95 (0.85-1.04)	112	0.97	0.10
Q= a *Pb					
diesel engine	0.93 (0.92-.94)	0.55 (0.53-0.58)	75	1.00	0.02
marine engine	0.96 (0.95-0.97)	0.48 (0.45-0.51)	35	1.00	0.01
generator	0.82 (0.79-0.85)	0.68 (0.63-0.73)	59	0.98	0.07
steam boiler	1.02 (1.01-1.03)	0.06 (0.04-0.08)	61	1.00	0.02
C= a*Pb					
diesel engine	0.85 (0.79-0.91)	2.46 (2.34-2.58)	117	0.85	0.21
marine engine	0.83 (0.67-1.02)	2.57 (2.09-3.06)	19	0.83	0.24
generator	0.83 (0.81-0.85)	2.86 (2.81-2.91)	651	0.90	0.21

3.2 Scale up methodologies for *solar systems*

As suggested by Nemet et al. [38], the effect of increasing plant size of a solar photovoltaic (PV) field can be estimated as a first approximation using *Eq. 4*, using a scaling factor b = -0.18.

$$\Delta C = C0\left(\left(\frac{S1}{S0}\right)^{b} - 1\right) \qquad \text{Eq. 4}$$

This value is borrowed from the semi-conductor industry, which production processes are the most like those of PV. This value is within the range of assumptions used in studies that calculate future cost savings for large-scale PV, >100MW per year. Other PV scaling factors

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include the following: b=-0.07, b=-0.09, b=-0.12, b=-0.20. As authors suggest, the selected value lies at the upper end of the range because it is being applied historically, when smaller plant sizes probably were yielding more economies of scale than they would at the levels of 100–500 MW/year in the other studies.

3.3 Scale up methodologies for hydropower systems

Around three-quarters of the total investment costs of hydropower projects are driven by site-specific elements that impact the civil engineering design and costs which are difficult to predict. However, the electro-mechanical equipment used in hydropower plants is a mature technology, and the cost is strongly correlated with the capacity of the hydropower plant. The proposed capacity of a hydropower plant can be achieved by using a combination of a few large turbines or many small turbines and generating units. This will be influenced to some extent by the hydro resource, but is also a trade-off between guaranteeing availability (if there is only one generator and it is offline, then generation drops to zero) and the capital costs (smaller units can have higher costs per kW) [39]. The work in 2008 by Ogayar et al.[40] intends to develop a series of equations which determine the cost of electromechanical equipment (turbine–alternator) from basic parameters such as power and net head. In particular their method developed different equations which are suitable for the most common types of turbines: Pelton, Francis, Kaplan and Semi for a power range below 2 MW. The following equation represents the general expression to scale the cost of electromechanical equipment, where P is the power of the plant and H is the net head, a is a constant, and b and c are the coefficients for power and head, respectively.

$$Cost = aP^{b-1}H^{c} \qquad \text{Eq. 5}$$

Basing on a great number of real plants data, which are direct accessible in the paper, the authors calculated the parameters for the different cases, carrying on a best-fit analysis. The results are summarized in ***Table 4***. In all cases, the coefficient of determination, R2, is higher than 75%, indicating an acceptable level of prediction.

Table 4: *Power laws for different hydropower plants per turbine plants together with prediction Error range and Coefficient of determination*

Turbine type	Plant Cost function (€/kW)	Error range (%)	R2(%)
Pelton	$Cost = 17.693P^{-0.3644725}H^{-0.281735}$	-23.83,+20.015	93.16
Francis	$Cost = 25.698P^{-0.560135}H^{-0.127243}$	+22.27,-15.83	72.26
Kaplan	$Cost = 33.236P^{-0.58338}H^{-0.113901}$	+23.50,-18.53	91.70
SemiKaplan	$Cost = 19.498P^{-0.58338}H^{-0.113901}$	+23.50,-18.53	91.72

3.4 Scale up methodologies for wind power systems

The capital expenses (Capex) to construct a wind power plant comprise multiple types of costs and are generally broken down into two major categories: turbine capital costs (TCCs) and balance-of-system (BOS) costs.

In order to estimate the Turbine capital cost, the 2006 NREL technical report 'Wind design cost and scaling models' [41] propose a methodology to assess the impact of technical changes on the initial capital costs of the turbine. The model does not refer to all potential wind turbine configurations, but rather focuses on those configurations that were most common in the commercial industry at the time of writing. This configuration focuses on the three-bladed, upwind, pitch-controlled, variable-speed wind turbine and its variants. Primary cost elements covered in the model include: Rotor (blades, hub, pitch mechanisms, spinner, nose cone), Nacelle (shaft, bearings, gearbox, mechanical brake, generator, yaw drive, main frame, nacelle cover, hydraulic and cooling systems, electrical connections), Tower, Control System. In most cases, cost and mass models are a direct function of rotor diameter, machine rating, tower height, or some combination of these factors. The relationships are the following:

- **Blade**
  mass (kg) = 0.1452 * R $^{2.9158}$ (per blade), R = rotor radius (m)
  cost ($) = [(0.4019 * R^3 – 955.24) * BCE+2.7445 * R $^{2.5025}$ GDPE]/(1-0.28) per blade, BCE = blade material cost escalator, GDPE = labor cost escalator
- **Hub**
  mass (kg) = 0.954 * (single blade mass) + 5680.3
  cost ($) = hub mass * 4.25
- **Total pitch** (three blades)

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cost ($) = 2.28 * (0.2106*D $^{2.6578}$), D = rotor diameter (m)

- **Nose Cone**
  mass (kg) = 18.5 * D – 520.5
  cost ($) = nose cone mass * 5.57

- **Low-speed shaft**
  cost ($) = 0.01 * D $^{2.887}$

- **Bearings**
  mass (kg) = (D * 8/600 – 0.033) * 0.0092 * D $^{2.5}$

cost ($) = 2 * bearing mass * 17.6

- **Gearbox**: there are a range of designs and multiple ways to configure them. The work assumes four basic designs possibilities:

  Three-stage Planetary/Helical
  Total cost ($) = 16.45 * MR $^{1.249}$, MR = machine rating in kW
  Single-Stage Drive with Medium-Speed Generator
  Total cost ($) = 74.1 * machine rating $^{1.00}$
  Multi-Path Drive with Multiple Generators
  Total cost ($) = 15.26 * MR $^{1.249}$
  Direct Drive this approach has no gearbox

- **Brake/coupling**
  cost ($) = 1.9894 * MR – 0.1141

- **Generator:** despite the wide range of choices, the model limits its attention to high-speed wound rotor coupled with high-speed gearboxes, permanent-magnet generators coupled with single-stage gearboxes, multi-generator gearboxes, and direct drive.

  Three-stage Drive with High-speed Generator
  Cost ($) = MR * 54.73
  Single-Stage Drive with Medium-Speed, Permanent-Magnet Generator
  Cost ($) = MR * 54.73
  Multi-path Drive with Permanent-Magnet Generator
  Cost ($) = MR * 48.03
  Direct Drive
  cost ($) = MR * 219.33

  Variable-speed electronics
  cost ($) **=** MR * 79

- **Mainframe:** Mainframe mass and cost are functions of the type of drive train. Each drive train design distributes its load in a different manner and will have a

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different length. Mass and cost for the mainframe are calculated as a function of the rotor diameter. The mass functions for all three designs were assumed to follow the same power law function, which is slightly less than a square relationship.

Three-Stage Drive with High-Speed Generator

cost ($) = $9.489 * D^{1.953}$
mass (kg) = $2.233 * D^{1.953}$

Single-Stage Drive with Medium-Speed, Permanent-Magnet Generator

cost ($) = $303.96 * D^{1.067}$
mass (kg) = $1.295 * D^{1.953}$

Multi-Path Drive with Permanent-Magnet Generator

cost ($)= $17.92 * D^{1.672}$
mass (kg) = $1.721 * D^{1.953}$

Direct Drive

cost ($) = $627.28 * D^{0.85}$
mass (kg) = $1.228 * D^{1.953}$

- **Platforms and Railings**

  mass (kg) = 0.125 * mainframe mass
  cost ($) = mass * 8.7

- **Electrical connection** (including switchgear and any tower wiring)
  cost ($) = MR * 40

- **Idraulic cooling system**
  cost ($) = MR *12

- **Nacelle Cover**
  Cost ($) = 11.537 *MR + 3849.7

- **Tower** (the following formula are derived for steel tubular towers, using 1.50 $/kg in 2002 dollars for steel price. This need to be adjusted to IANOS case)
  mass (kg) = 0.3973 * A * H – 1414, A = swept area (m^3), H = hub height (m)
  cost ($) = mass * 1.50

Turning back to the BOS costs, it is worth to mention the NREL's Land-based Balance of System Systems Engineering (LandBOSSE) model [42]. It is an open-source tool for modelling the balance-of-system (BOS) costs of land-based wind plants. BOS costs currently account for approximately 30% of the capital expenditures needed to install a land-based wind plant, and it is expected to increase to 43% of wind power plant capital costs by 2030. The model includes all costs associated with installing a wind plant broken down into

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eight categories: 1) development, 2) management, 3) site preparation, including road construction, 4) foundation construction, 5) turbine erection, 6) collection system construction, 7) grid connection costs, including transmission and interconnection, and 8) substation construction. Reporting the equations in this report it has been considered beyond the scope of the work. However, since the model could be inspiring for the IANOS tool, Figure 2 shows the results of the application of the model [43] to study how the capex of a wind turbine plant scale as a function of the turbine size and the plant capacity, simultaneously. The tool could be also used to calculate cost for different plant capacity and then calculate a comprehensive scaling coefficient according to Eq. 3.

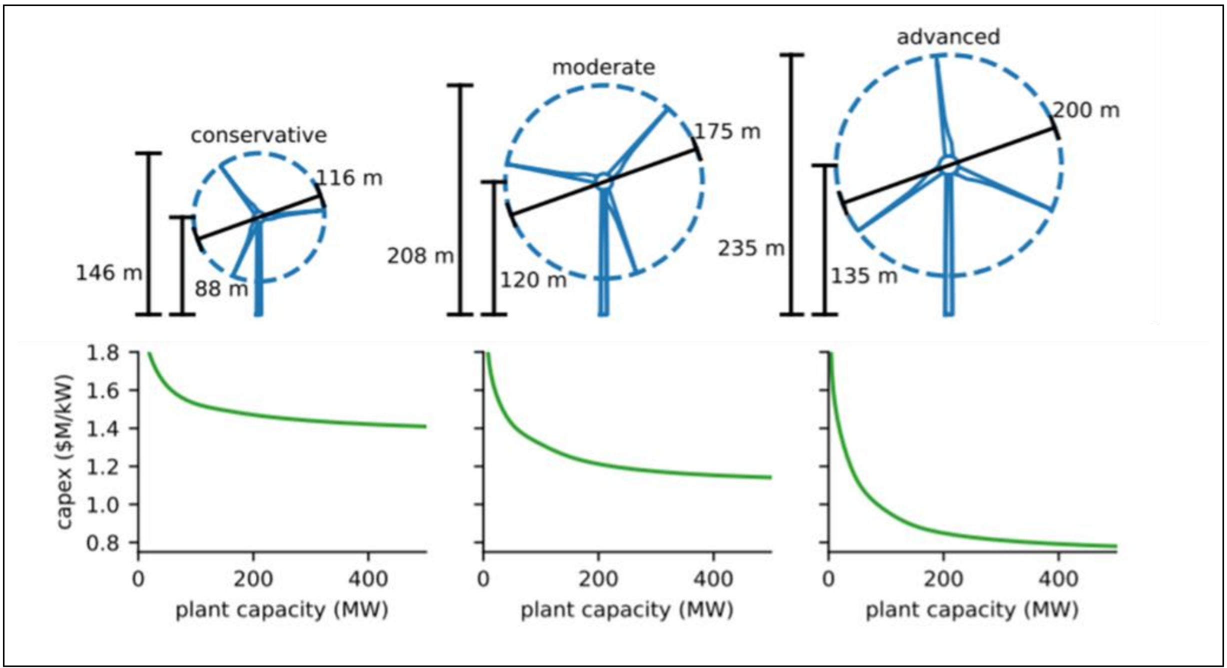

Figure 2: *Capex scaling with turbine and farm size. Result of the application of the NREL LandBosse MODEL as applied by ref [43]*

Increasing turbine size is one of the major factors that has been attributed to the sharp cost declines in offshore wind. This is because larger capacity turbines generally yield lower balance-of-plant costs (as depicted in Figure 2, fewer and faster installations, and lower maintenance, as well as more energy per unit of area. Moreover, recent cost information also indicates that in addition to these project cost-scaling benefits, unit turbine costs may not be rising with turbine capacity as originally predicted by early models (such as the 2006 NREL Cost and Scaling Model previously analyzed) In fact, a higher turbine rating may not result in an increase in per-unit turbine capital expenditures (Capex) ($/kilowatt [kW]) when the turbine dimension is scaled using innovative materials.

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3.5 Scale Up Methodologies for energy storage systems

In order to process an effective integration of the renewable energy sources into the energy distribution grid, IANOS forecasts a variety of energy storage systems, which will be implemented both on a private, industry and community level. This report focuses on heat batteries and lithium batteries.

As underlined in the work carried out within the European Project FLEXYNETS [10], the specific investment costs of heat storages (defined as costs C per unit of volume) are dependent on its dimensions. Consequently, the total cost can be expressed in function of the storage Volume with the following power law:

$$\frac{Cost}{V} = a * V^{b} => Cost = a * V^{b+1} \qquad \text{Eq. 6}$$

For a given type of storage, the constants a and b can be found by fitting a power-law to a data set containing investment cost data for an array of differently sized storages.

Making the right substitutions, the cost can be directly scaled with the storage capacity, according to Eq. 7, where ρ is the density of the storage medium (kg/m3), cp is the specific heat (kJ/kgK) and ΔT (K) is the difference between the maximum and minimum operating temperature of the storage to store an energy Q (kJ) in a volume V (m3).

$$Cost = a * \left(\frac{Q}{\rho * cp * \Delta T}\right)^{b+1} \qquad \text{Eq. 7}$$

The work analyzed covers the following cases: Tank Thermal Energy storage (TTES), Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES). Figure 3, Figure 4, Figure 5, and Figure 6 show the specific investment costs scaling according to both Eq. 6 and Eq. 7 for the previous listed technologies.

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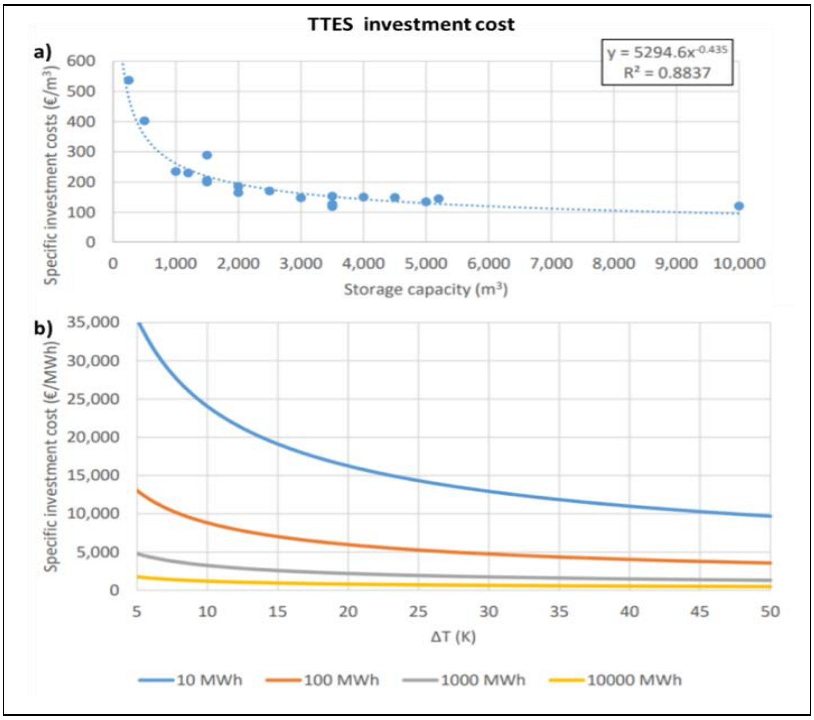

Figure 3: *Specific investment cost for TTES a) as a function of volume and relative regression curve b) as a function of the maximum temperature difference in the storage for four different capacities. Readapted from ref.[44]*

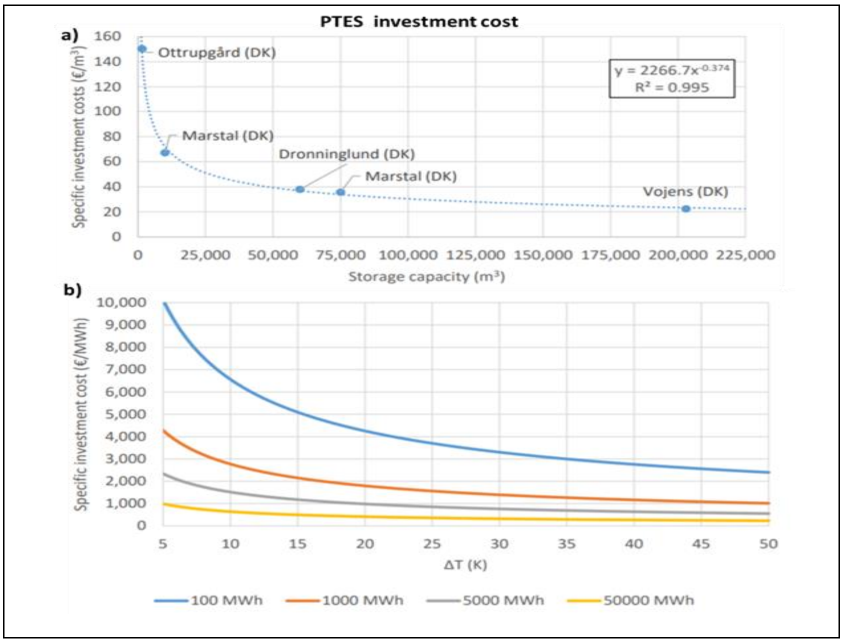

Figure 4: *Specific investment cost for PTES a) as a function of volume and relative regression curve b) as a function of the maximum temperature difference in the storage for four different capacities. DK=Denmark. Readapted from ref [44]*

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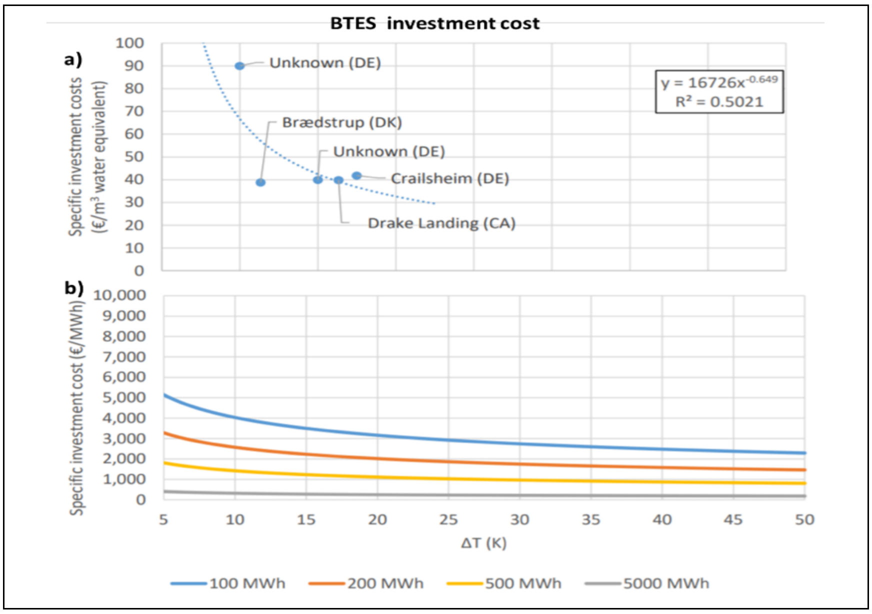

Figure 5: *Specific investment cost for PTES a) as a function of volume and relative regression curve b) as a function of the maximum temperature difference in the storage for four different capacities. DK=Denmark, DE=Germany, CA=Canada. Readapted from ref [44]*

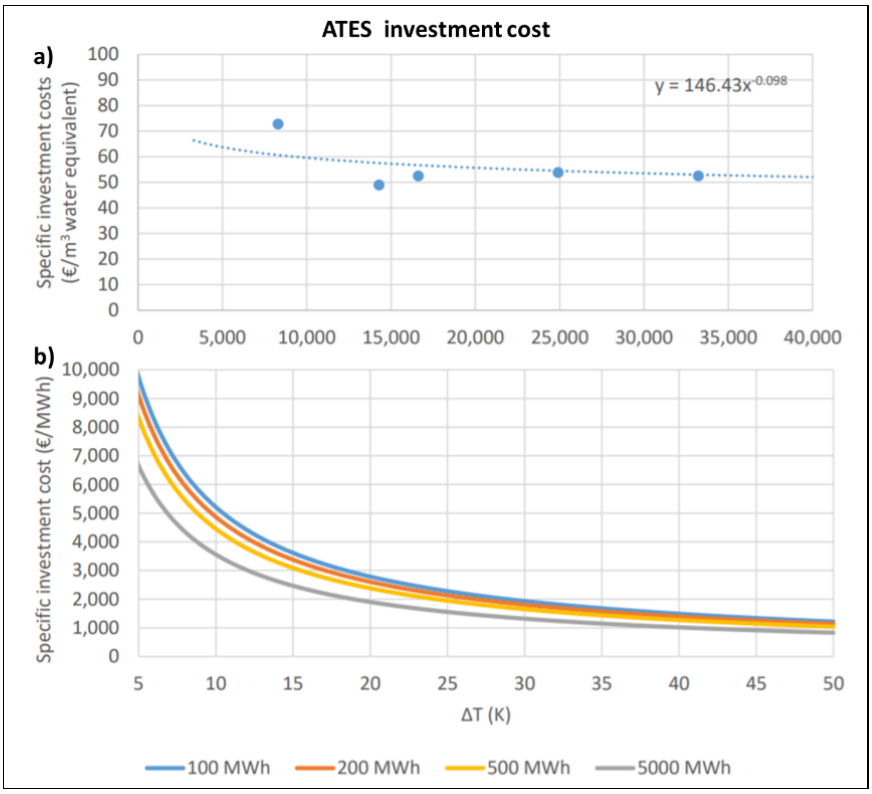

Figure 6: *Specific investment cost for PTES a) as a function of volume and relative regression curve b) as a function of the maximum temperature difference in the storage for four different capacities. Readapted from ref [44]*

Regarding Lithium-ion batteries, to the best of our knowledge, there is no report in literature reporting cost scaling coefficients for this energy storage category. However as depicted in Figure 7, this type of battery does experience only little economy of scale increasing the Power Capacity, while there is a strong dependence on the duration (maybe because it directly impacts the inverter sizing) [45].

