H2020-LCE-2016-2017

EUROPEAN COMMISSION

Innovation and Networks Executive Agency

Grant Agreement no. 731249

SMILE

Smart Island Energy Systems

Deliverable D6.3
Report on LCA/LCC tool and results

Document Details

Due date	31-10-2019
Actual delivery date	30-04-2020 (final complete version)
Lead Contractor	CERTH
Version	Rev 1 Final
Prepared by	CERTH
Input from	CERTH, Community Energy Scotland, Samsø Energiakademi ACIF-CCIM, PRSMA, Samsø Kommune, Lithium Balance
Reviewed by	RINA Consulting
Dissemination Level	Public

Project Contractual Details

Project Title	Smart Island Energy Systems
Project Acronym	SMILE
Grant Agreement No.	731249
Project Start Date	01-05-2017
Project End Date	30-04-2021
Duration	48 months

The project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 731249

Executive Summary

The overall scope of SMILE project is to demonstrate, in real-life operational conditions, a set of both technological and non-technological solutions adapted to local circumstances targeting distribution grids to enable demand response schemes, smart grid functionalities, storage and energy system integration with the final objective of paving the way for the introduction of the tested innovative solutions in the market in the near future. To this end, three large-scale demonstrators are under implementation in three island locations in different regions of Europe with similar topographic characteristics but different policies, regulations and energy markets: Orkneys (UK), Samsø (DK) and Madeira (PT).

The present document was prepared in the framework of SMILE work-package 6 (WP6) “Life Cycle Assessment/Costing (LCA/LCC), socio-economic studies, cost/benefit analysis, market analysis, business cases and financial mechanisms”, concerning the environmental and economic issues raised by SMILE project, with particular reference to the evaluation of combined RES and storage solutions demonstrated. Scope of this document is the Life Cycle environmental and economic assessment based on the gathered primary and secondary data inventory of the demonstrated solutions.

For the extraction of the LCC/LCA evaluations, the three (3) representative demo sites of Samsø, Madeira and Orkney are studied in order to draw conclusions and provide guidelines for the optimization of the proposed RES and BESS equipment and strategies both from an environmental and economic perspective. In specific, for the Samsø pilot and Pilots 1 and 2 of Madeira respectively, models have been developed according to the BESS operation based on the price zones of grid electricity. For the pilots with EV charging, pilots 3 and 4 in Madeira, scenarios based on price shifting and maximisation of RES penetration were developed and evaluated. All the assessed models were dynamic multi-parameter simulations using hourly and minute steps throughout the life cycle of the corresponding equipment.

For Orkney, the assessment of the replacement of an oil boiler with an air-sourced heat pump for space and water heating in an indicative domestic property was carried out. Moreover, the implementation of heating storage was evaluated in order to exploit much of the otherwise curtailed RES energy of the local electricity grid. The evaluation was again made with the calculation of the LCA and LCC indicators.

The methodology is based on the ISO standards 14044:2006. The evaluation of technologies was undertaken with a list of Key Performance Indicators (KPIs) developed in deliverable D6.1[1], such as Energy Returned on Energy Invested (EROI), CO_2 Payback Time, Annuity Gain (AG), Life Cycle Cost (LCC). The environmental assessment was carried out according to life cycle analysis principles by using the commercial software SimaPro including manufacturing phase and operational phase of the installed PV and BESS components throughout their whole life cycle. The analysis was conducted with the use of hourly and minute time series along with technical data of the equipment used and economic data provided by the local environments of the SMILE consortium.

According to the results of the study, it seems that the implementation of a BESS contributes by a positive way in environmental terms (LCA). However, this implementation increases the investment costs. It is mentioned that the selection of an appropriate operating scheme of the BESS could lead to significant savings in both economic and environmental impacts. In parallel, a sensibly defined sizing of a PV seems to always enable the reduction of CO_2 emissions and cost compared to baseline scenario corresponding to the grid electricity.

[1] D6.1 “Report on selected evaluation indicators” (https://cordis.europa.eu/project/id/731249/results)

Table of Contents

Table of Figures

Table of Tables

Keywords, Acronyms

ASHP	Air-sourced Heat Pump
BESS	Battery Energy Storage System
BOS	Balance of System
CED	Cumulative Energy Demand
CF	Carbon Footprint
CoP	Coefficient of Performance
CRM	Customer Relationship Management
DfE	Design for Environment
DoD	Depth of Discharge
DSO	Distribution System Operator
EoL	End of Life
EV	Electric Vehicle
GHG	Green House Gas
IPCC	Intergovernmental Panel on Climate Change
IPP	Integrated Product Policy
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCM	Life Cycle Management
LCSA	Life Cycle Sustainability Assessment
NMC	Nickel-Manganese-Cobalt
PDF	Potentially Disappeared Fraction
PV	Photovoltaic
RES	Renewable Energy System
TOC	Total Ownership Cost
TSO	Transmission System Operator

1 Introduction

1.1 Scope and Objectives

Aim of this deliverable is to provide a comprehensive context and detailed evaluation methodology of technologies for energy storage such as Battery Energy Storage System (BESS) for self-consumption and DSM, for electric vehicles (EVs) and boats, as well as thermal energy storage system when integrated with RES based systems for the demonstration sites of Samsø, Madeira and Orkneys. In order to achieve that, a holistic methodology for the environmental and economic evaluation of the proposed solutions have been implemented.

First step of this methodology is the definition of a list of environmental and economic KPIs, which has been accomplished in the previous public report D6.1[2], based on similar results from other on-running EU projects and on the feedback received from most of the SMILE project participants.

In the second step, the baseline scenarios, as well as new scenarios with the SMILE implementations were defined in order to test the impact of each pilot solutions. The simulation of each scenario was developed in order to provide the technical results and energy flows of each one of them.

The environmental assessment was carried out according to life cycle analysis principles by using commercial software SimaPro which uses primary and secondary data for input. Primary data (e.g. capacities, efficiencies) has been derived from technical specifications given by the demo site operators or the foreseen measurements (e.g. energy consumptions) during demo activities. Secondary data, defined as the input values for which no actual measurements exist in fields of electricity production, has been acquired by databases (e.g. Ecoivent Database).

Finally, a main pillar of this deliverable was to perform an economic assessment based mainly on the LCC indicator, in order to assist the holistic evaluation of the proposed systems and strategies, as well as the optimization of their integration concerning both the environmental and economic perspective.

The results and conclusions will enable the development of the new business models that link the SMILE system with the customers in novel, engaging ways, building on big data knowledge, enabling dissemination and diffusion of SMILE across European member states.

1.2 Structure of the deliverable

The document is structured on the following chapters:

- In chapter 2, a detailed methodology approach of Life Cycle Analysis framework, based on the ISO defined stages, is presented. Certain guidelines concerning the available assessment impact methodologies are provided in order to explain their utilization. Finally, the selected impact methodologies for the SMILE implementations are presented.
- In chapter 3, there is a presentation of the basic principles of the Life Cycle Cost assessment used to enable the determination of the total cost of owning, operating and disposing of a product/service/technological system throughout its life, mainly by the perspective of the local economy. The corresponding literature review provides the various approaches of an LCC study according to whether it is supposed to serve mostly the environmental, economic or social point of view.
- Chapter 4 provides the application of the above mentioned assessment tools in the SMILE demonstrators. Regarding the scopes and system boundaries of each pilot, new scenarios were proposed in order to be compared to the baseline situation. A multi-parameter simulation was conducted for each scenario in order to reach specific results concerning the environmental and financial cost of each scenario. In the end, these results were presented and discussed.

[2] D6.1 "Report on selected evaluation indicators" (https://cordis.europa.eu/project/id/731249/results)

- The Chapter 5 includes the main conclusions and suggestions for the application of SMILE concept in similar projects.
- Annexes with a list of KPIs (Energy Returned on Energy Invested, CO2eq Payback Time, Annuity Gain, Life Cycle Cost) and relevant literature review are presented in the end of the deliverable.

1.3 Relation to other Tasks and Deliverables

The present document provides an environmental and economic assessment for the Samsø and Madeira demo sites under the SMILE project framework, and is to be used as main input for remaining deliverables, in particular D6.4 and D6.6 dealing in particular with cost benefit analysis and business cases and financial mechanisms respectively. The derived results from LCA and LCC studies will work as a decision-making tool for the most sustainable solutions. The input utilized will be provided by the environmental and economic data being actually monitored during the demo activities and/or dynamically simulated in WP2 related to the Orkney demonstrator, WP3 related to the Samsø demonstrator and WP4 related to Madeira demonstrator. Hence the results of the LCC will serve a) as a complete view of the total cost of each proposed system, and b) will feed with cost units the following Business plans and Cost Benefit Analysis (Task 6.5). Moreover, business opportunities and financial mechanisms for market uptake of the proposed technologies/services, as expected in report D6.6, will be identified according to the results of the present document, since the parameters with the highest contribution to the environmental impact and the overall LCC have been identified accordingly.

2 Life Cycle Analysis: Methodology, steps and basic principles

Life Cycle Analysis (LCA) can be defined as a method that studies the environmental aspects and potential impacts of a product or system from raw material extraction through production, use and disposal. The general categories of environmental impacts to be considered include resource use, human health and ecological consequences. To allow for a consistent comparison between the different scenarios, it is necessary to define a common reference to express the results for the same output: this common reference is called the functional unit. The functional unit is the common reference in order to express the data, as well as the results in the same output. The methodology is based on the ISO standards 14044:2006. More specifically, a typical LCA study consists of the following stages [1], [2], [3].

- **Goal and scope definition**

This step includes the objectives of the study, the functional unit, the system boundaries, the data needed, the assumptions and the limits that must be defined. Particularly, the functional unit is the reference unit which is used to normalize all the inputs and outputs in order to compare them with each other.

- **Life Cycle Inventory**

This step refers to the analysis of the material and energy flows and the study of the working system. On the other hand, the data collection for the entire life cycle implies the modelling of the analyzed system. Moreover, one of the most critical aspects of this phase is the quality of inputs, which must be verified and validated in order to guarantee the data reliability and correct use. During this stage, a conversion of the available data to appropriate indicators takes place. The indicators are given per functional unit used. The Life Cycle inventory is the most crucial stage in the LCA study. It corresponds to the finding and selecting of the input data, in order to express the examined scenarios in quantified terms. More specifically, at this stage, all emissions are reported on a volume or mass basis (e.g., kg of CO_2).

- **Impact assessment**

This step includes the assessment of the potential impacts associated with the identified forms of resource use and environmental emissions. The impact assessment methods, which are used in LCA can be divided into two categories: those that focus on the amount of resources used per unit of product (upstream methods), and those which estimate the emissions of the system (downstream methods).

- **Interpretation**

In this phase, the analyst aims to scrutinize the results and discuss them, giving as precise information as possible to the decision makers. Moreover, this step may highlight some problems in the LCA development which need a more detailed approach: for instance, it can be decided to improve the quality level of some data collected from the literature, because they describe a process which significantly influences an environmental pressure and therefore a more elevated accuracy of them may guarantee less variability in the results. This mechanism of the LCA assures the improvement of results.

The results of LCA contribute to inform the stakeholders about the environmental impact of technologies/systems/products, along their whole production–consumption chain, thus contributing to their rational decision-making if it deserves (additional) investing and what type of improvements are still required. Figure 1 presents namely all of the intermediate phases of a life cycle of a product or a service, each one requiring a specific amount of energy and water that needs to be consumed.

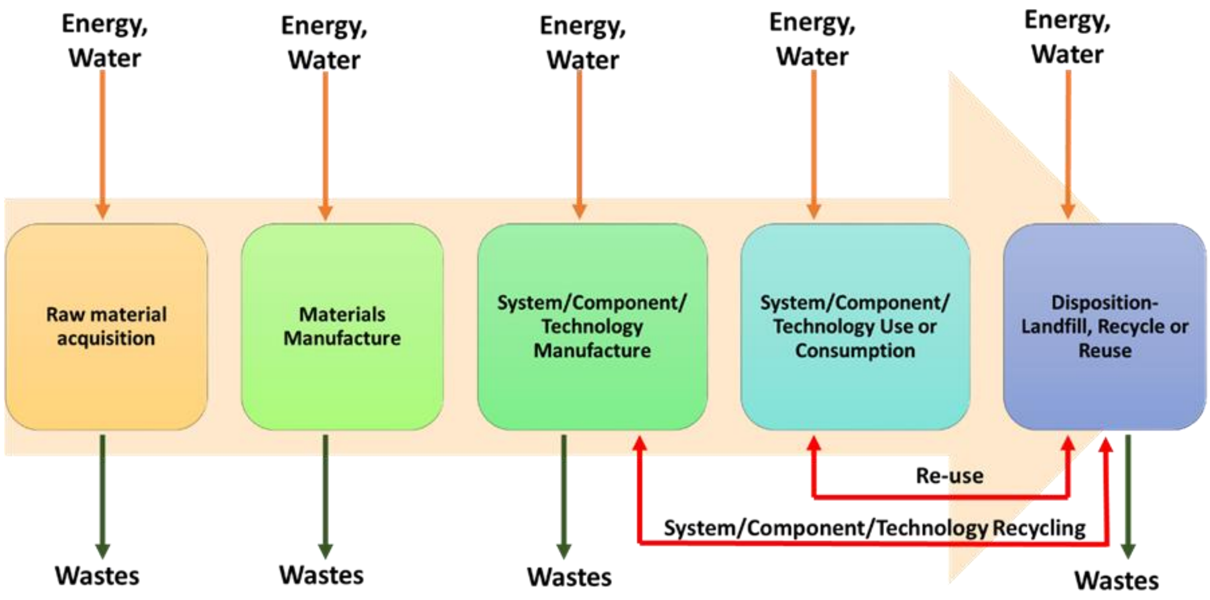


Figure 1: LCA cradle-to-grave life cycle approach with the depiction of all intermediate life-cycle phases of a system/component/technology

2.1 Dynamic LCA modelling: Taking into consideration the future challenges of the energy systems

In the established status-quo LCA approach, future developments of the energy systems themselves, and of the context in which the systems are to be applied, are typically not considered, thus severely distorting the analysis of the environmental characteristics of future energy systems. Typical influential parameters which can be changing in time and are considered in the case of a dynamic LCA are a) the energy mix, b) the share of RES, c) the recycling rate, d) the module efficiencies, and e) the quality of materials etc. Time-related issues affect LCA in numerous ways; broadly, they can be categorized into i) industrial and environmental dynamics and ii) time horizons and discounting of future emissions [4].
All the environmental and economic studies in the present deliverable (mostly LCA and LCC) consist of simulations throughout the life time of the tested equipment. In fact, the time parameter is not applied only in the sequence of years (with a different value in each year), but it is also applied throughout the year in an hourly or even minute step regarding its operation. Indicative sizes influenced by the time parameter in the present study are the following:

- PV generation (there are annual time series, which are changed every year due to equipment degradation);
- Load (there is a specific annual time series, which is kept steady concerning the next years of the life cycle);
- Battery (its reserve is expressed in a time series as a mixture of other parameters like PV generation, load and applied strategy – its capacity is shortened every year due to equipment degradation);
- The emission factor of the grid is expressed in a dynamic hourly manner when this was feasible (pilots 3 and 4 of Madeira)
- The discount rate is applied in all economic studies influencing the future cash flows, although it is supposed to be steady throughout the time period of the use case;
- All the results (CO_{2eq}/kWh and €/kWh) are calculated after normalization of the dynamic results that occurred at the simulation.