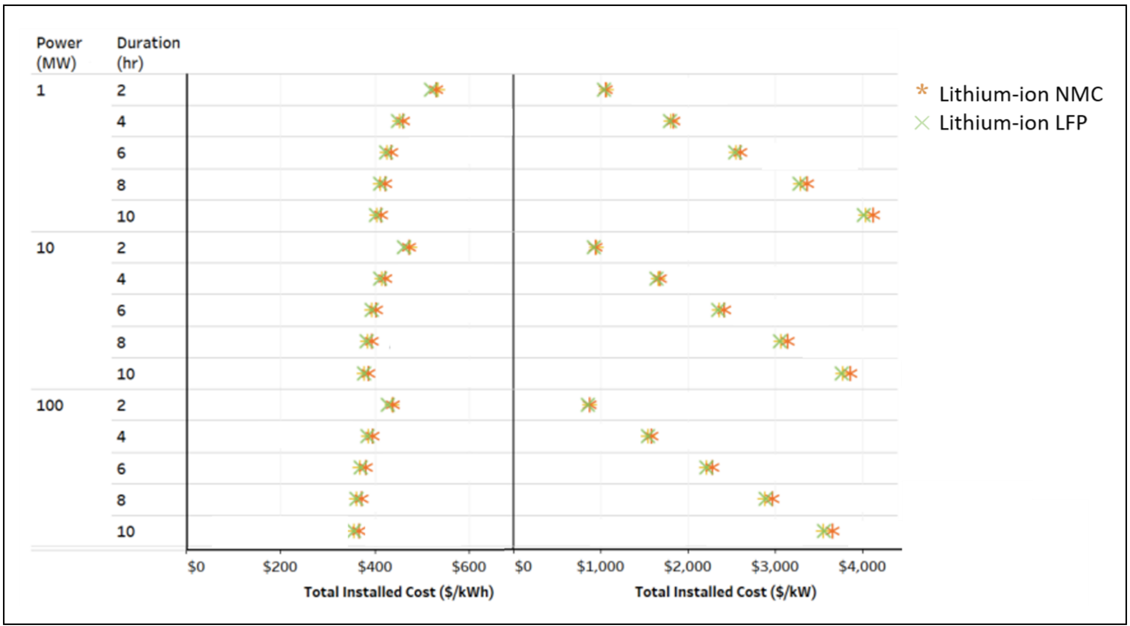

Figure 7: *2020 Total Installed Energy Storage System Cost for Lithium-ion batteries. Readapted from ref [45]*

A study made in 2015 by Nelson et al.[46] took into account 3 types of batteries with the same number of cells for each battery: a baseline battery, a second battery with twice the power of the baseline battery, a third battery that has the same power as the baseline battery, but twice the capacity. They found that overall, doubling the power of the battery increases the price of the battery pack by only 25 %. Doubling the capacity of the cells increases the cost by 56 %. In a fourth case, doubling the number of baseline cells and modules within larger battery jacket (two rows of modules instead of one, twice the voltage, energy, and power) would increase the cost by 75 %. A Table with the detailed cost analyses for the four cases can be found in the primary source.

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In the Annex 3, the main results of some alternative scaling methodologies studied and examined are presented. The research on the alternative methodologies, is not planned to be utilized in VERIFY-D although it helped us to point out the possible approaches and identify the optimal one for IANOS demo cases. Our selected approach is based on cost-to-capacity methodology and is extended to multiple energy grid sectors as analysed in Section 3.6

3.6 Scale-up methodology for IANOS cases' energy grid

The overall aim of the literature review regarding LCA, LCC, and scale-up methodologies, was to provide necessary information regarding the existing situation of the technologies of interest and serve as a mapping process outlining required data. Utilizing these data and considering the specific needs of IANOS pilot sites, led to the development of a methodology, necessary for the development of the VERIFY-D tool. The steps followed for the methodology are described below:

- Clear definition of the overall goal: In the case of IANOS project, the aim is to examine the environmental impacts and associated costs from the implementation of RES based and grid counter-congestion strategies on a user and/or community level.
- Boundary selection for LCA: Based on literature review, it is noticeable that most of the existing case studies follow a cradle-to-grave lifecycle approach. IANOS project will follow the same approach, considering all stages of a product's lifetime (from extraction of materials required for the production of the technology, production, transportation to the installation site, use phase, end-of-life scenarios).
- Definition of Cost categories for LCC: Following the LCA approach, the LCC calculations will take into account all cost categories related to the implementation of each component (Acquisition costs, Operation and Maintenance costs, External/Environmental costs, End-of-life costs).
- KPIs for calculation: To present a more holistic approach, IANOS methodology aims to perform various calculations. In terms of Environmental KPIs specific emphasis will be given to the calculations of GHG emissions, however other KPIs could be calculated (such as Cumulative Energy Demand etc.). In financial terms the focus is the overall LCC calculations, however as in the case of environmental analysis, other

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KPIs could potentially be calculated (Internal Rate of Return – IRR, Net Present Value – NPV, etc.).

- Scale-up scenarios: IANOS project aims to examine the potential interventions not only at a single user/building level, but also from a district perspective. To achieve this goal, the proposed methodology follows a scale-up approach based on the literature review. There is the possibility to examine the implementations as a whole or focus on specific components. Based on the incorporation of various technologies and the complexity of IANOS project demo sites, Cost-to-Capacity methodology is proposed for implementation as the appropriate scale-up methodology. As discussed, one of the main advantages of Cost-to-Capacity methodology is the fact that could be used with ease in various applications, in order to quickly generate cost of magnitude estimates. Due to the complex data for each demo site, it is further proposed to utilize the 0.6 rule, meaning that the scale exponent for the cases of IANOS will be equal to 0.6.

Initially, the analysis is planned to be divided into two categories: a) the analysis of the current energy grid, and b) the analysis of the energy scenario with the planned interventions. The adoption of this approach will facilitate the comparison of the results, and lead to holistic conclusions regarding the benefits of the planned energy interventions.

Taking into consideration the planned energy interventions as a whole, the corresponding components data are collected, forming the relevant life cycle inventories. As the pilot demonstrations touch on various regions of the energy grid, it is useful to be allocated in predefined sectors. It is worth mentioning that the sectors are defined in order to fit on project objectives. Details about the sectors selection/definition for the current analysis are provided in Section 3. Regarding the environmental and financial analyses, various stages of the lifecycle (e.g. production, transportation, installation, use phase, end-of-life) will be taken into account. The usage of the various components is calculated either from simulations in external software tools (in the form of synthetic data), or from real data retrieved from sensors/meters. It is of utmost importance to note at this point that, when possible, the usage of an asset is estimated by encompassing it into the system, in which it is located. For example, to measure the consumption of a boiler into a building, a thermal analysis for the whole building should be realized, taking into consideration the wall insulation, the glazing etc. On the other hand, the production of a solar farm is estimated independently of the electrical grid, at which this is installed. The components for potential installation on the IANOS demo sites are categorized in specific sectors based on their potential use. The aggregated results of each separate component provide the overall results per sector both from environmental, and financial standpoint. Hence, a comparative analysis between the same sectors of the current and the planned energy scenario can be performed. Furthermore, the results are aggregated for all sectors, leading to a holistic comparative analysis of the two scenarios, providing a general overview of the planned demonstrations in terms of environmental and financial performance.

The methodology described above is presented in Figure 8, in the form of a flowchart presenting the steps from data collection to results extraction.

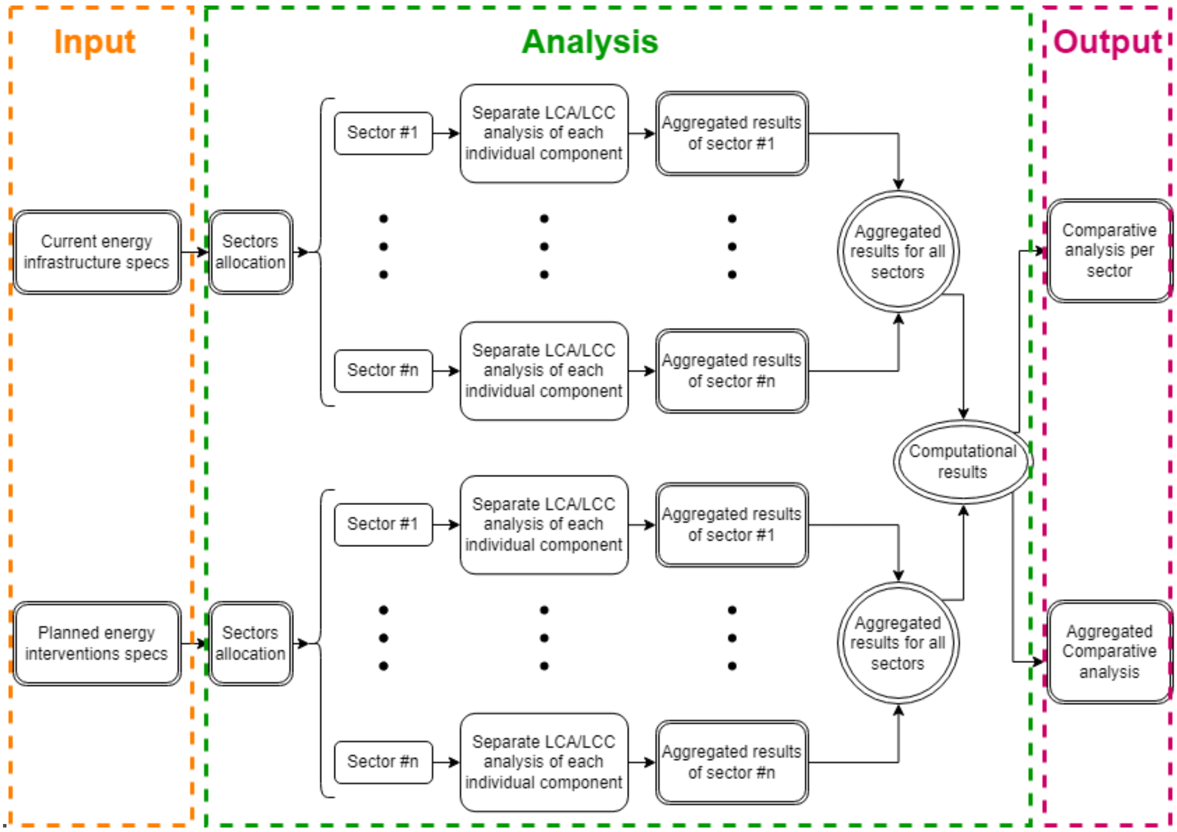

Figure 8 *Methodology for environmental and economic analysis at district/city/island level*

4 Description of VERIFY–D

4.1 VERIFY – D Platform overview and objectives

A variety of tools have been emerged by researchers and technical experts for the lifecycle analysis in terms of environmental and economic impact. An online tool to estimate building lifecycle CO2 emissions and evaluate the produced carbon footprint in the construction of residential buildings was developed by Solís-Guzmán et al. (2018), named “OERCO2 tool”, attributed to the respective project [49]. Jayathissa et al. [50] applied an open-source LCA software to assess the environmental impact of dynamic Building Integrated Photovoltaic (BIPV) systems. The tool was developed for first time by Ciroth in 2007 [51], named OpenLCA. Becalli et al. (2016) [52] implemented a LCA tool specifically developed for the evaluation of energy and environmental performance, and payback time calculation of solar thermal systems, provided for free online by the International Energy Agency (IEA). The tool was further developed and named “ELISA tool” aiming to assist in the benchmarking of solar heating and cooling systems (SHC) with conventional systems as well as with systems assisted by PV. Di Bari et al. (2020) [53] developed a tool named “Storage LCA Tool” and combined LCA and energy simulation to evaluate and compare the environmental impacts of Phase Change Material (PCM) systems with those of traditional systems in buildings, for different climatic zones and building typologies at European level. “Storage LCA Tool” is an online free software aiming to provide indicative results and insights for the environmental performance of thermal storage materials and systems for building applications. Regarding the LCC analysis, Pernetti et al. (2019) [54] developed, within the context of H2020 CRAVEzero project, an nZEB cost spreadsheet to estimate the life-cycle costs and identify the main barriers and best practices for cost optimization of nZEBs across Europe. The need for real-time LCA calculations led to the development of tools that take into account the dynamic behavior and temporal variations of the systems. In this context, Su et al. (2017) [55] proposed a dynamic LCA (DLCA) framework for the environmental impact assessment of buildings and constructions.

Literature research indicated the lack of software tools aimed to cover the environmental and costing analysis under multiple energy grid sectors such as the renewable energy production, the energy storage etc. within a district/city/island level. In contrast, the developed “VERIFY-D” software platform offers: 1) an integrated LCA & LCC calculation methodology based on a holistic life cycle approach considering both existing energy grid infrastructure and planned energy grid transition, under specific interventions; 2) a personalized project setup and creation by capitalizing on country specificities, meteorological data, material data, building properties and specific user preferences divided into multiple sectors; It also consist of 3) a private database for materials and technologies (both conventional and innovative) taking into account the primary energy and the carbon emissions during infrastructure stage. It provides also 4) the ability to store a large amount of data in private data repositories through the CPERI/CERTH Data Lake; 5) the possibility to communicate with external tools related to energy modelling and simulation in order to obtain synthetic energy data (i.e., energy simulation data) useful in the LCA and LCC analysis and finally 6) the ability to perform real-time LCA and LCC analysis in hour basis starting from building to district/city/island level.

The VERIFY-D methodology can be further applied to model and perform multi-domain LCA analysis, considering the impacts of 1) private and public buildings, 2) transportation infrastructure elements, 3) produced energy of RES and non-RES technologies, 4) energy storage systems.

For obtaining more accurate results almost all the stages of the value chain are considered (e.g., production, use phase). VERIFY-D as a software tool combines the static LCA-LCC analysis with the dynamic use phase of system components set during the specified lifetime. Input data (either real-time or near real-time or synthetic) from multiple external sources or tools (specifically for synthetic type of data), will be supported through custom API implementation. A large variety of innovative technologies will be demonstrated, as main scope of IANOS. The operation and environmental assessment of which, in terms of LCA and LCC terms, will be analysed using VERIFY-D. In addition, data repositories will assist the platform functionality, by storing large amount of data in specific ontology frames (e.g. SAREF[8] ontology). In contrast with other LCA-LCC applications, VERIFY-D is based on open-source libraries, frameworks and databases (e.g., Python, Ruby on rails, PostgreSQL etc.) eliminating the dependencies with closed code tools. During the next sections, a detailed presentation of the various parts of the platform is provided.

[8] https://saref.etsi.org/

4.2 VERIFY – D platform architecture

VERIFY-D is completely developed by CERTH/CPERI using solely open-source and proven technologies. The architecture of the application is designed so that it allows the implementation of the following features:

1. Multiple user accounts (device gem Ruby on Rails[9])
2. Effortless setup of energy plans through interactive forms (Bootstrap[10] framework)
3. Storage of application data into a reliable database (PostgreSQL[11])
4. Monitoring and gathering of remote sensor data (MQTT[12], Sidekiq[13])
5. Methodology framework for the environmental planning and the operation of the energy/smart grid systems through well-defined performance indicators. (Python[14] programming language)
6. Connection with external software tools through RESTful custom APIs (Ruby[15])

The core of VERIFY-D follows the classic design of a web application and is divided into three layers: 1) The front-end, 2) the back-end and 3) the middle-end. Each layer is responsible for a specific set of actions. Moreover, background processes are incorporated into the main application to handle demanding tasks. VERIFY-D can be described as a monolith application, meaning that all the individual parts are implemented in the same program. The source code resides in the same project structure, contrary to other designs where each part of the application is separated into different services. The technologies used and the way they are interconnected to provide the final form of VERIFY-D are thoroughly presented in the paragraphs below.

[9] Device Ruby Gem
[10] Bootstrap
[11] PostgreSQL
[12] MQTT
[13] Sidekiq
[14] Python
[15] Ruby Programming Language

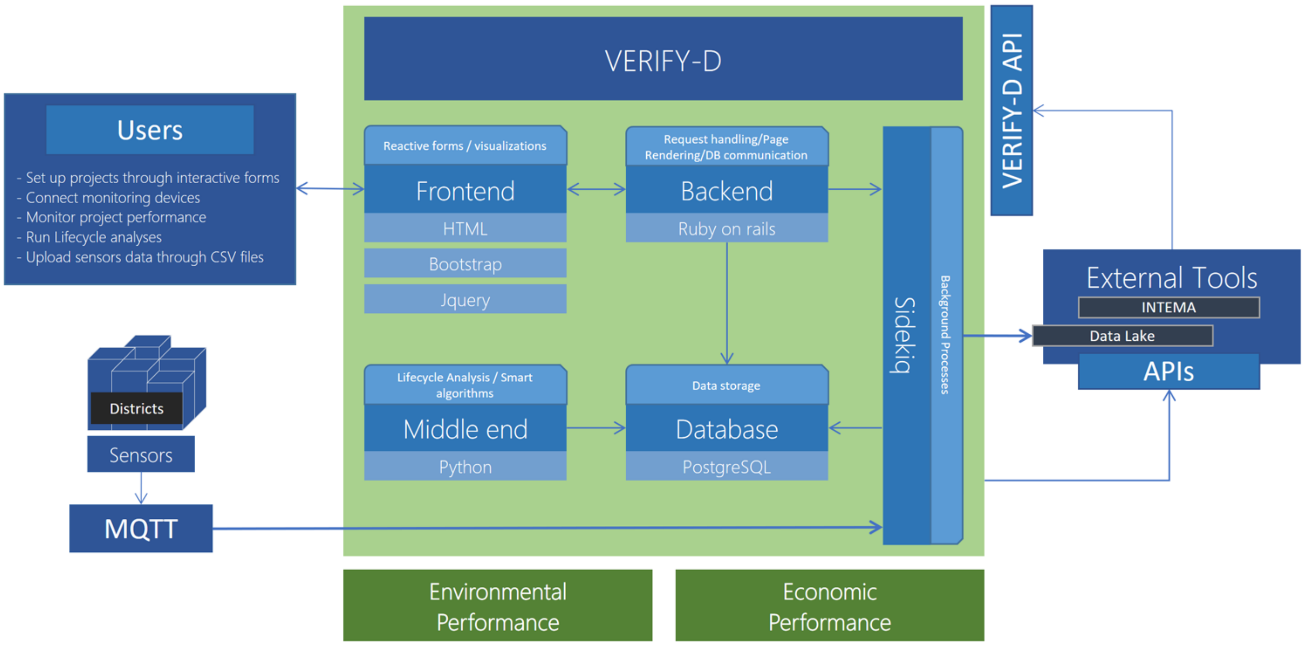

Figure 9 *VERIFY-D overall Architecture*

4.2.1 Front-end platform environment

The architecture of VERIFY-D, as depicted in Figure 9 starts from the interaction of the end-user with the Front-end layer of the application. The front-end layer assists users to perform the following actions: 1) set up a district/city energy grid plan, 2) connect monitoring devices responsible to gather real time data from distributed energy infrastructure of a district/city/island, 3) upload historical sensor data using files in CSV format and 4) perform life cycle analysis (under environmental and costing terms) of a district/city/island energy plan. VERIFY-D supports these user actions through a user-friendly and responsive graphical interface, interactive forms that enhance user experience and finally dynamic charts that plot useful information, such as the results of the life cycle analysis.

Several tools were orchestrated to design and implement the VERIFY-D tool. More specifically, the basic HTML view of a VERIFY-D's page is given form using the Bootstrap[16] CSS framework, an open-source toolkit that is used to quickly design responsive websites. Along with Bootstrap, JQuery was used to add extra functionality to the view, such as opening/closing modal forms. JQuery[17] supports easy document manipulation, event

[16] Bootstrap

[17] jQuery

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handling and animations, is a mature project and is used vastly in the development of web applications. Finally, various JavaScript libraries are used to facilitate the fast development of the platform. One JavaScript library worth mentioning is ChartJS[18], an open-source data visualization project which is used to plot the data in dynamic and interactive charts.

4.2.2 Back-end platform environment

The front-end of the application communicates directly with the back-end through the HTTP protocol. Under the back-end layer, the core of the application and the actions coordination takes place during the VERIFY-D operation. The back-end layer is responsible for handling user requests, performing the corresponding actions and generating the expected analysis results. The communication between back-end system and the database of VERIFY-D, serves the ability to add or remove records from the database, as well as perform validation on these data to ensure the system's integrity. For the implementation of VERIFY-D's back-end Ruby on Rails[19] (RoR) was used. Ruby on Rails is a full-stack web framework which is used to develop web applications and contains a set of tools to make the development quick and easy. It is shipped under the MIT Open-Source license and it is supported by a large community of developers. RoR follows the Model-View-Controller development pattern that offers a clean code structure. It is written in Ruby[20], an object-oriented programming language, which has been also used for the development of VERIFY-D's back-end system. A strong point of RoR is the easy modelling of the database's Tables. More specifically, each Table can be modelled as a Ruby class and the data can be easily fetched or removed, without the need of composing complex queries. Additionally, constraints can be imposed on the various models of the database so that invalid data will never be inserted into the database. The aforementioned features render the back-end easily extendible and less prone to programming and user errors.

4.2.3 Database scheme of VERIFY-D

VERIFY-D needs to store various data into a database to keep track of 1) user preferences, 2) energy plans created and their details, 3) time series data and 4) the results of the life cycle analysis. To achieve that, a strong and reliable database system is required.

[18] Chart.js
[19] Ruby on Rails
[20] Ruby Programming Language

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PostgreSQL[21] was selected, based on: 1) the object-relational approach, 2) the open-source formation, 3) the ability to manage various volumes of data as well the support of complex data types. It conforms with the SQL prototype, however, it is easily extensible and offers a variety of additional features compared to a classic SQL database, such as custom type columns. PostgreSQL is released under the PostgreSQL License, which is similar to BSD or MIT licenses. As the communication with the database must be rapid and accurate, due to the usage by many peripheral components it is installed under the platform framework. As a result, we aim to avoid confidential data transfer through external networks.

4.2.4 Background task scheduler of VERIFY-D

Besides the jobs that the back-end performs in the foreground after receiving user requests, VERIFY-D also supports background jobs (i.e. tasks) that run independent tasks along the main application. Such tasks can be of two types: 1) tasks that run indefinitely, such as a daemon that listens to an MQTT queue and 2) tasks that are initiated from the back-end to perform a long process in the background and they are terminated after the task is completed, such as requesting data from an external tool that takes some time to respond. The second type of tasks is required so that the user can continue using the platform without interruptions. After such tasks finish their execution the front-end is instructed to show a notification so the user is aware that the request is completed. To implement such functionality Sidekiq[22] is used. Sidekiq is a Ruby library that is usually used along RoR applications and handles background processes efficiently. Sidekiq is not a part of the main application, but it is tightly connected to it as they share the same database and the back-end can start jobs in the background using it. Sidekiq is an open-source project, under the LGPv3 license. The standard-free version is enough to cover VERIFY-D needs in terms of IANOS.

4.2.5 Middle-end platform environment

Middle-end environment introduces the layer where smart algorithms considering LCA and LCC analysis are implemented. The need for fast performance and complex mathematical computations leads to the selection of Python[23] programming language. Python is a

[21] PostgreSQL
[22] Sidekiq
[23] Python

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versatile, easy to use language supporting fast development of software. It also supports efficient, well known and vastly supported libraries for arithmetic operations (numpy[24]) and the manipulation of large data (pandas[25]). To be successfully executed, the smart algorithms require time series data regarding the district/city's energy consumption/production. To obtain this data the middle-end communicates directly with the PostgreSQL database. After the analysis is conducted, the middle-end layer exports the results to the front-end layer, which is responsible for the environmental and costing KPIs display to the user.

4.2.6 Communication protocol VERIFY-D - external software tools

As mentioned earlier in this section, VERIFY-D needs time series data to proceed to analysis perform. Time series data can be divided into three types: 1) historical, 2) synthetic and 3) real time. Historical data are archived data that originate from past monitoring, while synthetic data are artificial and closely approximate the real time series. Real time data are gathered live from smart IoT devices and gradually transition to historical data. Generating synthetic data is out of VERIFY-D's scope, so communication with external tools is necessary. Moreover, VERIFY-D's database is designed to store the minimum amount of time series data needed to perform it analysis for a district/city, however, real time data emerge continuously, imposing the need for a big data repository, which holds large time series data and is readily available to provide a subset of this data upon request. In the following paragraphs the various data sources and external tools VERIFY-D communicates with are presented in detail.

The first source of measurements is CSV files uploaded by the user. This way of inserting measurements into the database requires the user's participation and that may not always be possible. For that reason, measurements can also be generated from an external tool and passed to VERIFY-D's database to be used for the analysis. That way the analysis can be conducted using synthetic data that are a realistic approximation of the real performance of the infrastructure. The historical or synthetic data can be augmented with the real measurements that come from IoT devices. This type of measurements come from the third source which is MQTT queues. Energy monitoring devices can be connected to VERIFY-D

[24] NumPy
[25] pandas

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and their measurements are collected and stored to VERIFY-D's database automatically. That way the Life Cycle Analysis can use a combination of existing or synthetic data and the latest data that come from the MQTT queues. These queues are monitored by a Sidekiq background service.

The main tool that VERIFY-D currently communicates with is INTEMA.grid. INTEMA.grid is a web service that is part of the VERIFY-D ecosystem and is used to provide VERIFY-D with time series data when the user is unable to do so. That way the Life Cycle Analysis can always be conducted, using synthetic data. The communication between the two platforms is achieved using INTEMA.gird's RESTful API. Upon a user's request for synthetic data, the back-end initiates a background job using Sidekiq, which in turn sends a request to INTEMA.grid and waits for the response without interfering with the user's actions, as INTEMA.grid requires a couple of minutes to complete its analysis. After the data is generated, INTEMA.grid sends back its response, the VERIFY-D's background process stores the time series into the database and sends a push notification to the front-end in order to inform the user about the completion of the task. After this point the user can run the analysis using the generated data from INTEMA.grid.

In case of large amounts of historical data combined with real time data to be stored and retrieved, dedicated repository schemes are necessary.

4.2.7 Big-data storage repository and connection to VERIFY-D

The necessity of complex computations and continuous update of life cycle analysis may demand large amount of data information. These historical and/or synthetic data combined with real time information demand a dedicated big data repository scheme. A custom Data repository scheme as presented in Figure 10, developed by CERTH/CPERI, can provide an accurate way to persist and filter large batches of data. Data can either be stored or utilized by any external software (VERIFY-D in this case). In Figure 10, the custom Data Lake repository architecture and the connection with VERIFY-D is presented. More specifically, hourly/daily measurements sent by remote locations (district/city/island) can be stored directly to the Data Lake scheme. A new Apache Kafka[26] topic is automatically created, for each of the remote sensors while a VERIFY-D's background service pushes the

[26] Apache Kafka

measurements into the repository. The Data Lake scheme is developed using HDFS[27] (Hadoop Distributed File System) as the file system to store the measurements information and performs three main activities: 1) data aggregation through Apache Kafka, 2) an ontology-data validator developed in Python and 3) the Hadoop directory for storing RDF data[28].

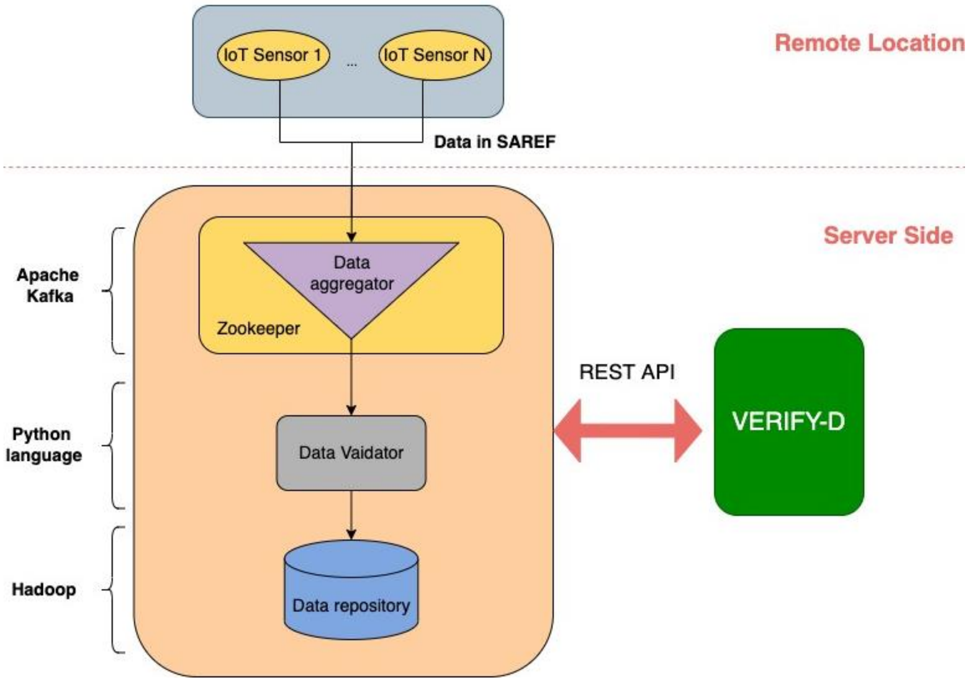

***Figure 10**: CERTH/CPERI Big data lake repository architecture and connection with VERIFY-D*

Remote sensors provide measurements in real-time formatted under the SAREF[29] ontology. After data aggregation is performed, inspection procedure starts (task responsible is data validator entity), to ensure that the incoming information is align with the predefined SAREF protocol. If case of successful operation, the data are stored permanently in the Data Lake. In any other case, data are discarded. Useful data information can be fetched by other applications (e.g.VERIFY-D in this case), using the Data Lake's RESTful API. The API uses SparQL[30] queries under the hood to select the requested data and return them to the requested application. VERIFY-D platform is dedicated only for storing the latest required measurements for the LCA and LCC analysis to be conducted. Large amount of historical data can be requested from CERTH/CPERI Data Lake or any other similar software.

[27] HDFS Architecture Guide
[28] RDF
[29] SAREF Portal (etsi.org)
[30] SparQL

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4.2.8 VERIFY-D conversion into Docker compose

Being a part of a more general tool (IEPT tool) VERIFY-D will eventually be containerized so that it can be used directly as a service. Using Docker, an open-source and mature technology for containerizing applications, VERIFY-D can run in its isolated environment which is set up and configured exactly as needed in order for VERIFY-D to run successfully. Moreover, the application can be easily deployed without the need of any local system configurations and software installation as long as Docker is installed. This way VERIFY-D can either run stand-alone or as a component of a larger system. Moreover, multiple instances of the application can be run using the same Docker image (i.e. a template) each one in its own space and database.

4.3 User interface for LHs setup through VERIFY – D

Following the previous two sections, in which the objectives and architecture of the platform were presented, this section presents the detailed information and steps for setting up energy grid scenarios and performing the environmental and economic analyses using VERIFY–D. Both conventional and innovative technologies can be modelled under the proposed platform.

VERIFY–D platform offers a friendly and functional user interface (UI) for realizing LCA/LCC analyses. Firstly, the user needs to fill a relatively small set of mandatory input fields provided with adequate data for the developed models of VERIFY – D to perform the environmental and economic analyses. Secondly, after UI-form filling a straight sequence of steps guides the platform user to complete the current and planned project creation. Thirdly, input data are accompanied by an explanation to clarify the requested data and help the user in the set-up process. Lastly, to perform the LCA/LCC analyses only two main steps should be followed: i) energy scenario configuration, and ii) timeseries fill/upload.

Considering the first step (energy scenario configuration), the effort is on conducting a categorization of the examined interventions based mainly on IANOS specific needs and objectives and taking into consideration the results from an extended literature review. As proposed through the national long terms strategies provided by the European Commission in [56], the proposed emissions targets are defined per sector: Power, Industry, Transport, Buildings, Agriculture, Waste, Land use/Land use change/foresting (LULUCF). Consequently, the categorization of the set targets into subcategories helps importantly the monitoring of the energy transition progress and the achievement of goals.

Furthermore, in [57], the boundaries of the LCA analysis include the energy consumption of four sectors: i) transport, ii) building, iii) public lighting and iv) tourist sector. Hence, it seems that the performing of an analysis through convenient sectors is applied also in LCA studies, which is one of the fields of interest of the developed platform. However, according to the nature of each analysis appropriate sectors should be selected to serve its specific peculiarities.

As in the IANOS project many demonstration activities concern the energy production from RES units and its storage in conventional and innovative energy storage systems, such as large Battery Energy Storage Systems, Flywheels, Biobased Saline Batteries etc, the division of the Power sector into Energy Production and Energy Storage sectors is expected to facilitate the analysis. Hence, the assessment of the generation and storage systems is conducted separately to be of the desired detail and depth.

Additionally, given that VERIFY–D is a platform for realizing LCA and LCC assessments, applied mainly in cities and/or islands for creating smart grids (and for serving the IANOS needs), the agricultural sector, proposed by the EC is not appropriate (at least in the current version of the platform). In IANOS there are not many plans for improving the waste management in the districts (except from the incineration plan, that can be also included in Energy Production Sector), and thus, a waste sector would be unnecessary. It is worth mentioning at this point, that VERIFY – D is a fully extendable platform, and in future releases, it can adopt any other category that could fit the objectives of new projects. Bearing in mind the above, VERIFY–D adopts five (5) sectors considering the LCA and LCC analysis:

1. The building sector, for taking into consideration all the energy renovations performed in residential buildings (hybrid heat pumps, roof solar panels etc.),
2. The transport sector, for assessing the environmental and economic benefits from electric vehicles integration,
3. The energy Production sector, mainly for estimating the impact of the renewable energy sources penetration (Wind parks, Solar farms, Hydro power plants etc.) in the grid,
4. The energy Storage sector, for assessing the results from the storage systems use (Batteries, Flywheel etc.) and
5. The public Infrastructure, for analyzing new technologies that are not included in the previous four categories, in the public domain (hybrid transformer, smart lighting etc.).

In the following two sections the two main stages that should be followed to perform an LCA/LCC analysis are described in more detail.

4.3.1 Energy Scenarios Configuration

The platform user should follow a number of steps in order to complete the set-up of the scenarios. In this section the configuration of a new energy scenario is described in detail. Apart from the figures that present the input fields of VERIFY-D, Tables can be found below with short explanations of the input forms.

As a first step, it is highly recommended to provide a project name not only for a more convenient classification of the various created projects, but also for easier future amendments and modifications. Afterwards, it is mandatory to choose the country where the project is located along with the coordinates of the district. Using this information, meteorological data are retrieved (solar irradiance, temperature) from appropriate APIs, economic and environmental country-specific values are selected (fuel prices, emission factors etc.), and a more realistic analysis is realized. In Figure 11 and in Table 5 the input forms of the project details are given.

Table 5 *Project details input information*

Project name	The name of the created project
Country	The country in which the project is examined

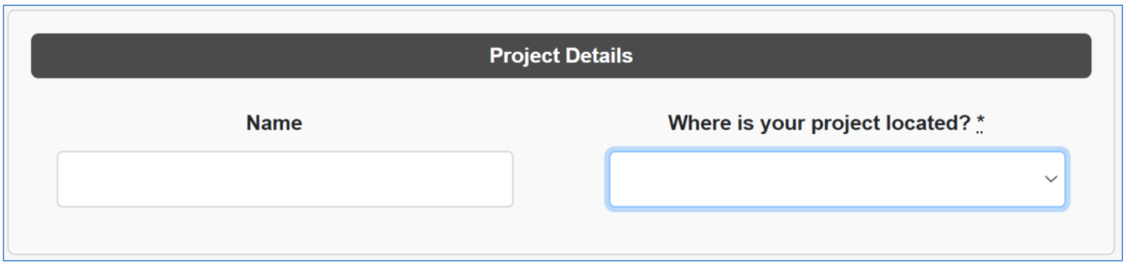

Figure 11 *User interface - Project details input forms*

The VERIFY – D platform has been created in order to compare different energy scenarios. For that reason, the user should provide data for two energy scenarios of the same project,

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namely the current and planned one. Naturally, the two scenarios are completely identical in terms of the fields that need to be completed, the filling procedure etc.

By choosing a scenario setup the various sectors, to which the analysis is divided, appears. This version contains 5 sectors: Building, Transport, Energy Production, Energy Storage and Public Infrastructure sector. The user can edit all or part of the sectors separately, without following a specific order. In the next sub sections, a detailed description of the input forms of each sector is presented.

4.3.1.1 Building Sector

The current sector contains only one category of buildings (private buildings) but can be extended to more building categories in future versions (e.g., schools, universities, hospitals). By selecting the type of a building, a new button is created which reveals the editable default values of the building envelope. Hence, if there is detailed information of the building at user's disposal, it can be inserted instead of the defaults values for more accurate results.

For each new building addition, the user can insert a number, which indicates the number of identical buildings that share common structural characteristics and energy demand/production profiles. If the latter field stays empty, one building is assumed. Afterwards, various components from a pre-specified list (Batteries, Photovoltaics, Wind Turbines, Heating Components and Cooling Components) can be added (Figure 12). For simplicity reasons, only one component per category can be chosen. Of course, the user can choose only a subset of the aforementioned categories. For every component selected, some specifications should be completed. Below are presented the figures with the mandatory data for each component category.