On the other hand, it was not feasible to implement a dynamic approach in certain cases. For example, the future change of the loads was not investigated in the present deliverable. The same applies to the discount rate and the changes in the grid electricity mixture (the share of thermal and RES sources in the grid some years later). Nevertheless, this dynamic approach could increase the accuracy of the simulations.

2.2 A short review of available assessment methodologies

As mentioned above for the case of impact assessment, the available LCA methodologies can be divided into two categories, i.e. a) those that focus on the amount of resources used per unit of product/process under evaluation (upstream category), and b) those which estimate the expected emissions of the system (downstream category). The main criteria for the selection of the most appropriate LCA method are:

a) the type of emissions that need to be estimated (for example GHG emissions, particulate emissions);
b) the performance of the system after being normalised on the basis of different profiles (e.g. characterisation, weighting, damage assessment);
c) the time horizon for which the impact is estimated (e.g. 20, 100 years);
d) the calculation method (e.g. single or multitasking impact method). For the latter, there is a plethora of calculation methodologies per impact category.

The methodologies are distinguished as either a) single issue ones that focus on the estimation of one impact category (e.g. the global warming potential impact) or b) the typical European methods that evaluate more than one impact categories by taking into consideration the most appropriate weighting factors. CO_2 was chosen by the Intergovernmental Panel on Climate Change (IPCC), as the reference unit for GHG emissions, because it is the most emitted substance from human activities. Hence, the reference unit upon which all emissions corresponding to the global warming potential impact are performed, is the CO_{2eq}. CO_{2eq} signifies the amount of GHG emitted, which would result in an equivalent global warming impact, as of the origin.
A distinction between fossil carbon emissions and biogenic carbon emissions is taken into consideration within the framework of the single issue impact methodology named as “Greenhouse Gas Protocol”. This distinction is made, based on the fuel source type (fossil and biomass), each time CO_2 is produced from, in order to avoid overlaps in the estimation. According to the guidelines compiled by the IPCC, CO_2 emissions from bioenergy sources should not be counted in national greenhouse gas inventories, because these are already inherently included in the Agriculture, Forestry and Other Land-Use sectors.

For the SMILE project, the chosen commercial tool for the calculations is SimaPro and the selected evaluation methodology is Impact 2002+[3]. The life cycle impact assessment methodology IMPACT 2002+ proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via several midpoint categories to several damage categories. **SimaPro** is a tool to collect, analyze and monitor the sustainability performance data of products and services. The software can be used for a variety of applications, such as sustainability reporting, carbon and water foot printing, product design, generating environmental product declarations and determining key performance indicators. In SimaPro the user can easily model and analyze complex life cycles in a systematic and transparent way, measure the environmental impact of your products and services across all life cycle stages, identify the hotspots in every link of your supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal[4]. The international ecoinvent database is the biggest life cycle inventory data source used in Life Cycle Assessment (LCA), Environmental Product Declaration (EPD), Carbon foot printing (CF), Integrated Product Policy (IPP), Life Cycle Management (LCM), Design for Environment (DfE), eco-labelling and other applications. The ecoinvent database contain life cycle inventory data of energy (electricity, oil,

[3] https://www.quantis-intl.com/pdf/IMPACT2002_UserGuide_for_vQ2.21
[4] http://www.pre-sustainability.com/simapro-lca-software

coal, natural gas, biomass, biofuels, bioenergy, hydro power, nuclear power, photovoltaics, wind power, biogas), materials (chemicals, metals, minerals, plastics, paper, biomass, biomaterials), waste management (incineration, landfill, waste water treatment), transports (road, rail, air, ship), agricultural products and processes, electronics, metals processing, and building ventilation.

3 LCC basic principles methodology

Life cycle cost (LCC) is the total ownership cost (TOC) of a product over its useful life. LCCs are all the anticipated costs associated with a project or program throughout its life. They are the sum total of direct, indirect, recurring, nonrecurring, and other related costs incurred, or estimated to be incurred, in design, research and development (R&D), investment, operations, maintenance, retirement, and other support of a product over its life cycle (i.e. its anticipated useful life span) [5]. All relevant costs are included regardless of funding source, business unit, management control etc.
Determining LCC is important for systems, because the acquisition is a small part in relation to the true or total costs associated with owning and operating the systems. Typical LCC assessments compare durable products with a purchase price that only makes up a small part of the life cycle cost. Other costs during the lifetime of the product (operation and maintenance costs, disposal cost, pollution costs to the local environment etc.) are discounted to current values [6], [7], [8] . Although discounting is a generally accepted practice, the applied discount rate is often controversial. In business environment high discount rates are applied such that current financial flows have a higher weight. In contrast, from a societal or environmental point of view, low discount rates are preferred to avoid the fact that current activities impose large costs in future generation [9], [10], [11].
In order to deal with financial, environmental and social concerns, different types of LCC analysis have been introduced as either stand-alone or mixed ones [12]. Conventional LCC assessments that only focus on private investments from one actor (a firm or consumer) are categorized as *financial LCC (fLCC)* [13]. Generally, only costs borne by the actor matter, and environmental or external end-of-life costs are omitted. Consequently, an fLCC assessment does not always consider the complete life-cycle, as only the economic life-time matters [5], [14]. Financial streams included in fLCC contain investment costs, R&D costs and sales revenues (presented as negative costs). Although the focus usually lays on these private costs, sometimes user cost can be included. For example, if companies are developing new products, they may take their customers' cost of ownership into account. It is common practice to discount the cash flows that occur within the time frame of the product life-cycle. In an fLCC assessment, a quasi-dynamic approach is used, where variables that remain constant over time are involved. The variables that do vary over time are discounted.
An *environmental LCC (eLCC)* builds upon data of fLCC and extends it to life-cycle costs borne by other actors [15], thus the full life-cycle cost of the product is considered [6] . The focus remains, however, on real cash flows that are internalized or expected to be internalized. There is no conversion from environmental emissions to monetary measures. Characteristic costs that are included in an eLCC are waste disposal costs, CO_2 taxes that are expected to be implemented and global warming adaptation costs. In contrast to fLCC, the variables of eLCC are kept constant over time. Thus, discounting is not applied [16].
The *full environmental LCC (feLCC)* extends eLCC with monetized, non-internalized environmental costs that can be identified by an environmental assessment method such as an environmental LCA. However, the transition to convert environmental impact figures to monetized figures is not always straightforward.
The *societal LCC (sLCC)* includes all the costs borne by the society as a whole, whether they have already occurred or they will occur in the future throughout the life-cycle of the product. Impacts such as public health and human well-being have to be quantified and translated into monetized measures, which is often quite difficult as it has to take into consideration various parameters like place, time and scaling. Since the analysis is carried out from a societal perspective, transfer payments like subsidies and taxes should be subtracted from the costs since they have no overall cost effect [17], [18] . For the same reason, low discount rate are preferred [11], [19].
The LCC analysis can be combined with LCA. For example, the environmental LCA (eLCA), which is the conventional type of LCA, has common features with all LCC types, except fLCC. As double counting is not a problem, LCA and fLCC can be used in parallel. Although the information resulting from both

assessments is complementary, the results may point to different actions. Indeed, an environmental measure may be positive for the environment, but negative from a purely financial point of view. Two methodological differences may complicate the interpretation of the results. Firstly, the perspective between both methodologies is different (private point of view versus life cycle point of view) and secondly, fLCC uses a quasi-dynamic approach with discounting whereas eLCA uses a steady state methodology where the weight of the impacts in time remains constant. The eLCC and eLCA do not only define system boundaries, time span and functional units in a similar way, but they also share the steady state approach without discounting of impacts. This is important, as eLCC is primarily set up as an assessment method that is carried out in combination with eLCA. As an eLCC only includes real money flows, the risk for double counting with environmental impacts included in eLCA is minimized [16] . By applying the same system boundaries, time span, functional unit and steady state cost model as eLCA and eLCC, also an sLCA is compatible. The relatively new and comprehensive tool that summarizes the results of these three sub-methodologies is called Life-Cycle Sustainability Assessment (LCSA) [20], [21], [22]. Combining the results, an LCSA can provide more comprehensive insights to invest limited societal resources in an optimal way.

3.1 LCC methodology

3.1.1 LCC function

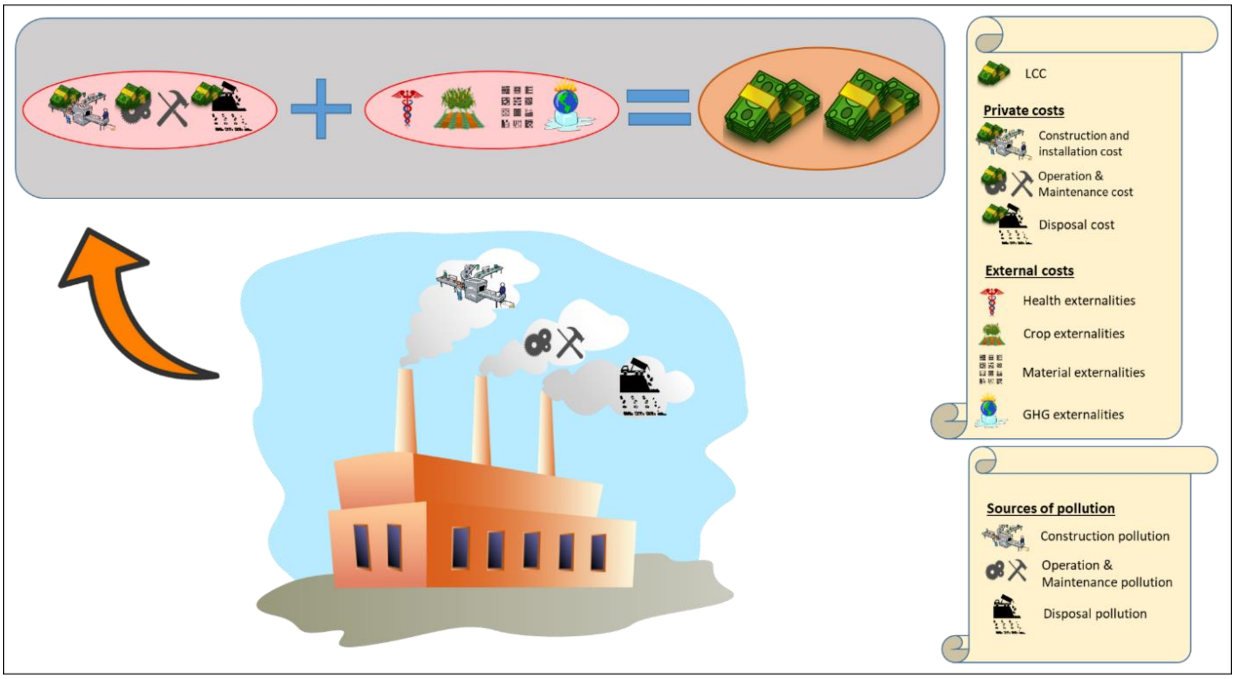


Figure 2: LCC methodology approach

An LCC analysis, especially when conducted by a societal organization, involves into the calculation of both primary and external costs (Figure 2). Primary costs acknowledge the initial cost of the investment/production C_{inv}, as well as the cost of operation and maintenance $C_{O\&M}$, and finally the cost of disposal C_{dis}. Hence, primary are all the costs faced by an investor during the life cycle of the investment. Thus, an LCC evaluation could be conducted using the following general formula:

$$LCC = C_{inv} + C_{O\&M} + C_{dis} + C_{ext} \qquad (1)$$

Environmental externalities C_{ext} refer to an economic concept of uncompensated environmental effects of production and consumption that affect consumer utility and enterprise cost outside the market mechanism. As a consequence of negative externalities, the private costs of production tend to be lower than its “social” cost. It is the aim of the “polluter/user-pays” principle to prompt households and enterprises to internalize externalities in their plans and budgets [23]. One question that arises in the context of LCC is whether there are other types of externalities that can be factored in, leaving aside environmental costs. Among these are the social costs, that have been taken into consideration and are provided in the corresponding paragraph.