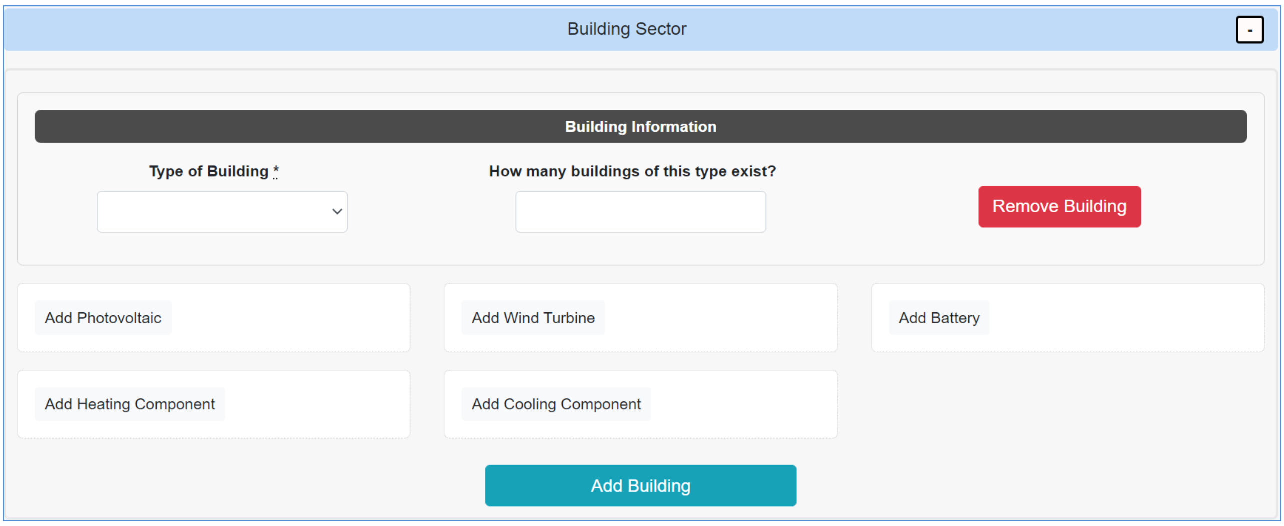

Figure 12 *User interface - Building sector input data*

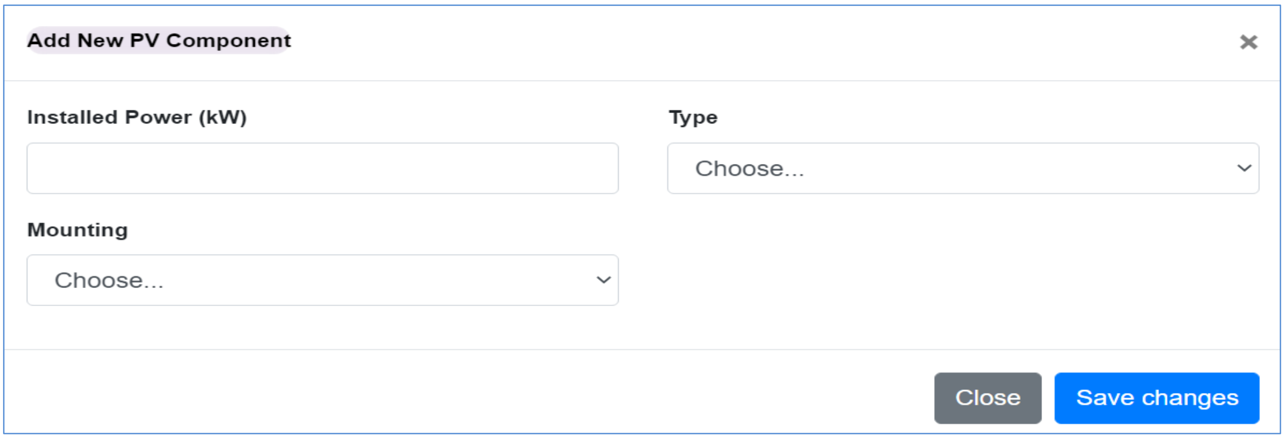

Figure 13 *User interface - PVs input data*

Table 6 *PVs input information*

Installed Power (kW)	The nominal power of the photovoltaic installation
Type	The type of the photovoltaic panel (monocrystalline/ polycrystalline)
Mounting	The way in which the panels are put (roof slated/ roof flat/ ground/ building integrated)

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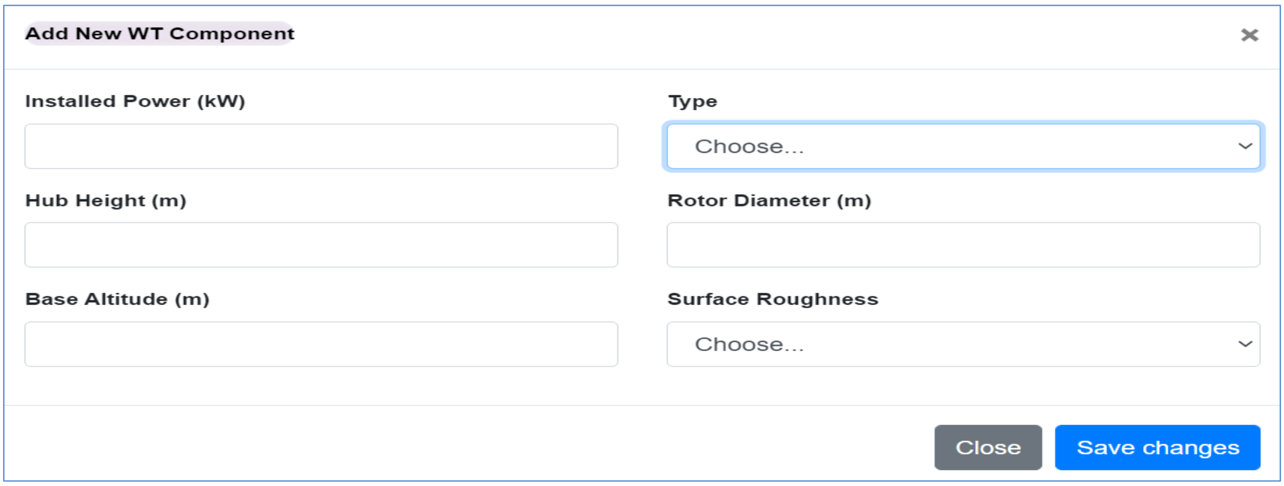

Figure 14 *User interface - Wind turbines input data*

Table 7 *Wind turbines input information*

Installed Power (kW)	The nominal power of the wind turbine
Type	The type of the wind turbine (vertical/ horizontal axis)
Hub height (m)	The height of the hub (distance from the ground to the middle of the turbine's rotor)
Rotor diameter (m)	The diameter of the rotor
Surface Roughness	The type of the surface in which the wind turbine is installed (completely open terrain with a smooth surface/ open agricultural area/ agricultural land, villages, small towns/ larger cities/ very large cities)
Base altitude	The altitude of the place in which the wind turbine is installed

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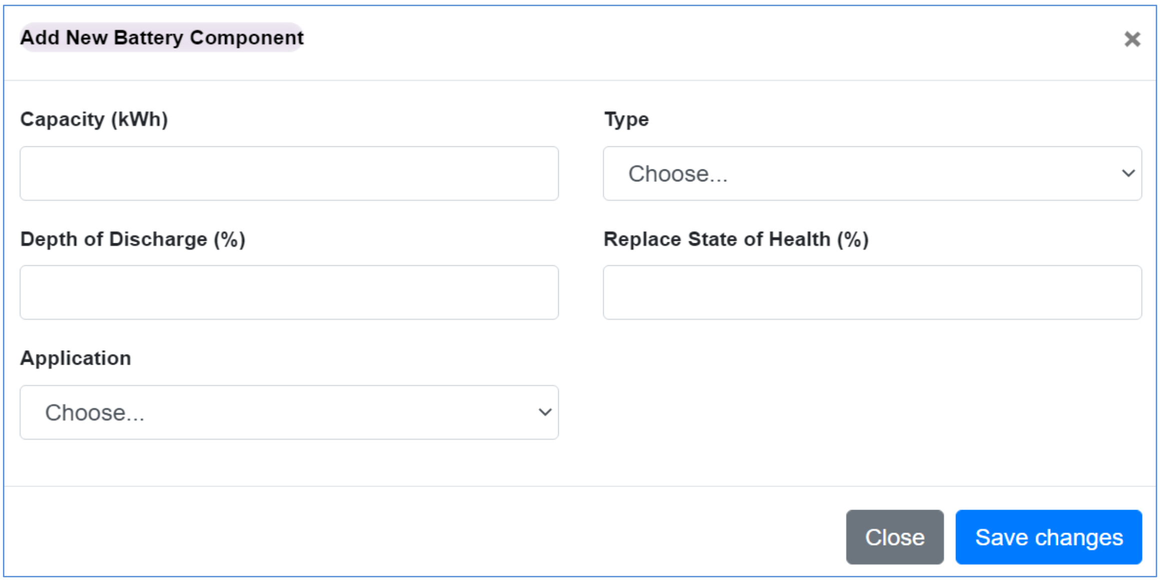

Figure 15 *User interface - Battery input data*

Table 8 *Battery input data*

Capacity (kWh)	The nominal capacity of the battery
Type	The type of the battery (Li-ion/Lead-acid/Biobased saline)
Depth of Discharge (%)	The maximum Depth of Discharge in every cycle
Replace State of Health (%)	The State of Health under which the battery should be replaced
Application	The use of the battery (increase the self-consumption/ improve grid stability/ support voltage regulation/ utility energy time-shift). It indicates the number of cycles per day.

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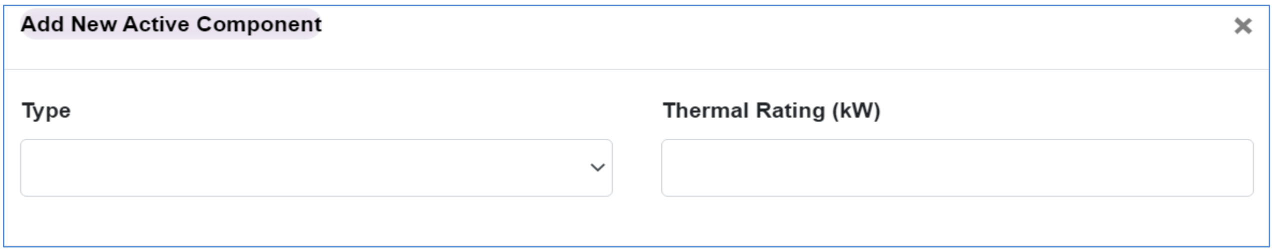

Figure 16 *User interface - Heating and Cooling systems input data*

Table 9 *Heating and Cooling systems input information*

Type	The type of the heating device (boiler-natural gas/ boiler-oil/ boiler-biomass/ air condition/ heat pump)
Thermal Power (kW)	The thermal capacity of the selected component

4.3.1.2 Transport Sector

During IANOS, interventions concerning the sustainable mobility area are going to be demonstrated. Specifically, 2 EV chargers are going to be integrated in Terceira and in Ameland. Similar activities are going to be implemented as well in Nisyros, in the frame of the replication plan. Until the writing of the current deliverable, regarding the transport sector, only the EVs' integration in VERIFY-D platform has been conducted (Figure 17, Figure 18). Below, the necessary input fields are presented (Figure 18, Table 11).

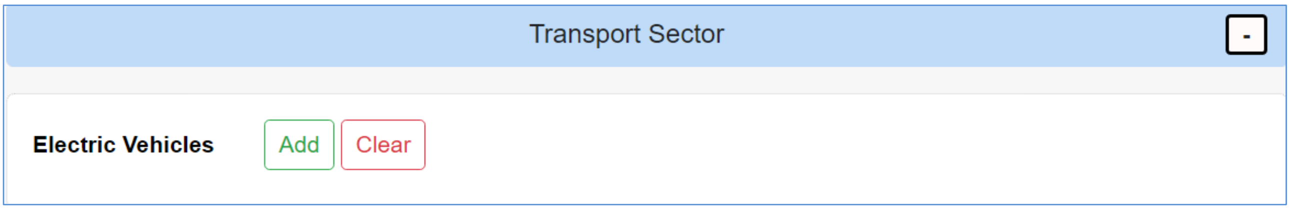

Figure 17 *User interface - Transport sector input data*

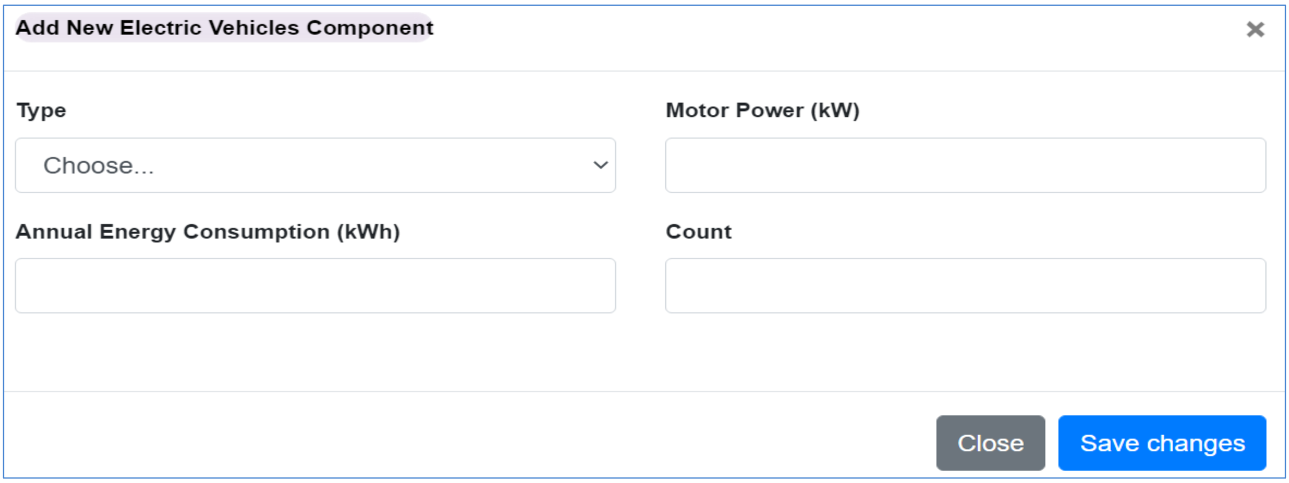

Figure 18 User interface - Electric vehicle input data

Table 10 Electric vehicle input information

Type	The type of the EV (battery electric vehicle/ hybrid electric vehicle/ fuel cell electric vehicle)
Motor Power (kW)	The power of the motor
Annual Energy Consumption (kWh)	The annual energy consumption needed for the EV
Count	Number of similar EVs (default = 1)

4.3.1.3 Energy Production Sector

This sector is divided into two sub domains: i) the energy production from RES units, and ii) the energy generated from conventional units. The first subcategory consists of Wind Parks, Solar Parks, Tidal Parks, Geothermal Plants and Hydro Plants (Figure 19, Figure 20). Unlike the building sector, the user has the possibility to add more than one component of the same type (e.g., 2 solar farms, 5 wind parks). Depending on the component category, the input forms vary significantly. The components are modelled with different levels of accuracy and detail, and thus, the number of the input data is not constant. In the following Figures and Tables, the relevant specifications of the renewable energy sources are given.

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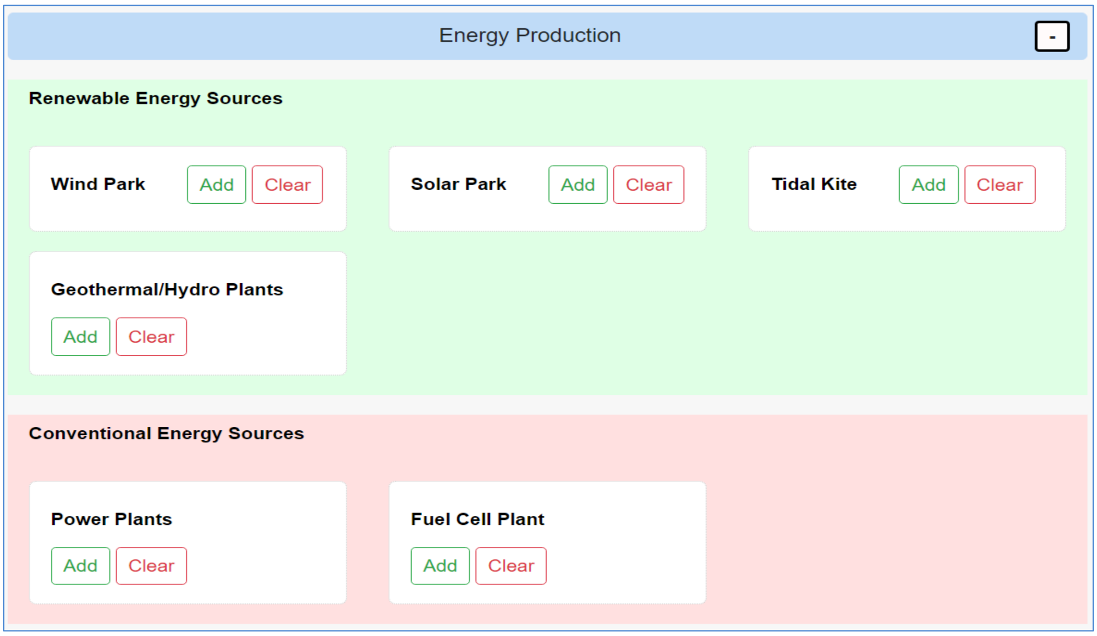

Figure 19 *User interface - Energy production sector input data*

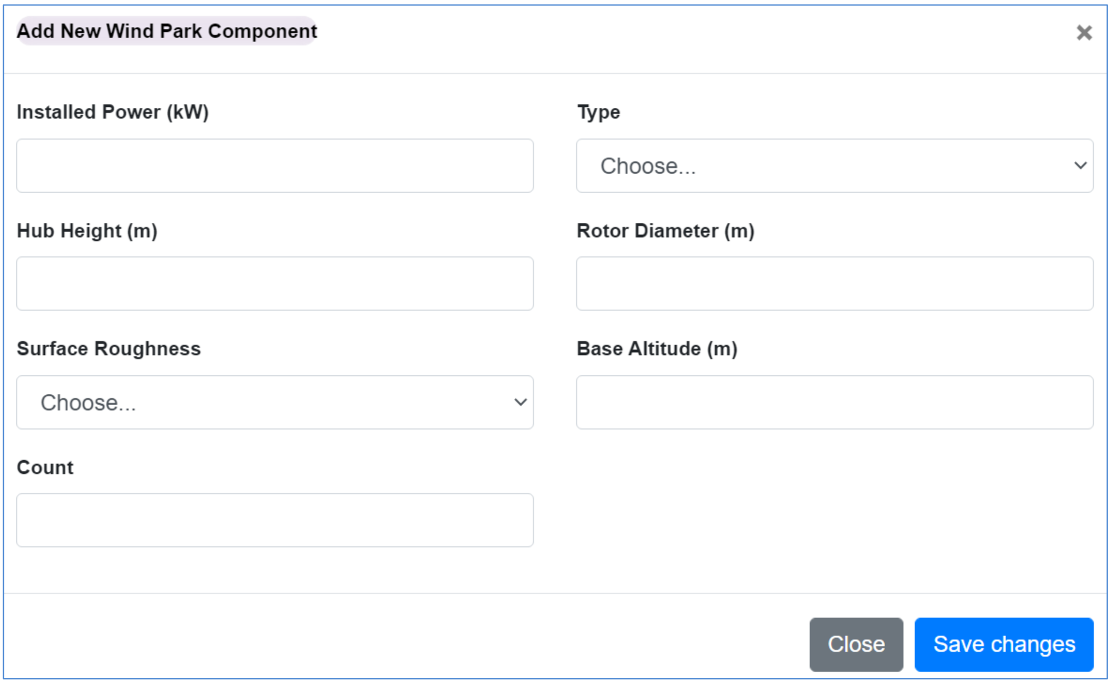

Figure 20 *User interface - Wind Farm input data*

Table 11 *Wind Farm input information*

Installed Power (kW)	The nominal power of the wind turbine

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Type	The type of the wind turbine (vertical/ horizontal axis)
Hub height (m)	The height of the hub (distance from the ground to the middle of the turbine's rotor)
Rotor diameter (m)	The diameter of the rotor
Surface Roughness	The type of the surface in which the wind farm is installed (completely open terrain with a smooth surface/ open agricultural area/ agricultural land, villages, small towns/ larger cities/ very large cities)
Base altitude	The altitude of the place in which the wind farm is installed
Count	Number of similar wind farms (default = 1)

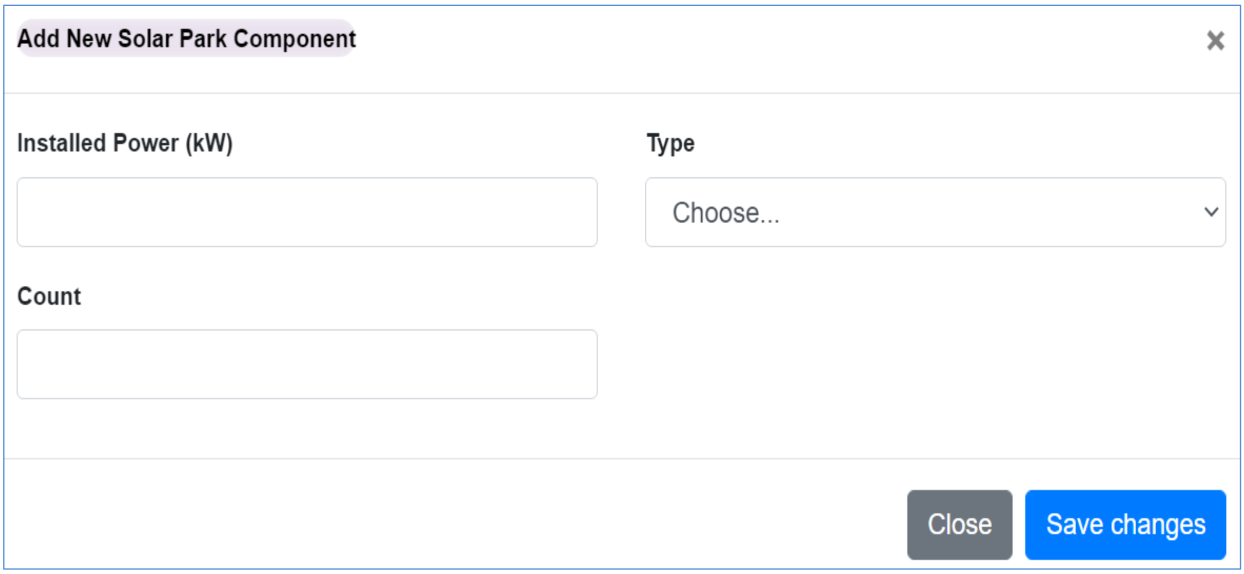

Figure 21 *User interface - Solar Farm input data*

Table 12 *Solar Farm input information*

Installed Power (kW)	The nominal power of the photovoltaic installation
Type	The type of the photovoltaic panel (monocrystalline/ polycrystalline)

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Count	Number of similar solar farms (default = 1)

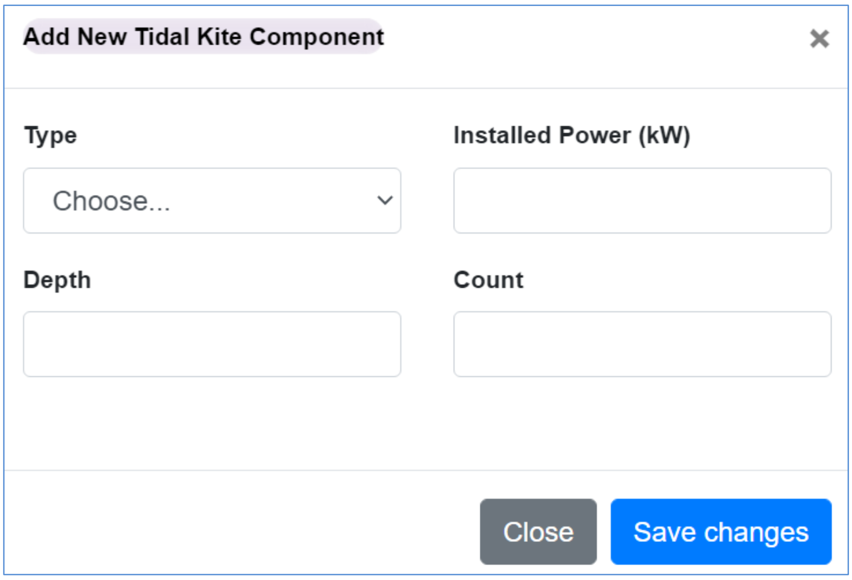

Figure 22 *User interface - Tidal Kite input data*

Table 13 *Tidal Kite input information*

Installed Power (kW)	The nominal power of the photovoltaic installation
Depth	The depth in which the Tidal Kite is located
Count	The number of similar tidal kites (default = 1)

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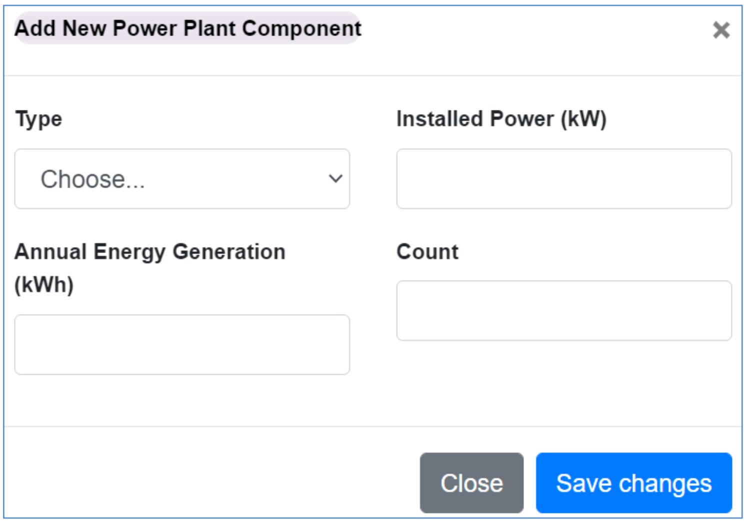

Figure 23 *User interface - Geothermal, Hydro power plant input data*

Table 14 *Geothermal, Hydro power plant input data*

Type	The type of the power plant (Hydro/ Geothermal)
Installed Power (kW)	The nominal power of the power plant
Annual Generation (kWh)	The annual generation. This value is mandatory when production time series are not provided.
Count	The number of similar power plants (default = 1)

Concerning the conventional energy sources, the current version includes two types of power plants: i) oil fuel power plants, and ii) fuel cell plants. Because of the difficulty of developing simple models of these power plants that serve the needs of the LCA/LCC analysis, the number of the input forms are reduced, and the approach has become more simplified. In Figures 24, 25 and Tables 16, 17 the necessary input data for the conventional power plants is displayed.

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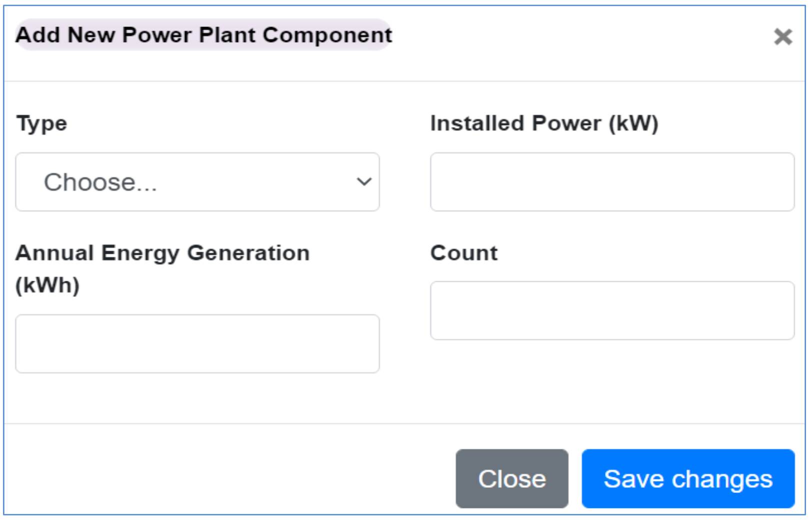

Figure 24 User interface - Power plant input data

Table 15 Power plant input data

Type	The type of the power plant (oil/ natural gas/ biomass)
Installed Power (kW)	The nominal power of the power plant

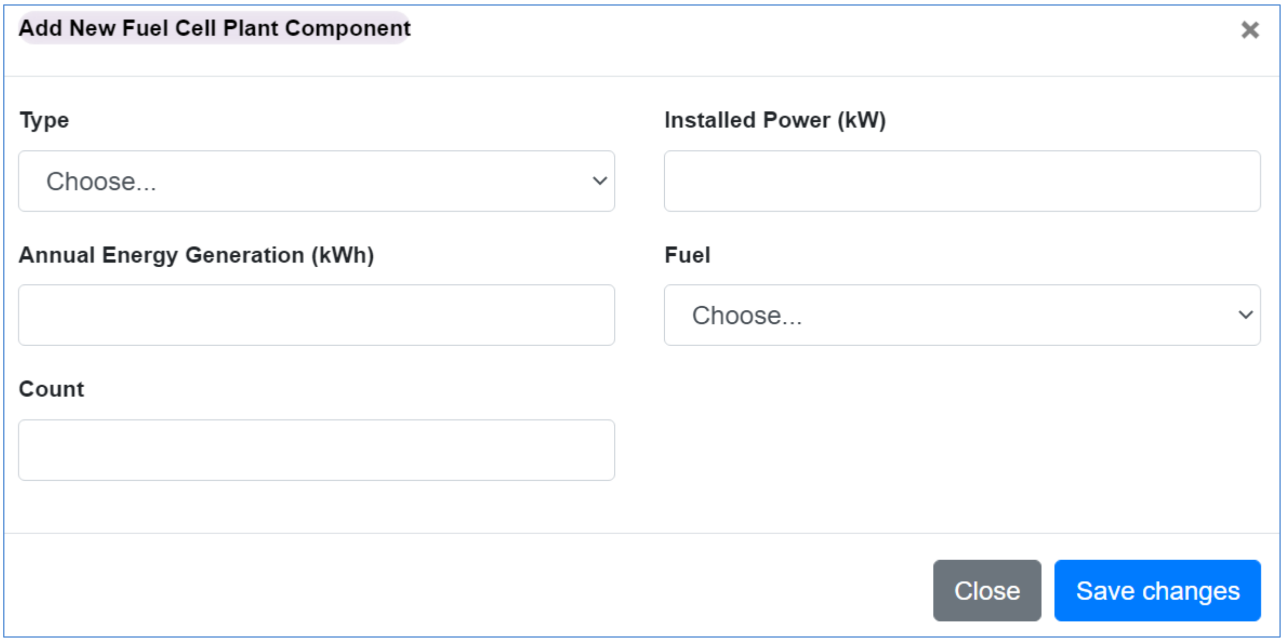

Figure 25 User interface - Fuel cell input data

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Table 16 Fuel cell input information

Type	The type of the fuel cell (PEMFC etc.)
Installed Power (kW)	The nominal power of the power plant
Annual Generation (kWh)	The annual generation of the fuel cell. This value is mandatory when production time series are not provided.
Fuel	The used fuel (Natural gas, Methane etc.)
Count	The number of similar fuel cell plants (default = 1)

4.3.1.4 Energy Storage Sector

The energy storage systems to be used in IANOS project, are included in this sector independently of their kind of use inside the grid (storage of the excess renewable energy, supporting the frequency and voltage stability etc.). Specifically, this sector contains Battery Energy Storage Systems (BESS) and Flywheels. The flywheel and battery energy storage systems input data are shown in Figures 26, 27, 28 and Tables 18 and 19.

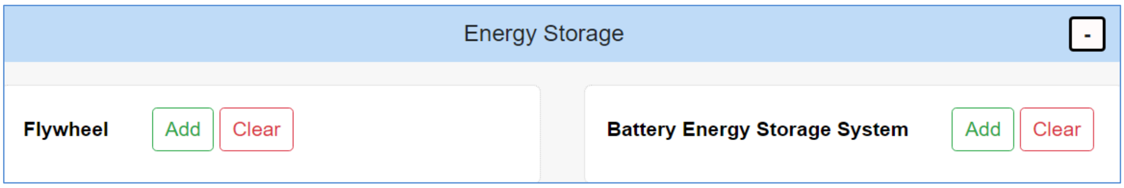

Figure 26 *Energy storage sector input data*

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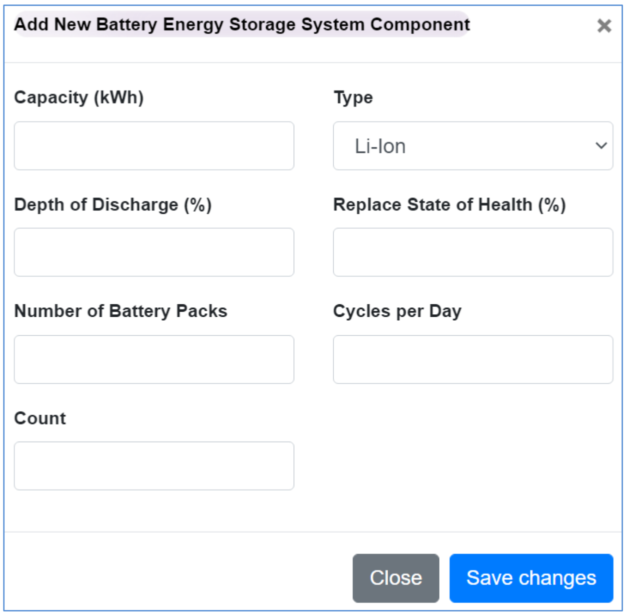

Figure 27 *Battery energy storage system input data*

Table 17 *Battery energy storage system input data*

Capacity (kWh)	The nominal capacity of the battery pack
Type	The type of the battery (Li-ion, Lead-acid etc.)
Depth of Discharge (%)	The maximum Depth of Discharge in every cycle
Replace State of Health (%)	The State of Health under which the battery should be replaced
Number of battery packs	The number of battery packs that constitute the battery energy system
Cycles per day	The total cycles per day (charge-discharge)
Count	The number of similar battery energy storage systems (default = 1)

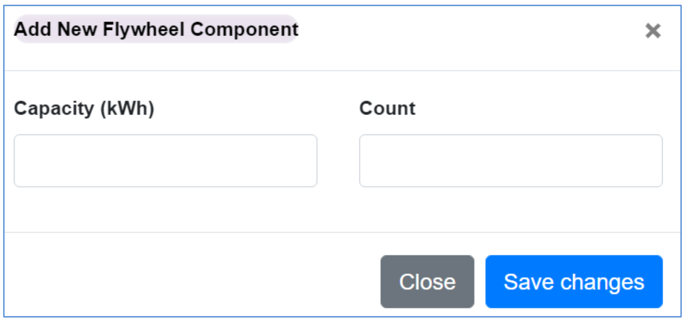

Figure 28 *User interface - Flywheel input data*

Table 18 *Flywheel input information*

Capacity (kWh)	The capacity of the flywheel
Count	The number of similar flywheels (default value = 1)

4.3.1.5 Public Infrastructure Sector

The various distribution infrastructure and consumption units compose the public infrastructure sector (Figure 29). Components that belong to the district, such as public lighting installations (smart or conventional), distribution transformers (hybrid or conventional) and EV charging stations are given in this sector.

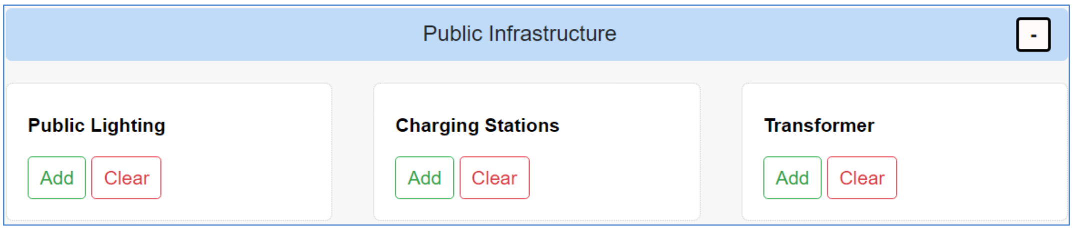

Figure 29 *User interface - Public infrastructure*

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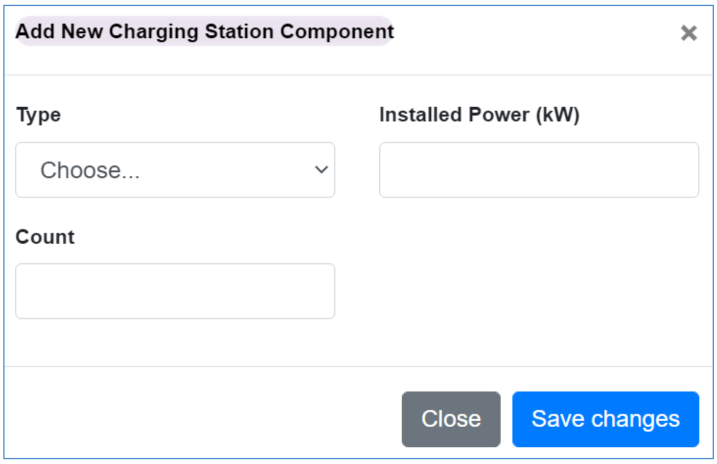

Figure 30 User interface - EV charging station input data

Table 19 EV charging station input information

Type	The type of the EV charging station (DC/AC)
Installed Power (kW)	The maximum power that can provide the EV charging station
Count	The number of similar EV charging stations (default = 1)

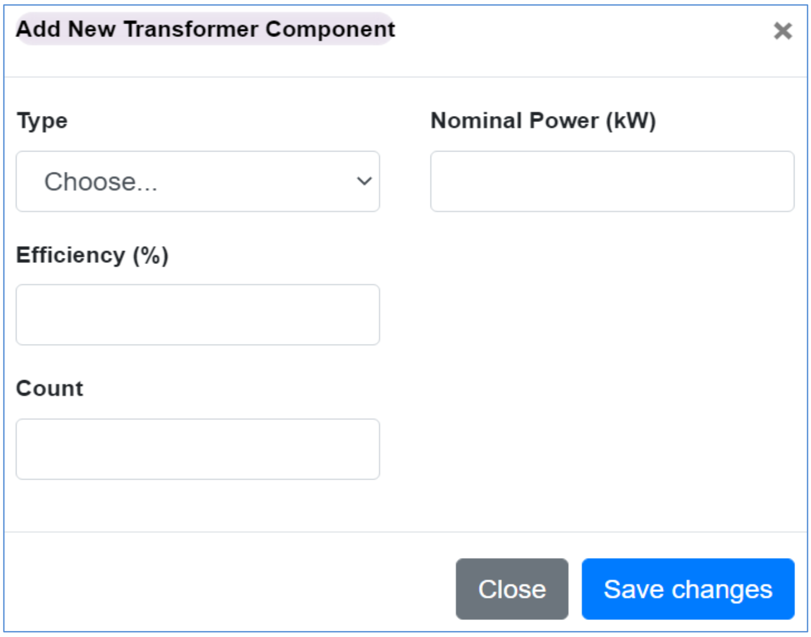

Figure 31 User interface - Transformer input data

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Table 20 *Transformer input information*

Type	The type of the transformer (conventional/ hybrid)
Nominal power (kW)	The nominal power of the transformer
Efficiency (%)	The efficiency of the transformer
Count	The number of similar transformers (default = 1)

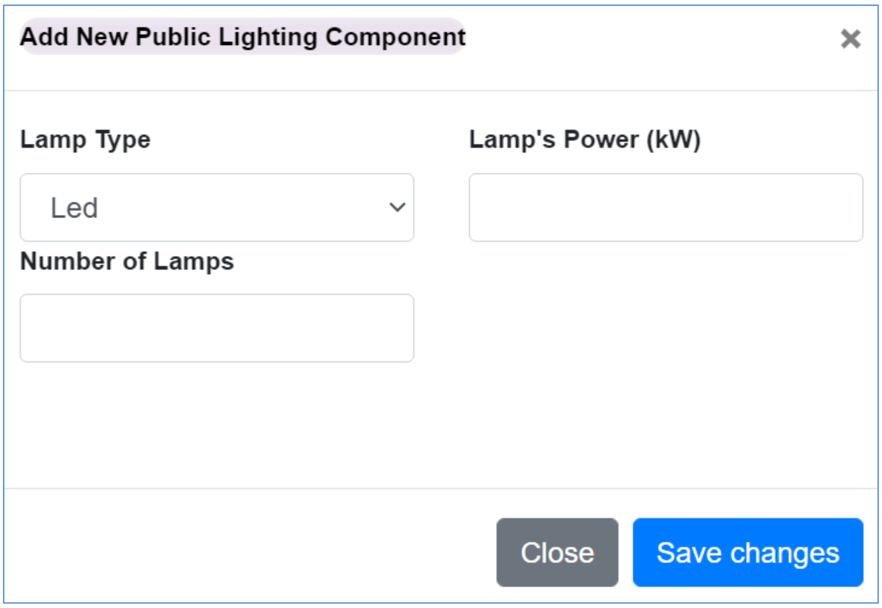

Figure 32 *User interface - Lighting input data*

Table 21 *Lighting input information*

Type	The type of the lamp (led, fluorescence.)
Power (kW)	The power of each lamp
Number of lamps	The number of lamps
Count	The number of similar lighting installations (default = 1)

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4.3.2 Timeseries data upload for LCA and LCC analysis

When the configuration of the two energy scenarios (the current and the planned one) has been completed, the user should match the components included in the two energy scenarios (e.g., buildings, power plants, batteries) with appropriate energy timeseries data (mainly consumption or production of the component). The innovation that VERIFY–D brings, is that the user has multiple options for the timeseries upload and performance.

Custom data gathering includes the historical data upload through csv files. VERIFY-D guides the user about the necessary data (e.g. PV production, Building energy consumption) for each one of the selected scenario components. The csv file must follow a specific format, including 1) the timestep of the sampling (e.g., 1-hour timestep), 2) the measured units (e.g., kW, kWh) etc. By pressing the button “Upload measurements” (Figure 33) a pop-up window arises, for selecting the file from the PC directories.

Semi-automatic data gathering includes the request of estimated timeseries provided by external software tools (e.g., INTEMA.grid tool through INTEMA’s RESTful API, as part of the IANOS IEPT) that realize simulations of integrated systems as described in D3.5 deliverable. The specifications of the components, for which the timeseries are created (e.g., solar park installed power, battery type), are defined from the energy scenarios configuration. The procedure is semi-automatic as the platform user needs to press “Request from INTEMA” button, as it is depicted again in Figure 33 , in order to trigger the data receive procedure.