3.1.1.1 Units and present value

The calculation of the LCC is based on the equivalence of the present value of the sum of discounted revenues and the present value of the sum of discounted costs [46]. It is basically the equivalent annual value of energy cost in a considered useful life in a given interest rate. LCC unit may be given in €/gallon, €/litre, €/MWh or any other commercial currency and measurement depending on the currency and energy being considered. In the case of electricity, LCC for RES is usually given in €/MWh. LCC may then be compared with market price to check if the net present value is positive in a given discount rate. The discount rate chosen is usually subjective because it depends on the investor’s opportunity costs and risk evaluation. A usual manner to address this factor is to decide if the rate of return on the money needed for the project could be a higher return if invested in an alternative investment.

3.1.2 Investment cost

The investment cost C_{inv} illustrates all the costs involved before the actual operation. This may include either the cost of design, mapping, production, licensing etc., or the purchasing of the final product or service along with the license of operation. This cost appears only in the beginning of the life of the examined product or service.

3.1.3 Operation and Maintenance Cost

The cost of operation contains the cost of the resources needed for the operation, the fuel cost, the wages of the human resources, the cost of land rental and generally any cost that has to be taken care of in a tactical (annual) base. The cost of maintenance also has a tactical (annual) frequency, although there may be unexpected maintenance costs, too, throughout the year.

3.1.4 Disposal Cost

The disposal cost C_{dis} involves the costs that has to be taken care of after the operation life of the invested equipment. Such costs may have to do with recycling or disposal at landfills, as well as the possible cost of equipment transportation to the disposal site and other management costs arising out of the disposal phase, such as the disassembly/dismantling. The initial manufacturing of each piece of equipment may cause a lower or higher cost of disposal, based on how easy it is to separate the recyclable parts from the non-recyclable ones. In the present deliverable, the disposal cost was taken as zero according to the partners of the demo environments, because of its low cost which would be even more reduced due to the discount rate.

3.1.5 Externalities

The externalities include many impact categories that do not represent money literally to the investor, but to the local society as a whole. Such impact categories may be the human health, environment, greenhouse gases and radio nuclides [24] . Of course, there may be other impact categories, too, according to the topic of the study. Following, the included impact categories are described:

3.1.5.1 Human health

Impacts to health in the local community that are caused by releasing either substances, particles and emissions in the atmosphere. This impact causes extra cost to the community either because of morbidity or due to mortality. Such costs refer both to the treatment costs paid by the local society, as well as to the lost revenues by the absence from work.

3.1.5.2 Environment

The environmental impact refers to loss of biodiversity, and damage to crops and materials, as a result of pollution. The approach of monetization of this impact is based, according to the CASES project [25] , on a relative measure of species' abundance – the "Potentially Disappeared Fraction" (PDF) – that is associated with land use, and, in a rather complicated way, with the deposition of acidifying pollutants. Concerning the damaged crops, the cost refers to the loss of productivity and, thus, revenues due to the damage caused by pollution. The material corruption because of pollution refers to the faster decay of materials such as building materials which need extra cost for maintenance or replacement. The effects of different fuel cycles and energy infrastructures on ecosystems and biodiversity have not yet been sufficiently assessed [26] .

3.1.5.3 Greenhouse gases

The impact pathway of the emissions of greenhouse gases is extensive as compared to the impact pathways of conventional air pollutants, both in time and in space. According to the CASES project [25], greenhouse gases are stock pollutants that through their build-up in the atmosphere cause an increase in temperatures and changes in related climate variables at a global scale and over a long time period. The time period over which the impacts of current emissions occur extends the lifetime of the gases in the atmosphere because of extensive time lags in the climate system. Apart from the geographical and temporal extend of the impacts, they are also manifold as climate change can potentially affect many sectors of society, including health and safety, economic production and consumption, recreation, and environmental and natural assets. Because of the unprecedented rate of warming and climate change that is predicted by scientific assessments, there is high uncertainty concerning the extent and the probabilities of some of the more extreme impacts.

3.1.5.4 Radio nuclides

The impact refers, according to the CASES project [27], to the effect of the radioactivity throughout the life cycle of a technology. The external cost calculation takes this cost into account, mainly in health, because of radioactivity. In fact, this mainly applies to the operation process of nuclear power plants. Thus, this impact will probably not play an important role in our study.

3.1.5.5 Impacts on employment

Employment is influenced by the labour market; thus impacts on employment are not, according to economic theory, external costs. However, they nevertheless are usually an important argument in any investment decision. In general, it is more the change of the distribution of working places that might have an important local effect, especially in small communities. For example, a town near a lignite thermal electricity generator, is strongly affected if the facility is abandoned, as many of the locals stay unemployed. However, these effects are currently not included in the ExternE methodology [24] .

3.1.5.6 Depletion of non-renewable resources

According to Hotelling's theory the depletion of exhaustible resources is considered in the prices of the resources, thus costs of depletion are internal. However, if one assumes that the current interest rates are higher than the social preference rate that should be used for social issues, then some adjustment should be made. However, this is not yet considered within ExternE [24].

3.1.5.7 External cost calculations

To apply the ExternE methodology, a software package called EcoSense [28] is used. EcoSense provides harmonised air quality and impact assessment models together with a database containing the relevant input data for the whole of Europe. In general, dependent on the question to be answered, the analysis is not only made for the operation of the technology to be assessed as such, but also including other stages of the life cycle (e.g. construction, dismantling, transport of materials and fuels, fuel life cycle).

3.2 Life-Cycle costing in RES

The methodology best adapted to sustainable public procurement is the environmental life cycle costing (eLCC). It takes into consideration the external impact on the environment, which may be based on LCA (Life cycle Assessment) analyses on environmental impacts. LCA evaluates the effects of a product on the environment over the entire period of its life ("cradle-to-grave" analysis) with a view towards increasing resource-use efficiency and decreasing liabilities. They measure for example the external costs of global warming contribution associated with emissions of different greenhouse gases [29]. Environmental costs can be calculated also with respect to acidification (grams of SO_2, NO_X and NH_3), eutrophication (grams of NOX and NH_3), land use ($m^2 \times$ year) or other measurable impacts.
A useful study was conducted by the ExternE project [24] which deployed a methodology for calculating environmental external costs called Impact-Pathway-Approach. These costs were divided to health, environmental, material and greenhouse (GHG) external costs according to the various effects the lifespan of an energy investment can have to the local environment. The project developed the tool Ecosense [28] which utilizes a large LCA database of monetarized emissions for many countries around the world. The parametrization of the investment model gives its overall external costs.

3.2.1 A literature review on LCC application in RES

Table 1: Indicative studies about LCC of RES investments

Reference	Description	Utilized parameters	Comparison/ Optimization
[30]	Optimization of power generation of a wind/PV system stand-alone or coupled with a battery storage system. Generation and storage units for the hybrid system are properly sized in order to meet the annual load and minimize the total annual cost to the customer.	• Investment cost (\$2000 kW^{-1} for wind, \$350 for solar, \$170 for battery, \$1000 for a 3.2kW back-up generator) • Maintenance cost (\$0.02 kWh^{-1} for wind and \$0.005 kWh^{-1} for solar)	Optimization Hybrid: • Wind: 10 Kw • PV: 3.8 Kw • Battery: 18.9 kWh

		• Electricity generated (N/A) • Life expectancy (20 years) • Interest rate (6%) • Electricity price by Power Service ($0.02 kWh^{-1}) • Distance of consumer from grid (determined in order to compare with use case) • Power line charge ($5.10 ft^{-1})	
[31]	Optimization of decentralized energy systems based on interdisciplinary comprehension. The selection and dimensioning of the energy systems depends on technical, financial, environmental and social conditions.	• Investment cost (N/A) • Investment revenues (N/A) • Operation and maintenance (N/A) • Salvage cost (N/A)	8 scenarios utilizing one or more of the following: • Wind: 1200-3600 Kw • PV: 220-520 Kw • Biomass: 220-520 kW
[32]	Presentation of the economic feasibility of rural electrification through various energy sources like solar energy alone, diesel engine generator alone, solar-diesel hybrid system and utility grid based system for the selected rural area. It has been found that the hybrid SPV-DEG system is the most economically feasible option for the selected area.	• Investment cost (N/A) • Operation and maintenance cost (PV: 2%, diesel: 10%) • Life expectancy (25 years) • Discount rate (10%) • Cost escalation factor (due to various reasons (7,5%) • Replacement cost (=investment component cost)	Comparison • PV (149 kW$_p$), 450 batteries (200 Ah, 12 V) • Diesel (45 kW) • PV (50 kW$_p$), 120 batteries (200 Ah, 12 V), diesel (20 kW)
[33]	Provides an updated literature review, of the most applied techniques used in sizing and optimization of PV-wind based hybrid systems for an isolated area aiming to reach the best compromise between power reliability and hybrid system costs. Furthermore, it discusses a comparison of the most common topologies used for the implementation of a hybrid system and presents a mathematical model of the hybrid system components with an emphasis on the importance of power reliability and system cost.	• Investment cost (N/A) • Operation cost (N/A) • Maintenance cost (N/A) • Replacement cost (N/A) • Salvage cost(N/A) • Interest rate (N/A) • Cost growth (due to inflation etc.) (N/A) • Life expectancy (N/A) • Inflation rate (N/A)	Review on hybrid analytical modelling
[34]	A methodology with the aim to design an autonomous hybrid PV-	• Investment cost (N/A)	Optimization

	wind-battery system is proposed. Based on a triple multi-objective optimization, this methodology combines life cycle cost, embodied energy and loss of power supply probability.	• Operation cost (N/A) • Maintenance cost (N/A) • Replacement cost (N/A) • Life expectancy (25 years) • Inflation rate (2%) • Discount rate (5%)	• Hybrid (PV: 2.6 kW, Wind: 0.9 kW, Batteries: 720 Ah)

The literature analysis of Table 1 shows that LCC is exploited on purpose of either comparison of different technologies, or of different methods of implementation of a technology comparing different configurations. The LCC can be used as a methodology towards the selection of the most appropriate implementation of RES technologies in economic terms, by determining the most cost efficient contributors.

Concerning the parameters considered, a different approach was carried out in each cases study. Although the main methodology remains the same in all studies regarding the private costs (investment, operation, disposal), parameters such as discount and inflation rate, interest rate have been taken into consideration resulting to the differentiation of the examined scenarios. In most of the studies, the environmental cost is not taken into consideration, because of the difficulty to define it. The data availability and the point of view of the stakeholders are the main factors for the determination of the LCC scenarios for the examined case studies.

4 Demonstration Sites

4.1 Samsø demo site

Samsø's transformation from a carbon-dependent importer of oil and coal-fuelled electricity to a reference as far as renewables implementation is concerned started in 1998. For many years, Samsø has been a pioneering island when it comes to developing sustainable solutions for nature and the environment. Combination of renewable generation schemes with storage solutions in a smarter way has become a crucial issue the last few years. The demonstration project will focus on one of Samsø's marinas, the marina in Ballen. The energy demand in the marina is very inconsistent as it is dominated by the demand from berthed yachts and associated tourism. This results in not only in significant fluctuations on a daily basis, but also significant seasonal variations, as tourism has its peaks during the summer. To address this issue, SMILE will seek to implement an integrated energy system at the marina comprising renewable generation (PV) linked to storage (battery).

4.1.1 Description of the Samsø pilot

This pilot refers to the implementation of an integrated energy system at the Ballen marina and its surroundings, comprising the renewable generation (PV panels) linked to a central storage unit (BESS). The plan is to install a BESS close to the service building, in order to store excess power from the PV plant during daytime, and deliver power during the evening and nights where most boats are docked in the marina and energy consumption is high. The capacity of battery is 240 kWh corresponding to a 60kW$_p$ Photovoltaic system. The BESS can be charged from both the PV and from the grid.

The PV system is expected to cover the electric consumptions of the following

- Boats
- Electric vehicles and
- Service building (located in Marina)

4.1.2 System Boundaries – Baseline Scenario

The system boundaries for the Photovoltaic and BESS environmental assessment will include manufacturing of the components and the operation during the lifetime as presented in Figure 3. The service building will be equipped with a heat pump in order to increase the use of renewable energy. The End of Life (EoL) phase (i.e. disposal or recycling schemes) of the PV and BESS components has not taken into consideration for the LCA and LCC analysis mainly because of the lack of data. In general, the EoL phase has been generally excluded or neglected from life cycle studies, mainly because of the low amount of panels that reached the disposal yet and the lack of data about their end of life [35]. Furthermore, the lack of scientific evidences about the potential impacts and benefits related to the PV waste treatment did not stimulate policy makers to intervene. As described in relevant studies [36], [37], [38] the EoL phase was generally excluded from the LCA studies on PV implementation technologies. Few information is available corresponding mainly to small-scale recycling processes.

In order to export meaningful results from environmental and economic perspective of view, a baseline scenario is defined. The baseline scenario represents the situation in Ballen Marina before the implementation of the SMILE solutions. This baseline scenario will be acting as a reference scenario in comparison to the SMILE approaches in order to enable the presentation of the environmental and economic benefits/costs at the end of the project.

Regarding the examined pilot for Samsø, since the examined situation will take into consideration renewable solutions (i.e. Photovoltaic panels) and BESS on the Ballen Marina charging the boats, the

selected baseline scenario will only include the electricity purchased by the grid without the installation of PV and BESS, for the same time period tested in the other scenarios.