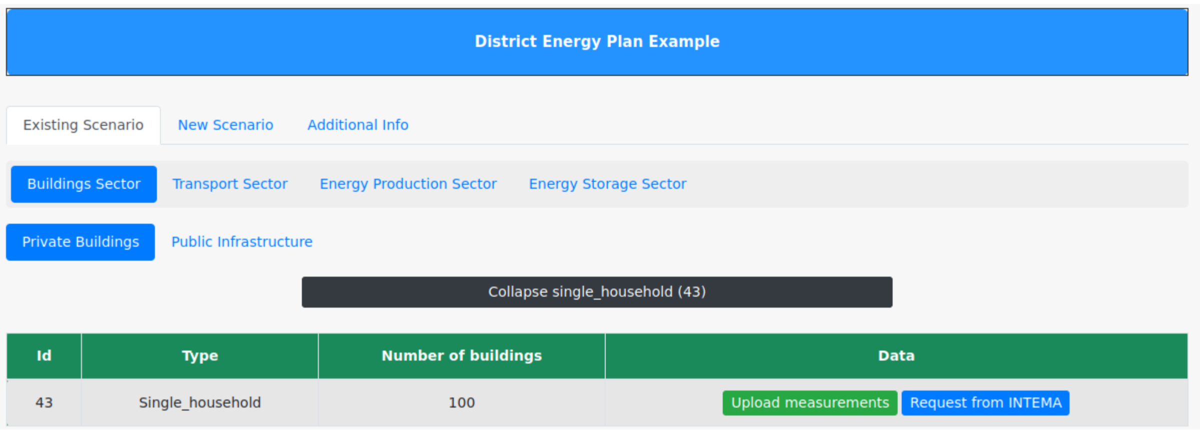

Figure 33 *Timeseries fill/upload*

Eventually, after the matching of the components and their timeseries, the user can perform the LCA or LCC analysis to obtain the results.

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4.4 Implementation and Integration

4.4.1 Sequence Diagram

In this subsection a sequence diagram of a basic usage scenario in VERIFY-D is presented. The diagram contains the entire process from the point at which a user signs into the platform until a Life Cycle Analysis using historical, estimated and/or real-time data is conducted and its results are presented. As previously mentioned, VERIFY-D supports user accounts and each district/city/island energy plan in the database, from now on called a project, is owned by a user. To create new projects and perform Life Cycle Analyses the user has to first log to the platform using the credentials given upon registration.

After a successful login the user is presented with the main page of VERIFY-D from where the user can navigate to the form dedicated to creating new projects. To complete the form, details about the current state of the project as well as the interventions to take place are required. After the form is completed, the user submits it to be validated by the back-end layer of VERIFY-D. If the validations are successful, the project is persisted into the PostgreSQL database and a project preview is presented to the user. Otherwise, the form is rendered again highlighting the errors to be fixed by the user. The process described is presented in Figure 34.

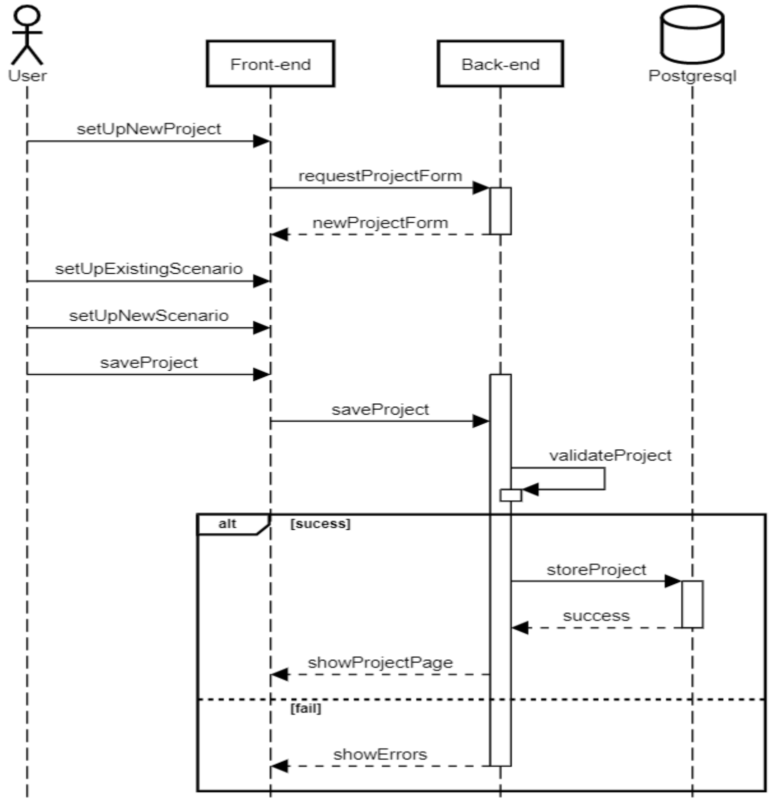

***Figure 34** Sequence Diagram: New Project*

The next action the user can perform is associating monitoring devices to a project. The user can add a device by visiting a project's page and following the link to the devices dedicated form. After the details about the devices are entered and submitted validations take place and if the validation is successful, the devices are persisted into the database and the user is presented with the newly created device's preview page (Figure 35).

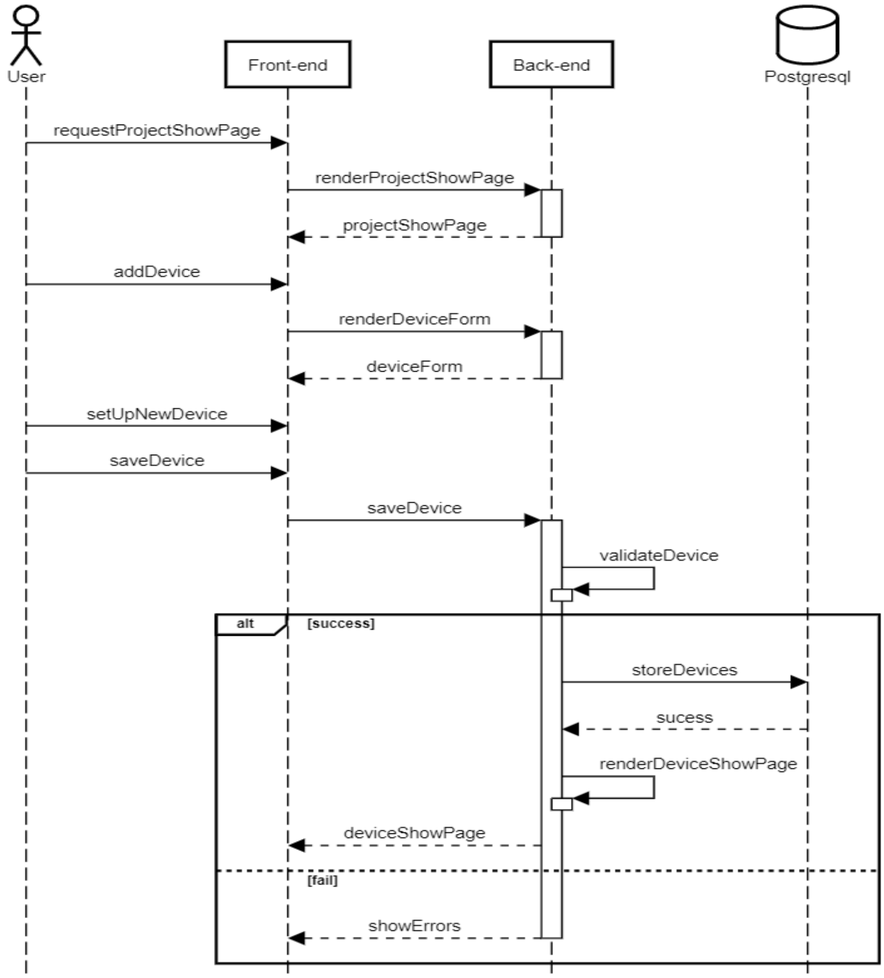

Figure 35 *Sequence Diagram: New device*

When the project set up is completed the user can upload historical time series data (Figure 36) for each component that was set up in the previous steps. The data are uploaded using a CSV file. The request is handled by the back-end, which parses the CSV file, stores the data into the database and associates the uploaded time series with the corresponding building or abstract component through the selected device, if no errors exist in the CSV file.

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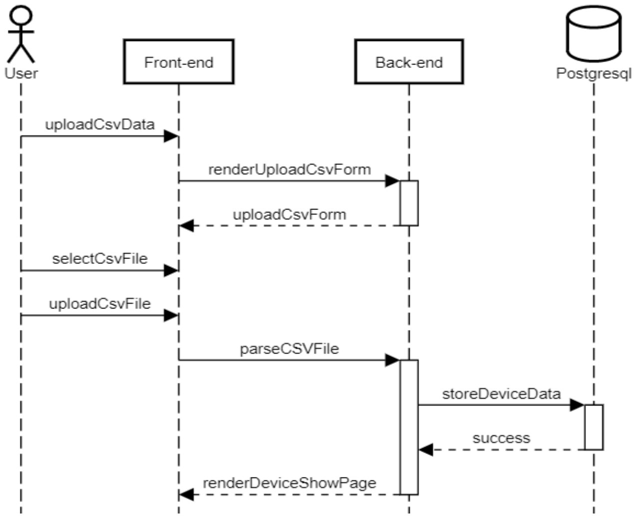

Figure 36 *Sequence Diagram: Upload data*

The project is ready for a Life Cycle Analysis upon user's request which is handled by the back-end. The necessary project's data are fetched from the database in order to generate a JSON string. JSON string is the input data served to the middle-end layer. Through the standard input, the back-end runs the middle-end's script which starts the Life Cycle Analysis. In the middle-end, the smart algorithm gathers the historical time series data from the database and conducts the analysis. After the analysis is completed, the results are passed through the standard output to the back-end in JSON format. Finally, the back-end parses the response and presents the KPIs through the front-end layer (Figure 37).

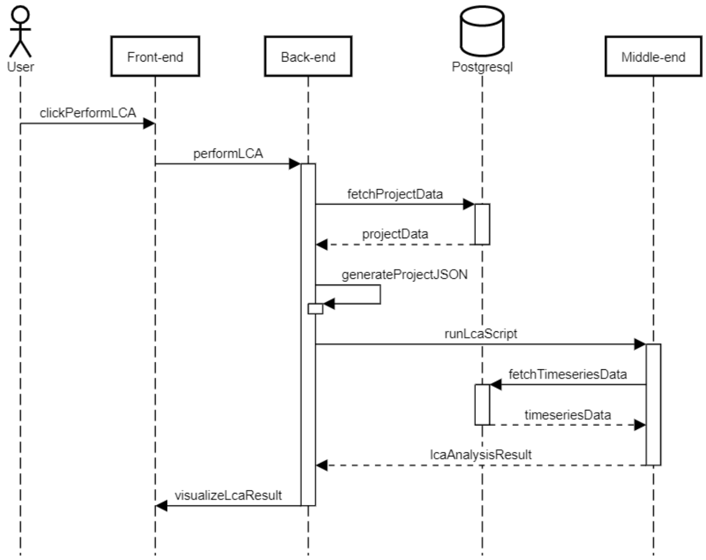

Figure 37 *Sequence Diagram: Run Life Cycle Analysis*

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4.4.2 IANOS dedicated database tables in VERIFY-D

In this section the part of the database schema that concerns IANOS LH is presented. The modelling of a district, city or island requires a large number of interconnected energy/grid components. The main entity of the modelling is the District Project, which contains up to two District Scenarios, i.e. i) one considering the current state of the district/city/island and the other ii) its state of operation after interventions. Each scenario includes a large set of components that might be installed in the district/city/island such as buildings, public lighting etc. Moreover, the database is responsible for holding the various historical time series data for several components of the system. In order to encapsulate the variety of relationships between the platform's entities the database schema not only needs to be well defined but also be highly extensible. On the top of the schema hierarchy stands the table that represents a user project, called *district_projects*. Each district project belongs to the user who created it. The table *district_projects* is used to correlate two district scenarios and it only contains fields for the name and the description of the project. A district/city/island scenario may contain a set of the energy/grid components, presented in Table 23. The main hierarchy described in this paragraph is depicted in Figure 38.

Table 22 *Energy Grid Components*

Energy Grid Component Name	
Private Buildings	Solar Parks
Public Lighting	Geothermal Plants
Charging Stations	Incineration Plants
Electric Vehicles	Hydro Plants
Transformers	Oil Fuel Plants
Wind Parks	Flywheels
Tidal Kites	Battery energy storage systems

District scenarios are saved in a table called *district_scenarios*, which holds information about which project a district scenario belongs to and which of the two states of the project it represents. A district scenario is used as a central point which connects a set of components listed above. Each type of component may appear zero or more times in a scenario. For example, a city might have no Geothermal plants while having two different types of Flywheels.

Each type of component, except for private buildings, has no further associations and only holds details about the component itself. However, the private buildings resemble district projects and district scenarios, acting as a component which consists of many other subcomponents. More specifically, a private building may contain one or more of the sub-components listed below:

1. Photovoltaics
2. Wind Turbines
3. Batteries
4. Heating Components (boilers, heat pumps etc.)
5. Cooling Components (insulation, glazing etc.)

Private buildings are saved in a table called *district_buildings*, which holds information about what district scenario a building belongs to and what is the type of building (e.g. residential).

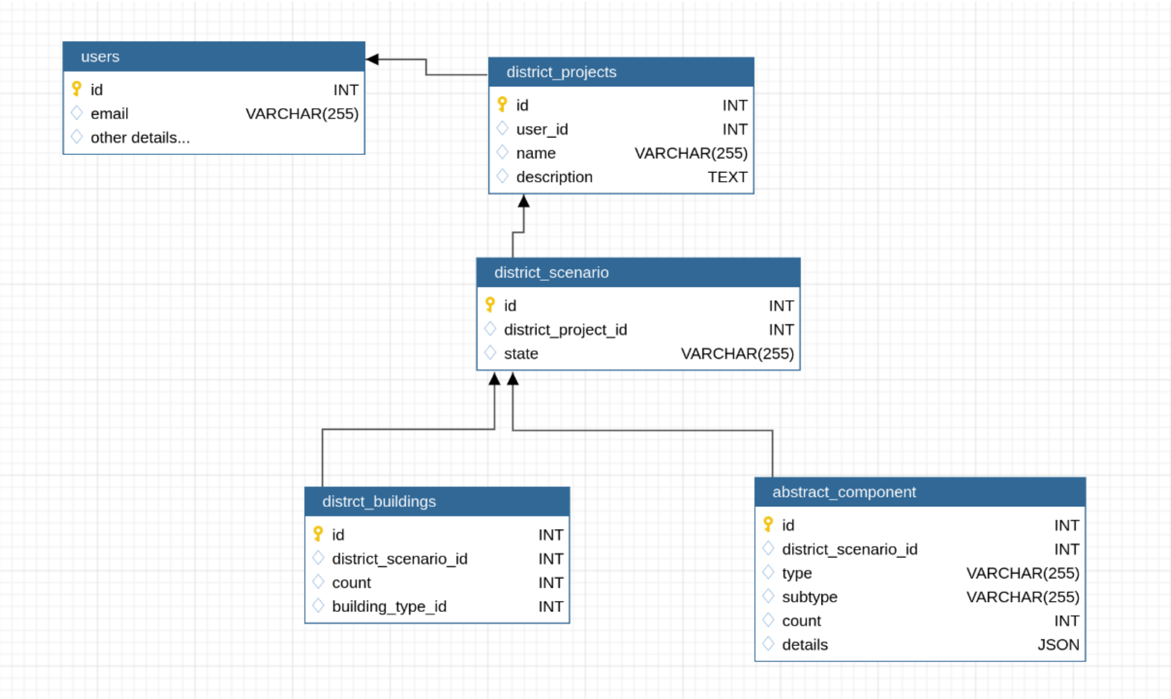

Figure 38 *DB Schema: Main hierarchy*

As it is evident by the previous paragraphs there is a large set of components that could be added to a district scenario. Each component has a unique set of attributes and is treated differently during the analysis. Moreover, the set of attributes of each component might change or other types of components could be added to VERIFY-D during the development of the platform, rendering the definition of a strict schema a difficult task. The representation of all this information in the database would require the creation of numerous tables, one for each component, regularly changing the columns of this table and adding a new table each time a new type of component is added to the system. That would pose a problem

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considering the maintenance of the database and the number of tables would overload the database schema. To avoid this problem a generic database table was added to the schema, named *abstract_components*.

Abstract components have a very basic and flexible structure that can support any type of component needed. It contains four main columns, namely 1) type, 2) subtype, 3) count and 4) details. The first column, named type, holds the main type of the component (e.g., Fuel Cell Plant, Solar Farm), the second column, named subtype, shows the subtype of a component (e.g., Li-on, Lead-acid for BESS), the third column, named count, shows the number of the installed components of this type and subtype, and the last column, named details, holds all the details of the component (the inputs given by user) in JSON format. This JSON string has different fields for each type of component. Using the two first columns the back-end, described in VERIFY-D's architecture section, infers the type of component and treats each component differently. By incorporating such a simple structure, the database is not bloated with tables of small size and with some extra configuration the back-end system can treat the components similarly to as if they were separate tables. It should be noted that the components connected to a private building (Figure 39) have their own tables in the database schema as they are specific and well defined from experience that came from previous projects and do not need to be flexible and dynamic.

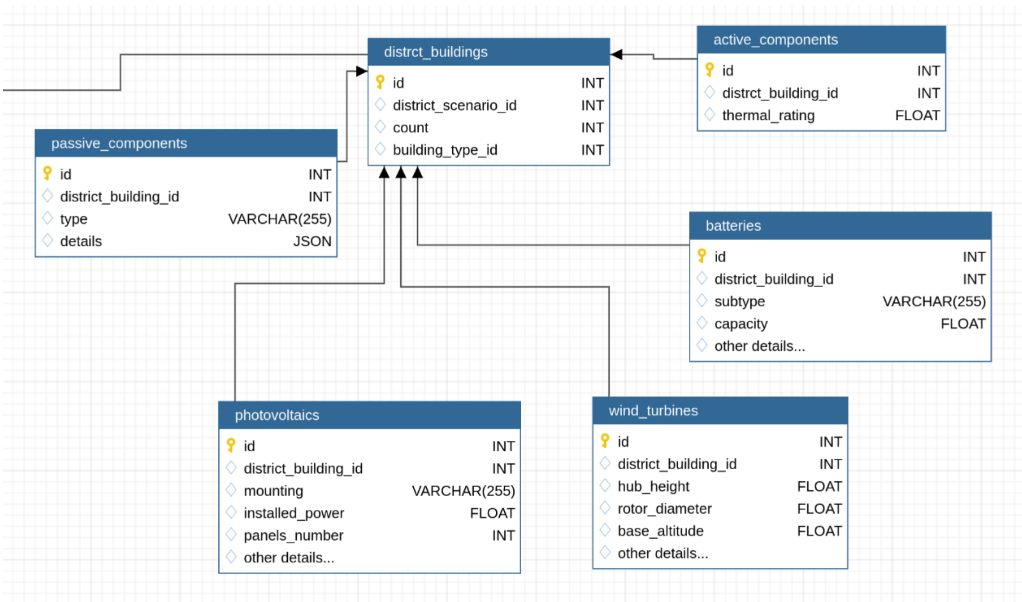

Figure 39 *DB Schema: District building*

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Finally, the database contains tables that hold time series data required for the Life Cycle Analysis. It should be reminded that the database is not used as a large repository that contains huge amounts of data. There are two types of measurements required for the successful execution of the analysis. The first category includes measurements for the district buildings, while under the second category measurements for the rest of the district components appear. District building measurements contain a column for each possible measurement at a time point (e.g., boiler consumption, photovoltaic production). Considering the other components of a scenario, only one type of measurement is enough for the Life Cycle Analysis to be conducted (e.g., energy production for Flywheels). For that reason, a second table is created which contains only three columns, 1st) representing the value of a measurement, 2nd) representing which component it belongs to and the 3rd) the timestamp of the measurement. The type and the unit of the measurement are defined in the *abstract_components* table for each component. Monitoring devices are also defined in the database schema, each device containing information about what it measures and to what queue (i.e. MQTT topic) it forwards its data. The table *devices* is used to represent and store the devices. A device may belong to a district building or an abstract component. Each time a measurement arrives into a queue it is filtered and stored into the correct measurements table. The schema considering the various measurements and devices is presented in Figure 40.

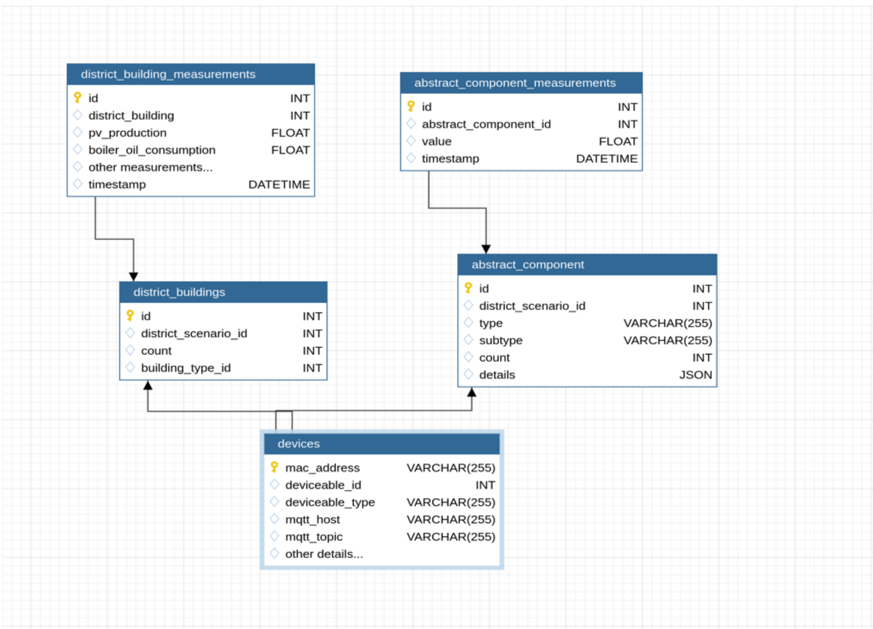

Figure 40 *DB Schema: Devices & Measurements*

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5 Conclusions

During this deliverable the further development of an online web platform/tool for LCA/LCC calculations has been performed. The tool calculates environmental impacts and associated cost savings from the implementation of RES based and grid counter-congestion strategies on a user and/or community level, taking into consideration the production, exchange and the disposal of all type of energy flow streams, through an automated process. The foundation for the development of the tool is the implementation of lifecycle perspective, in which various stages of a product's lifetime are considered under multiple energy grid sectors.

To establish a clear overview of the current situation regarding the environmental and financial performance of the proposed technologies, a comprehensive literature review was performed. From the environmental perspective, 20 case studies were assessed regarding the electricity production from various technologies, conventional and innovative. Through the literature review the boundaries and functional unit of the selected case studies were examined, as well as the overall environmental impacts, with specific focus on the overall GHG emissions measured in gCO_2/kWh. The results, from the examined technologies, show that geothermal and mini-hydro produced energy has the lowest GHG emissions with less than 50 gCO_2/kWh of produced electricity, while solid oxide fuel cells have the highest emissions with more than 700 g CO_2/kWh.

From the financial standpoint, the literature review provided relevant information regarding the cost categories and variables considered on relevant studies. Not every technology of interest for the IANOS project had available information, which further proves the complexity, and originality of the project. As far as the available technologies, wind parks and solar parks presented the lowest LCOE ranging from 0.033 – 0.075 €/kWh, while BESS presented the highest LCOE with 0.61 €/kwh, followed by flywheel produced electricity with an LCOE of 0.59 €/kWh. The high LCOE is noticed on technologies that are not yet widely implemented, which could lead to the conclusion that market penetration is not on a stage that allows lower costs, due to complexity of the technologies, and costly production processes.

Furthermore, an important aspect of Task 3.1 is the examination of the potential implementation of the various solutions on a larger scale. Therefore, a literature review of the existing scale-up methodologies was performed. Scale-up methodologies help to determine the economic scalability and feasibility of a project, from the design stage. The most common method implemented in literature, in a widespread variety of applications, is the cost-to-capacity methodology. The fundamental concept behind the cost-to-capacity method is that the costs of facilities (or pieces of M&E) of similar technology but with different sizes vary nonlinearly. Moreover, several other methodologies were examined, specific for different technologies such photovoltaics, hydropower etc. The complexity and multi-dimensional nature of IANOS project present a challenge in order to select the appropriate scale-up methodology to be implemented on the VERIFY-D. Due to its wide variety of applications, Cost-to-capacity methodology was chosen for implementation, utilizing the 0.6 rule, meaning that the scale exponent taken into account for IANOS demo sites will be equal to 0.6.

With the clear objectives of IANOS demo pilots, and the information received from the literature reviews, a specific methodology for assessing the environmental and financial performance of IANOS pilots was developed accompanied with the development of a technologies database planned to consist of the crucial components initial data. Data collected from the literature and the IANOS innovative components information consist of the VERIFY-D technologies-database, that feed the methodology of the LCA and LCC in the energy grid. The combination of database and the LCA-LCC methodology, over the platform user interface and extended functionalities (e.g. device monitoring, communication with external software tools) led to the implementation of VERIFY-D.

The defined LCA and LCC methodology and the performance through VERIFY-D platform can be applied at district level to model multi-domain energy sectors, considering the impacts of 1) private and public buildings, 2) transportation infrastructure elements, 3) produced energy of RES and non-RES technologies, 4) energy storage systems, 5) public infrastructures. VERIFY-D as a software tool combines the idea of static LCA-LCC analysis with the dynamic use phase evaluation of energy grid components. Input data (either real-time, near real-time or synthetic) from external sources or tools (specifically for synthetic data), will provide accurate information demanding through the evaluation assessment. The current deliverable will be further enhanced in later version 2, with extended IANOS innovative technologies inventories and operation data, providing detail demonstration KPI results in terms of environmental and cost planning within the IANOS use cases.

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7 Annex

7.1 Annex 1

Case	Detail Analysis
[1]	Case study 1 aimed to quantitatively identify advantages and disadvantages of a **Condensing Gas Boiler (CGB)** and a **Hybrid Heat Pump (HHP)** for an existing semi-detached house in the UK. The scope of this study is to analyze the heating system from cradle to grave within a lifetime of 20 years. The functional unit was defined as the generation of 252,000 kWh of space heat for a time period of over 20 years. The results depict values of 4.5×104 kg CO2eq/FU and 6.4×104 kg CO2eq/FU for the HHP and the CGB respectively, revealing that the use of the HHP i) saves 30% of greenhouse gas (GHG) emissions compared to the CGB and ii) could reduce fossil depletion (FD) by 48% and terrestrial acidification (TA), photochemical oxidant formation (POF) and particulate matter formation (PMF) by 20%. Moreover, the HHP shows lower environmental impacts than the CGB in five out of nine impact categories, i.e. climate change (CC), TA, FD, POF and PMF. On the other hand, the CGB shows 3 to 6 times smaller values in 3 out of 9 impact categories, i.e. human toxicity (HT), water depletion (WD) and metal depletion (MD). Producing electronic components and copper in the production phase for both heating systems caused a contribution of around 60% of the total for MD and between 40% to 50% for HT. The use phase is the main contributor to all impact categories for both heating systems, except MD and HT and the major causes for this dominance are the combustion of natural gas and the electricity production, which is based on natural gas and hard coal. Continuing, the leakage of the refrigerant (R410A) in the use phase also leads to 17% of the total GHG emissions for the HHP scenario. The environmental

	impacts caused by transportation, in the end-of-life phase both scenarios have negligible influence on the results [1].
[2]	In case study 2, the life-cycle GHG emissions of onshore and offshore wind turbines with a nominal capacity of 2 MW each, for a 20-year lifetime were estimated. The breakdown of these emissions, to identify the most GHG intensive process showed that for onshore wind turbine the transport and installation were responsible for 91.86%, followed by the dismantling and disposal 5.06%, and the manufacturing stage 2.41%, while the operation and maintenance represented only 0.67% of the total emissions. For offshore wind turbine, the transport and installation accounted for 90.98%, whilst the operation and maintenance accounted for only 0.27%. Another result showed that GHG emissions concentration was 0.082 kg CO2eq/MJ and 0.130 kg CO2eq/MJ for onshore and offshore wind turbine, respectively. Overall, offshore wind turbine had larger life-cycle GHG emissions than onshore wind turbine [2].
[3]	In case study 3, an LCA was applied to examine the environmental impacts of generating 1kWh of energy in a geothermal combined heat and power (CHP) plant, based on high temperature geothermal utilization for 30-year operational time. The plant produces 303 MWel and 133–267 MWth in a double flash cycle located in SW Iceland. The results show that drilling and casing of geothermal wells along with construction of collection system for geothermal fluid, is largely responsible for most of the impact category outcomes. Still, the global warming potential (GWP100), acidification potential (AP) and the renewable CED from wind, solar and geothermal energy are mostly affected by the operational phase of the plant, due to direct emissions of CO2 and H2S, and the extraction of geothermal fluid from the ground. Furthermore, the paper investigates two sets of life cycle inventory (LCI), i.e. i) a base case inventory with operational conditions of 2012 and ii) an updated dataset based on inclusion of implemented mitigation methods until the operating year 2017. Moreover, there is a reduction of GWP100 from 15.9 g CO2eq/kWh down to 11.4 g CO2eq/kWh for electricity and 15.8 g CO2eq/kWh to 11.2 CO2eq/kWh for heat occurred due to carbon capture and storage (CCS) by reinjection of CO2. The overall CED results in 5.2 kWh of energy demand for generating 1kWh of either electricity or heat, dominated by the use of geothermal energy. Non-renewable energy demand decreases from 6.8×10^{-3} and 5.9×10^{-3} kWh to 5.8×10^{-3} and 5.0×10^{-3} kWh, for electricity and heat respectively, by using electrical drills instead of diesel fuelled drills for additional wells during the operational time of the power plant [3].
[4]	Case study 4 assessed the carbon footprint related to a residential electricity supply system based on photovoltaic roof tiles. Regarding the ceramic photovoltaic tiles, approximately 6% of the final overall emissions are associated with the production of the ceramic tiles (in firewood kilns), while roughly 94% of the final emissions are associated with the production of the photovoltaic cell (mono-Si wafer). On the other hand, in the panel-based system, approximately 95% of the overall emissions are associated with the panel façade system, which includes the panels and roof structure. The comparison revealed that 1,160 kgCO2eq was emitted when photovoltaic mono-Si roof tiles were installed comparable to 950 kg CO2eq for a photovoltaic panel system, when

	considering a 0.52 kWp system. Once the photovoltaic cell of the roof tiles changes to poly-Si, its environmental impacts decreased matching the respective photovoltaic panel-based system [4].
[5]	In case study 5 a quantitative analysis through LCA of CO2 emissions and energy consumption of the construction and operation of a wind park, was presented, for an operation lifetime of 25 years. The findings indicated that the environmental hotspots in the transportation stage are due to overseas shipping of major wind turbine components to the United States. Similarly, the material production, and the earthwork and construction phase, are responsible for the highest GHG emissions. The outcomes showed that the studied wind farm, as a power generation source, will lead to considerable savings in terms of GHG emissions and energy consumption compared to other conventional power sources [5].
[6]	Case study 6 reported an LCA study for a **distributed concentrating solar combined heat and power (DCS-CHP) system** across 1,020 sites in the US, combined with a sensible cost allocation scheme. The author's assumption from the economic results for air cooling combined with the fact that CHP system reduced the need for cooling but simultaneously enhanced the overall solar efficiency of the system, is that DCS-CHP can be included among the best electric power generation systems in terms of minimization of water use in the maintenance and operation of the plant. When primarily common metals and glass are used in simple manufacturing processes, the LCA of the embodied water during the manufacture phase of a concentrating solar system is predicted to be minor. Consequently, the LCA of the system indicates that small scale solar CHP systems can economically compete with other renewable energy systems and have comparable environmental footprints to PV systems [6].
[7]	In case study 7 a comparative LCA study was conducted between a r-SOFC with hydrogen storage and a gas-fed SOFC, for a single-family house located in Milan, Italy. The higher electricity production of the natural gas-fired SOFC, mainly resulting from its continuous operation, led to a higher self-consumption referred to the total alternating current (AC) load on a yearly basis. Regarding the r-SOFC, the major part of the electrical energy needed to power the H2 production and AC loads during the cold seasons must be fed from the external grid. It is assumed that the gas-fed SOFC technology will be particularly useful in the transition phase from a fossil-fuel based energy system to a clean energy phase since it presents economic and environmental advantages compared to the r-SOFC with hydrogen storage. Nevertheless, the r-SOFC-based system will become more and more competitive along with the diffusion of distributed renewable electricity generation and with a larger renewable energy share in the energy mix [7].
[8]	Case study 8 presented an LCA of the **French MSW incineration system**, based on operational data from 90 plants. Nine midpoint impact categories were assessed, while seven of them pointed that this procedure in the current location provides a ‘‘negative” impact meaning it is environmental beneficial. In these categories “energy recovery and consumption” stands for between 33 and 54% of the total impacts and benefits of MSW incineration in absolute value. Further, 333 and 283 kg CO2eq per ton of MSW incinerated in France is observed in the cases of plants derived from energy

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	recovery (2% of the MSW incinerated), and of plants equipped with energy recovery and delivery as electricity (22%) respectively. On the contrary, energy recovery as heat (9% of the mass of MSW incinerated) and as CHP (67%) enables to supersede primarily fossil-fuel based heat consumption and therefore brings a benefit in terms of climate change (respectively -18 and -40 kg CO2eq per ton of MSW). However, the contribution of direct emissions to the total climate change impacts of MSW incineration is essential due to fossil-CO2 (98%). Similarly, in the case of climate change, the impact of plastic waste incineration overall amounts to 1,663 kg CO2eq per ton [8].
[9]	Case study 9 investigated a potential strategy to use **animal by-products** for energy purposes with the target to meet the general EU directives, concerning the residues utilization and percentage contribution for the total energy consumption by 2020. LCA methodology was adopted for the treatment of animal waste from slaughterhouse and the subsequent conversion to power and heat generation (CHP), in the Campania Region, Italy. The environmental impacts of the above-mentioned process were compared to the impacts of the Italian electricity production (mix of fossil fuels and renewables). The results show that the highest impacts in all categories come from the operation step, while construction (e.g., machinery and capital goods) plays a minor role, except for metal depletion which accounts 16% of total impact. The use of urea (for the control of NOx emissions in the co-generation plant) results 54% and 70% of the global warming potential and of the fossil depletion respectively. Similarly, the contribution of urea is also high in the terrestrial acidification, freshwater eutrophication, human toxicity, metal and water depletion categories. Besides urea, the second main contribution to environmental burdens comes from the use of methane (for the generation of steam) in global warming, human toxicity, freshwater eutrophication and water depletion, ranging from 28% to 50%. Lastly, local emissions provide a major contribution to terrestrial acidification and photochemical oxidant formation with values of 62% and 84%, respectively [9].
[10]	Case study 10 includes estimates for GHG emissions arising from a **hypothetical carbon capture use storage (CCUS)** case with a natural gas combined cycle power plant (NGCC) and GWP impact, by using LCA methodology in a novel “well-to-well” approach. The stages that were included in this approach from natural gas supply to permanent CO2 geological sequestration, transport, EOR and final geological storage of CO2 were captured Furthermore, a LCA comparison with other electricity generation technologies, including super critical pulverized carbon (SCPC), NGCC without CO2 capture, geothermal, mini-hydro, wind and nuclear was conducted. The study concluded that the stages with major contributions were “natural gas supply” and “electricity generation”, with approximately 56% and 32% of the total CO2eq emissions. These results also indicate that CCUS practices may be compared to geothermal energy in terms of the carbon footprint generated or GWP of 0.177 and 0.232 kg CO2eq/kWh [10].
[11]	In case study 11 the GWP per kWh for each hour of the year for **electricity generation in Belgium** was calculated using a LCA approach. With this method, the CO2 equivalent content reflected activities related to the production of the electricity in a power plant. Moreover, it also included

	carbon emissions related to the construction of the infrastructure and the fuel supply chain. The shares of different feedstocks per type of power plant along with the shares of the different power plants in the Belgian production mix are taken into account. Considered raw materials were nuclear combustible, oil, coal, natural gas, biowaste, blast furnace gas and wood. From the comparison of conventional fossil fuels (coal, oil and natural gas), the full supply chain of the product was considered leading to a conclusion that coal has the highest GWP (0.9 kg CO2 per kWh versus 0.4 kg CO2 per kWh for natural gas). Furthermore, in this study several renewable electricity production technologies like photovoltaic cells, hydro installations and wind turbines were examined. The findings revealed that the production of the wind turbines and solar panels was more carbon intensive than the production of other conventional power plants, due to the lower electricity output. Power plants with shorter lifetime and lower production factor will have a higher GWP per kWh [11].
[12]	Case study 12 evaluated the cradle to gate environmental impacts of five existing **mini-hydropower plants** for electricity production in Thailand via LCA perspective. The obtained findings demonstrated that the stages with the highest environmental burdens were construction and transportation. The first occurred due to the large amount of construction materials required, not available locally. The overall high environmental impacts of the transportation process were justified due to long transportation distances, not only in Thailand, because most of the mini-hydropower plants must exist in mountainous and remote areas, but also overseas. Operation and maintenance of these plants presented relatively less emissions because the main process in this stage was electricity production from water. Lastly, mini-hydropower plants were compared with natural gas power plants, which account more than 70% of overall electricity in Thailand, concluding that the GWP of mini-hydropower plants was lower by more than 95% and their acidification potential (AP) by almost 90% [12].
[13]	Case study 13 presented the environmental impacts related to **potential energy systems in Ireland** with high penetration of wind power, with focus on cycling emissions (due to part-load operation and start-ups) from dispatchable generators. The outcomes showed that an increase in wind power resulted also an increase in cycling emissions. Nevertheless, there was a decrease in cycling issues when new storage capacity was presented. However, the plant's portfolio affected feasible emission reductions mostly the base load plants which realized an increase in capacity factor upon the introduction of bulk storage. These results indicated that the main concern for Ireland, in terms of emission reductions, was related on phasing out coal plants, instead of investing in new storage capacity to increase wind share and limit cycling. Overall, emissions from cycling amounted to less than 7% of life cycle emissions for all portfolios: their contribution was therefore limited and cycling emissions did not change the ranking of scenarios. In the scenarios presented, all power plants had an average yearly efficiency lower than the optimal value. Load following power plants had efficiencies up to 11% lower than optimal, which resulted in a potential underestimation of emissions by up to 65% for oil power plants, the extreme case. The authors concluded that in order to have a complete evaluation, the inclusion of the expected cycling emissions from a power

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	plant should be considered along with the comparison of units with a similar role – load following, mid merit, or base load [13].
[14]	Case study 14 provided a cradle to grave LCA of **Italian geothermal power plants**. The calculated LCA results showed that in the commissioning phase the CO2 emissions are associated to diesel combustion used to drive the drilling rig. Similarly, in the operational stage direct emissions of NH3, CH4, CO2 are released to atmosphere in percentage of 84%. These were the stages that accounted for more than 95% of the environmental impacts of the studied plant. In particular, out of the sixteen impact categories selected, climate change, acidification, terrestrial eutrophication and particulate matter were mostly affected in a global scale. However, a comparison between the studied plant and the production process of the average Italian electricity mix showed that the balance was always in favour of geothermal energy production, except in the climate change impact category. This outcome is due to the significant contribution given to the average Italian electricity mix from RES like hydro, photovoltaics and wind energy, whose CO2 emission contributions in the atmosphere during the operational phase are negligible [14].
[15]	Case study 15 analyzed the GHG emissions of **two geothermal power plants**. From a lifecycle perspective, five different scenarios comprising a heat plant, power plants and cogeneration plants were evaluated. The obtained results showed that for all scenarios prolonging the lifetime of the plant leads to less overall GHG emissions because the construction stage is the most GHG intensive process. Moreover, the development of the wells, including drilling and stimulation, contributed the most to GHG emissions unless transport piping was needed, where its construction could emit more. In term of resources, metal product consumption and production was responsible for most of GHG emissions, while these releases of an ORC plant varied with the type of electricity mix due to its electricity auto-consumption. The highest reduction could be achieved using geothermal heat for industrial use. Furthermore, site-specific approaches were assessed to examine potential GHG reduced emissions. Feeding on Alsace electricity mix during drilling will result in highest GHG emissions reduction, at least 15% for ORC plants. Reducing the total transport distance or frequency of drilling machine will potentially reduce 4% of total emissions. Lastly, treating post-drilling mud in nearby regions achieves a 2.9% total emissions reduction [15].
[16]	Case study 16 evaluated the energy and environmental profile for **photovoltaics and solar thermal collectors** through detailed cradle to grave LCA for residential applications. For each technology, various technical solutions were examined (i.e. thin film-crystalline silicon photovoltaics and flat plate-vacuum tube solar collectors). Regarding the studied photovoltaics systems, the production stage contributed the most to the overall environmental impacts, followed by the inverter and the construction process of the mounting systems, 60 - 70% (depending on the system) of inflows of materials and energy for both thin-film and crystalline PV systems occurred during the cell and panel production phase. In terms of the studied solar thermal collectors, the outcomes of this analysis revealed that the production phase of the collector component is the leading process accounting for 57% and 45.3% (of all total inflows and outflows) for the flat plate and vacuum tube