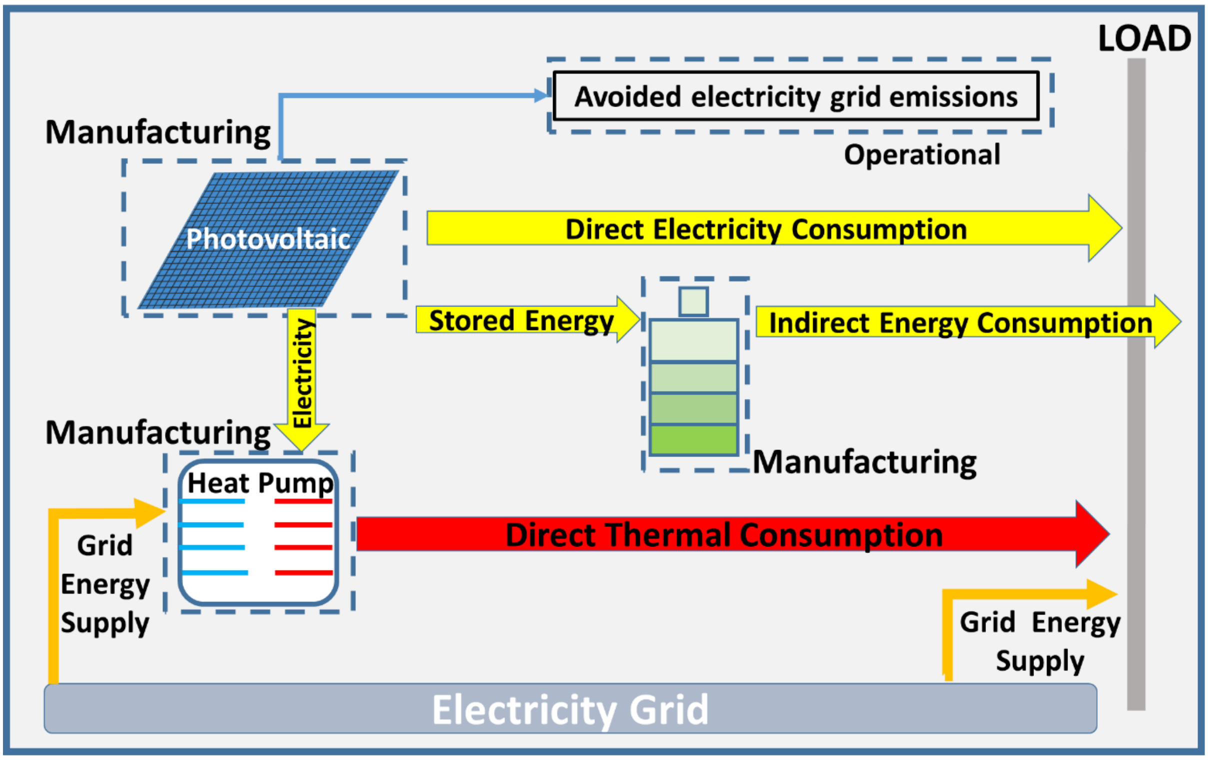


Figure 3: System boundaries of the installed technology for the 1st Pilot. Manufacturing phase of PV, BESS and Heat Pump will be taken into consideration

4.1.3 Definition of scenarios and configuration Scheme for SMILE Components in Ballen Marina

The examined scenarios for the Ballen Marina are **four,** including the reference/baseline scenario, and are presented in Table 2. The first scenario is before SMILE implementation activities where no PV and BESS were installed. The second scenario is about the installation of a 60 kWp PV without any storage solution. Scenario 3 describes actually the examined SMILE activities, including the installation of a 60 kWp PV and a 240 kWh BESS in the Ballen Marina. Based on the technical requirements that the municipality set, the PV should be extendable up to 120 kWp referring actually to a scale-up situation (scenario 4) for future PV installations in Ballen Marina.

Table 2: Examined Scenarios for Samsø demo site

Scenarios	Description
1	0 kWp Photovoltaic – 0 kWh BESS (Baseline scenario- No installations)
2	60 kWp PV – 0 kWh BESS
3	60 kWp PV – 240 kWh BESS (SMILE scenario)
4	120 kWp PV – 240 kWh BESS (Scale up future scenario)

The configuration scheme of Scenarios 3 and 4 (the ones including the BESS installation) is presented in Figure 4.

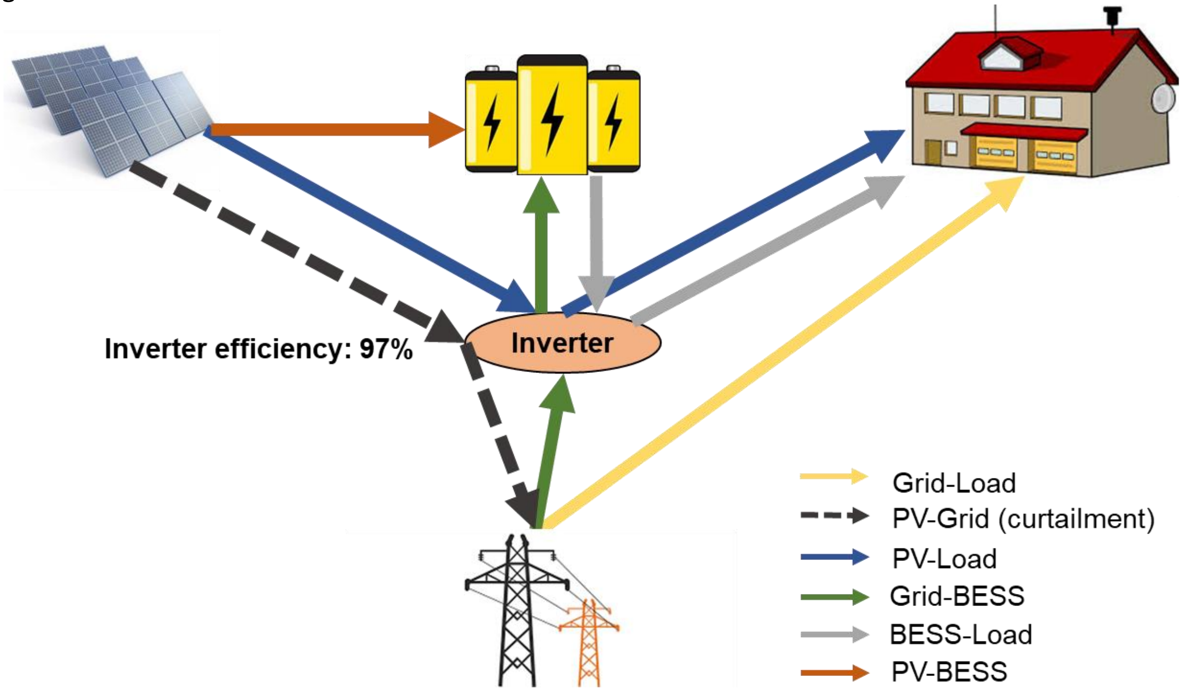


Figure 4: Configuration scheme for the integration of PV/BESS in the Ballen Marina of Samsø

4.1.4 Definition of the examined models of the battery exploitation

All of the aforementioned scenarios were analysed upon **three technical models** which differ on the BESS discharging. The three models are presented in Table 3 and the 2 scenarios including the use of a battery were analysed through these models.

Table 3: Simulation models for the different profiles of BESS charging

Model	Description
(1)	The first model includes **discharge of battery only during the hours of expensive electricity** (i.e. **06.00 – 09.00** and **17.00 – 00.00**) In this scenario the load fulfils in priority by • PV • BESS (during peak) • Grid The BESS is charging in priority by • PV excess • Grid (partial charging) every morning (5.00 - 6.00 a.m.) during November to March
(2)	In the third model the **discharge takes place during the hours of non-cheap current.** Non-cheap is the current in all the time zones except 06.00 – 09.00 a.m. and 17.00 – 00.00.
(3)	In the second model the **discharge is carried out** any time the production of the PV is not enough to satisfy the load needs

The dilemma between the policies among the 3 models stands on the fact that, although the higher use of the battery provides cheap energy generated by the PV, it also leads to a lack of this cheap battery energy in times when the grid electricity is expensive. Thus, it was sensible to study different models which prefer the cheap (not peak) energy of the grid in order to keep the battery reserves for the expensive time zones of the day. The main indicators that directed the study was the simultaneous optimization of RES curtailment and cost (operational cost of the grid electricity needed for the load fulfilment). Table 4 gives the time zones of the grid electricity price as described in deliverable D3.1[5].

Table 4: Pricing (€/kWh) of Samsø grid throughout the day (taxes included[6])

Time zones	Price (€/kWh)
00.00 – 06.00	0.168
06.00 – 09.00	0.273
09.00 – 17.00	0.21
17.00 – 00.00	0.273

In all models, the BESS is charging in priority by:
- PV excess
- Grid (partial charging) every morning (5.00 - 6.00 a.m.) during November to March.

The following pseudocode briefly describes the charging policy of the battery:

```
if Month>=November or Month<=March then
      if Hour=6 then
            bat←bat+morning
      end if
else
      if PV>=load then
            bat←bat+(PV-load)
      end if
end if
```

where *bat* stands for the battery reserve, and *morning* stands for the early morning partial charging of the battery, the amount of which is also based on the simultaneous optimization of RES curtailment and cost (operational cost of the grid electricity needed for the load fulfilment).
Following there is a description of the 3 models with an explanation of their process along with conclusions concerning their results.

[5] D3.1 “Specifications and data report for the Samsø pilot” https://cordis.europa.eu/project/id/731249/results
[6] D3.4 “Requirements Specification”

4.1.4.1 Model 1

The first model includes discharge of battery only during the hours of expensive electricity. In this scenario the load fulfils in priority by:

1. the PV (which has the cheapest operational cost)
2. the BESS reserves (only during the peak hours when the grid electricity is expensive)
3. the grid when the electricity cost is at its low or medium price, or when it is expensive but the PV cannot provide enough power and the BESS reserves are empty.

In order to give a better description of the specific model, a simple form of the battery discharging pseudocode is presented below:

```
if PV<load then
      if price=exp then
            if load>=PV+bat then
                  bat←0
            else
                  bat←bat-(load-PV)
            end if
      end if
else
      bat←bat
```

4.1.4.2 Model 2

The second model includes discharging of battery during some of the hours throughout the day. In this scenario the load fulfils in priority by:

1. the PV (which has the cheapest operational cost)
2. the BESS reserves (during the peak hours when the grid electricity is expensive, and during the medium price time zone)
3. the grid when the electricity cost is at its low price, or when it is more expensive but the PV cannot provide enough power and the BESS reserves are empty.

In order to give a better description of the specific model, a simple form of the battery discharging pseudocode is presented below:

```
if PV<load then
      if price=exp or price=mid then
            if load>=PV+bat then
                  bat←0
            else
                  bat←bat-(load-PV)
            end if
      end if
else
      bat←bat
```

4.1.4.3 Model 3

The third model includes discharge of battery any time of the day it is needed. In this scenario the load fulfils in priority by:

1. the PV (which has the cheapest operational cost)
2. the BESS reserves (whenever the PV generation is not enough to support the load fulfilment)
3. the grid when the PV power is not enough and the BESS reserves are empty.

In order to give a better description of the specific model, a simple form of the battery discharging pseudocode is presented below:

```
if PV<load then
      if load>=PV+bat then
            bat←0
      else
            bat←bat-(load-PV)
      end if
else
      bat←bat
```

4.1.5 Life Cycle Inventory for Samsø

The Life cycle inventory phase of LCA involves data compilation of materials and energy inputs as well as and product outputs for the complete life cycle of the system under analysis. For the LCA modelling of the pilot, the necessary data are summarized in Table 5.

Table 5: Inventory data for the SMILE installations in Ballen Marina

Dataset	Value
Type of Battery/Chemistry	Lithium/NMC
Type Photovoltaic panel	Single crystalline silicon
Manufacturer of PV	Better Energy Solutions
Manufacturer of Battery	Nissan/LiBal
Electricity mix of Samsø	0.321 kg CO2eq/ kWh (derived from SimaPro database)
Capacity of Photovoltaic module	60 kWp
Lifetime of Photovoltaic	25 years
Lifetime of BESS	15 years
Annual Degradation of BESS	2%
Lifetime of inverter	15 years
Annual Degradation of Photovoltaic module	0.32%
Capacity of BESS	Capacity 240 kWh, 225 kWh accessible
Capacity of Inverter	50 kW
Electricity Consumption (annual)	104 550 kWh
Energy Density of battery cells	224
Energy density of BESS grid support system	130
Round-trip efficiency for the system with inverter	97%
Manufacturer of Heat Pump	DAIKIN (MODEL RXS25L3V1B)
Net Weight of Heat Pump	34
Lifetime of Heat Pump	25 years
Heat Pump Heating capacity	3.4 kW
Heat Pump Cooling capacity	2.5 kW

4.1.6 LCA Calculations

This section characterizes the environmental performances of ground-mounted PV installations when integrated with Storage solutions by considering a life-cycle approach. The methodology is based on the application of the existing international standards of Life Cycle Assessment (LCA). For the pilot analysis, the phases that will be taken into consideration are the manufacturing phase and operational phase through components lifetime for all the 4 scenarios based on the two different discharging models.

4.1.6.1 Manufacturing impact for PV-BESS-Heat Pump

Photovoltaic System

PVs have been installed in 3 different spots of Ballen Marina until April of 2019. The type of the installed PV is single Crystalline silicon with a total nominal capacity of 60 kWhp.