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	collector respectively. In order to stress the environmental benefits and drawbacks of each type of collector a comparison between the two systems was conducted. Both collectors exhibited quite close environmental impacts in most categories with the vacuum tube system having highest values in most cases except the cumulative CO2eq where the values ranged between 2.22×10-2 and 2.38×10-2kg CO2eq/kWh·m2, and the lowest value corresponds to the vacuum tube collector. The carbon footprint for the studied renewable systems was calculated, and in addition, typical values for other energy production technologies (either renewables or fossil-fuel based) were also depicted. Overall, the carbon footprint for solar thermal collectors is lower compared to photovoltaics, while both technologies alongside wind, hydroelectric, and nuclear energy, are more beneficial from fossil fuel based power plants [16].
[17]	Case study 17 presented a LCA methodology to evaluate energy use and CO2 emissions from **construction, maintenance and decommissioning of support infrastructures** for electricity and fossil fuel supply of vehicles applied to Portugal case study. Three light-duty vehicle technologies were considered: Gasoline, Diesel and Electric in terms of GWP and CED. For conventional fuels (Gasoline/Diesel) the oil well, platform, refinery, main distribution pipelines and refueling stations were analyzed while for the electric vehicle, a natural gas pipeline supply infrastructure, power plants according to an electric mix, transport and distribution grid and charging points were examined. The findings revealed that the electric vehicle energy supply infrastructures were more carbon and energy intensive per MJ of supplied fuel than conventional ones. In addition, under specific conditions like the studied current scenario of 2,269 vehicles per conventional refueling stations and the foreseen service rates scenarios of 7 vehicles per quick charger and 4 vehicles per normal charger, the LCA of conventional fuels infrastructure, potentially represented an energy use of 0.01–0.03 MJ/MJfuel for both Gasoline and Diesel fuels. Finally, charging facilities were the higher contributors per km among with energy supply infrastructures, both for carbon and energy intensity with about 57% and 66%, respectively. Electric power plants including maintenance activities, also contributed with a significant portion of about 33% in terms of energy use and 43% in emissions. Another conclusion could be that the closer the infrastructure is to the vehicle along the supply chain, the higher the weight of its contribution per km. Overall, with uncertainty in mind, energy supply infrastructure contribution in vehicle LCA did not exceed 8% under the assessed conditions. With a friendlier choice of materials used in charging points there could be a reduction in the carbon and energy intensity of overall infrastructures. Furthermore, if the Portuguese electric mix could contain higher contribution of renewable energy sources this could both lower the energy and carbon intensity and would require lower maintenance [17].
[18]	Case study 18 assessed cradle-to-gate GHG emissions for **the lithium-ion battery pack** used in the Ford Focus battery electric vehicle (BEV) based on primary data for large scale production and battery design. However, the outcomes showed that estimated GHG emissions of 140 kg CO2eq/kWh battery lied in the midrange of the literature values for BEV batteries. Roughly half of the GHG emissions of the analysis 65 kg CO2eq/kWh battery were associated with utility use

	(electricity, natural gas, and water) during cell manufacturing and pack assembly. Something that was well established was also the fact that cradle-to-gate life cycle stage for BEVs is more energy intensive than for internal combustion engine vehicles (ICEVs) mainly reflecting energy use and GHG emissions associated with battery production. In addition, the current estimation of a 39% increase in the cradle-to-gate GHG emissions of the Focus BEV compared to the Focus ICEV fell within the range of literature estimates. Despite their higher cradle-to- gate GHG emissions, switching from ICEVs to BEVs potentially would save a large amount of GHG emissions during their life cycle. However, it was also reported that published studies have estimated approximately 30−40% life cycle GHG emissions reduction for BEVs powered by the average U.S. or European electric grid mix. Finally, the present GHG estimate for BEV battery confirmed the potential for BEVs to curb GHG emissions from the transportation sector [18].
[19]	Case study 19 compared the cradle to grave environmental impacts of **nuclear, wind and hydro power generation in Ontario**, Canada through a comprehensive LCA approach. The output emissions examined in the study were CO2, CH4, SOx, NOx and total particulate matter. In conclusion, wind power was estimated to have comparatively higher environmental impacts, between 50 and 80% for each impact category, due to the manufacturing phase of the wind turbine. The estimated GWP was 12.05 g CO2eq/kWh. Furthermore, hydroelectric reservoir facilities with biomass decay yielded comparatively higher global warming potentials of 15.2 g CO2eq/kWh. On the contrary, hydropower reservoirs with no biomass decomposition was found to have comparatively lower life cycle environmental impacts (2.7 g CO2eq/kWh). Last but not least, in the nuclear power life cycle, the estimated emissions was 3.402 g CO2eq/kWh. Mining and milling contributed almost 50% of the global warming and eutrophication potentials, while decommissioning stages significantly contributed to life cycle environmental impacts [19].
[20]	Case study 20 applied a cradle-to-gate LCA for technologies like **solar thermal collector, photovoltaic panel, Combined Heat and Power System (CHP), absorption chiller, Air Source Heat Pump (ASHP), Ground Source Heat Pump (GSHP), pellet boiler and hot water storage** which are widely used for residential applications. The goal of this paper is to evaluate the Cumulative Energy Demand (CED) of the considered systems. Moreover, a comparison between the different technologies by varying their capacity was conducted. This study reveals the following: i) increased capacity of the systems leads to lower specific impact per unit of installed nominal power, ii) components can be size dependent or independent which results to an alteration of the contribution of the components to the total impact and this affects the reliability of LCA studies, iii) from the comparison between the CHP system and PV with the same installed electric power, the total CED of the CHP is higher than the CED of the PV up to electric power of 10 kW, but this trend is reversed when the installed power is higher, iv) for sizes greater than 10 kWel the comparison between the CHP and the aggregate system composed of STC + PV, GSHP + PV and ASHP + PV shows that producing electric and thermal energy by using a CHP unit is more convenient than the other options, v) from the comparison between the GSHP and ASHP units, the results show that

	GSHP systems have less environmental impacts than ASHP systems for sizes larger than 100kWth while for a given installed thermal power of the STC, GSHP and ASHP, the highest impact is related to the STC (except from the cases of 1 and 5 kWth power capacity) [20].

7.2 Annex 2

Case	Details
[21]	An economic analysis of the production of photovoltaic solar energy utility scale facilities is performed, while a comparison of different tracking technologies (fixed, one-axis, two axis) is also presented. Hence, useful and updated information is extracted regarding the CAPEX, OPEX, LCOE of photovoltaic installations. Furthermore, according to [30] the CAPEX can be decomposed into the following components: CAPEX = H (Hardware Costs) + S (Soft Costs) + I (Installation Costs) where: • Installation costs are the expenditures related to the setup of the PV system, including mechanical and electrical installation, • Soft costs include not only the expenditures of all relevant permits, but also all overhead costs such as marketing, sales and administrative costs associated with the system, and hardware costs comprise every piece of material needed to build the system: module, inverter, racking and electrical wiring. A typical cost breakdown of PV installed in residential areas is: 80% the initial investment, 8% the inverter replacement, 12 O&M costs. Note that, the inverter replacement constitutes the 10% of the initial investment (lifetime 15 years, degradation rate 0.5%)
[22]	Five different wind turbines installations are examined, two offshore and three onshore. A CAPEX cost – breakdown for the first wind farm mentioned (onshore, 200 MW total installed capacity at a 450m height above sea level) confirms the known practice of investing the greatest up – front share for the mechanical components of the wind turbines (tower, rotor, nacelle). As derived from the indicative 4 UCs, the foundation costs exceed significantly those of onshore wind turbines. This is more evident in the case of a floating buoy basis, with the relative expenditures accounting for 27.1% of the overall CAPEX (as opposed to the 4.1% and 20.1% shares for the onshore and fixed offshore shares respectively). However, the influence of the high initial CAPEX for overseas wind farms is also shown in terms of each project's IRR, with the 200 MW onshore plant offering the most attractive investment opportunity for the same life cycle (25 years). Interestingly, the highest LCOE recorded in [22] corresponds to the small – scale (20kW) Residential Wind turbine installation. Given the 5.58 m/s average wind speed assumed, as well as the typical lack of periodic maintenance availability on a residential level, the discount and inflation rates commonly applied on a local industrial level can't mitigate the resulting slow profitability of such a project.
[23]	Although the use of geothermal generation in most countries remains economically unattractive, with LCOE multiple times higher than conventional or standard renewables (wind, solar), recent

	findings show that with abundant resources (high steam flow and temperature) it can prove to be competitive to them. In fact, a thorough feasibility comparison of various renewable (wind, solar, biomass, geothermal) and conventional plants (coal, CCGT, nuclear) of a wide capacity range (5 – 600 MW) conducted by a major German utility [23] describes the industry's gradual shift of interest towards geothermal applications. It seems that although wind and solar generation concern most of the investments and acquired revenue, their volatility has attracted investment interest to the point where man – made engineered geothermal fields have been conceived as a concept. Total costs per unit of produced electric energy still remain high (e.g. 7000 €/ MWh for a 100 MW heat geothermal plant compared to 8000 €/ MWh for a 600 MW nuclear station). However, it is estimated that the ongoing efforts to consolidate and expand geothermal technologies will provide a very efficient solution on a distributed level.
[24]	A detailed cost – breakdown for the construction and operation of a Hydropower plant per 1 kW of capacity installed is conducted in the current research. These plants typically require significant up – front CAPEX due to the long construction phases (e.g. excavations, dam erection and fortifications, river diversion). However, although considerable, the annual OPEX which reflect the station's 0&M costs don't reach prohibiting levels (ranging between 3 – 7% of the CAPEX).
[25]	The specific UC investigates the performance of a combustion engine (5 kW electrical and 15kW thermal peak power) that utilizes H2NG fuel enrichment for both power and heat recovery. For a total of 160 operating working hours, operational results were compared for the use of the enriched fuel, as opposed to the supply of conventional NG. The improved fuel combustion cycle efficiency of the H2NG blend leads to a better mechanical performance, while the effects on heat recovery efficiency are rather negligible. Overall, the proposed method leads to shorter operating time, as well as heat production, which in turn guarantee reduced emissions. Consequently, typical carbon avoidance tariffs provide revenue in the form of CAC (Carbon Avoidance Costs) that mitigate the increased LCOE.
[24]	A similar approach of cost – breakthrough for an Oil – Fuel (e.g. Diesel) based plant, as followed in (HYDRO), is also presented in [24]. Interestingly, the high LCOE deriving from the fuel expenses (and their occasional volatility) result in a longer payback period (almost 15 years). However, relatively lower CAPEX for such a station's initial construction than a brand-new renewable plant of great capacity, along with the reasonable OPEX (2 – 4% of the CAPEX) reflecting mainly periodic maintenance needs mitigate the financial risk. This also confirmed by the indicative project's high IRR (9.43%), and the industrially known long life cycle of conventional power plants (typically exceeding 30 years).
[26]	In this case, an underwater kite with a turbine that utilizes the water current's flow to rotate a generator is presented in a technical and financial perspective in 3 stages. The first stage refers to the period when the first version technology is deployed. The second one corresponds to the project before commercialized use while the third and final stage concerns the product's post commercialization period. In its initial deployment, the tidal energy conversion project requires

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	significant CAPEX due to its lack of technological maturity up to date. Combined with the high maintenance needs due to the extended exposure of the equipment in intense conditions, the resulting LCOE are high, although they seem to stabilize in a more reasonable range during the second stage. Upon commercialization and further growth of the employed technology, tidal generators seem to guarantee lower OPEX, as well as improved Capacity Factor and availability performances.
[27]	Findings from a survey in Germany show that 2 different waste treatment methods are funded systematically on both a local and industrial level, accounting for a 12 million € total investment. An average of 0.55 €/ kWh is noteworthy given the financial burdens of the country's decarbonizing effort, although counteracted with a relatively low RR (5.5%).
[28]	An indicative LI battery – based project is assessed in [28], with significant up – front CAPEX due to the lack of industrial experience related to them, as opposed to LA batteries. On the contrary, the operating cost seems almost negligible (6.9 €/ MWh), hence providing very attracting LCOE and IRR indexes. A downside on this effort should be noted in terms of long – term hardware requirements, since even though the project is deemed viable for a period of 25 years and LI batteries are proposed, the latter are expected to be replaced twice during this period.
[28]	The highly experimental nature of the flywheel leads to significant CAPEX, however the flywheels' time endurance and minimum maintenance requirements eliminates OPEX. The proposed capacity (1 MWh) confirms the rather ancillary nature of such devices, although the resulting LCOE (0.59 €/ MWh) should be considered in comparison with the respective ones of mainly the volatile renewables (wind, solar).
[32]	Given the ongoing research on them, a power performance and LCOE assessment analysis on a Solid Oxide FC (SOFC) based power plant, supplying small – scale agricultural enterprises is conducted in this case. With the aim of optimal biogas (produced by livestock) exploitation, the cooperation of a SOFC with a biogas electricity generator (BEG) is proposed as a feasible solution, with the potential of lower LCOE than that calculated, due to the SOFC technology expected progress. Indicatively, a $0.068 LCOE for the supply of a 120kW agricultural consumption through a 10 – year lifespan is calculated.
[33]	As FACTS devices, their initial purchase and installation, as well as the required maintenance costs, hybrid transformers can offer numerous network benefits which in turn result in increased revenue. In fact, their built – in capabilities of voltage and power (active and reactive) regulation (±10-20%), combined with their high typical efficiency (above 98%) and long life – cycle, HTs constitute an attractive upgrading investment for distribution networks. In other words, the optimized voltage and power flow levels prevent the excessive losses and distribution equipment strain that usually burdens financially both the end – users and the DSOs.
[29]	A comparative study was conducted for electric water heating systems ranging from small domestic applications (5 – 300 m2 roof coverage, 380 – 400 kWh/m2gross yield) to complete solar district heating systems (up to 20,000 m2 ground surface coverage, over 400 kWh/m2gross yield),

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	operating on typical solar irradiation profiles met in central and northern Europe. A steady discount rate of 3% is assumed in common, while different short term thermal storage technologies are applied. The Fixed and variable O&M costs [€/m²gross] decline with the system's increase in capacity, as does the initial CAPEX requirement per m²gross. It is typical for such equipment to have negligible maintenance demands, thus even though inflation and module degradation have been assumed in a simplified way, the results indicate that large – scale heating networks can prove a feasible practice.
[31]	Amirkhizi et al, corelate socio – economic factors (gas and electricity costs, related tariffs, standard scale of investment etc) with resource demand (heat, water) on an indicative Danish residential profile to determine the optimized operation of a 5 kW Bosch GEHHP. Despite the gas boiler's significant start – up consumption compared to the heat pump (1500Wh and 50Wh respectively), given the assumed temperature variations the GEHHP system proves to be the most feasible choice compared to other heating options. In fact, the gas boiler is expected to be employed at 24% of the time, mitigating the fuel requirements and leading to a LCOE of 0.11 €/ kWh for a lifespan of 15 years.

7.3 Annex 3

Regarding solar photovoltaics (on which only little information has been found on cost-to-capacity) we consider a methodology developed by Khawaja et al. [47] in 2017 which presents a technical and economical evaluation of grid-connected photovoltaic-battery energy storage (PV-BES). Matlab simulations run to verify an energy balance ensuring that hourly energy demand is mainly covered by the PV-BES, while the grid is treated as a backup only (equations and system modelling are found in the primary source). An optimization approach is used to determine the size of the PV system by iteratively changing the PV contribution from 200 kW to 1400 kW with a step of 30 kW each time for the batteries. This is followed by an economic model to calculate the system levelized cost of energy (LCOE) for all possible PV-BES sizes. LCOE methods are widely used to evaluate the economic feasibility of PV systems and BESS. The costs distributed over the project lifetime are considered and this provides a more accurate economic picture of the project under analysis. In this study the lifetime of the system is assumed equal to 30 years during which the batteries, inverter and charge controller are replaced twice. In this context, an improved formula of LCOE is proposed which includes new parameters reflecting the impact of surplus PV output and the energy purchased from the grid. Additionally, the proposed model uses the levelized cost of delivery (LCOD) for BES and compares it with system LCOE.

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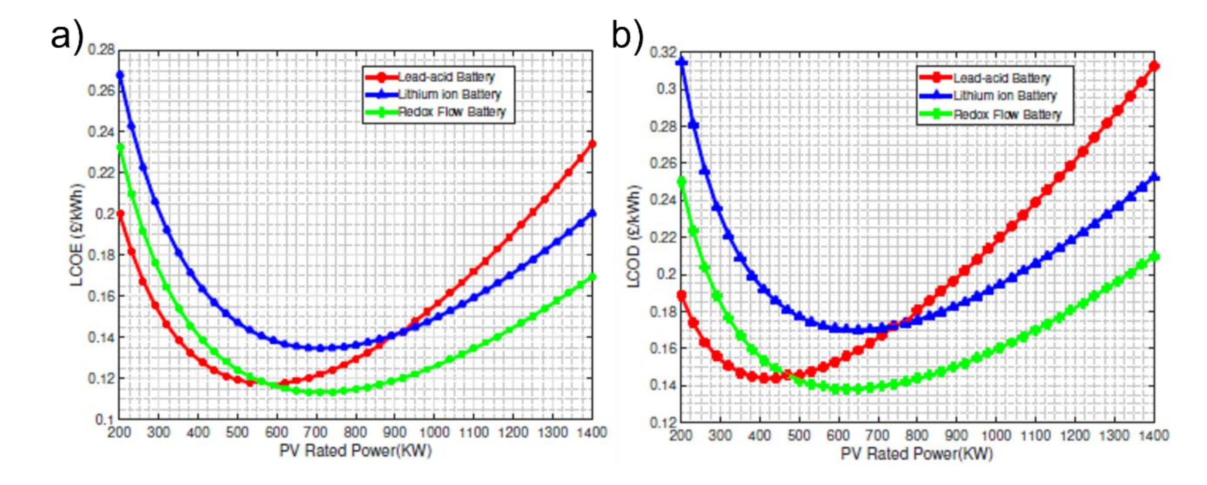

Figure 41: *a) LCOE of the grid connected PV-BES for different type of batterie b) LCOD for the BES system. Readapted from ref* [47]

For Lithium-ion batteries the optimal rated power of the PV system is around 710 kW. It is also clear that the LCOD for the batteries is higher or similar to the LCOE of the whole system and this is due to the high cost of the batteries and to the fact that the energy storable in the system is small compared to the energy produced by the system.

Skipping the necessity to scale the environmental impact with the size of the equipment, a suitable approach for IANOS would be the collection of LCA studies relative to similar system of different size, the harmonization of the results and the subsequent statistical analysis and retrofitting to derive 'impacts power law'.

As an example we consider this methodology as applied by Caduff et al.[48] to scale the environmental impact of a wind turbine with its size. They collected twelve LCA studies covering a turbine rated power between 660 and 3000 kW. They harmonized the results in terms of life cycle system boundaries and recalculating the rated power to standard conditions basing on the turbine Diameter D. They fitted all the data according to Eq. 8, where y is the selected impact category and x= D 2 h 3/7

$$\log y = \log a + b \log x \qquad \textit{Eq. 8}$$

The results of the statistical retrofitting are summarized in Table 23 which reports the values for the scaling factor b and intercept a for ReCiPe impact categories versus D 2 h 3/7 (which is proportional to the power).

Table 23: *REciPE impact categories and relative scaling coefficients [14]*

Impact category	Unit	log (95% CI)	b (95% CI)	R2	SE
Ozone depletion	kgCFC-11eq/kWh	-8.15 (-8.48, -7.83)	-0.22 (-0.16,-0.30)	0.79	0.066

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Human toxicity	kg1,4-DBeq/kWh	0.66 (0.01, 1.32)	-0.55 (-0.42,-0.72)	0.85	0.134
Photochemical oxidant formation	kg NMVOC/kWh	-3.14 (-3.55, -2.72)	-0.28 (-0.20, -0.39)	0.79	0.084
Particulate matter formation	kg PM10 eq/kWh	-3.08 (-3.49, -2.67)	-0.30 (-0.22,-0.41)	0.81	0.084
Ionising radiation	kg U235 eq/kWh	-1.65 (-2.01, -1.28)	-0.23 (-0.17,-0.33)	0.77	0.075
Terrestrial acidification	kg SO2 eq/kWh	-2.61 (-3.06,-2.16)	-0.37 (-0.28,-0.49)	0.85	0.092
Freshwater eutrophication	kg P eq/kWh	-2.75 (-3.35, -2.15)	-0.51 (-0.39 ,-0.67)	0.86	0.123
Marine eutrophication	kg N eq/kWh	-4.08 (-4.52, -3.64)	-0.30 (-0.22,-0.41)	0.79	0.089
Terrestrial ecotoxicity	kg1,4-DBeq/kWh	-3.95 (-4.38, -3.52)	-0.40 (-0.31, -0.51)	0.88	0.087
Marine ecotoxicity	kg1,4-DBeq/kWh	-1.57 (-2.05, -1.08)	-0.40 (-0.30,-0.52)	0.85	0.098
Agricultural land occupation	m2a/kWh	-2.54 (-2.88,-2.19)	-0.24 (-0.17,-0.33)	0.79	0.070
Natural land transformation	m2/kWh	-4.75 (-5.20,-4.30)	-0.28 (-0.20,-0.39)	0.76	0.092
Water depletion	m3/kWh	-2.78 $(3.11, -2,45)	-0.25 (-0.19,-0.34)	0.82	0.068
Fossil depletion	kg oil eq/kWh	-1.47(-1.85, -1.09)	-0.22 (-0.15,-0.31)	0.73	0.078