The energy requirements for production of single crystalline silicon (sc-Si) modules are 16–20% higher, than that for mc-Si [39] . **The chosen functional unit is the manufacturing of 1 kWp of Photovoltaic module.** In SimaPro a 3 kW_p module has been chosen as the basic module for the calculations. Larger system can easily be scaled from the 3 kW_p module without producing a significant error. The environmental impact in order to produce a 60 kW_p Photovoltaic system was calculated as **136,800 kg CO_{2eq}** and, as a result, the environmental impact expressed in functional unit is **2280 kg CO_{2eq}/kWp.**

Heat Pump

In comparison to the already installed Electric Heater, a highly efficient heat pump system will reduce hazardous emissions locally. Depending on the generation of electricity, emissions do occur at the plant site. The indirect emissions from heat pumps are, thus, dependent on the efficiency of the heat pump system as well as the efficiency of the plant generating the electricity. Mitigation of emissions is the most pronounced environmental benefit offered by heat pumps. The magnitude of the possible benefits will vary, depending on the local generation of electricity. Heat pumps do, however, contribute to direct emissions by means of refrigerant leakage over their lifecycle. In addition to leakage that occurs during operation, losses will occur at demolition of the appliance. The impact of these losses on the environment will depend on the refrigerant in use. The most commonly used refrigerants today are hydroflourocarbons (HFC).

In Ballen Marina, the system consisted of a 3.4 kW air-to-water heat pump (model RXS25L3V1B) and the used refrigerant during operation is the R410a. Medium voltage electricity from the grid and natural gas is needed in order for the heat pump to be produced. The environmental impact for the production of the Heat Pump is 1900 kg $CO_{2eq.}$

Due to lack of data, the SimaPro analysis of the Heat Pump includes only the manufacturing phase of the Heat Pump. Although, a distinguished method to calculate the greenhouse gas emissions from refrigeration and heat pump operation through lifetime will be implemented. This method is the Total Equivalent Warming Impact (TEWI) method which was developed at Oak Ridge National Laboratory in the early nineties. A TEWI calculation integrates direct and indirect greenhouse gas emissions over the whole lifetime into a single number expressed in terms of CO2eq based on the following formula

$$TEWI = \underbrace{(n \cdot L \cdot m \cdot GWP)}_{\text{Direct Emissions due to leakage}} + \underbrace{(n \cdot E_{annual} \cdot EF)}_{\text{Indirect emissions related to electricity generation}} + \underbrace{(L_{demolition} \cdot m \cdot GWP)}_{\text{Direct emissions at demolition}}$$

where:

- n: equipment lifetime [year]
- L: annual leakage rate [%]
- m: refrigerant charge [kg]
- GWP: global warming potential [kg CO_2/kg refrigerant]
- E_{annual}: annual energy use [kWh/year]
- EF: emission factor driving energy [kg CO_2/kWh]
- $L_{demolition}$: refrigerant losses during demolition [%]

For the model RXS25L3V1B which installed in the Ballen Marina the abovementioned values are presented in

Table 6. Parameters of RXS25L3V1B Heat Pump.

Parameter	Value	Source
n	25 years	Smile Partners
L	2 %	[40]
m	1 kg	DAIKIN Technical Specifications
GWP	1980	[40]
Eannual	3600 kWh/year	DAIKIN Technical Specifications. Taken into consideration that Heat Pump operating 4000 h annually
EF	0.321 kg CO2/kWh	Smile Partners
Ldemolition	15 %	[41]

$$TEWI = (25 \cdot 0.02 \cdot 1 \cdot 1980) + (25 \cdot 3600 \cdot 0.321) + (0.15 \cdot 1 \cdot 1980) = 30{,}177 \text{ kg CO2eq/kWh}$$

Indirect emissions related to the generation of electricity (95.7%) are by far the largest contributor to greenhouse gas emissions. In countries like Denmark, where the vast majority of the electricity is generated by RES, the Emission factor remains low leading to lower indirect emissions which are related to generation of electricity. At the other end of the scale, in countries that are heavily dependent on fossil fuel for generation of electricity, will consequently end up at significantly higher TEWI.

Battery Energy Storage System

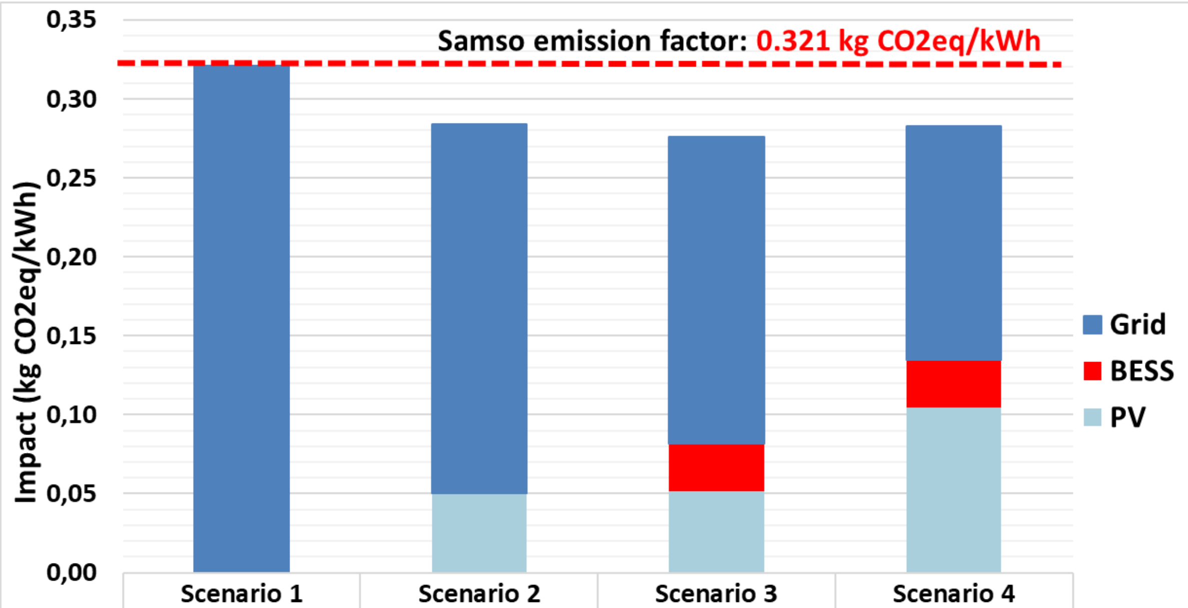
The selected installed battery is a Li-ion battery with cathode combination of nickel-manganese-cobalt (NMC). A 240 kWh BESS System manufactured from LiBal will be installed in the Ballen Marina of Samsø. First step of the battery modelling in SimaPro is the construction of the specific battery capacity. In Ballen Marina, the installed BESS is operated with 94% Depth of Discharge (DoD) which leads to 225 kWh of accessible storage capacity. Assuming an energy density of **224 Wh/kg** and since the installed BESS has **225 kWh** accessible storage capacity the battery weight will be 240,000/224 = **1071 kg.** In order to compose the battery component, the percentage weight of materials has been taken from the study of [42]. The electricity consumed for the assembly of the materials is **6 kWh_{el}/ kWh_{stored}** according to the study [42].The manufacturing impact for a 240 kWh BESS through SimaPro analysis is **19,800 $kgCO_{2eq}$.**

As a result, the environmental impact per **kWh stored** is (19,800 kgCO_{2eq}/240 kWh =) **82.5 kgCO_{2eq}/kWh** and per **kg of battery manufactured** is **18.5 kgCO_{2eq}/kg**.

4.1.6.2 Operational impact for system of PV/BESS

4.1.6.2.1 Discharge of BESS only during the high electricity price zones (Model 1)

Figure 5 illustrates the results of the weighting phase, expressed as kg CO_{2eq}/kWh, to give a measure of the total impact of the four examined scenarios. The lifetime of battery (15 years) is shorter than the lifetime of the PV and, as a result, an extra battery will need to be used during PV's lifetime (25 years). The installation of PV (Scenario 2) has positive impact in environmental profile compared to the baseline scenario of Samsø. Moreover, scenario 3 introducing BESS has an even lower environmental impact, with a 24% reduction of kg CO_{2eq}/kWh compared to Scenario 1 (baseline) after 25 years of operation. Since the energy storage leads to lower amount of curtailed electricity causing a decrease of grid energy contribution, BESS installation in scenario 3 has positive impact in the environmental profile compared to scenario 2. Scenario 4 is a scale-up (theoretical) scenario in which the PV capacity becomes 120 kWp. Despite the fact that the scale-up of the PV's capacity leads to an increase in the environmental impact from PV, the total environmental impact of Scenario 4 is still lower than baseline scenario. The reason for that lies in the fact that there is a high reduction of the grid electricity contribution which is the main parameter affecting the environmental footprint. This decrease of the grid energy offsets the increase in the PV environmental impact leading to the environmental impact of Figure 5.



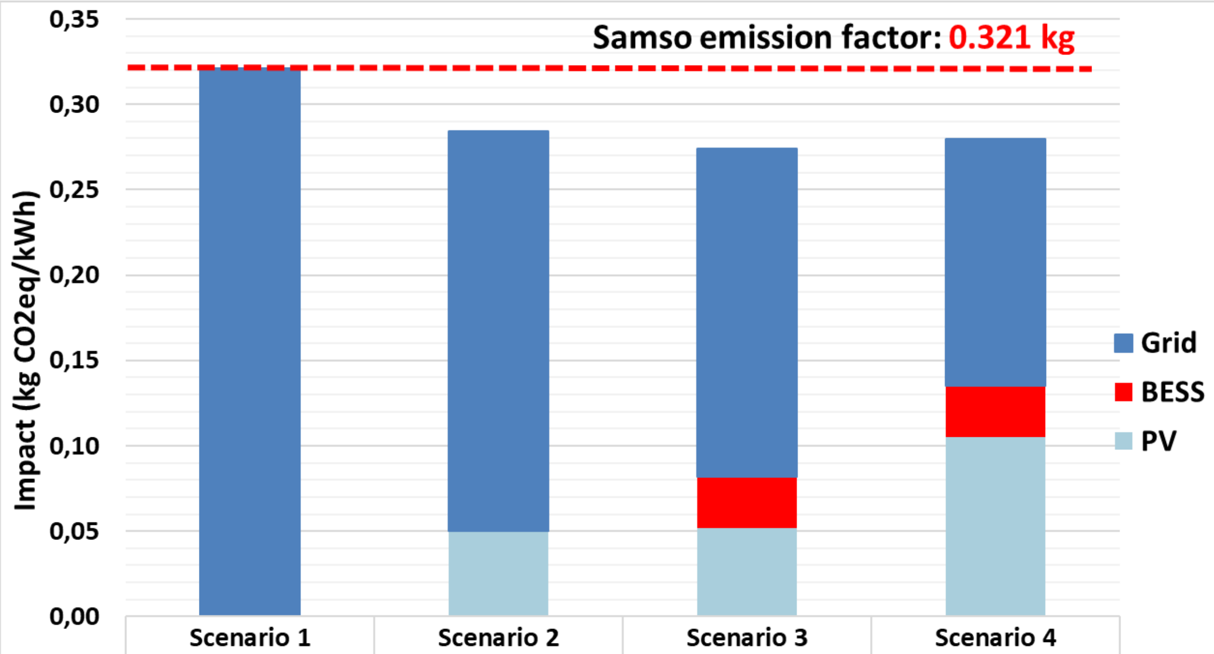
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Grid	0,321	0,234	0,194	0,147
BESS	0,000	0,000	0,031	0,030
PV	0,000	0,050	0,051	0,104

Figure 5: Environmental impact (kg CO_{2eq}/kWh) for model 1 in which priority is given to avoid the expensive price zones of the grid

4.1.6.2.2 Discharge of BESS during the non-cheap electricity price zones (Model 2)

This model is about the discharge of the battery which only takes place during the hours of non-cheap current, which are all the hours throughout the day except the peak hours. This model has been chosen as a ‘hybrid’ model between the models 1 and 3, in order to reduce the cost of buying electricity during winter months and, on the other hand, to reduce the curtailment in the summer.

Figure 6 presents the operational environmental impact for Model 2. The PV installation (scenario 2) is, as mentioned, profitable in environmental terms compared to baseline scenario 1. Moreover, BESS installation (scenario 3) has, again, positive impact in the environmental profile as it can reduce CO_2 emissions by 19%. Increasing PV penetration in the power system can reduce Ballen Marina’s GHG emissions, and BESS is a viable method to achieve this goal.
Despite the fact that the scale-up of the PV’s capacity leads to an increase in the environmental impact due to the PV manufacturing, the total environmental impact of scenario 4 is lower than the baseline scenario which occurs because there is a reduction in the contribution of the electricity of the grid.



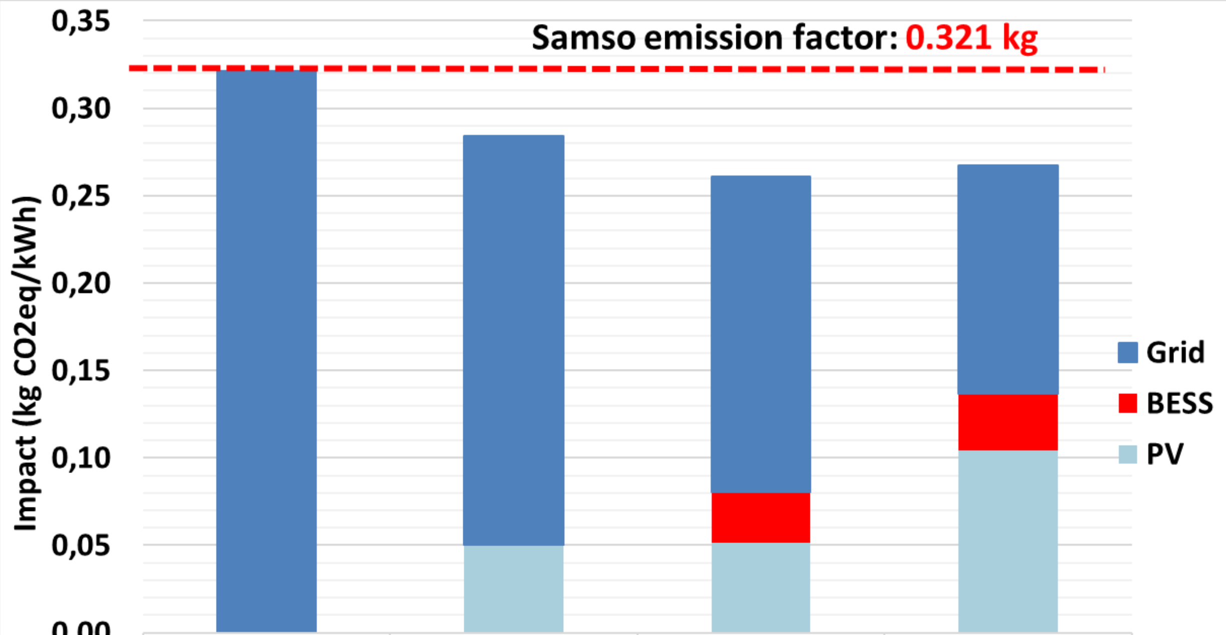
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Grid	0,321	0,234	0,193	0,145
BESS	0,000	0,000	0,030	0,030
PV	0,000	0,050	0,052	0,105

Figure 6: Environmental impact (kg CO_{2eq}/kWh) for model 2 in which discharge occurs during the time zones of non-cheap current

4.1.6.2.1 Discharge of BESS every possible time of the day (Model 3)

Model 3 is about the discharge of the battery whenever the generation of the PV is not able to cover the demand.
The analysis evaluates several scenarios concerning a PV and a BESS installation in the marina of Ballen. Figure 7 illustrates the environmental impact for Model 3 and presents similar results to those in Figure 5 and Figure 6 of Model 1 and 2. In Model 3, the PV installation (Scenario 2) is profitable in environmental terms for all scenarios compared to the baseline scenario 1.
In Ballen Marina, BESS integration with Photovoltaic systems is a feasible option as it can reduce CO_2 emissions by 14%. Battery storage displays great promise as a solution that can reduce the climate change impacts of delivering electricity to the demand of Ballen Marina.

The increase in PV capacity (scenario 4) leads to an increase in the environmental impact compared to Scenario 3, although the PV contribution to the impact (both on manufacturing and operation) still contributes in a positive way compared to the baseline scenario.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Grid	0,321	0,234	0,181	0,131
BESS	0,000	0,000	0,029	0,033
PV	0,000	0,050	0,052	0,104

Figure 7: Environmental impact (kg CO_{2eq}/kWh) for model 3 in which discharge of the battery occurs whenever there is not enough PV energy to cover the demand

4.1.7 LCC Calculations

The LCC analysis in Samsø is performed on the same 4 scenarios as the LCA. The specific costs participating are the purchase costs of the PVs and the BESS, the cost of their maintenance, the cost of the electricity purchased by the grid and the external costs.

4.1.7.1 Purchase and installation costs

The costs in Table 7 represent indicative market prices of the PVs and BESS implemented. The life time of these components also needs to be taken into account. The cost data of the PVs was provided by the partners of the Samsø environment, while the BESS data was provided by LIBAL.

Table 7: Purchase and installation cost (€) for Samsø demo site

Components	Life time (years)	Purchase and installation cost (€)
PV (60 kWp)	25	28,000
PV (120 kWp)	25	56,000
BESS (240 kWh)	15	170,000

Since the highest life cycle is the PV's (25 years), the simulation study is done for this period. During this, a BESS is purchased in the 1st year of study, and another is bought in the 16th. For the purpose of the study's accuracy, in the 25th year the BESS is resold for the 1/3 of its initial price. These values are affected by the discount rate, as will be explained in the respective paragraph.

4.1.7.2 Maintenance costs

The maintenance costs took certain annual values, since it is impossible to foresee any unexpected damage which would require a higher amount of money to be repaired. Thus, the values used take into account the actual cost of the annual maintenance services, as well as an extra amount for unexpected damages. The expected maintenance costs for the Samsø pilot, provided by the Samsø environment of the consortium, are the following:

- Concerning the PV (60 kW_p) the maintenance cost is determined at 750 €/year, which is doubled for the double PV capacity (120 kW_p) of scenario 4.
- Concerning the BESS (240 KWh) the maintenance cost is determined at 500 €/year.

As mentioned above and will be described later, these annual costs are affected by the local discount rate.

4.1.7.3 Grid electricity costs

The cost of the electricity purchased by the grid represents the operational costs for the 4 scenarios, since the energy derived from PV and battery have zero operational costs. The incremental implementation of PV and BESS decreases the need for grid energy and, thus, its cost. Although it is not studied in the present deliverable, the DR policies can direct the loads to times of the day when the price of electricity is cheaper, in order to further decrease this cost. Table 8 presents indicatively the participation of the grid in each scenario and model for the 1st year of the simulation model.

Table 8. Grid Electricity cost (€) from the participation of the grid in the examined scenarios.

Scenarios	Description	Model 1 grid cost (€)	Model 2 grid cost (€)	Model 3 grid cost (€)
1	PV: 0 kW_p BESS: 0 kWh	23,739	23,739	23,739
2	PV: 60 kW_p BESS: 0 kWh	16,900	16,900	16,900
3	PV: 60 kW_p BESS: 240 kWh	11,987	11,902	11,688
4	PV: 120 kW_p BESS: 240 kWh	8,582	8,579	7,279

This is also supported by the early-morning charging during the colder months of the year, where the further battery exploitation requires its partial charging by the grid with cheap electricity, in order to provide the load during peak hours when the grid electricity is expensive.
The annual costs of the grid electricity are affected by the Danish discount rate, too.

4.1.7.4 Externalities

Since they represent external costs of each scenario due to the environmental pollution, it is expected that a higher PV penetration results in a reduction in pollution, because the grid electricity is highly pollutant compared to the manufacturing of PV and BESS. Table 9 shows the participation of the external costs in the final LCC (€/kWh) for each model and scenario.

Table 9. External costs (€/kWh) for the examined scenarios of Samsø demo site.

Scenarios	Description	Model 1 external cost (€)	Model 2 external cost (€)	Model 3 external cost (€)
1	PV: 0 kW_p BESS: 0 kWh	0.026	0.026	0.026
2	PV: 60 kW_p BESS: 0 kWh	0.020	0.020	0.020
3	PV: 60 kW_p BESS: 240 kWh	0.017	0.018	0.017
4	PV: 120 kW_p BESS: 240 kWh	0.014	0.015	0.014

4.1.7.5 Discount rate

A financial analysis that simulates the cash flows of such a long period has to take into account the discount rate of the local economy. Concerning the Danish economy, the discount rate is defined at 4% according to the Danish Energy Agency.
The calculation of the discounted cash flows is made according to the ordinary formula:

$$DCF = \frac{\sum_{i=1}^{N} CF_i}{(1 + DR)^N}$$

where:
DCF= Discounted Cash Flow
CF_i= Cash Flow of year i
N= the number of years during which the cash flows are examined
DR= Discount Rate

The effect of the discount rate application is higher when moving forward in the life cycle of the examined scenario because the exponent *N* takes higher values. Thus, a high cost appearing in the first year is much more considerable than the same cost appearing discounted during the 10th year.

4.1.7.6 LCC results

The final calculation takes into account all the parameters mentioned in the paragraphs above. The results are presented in the Figure 8.

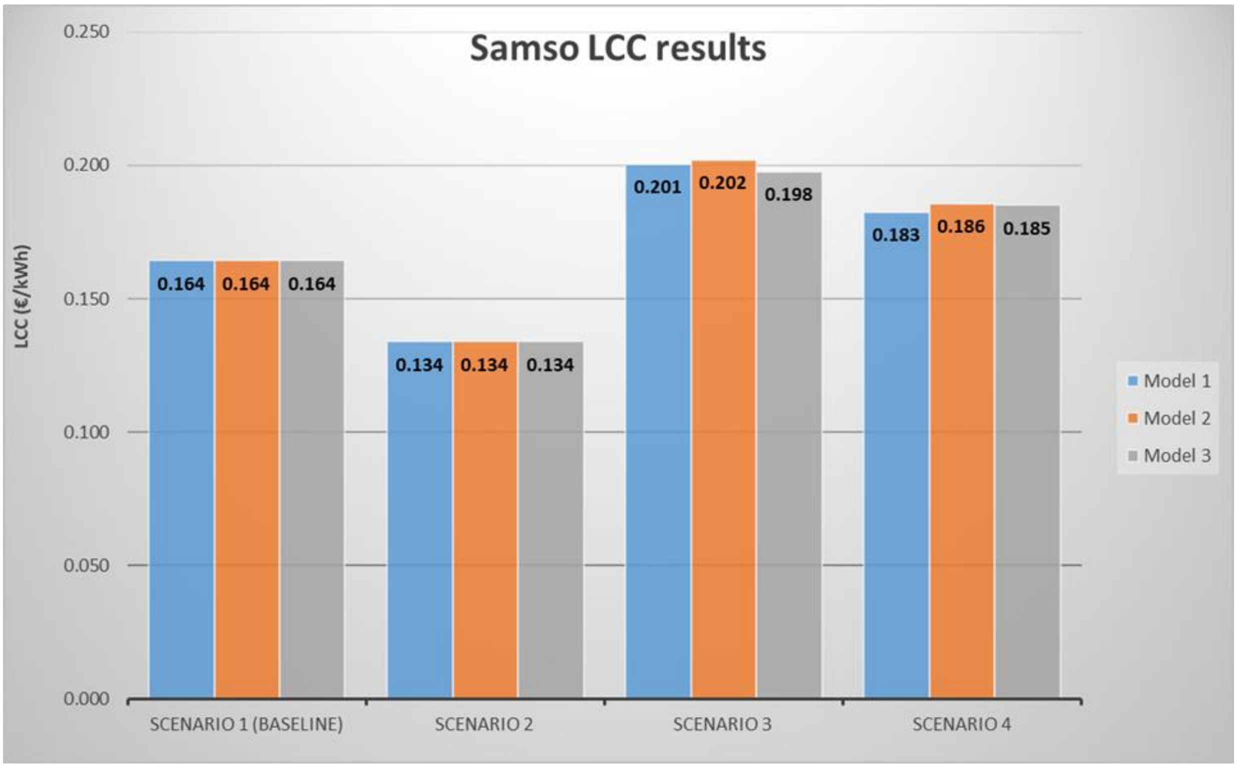


Figure 8: Presentation of all Samsø LCC results

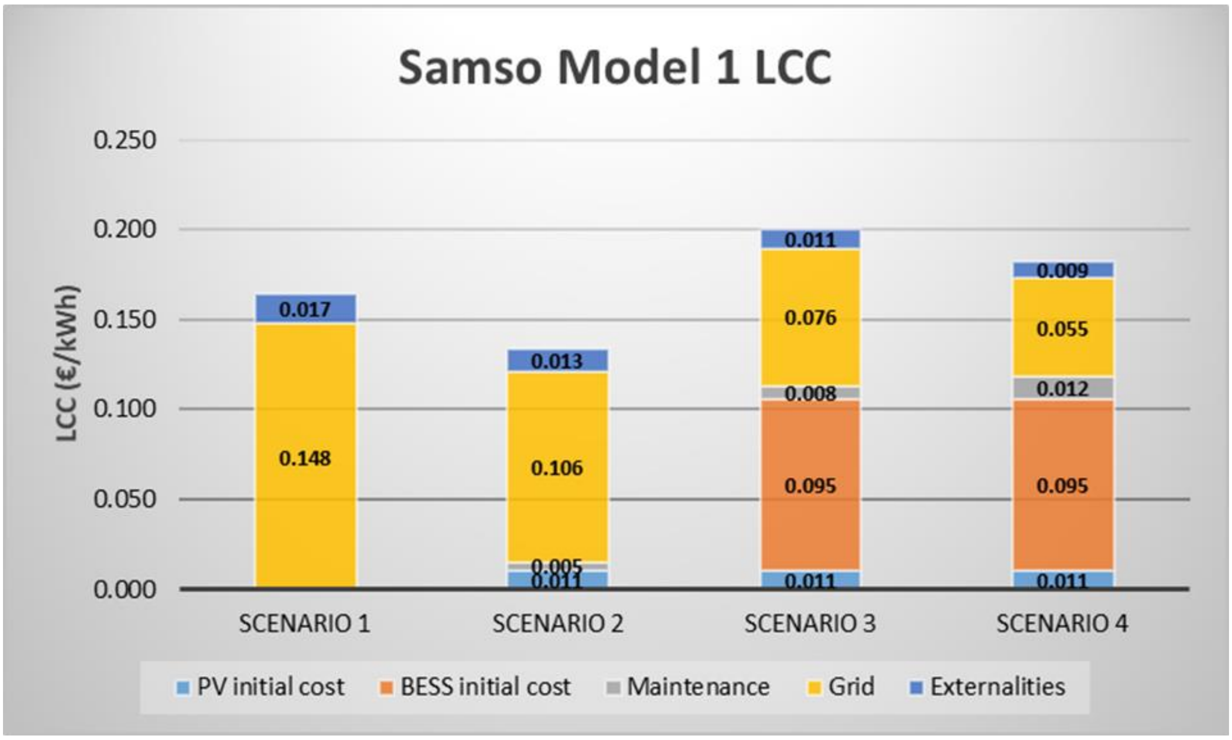


Figure 9: LCC share for Samsø Model 1

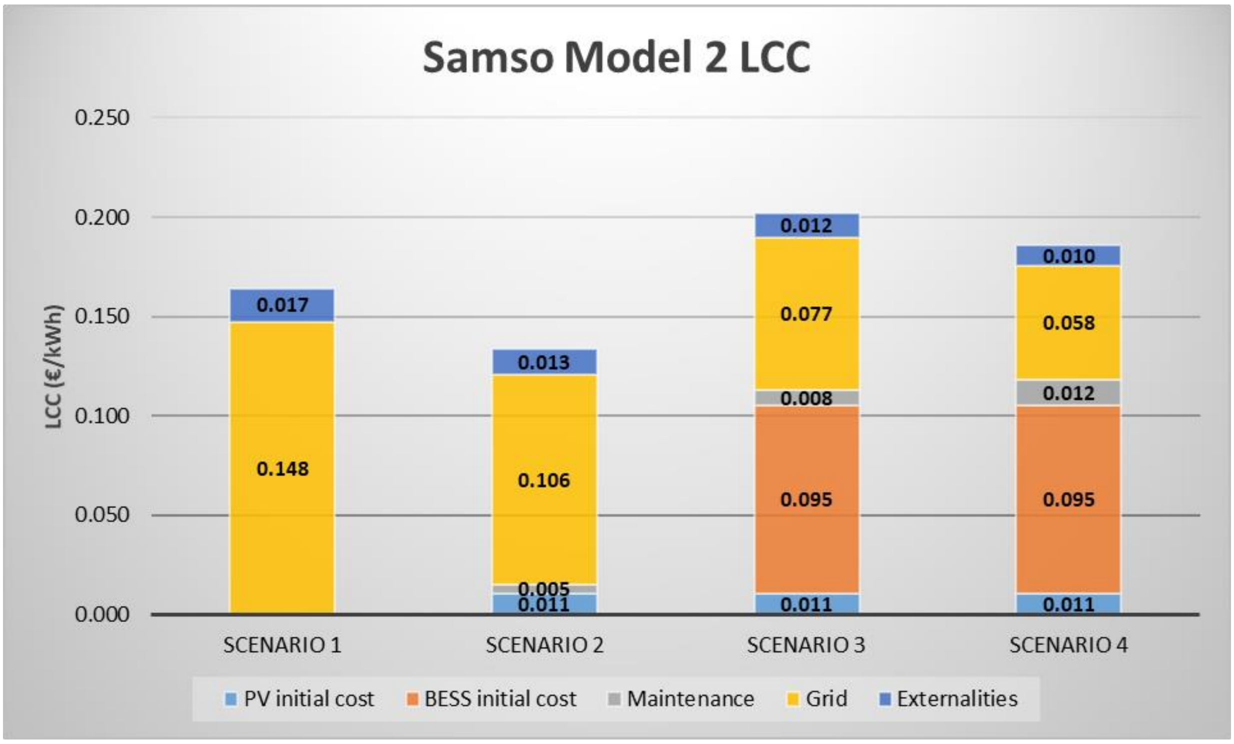


Figure 10: LCC share for Samsø Model 2

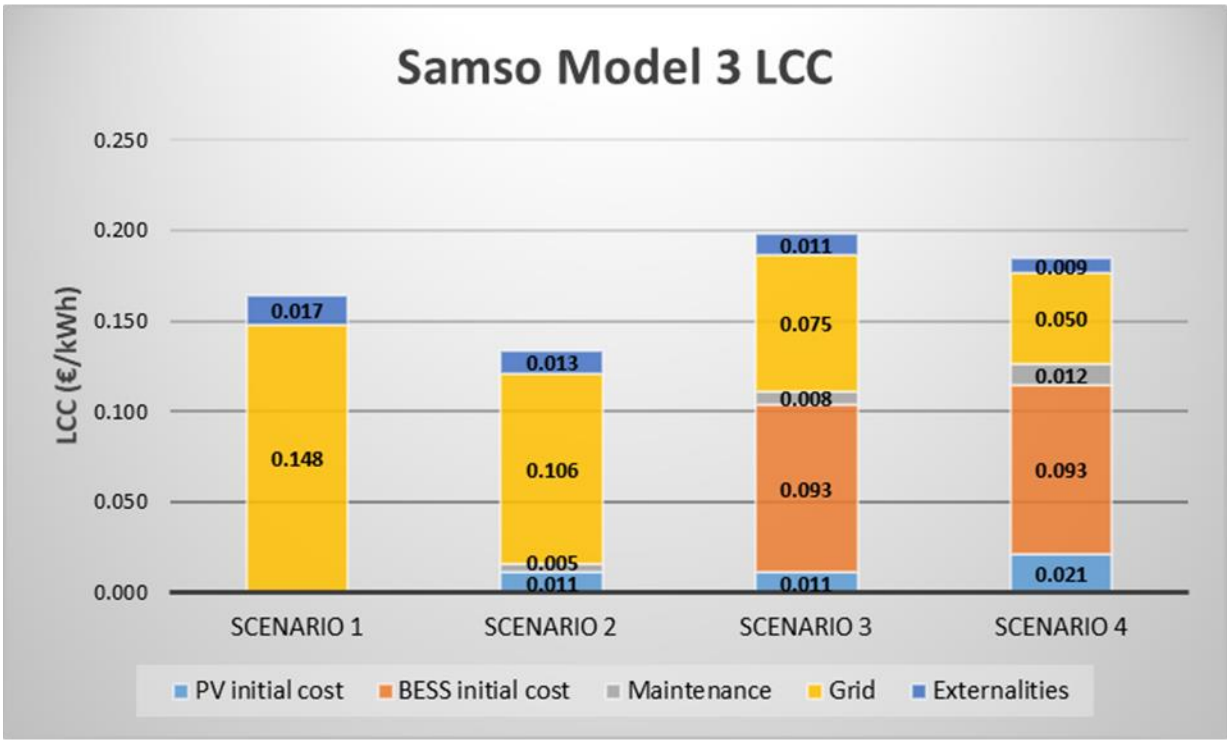


Figure 11: LCC share for Samsø Model 3

Regarding the results of Figure 9, Figure 10 and Figure 11, the investment cost of 240 kWh BESS is significantly higher than the investment cost of PV. Scenario 2 has the lowest LCC, since no BESS installation has been considered (BESS investment cost has the highest contribution). PV implementation slightly increases the investment cost, while it causes reduction to the O&M costs. BESS implementation results in:

- significant increase in investment cost;
- decrease in O&M costs (lower grid share)

These observations concerning the participation of the PV and BESS investment costs are shown in Table 10.

Table 10. Life Cycle Costs (€/kWh) for the examined scenarios

Scenario	PV investment cost share (%)	BESS investment cost share (%)	LCC (€/kWh)
1	0.0%	0.0%	**0.164**
2	8.0%	0.0%	**0.134**
3	5.3%	47.3%	**0.201**
4	5.9%	51.9%	**0.183**

As a conclusion, it seems that the PV implementation has a positive effect on the LCC, while the BESS integration influences negatively the final cost due to its large investment cost. The negative financial effect of the BESS's high investment cost is even worse due to the application of the discount rate.

Such a hybrid system could be more feasible if the cost of the grid electricity was much higher, or in a case where the majority of the load is during the night, when the PV generation is zero. Moreover, a much lower cost of the BESS, based on lower-cost manufacturing materials (or even a granting), could provide a more feasible profile.

4.1.8 Study and comparison between the 3 models

Having reached to the final results of the LCA and LCC studies for the Samsø pilot, it was feasible to compare the 3 models of BESS exploitation, using the results of both studies. An indicative comparison was made for scenario 3 of each model. Table 11 presents this comparison:

Table 11. LCA and LCC results for the three implemented models of scenario 3 of Samsø.

Model	LCA (kg CO_{2eq}/kWh)	LCC (€/kWh)
1	0.276	0.201
2	0.275	0.202
3	0.262	0.198

Regarding Figure 1, it seems that Model 3 provides slight better results, due to the more optimised exploitation of the BESS in the specific allocation of the load.

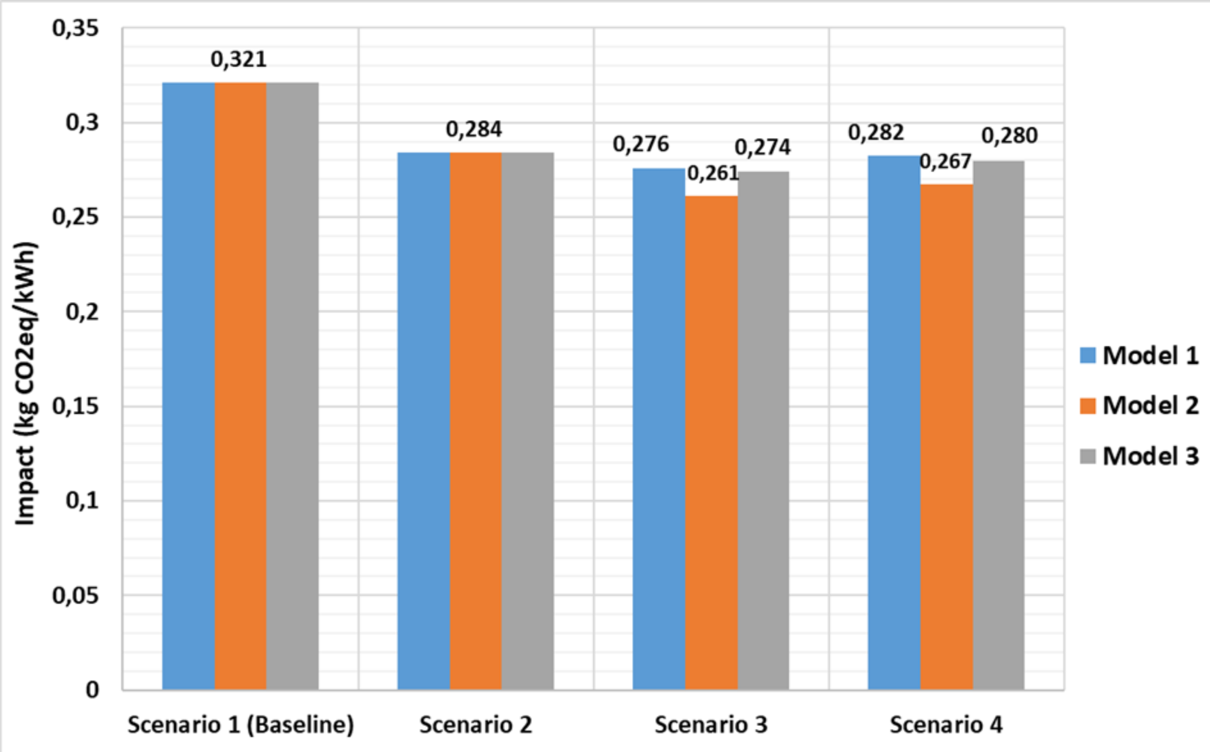


Figure 12. Environmental impact comparison per scenario for the three implementation models.

Regarding the results of Figure 12 and the amount of curtailment derived from Table 11, **Model 1** has the highest curtailed energy and, as a result, the highest grid contribution which leads to the highest environmental impact. On the contrary, **Model 3** presents the lowest curtailment and consequently the lowest amount of energy from grid which leads to lowest environmental impact.

4.2 Madeira demo site

4.2.1 Description of the pilots

Madeira is a total energy island, and all the energy is generated locally. Madeira electric energy system is based on conventional thermal power plants and hydro plants, complemented by a solid amount of wind energy and steady growing solar energy production.

1st Pilot: Getting started with BESS and DSM (domestic scale)
The pilot refers to 4 domestic UPACs equipped each with a PV module. The SMILE approach is about the installation of an 8 kWh BESS in each UPAC in order to maximize the self-consumption. This need was born by the barrier that UPACs have to sell the excess energy production from the PV to the utility really cheaply.

2nd Pilot: Moving forward with BESS and DSM (commercial scale)
The pilot refers to a commercial UPAC, which is expected on a daily basis to consume all its PV production. There, a BESS can be pre-charged during off-peak periods to cover early morning loads, and then re-charged by the PV power to compensate the evening loads. The current state of technology in this scenario consists of one PV panel installed in a commercial prosumer.

3d Pilot: Getting started with EVs and smart charging
The approach on EVs' pilot will take into consideration:

- **Pricing:** Controlling the state of the charge based on the price of the electricity. The charger will be turned OFF during peak prices and ON during off-peak prices.
- **Renewable availability:** The charging can also be controlled based on the energy mix. This can be done considering the availability of renewables in the grid, thus being more advantageous to the DSO. Alternatively, it can be implemented considering local renewable availability for micro-producers, which can reduce the impacts (financial and environmental) of charging the EV directly from the grid.

4th Pilot: Electric Vehicles are our future
The second EV and smart charging pilot will focus on providing a smart charging solution using standard chargers by taking control of the ON/OFF status of the charge. The overarching goal of this pilot is to retrofit existing installation with hardware/software which would allow controlled charging.

5th Pilot: Voltage and Frequency Control
This pilot is focused on a properly dimensioned BESS which will support grid operation from voltage and frequency fluctuations due to the intermittency of photovoltaic production. The BESS will be discharged when the grid analyzer detects Voltage and/ or Frequency issues.

4.2.2 System Boundaries

BESS Installation: 1st and 2nd Pilot
The SimaPro analysis will include environmental impact during the **manufacturing phase** of the installed components which is an 8 and 25 kWh BESS for the 1st and 2nd pilot respectively. Regarding the **operational phase,** the maximization of the use of PV by avoiding curtailment will contribute to avoid grid emissions. The boundaries for the analysis are presented in Figure 13.

EVs Smart Charging: 3rd and 4th Pilot

These pilots do not involve the implementation and evaluation of new equipment. The main purpose is the control over the charging of the EVs according to the grid needs, both in matter of policy and smart control. Thus, 4 different policies are to be evaluated in order to provide directions concerning the application of a sensible charging model. This means that the life cycle approach could not provide useful results, since there is no certain equipment to be examined based on life cycle analysis principles. On the other hand, the comparison on the application of the various models on a certain given load on an environmental (kg CO_2/kWh of load) and economic (€/kWh of load) approach can provide the remarks and conclusions needed.

BESS Installation: 5th Pilot

The environmental analysis has carried out in SimaPro tool and includes only the manufacturing phase of the installed BESS which has a capacity of 80 kWh.

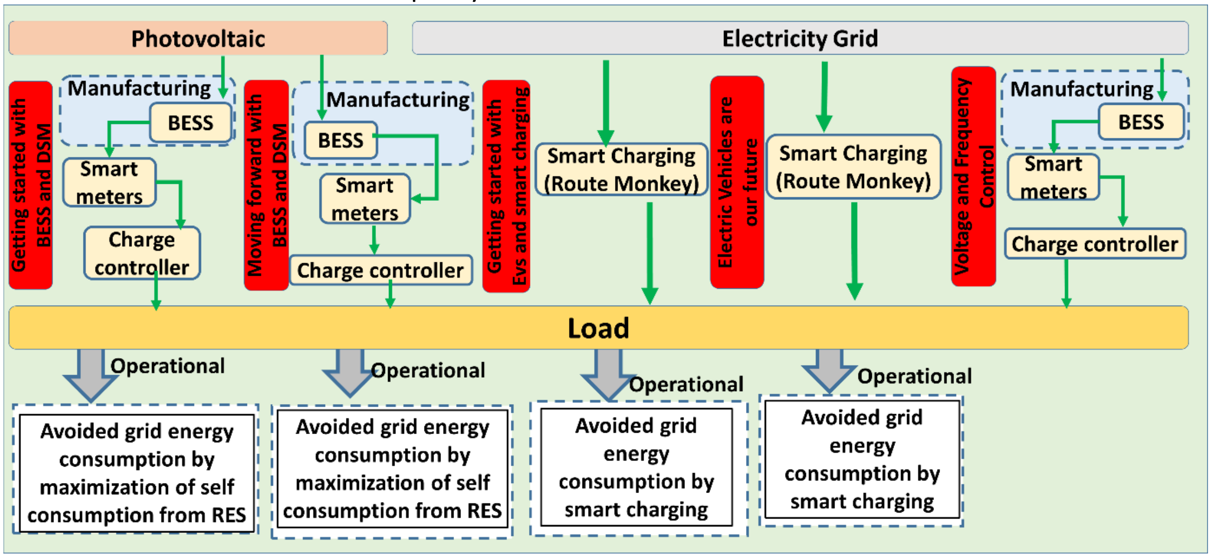


Figure 13. System boundaries of the installed technology for all the Pilots in Madeira. Manufacturing phase of PV and BESS will be taken into consideration

4.2.3 Baseline Scenario for Madeira

BESS Installation: 1st and 2nd Pilot

The reference scenario is domestic consumption of PV energy **without** storage solution. More specific the environmental and economic impact of PV operation for 25 years' lifetime will be calculated together with the contribution of grid electricity.

EVs Smart Charging: 3rd and 4th Pilot

The reference scenario is the charging of EVs from the grid without the implementation of smart charging approach. The charging of the EVs in these pilots occurs at any possible time throughout the day.

4.2.4 Life Cycle Inventory for Madeira

The Life cycle inventory phase of LCA involves data compilation of materials and energy inputs as well as and product outputs for the complete life cycle of the system under analysis. For the LCA modelling of all the pilots, the necessary data is summarized in Table 12, Table 13 and Table 14:

Table 12: Getting Started with BESS and DSM (1st pilot)

Dataset	Status	Value
Electricity mix of Madeira	Provided	0,429 kg CO_{2eq}/kWh
Type of Battery	Provided	Lithium
Manufacturer of Battery	Provided	Libal
Lifetime of BESS	Provided	15 years
Capacity of BESS	Provided	8 kWh
Annual degradation of BESS	Provided	2%
BESS Depth of Discharge	Provided	95%
BESS Energy Density	Provided	224 Wh/kg

Table 13: Moving forward with BESS and DSM (2nd pilot)

Dataset	Status	Value
Type of Battery	Provided	Lithium
Manufacturer of Battery	Provided	Libal
Lifetime of BESS	Provided	15 years
Capacity of BESS	Provided	24 kWh
Degradation of BESS	Provided	2%
BESS Depth of Discharge	Provided	95%
BESS Energy Density	Provided	224 Wh/kg
Capacity of Inverter	Provided	3 kW

Table 14: 3rd and 4th pilots

Dataset	Status	Value
Time series of Tukxis charging	Provided	kWh
Time series of RES share	Provided	Kg CO_{2eq}/kWh
Time series of EEM garage charging	Provided	kWh

Table 15. 5th Pilot

Dataset	Status	Value
Type of Battery	Provided	Lithium
Manufacturer of Battery	Provided	Libal
Lifetime of BESS	Provided	15 years
Capacity of BESS	Provided	80 kWh
Degradation of BESS	Provided	2%
BESS Depth of Discharge	Provided	95%
BESS Energy Density	Provided	224 Wh/kg

4.2.5 Pilot 1 and Pilot 2: Getting Started and Moving forward with BESS

4.2.5.1 Definition of scenarios and configuration Scheme

Regarding the SMILE installations, the **examined scenarios** for the Madeira are **three,** including the reference/baseline scenario and are presented in the Table 16. The first scenario is before SMILE implementation activities where no BESS was installed. The two SMILE scenarios the installation of a BESS for every participated UPAC.

Table 16: Definition of scenarios for Pilot 1 and Pilot 2 of Madeira demo site

Scenario	Description
No BESS	UPAC PV installed – No BESS installation (Baseline Scenario)
Greedy	The BESS offsets the residual load (load subtracts the generation equal to the residual load). In this strategy, excess PV power is stored in the BESS, and excess demand is supplied by the BESS. This is the simplest operation strategy possible, as it determines the residual load (i.e., the difference between production and consumption) and instantly actuates the BESS accordingly by storing excess production until the BESS is fully charged or supplying the excess demand from the BESS as long as there are available reserves.
Enhanced	In this enhanced version of the greedy strategy, the demand is supplied by the grid during off-peak periods. During the peak time zones, the demand is supplied by the BESS, as long as there are available reserves. If not, the demand is again supplied by the grid.
Grid2BESS	This model applies only to UPAC 8 (pilot 2), where the PV capacity is very low compared to the load, so there is no need for BESS to exploit the otherwise curtailed PV energy. In the specific model the BESS fully charges during the cheap price zones of grid electricity. This stored energy is consumed during the rest (non-cheap) price zones throughout the day.

The configuration scheme for the Madeira for the Pilots of BESS installation (i.e Pilot 1 and Pilot 2) is presented in Figure 14 and is common for all the three models.

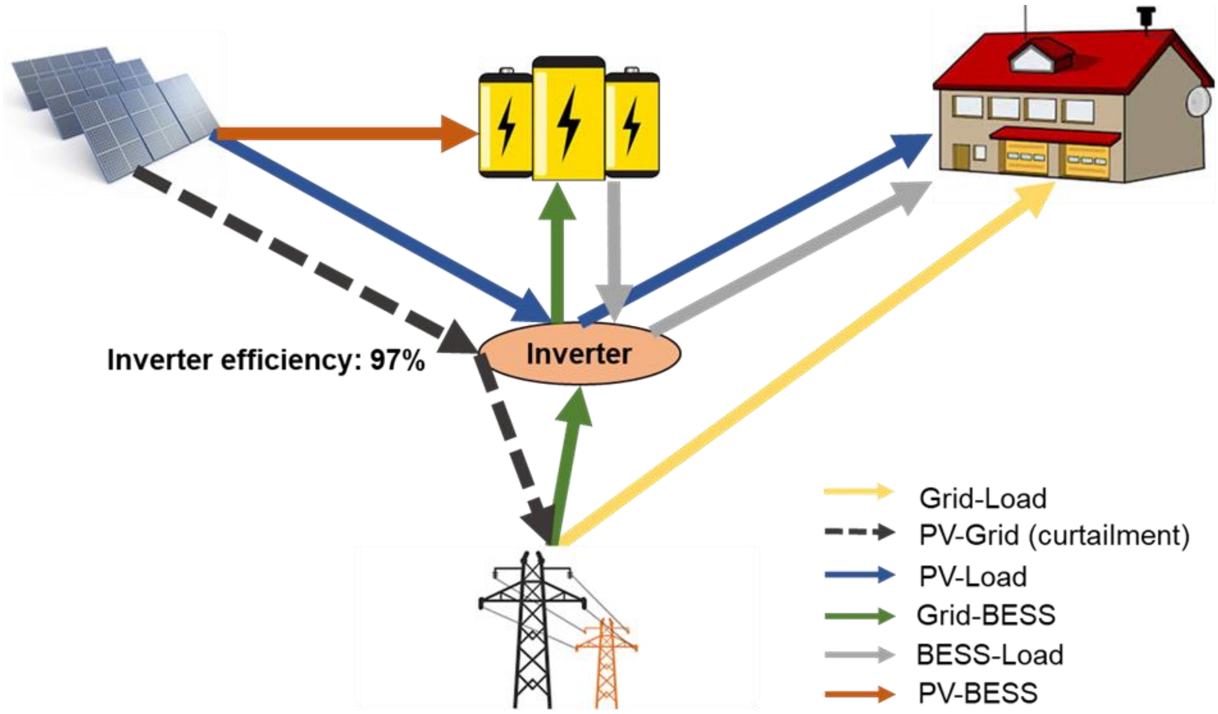


Figure 14: Configuration scheme for the integration of PV/BESS in the UPACs of pilot 1 and 2 in Madeira

4.2.5.2 LCA Calculations

This section characterises the environmental performances of ground-mounted PV installations when integrated with Storage solutions by considering a life-cycle approach. The methodology is based on the application of the existing international standards of Life Cycle Assessment (LCA). **For the analysis, the phases that will be taken into consideration are the manufacturing phase of BESS and operational phase through components (i.e PV and BESS) lifetime.**

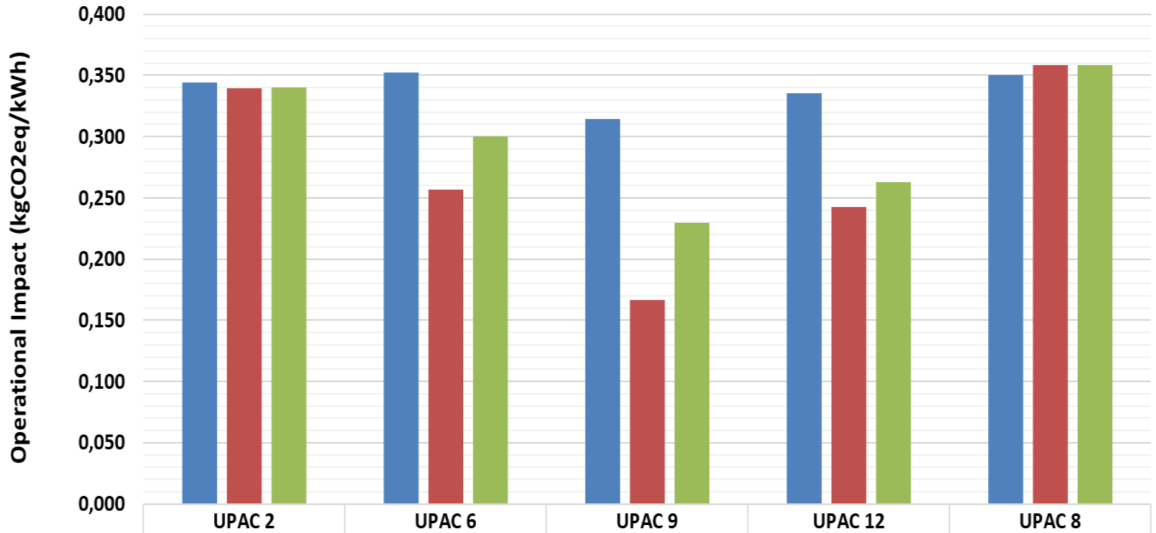
4.2.5.2.1 Manufacturing impact of BESS for Pilot 1, 2 and 5

The environmental impacts are simulated through the software SimaPro 7.1, developed by PRé Consultants. For the data implementation, the database used was Ecoinvent. The environmental assessment was based on the Impact 2002+ methodology. The selected battery is a Li-ion battery with cathode combination of nickel-manganese-cobalt (NMC). An 8 kWh BESS System manufactured by LiBal will be installed in the selected domestic UPACs in Madeira. The lifetime of the installed BESS is 15 years. First step of the battery modelling in SimaPro is the manufacturing of the specific battery capacity. In the participating UPACs, the installed BESS is operating with 95% Depth of Discharge (DoD) which leads to 7.6 kWh of accessible storage capacity. Assuming an energy density of **224 Wh/kg** and since the installed BESS has **8 kWh** accessible storage capacity the battery weight will be (8000/224=) **36 kg.** In order to compose the battery component, the percentage weight of materials has been taken from the study of [42]. The electricity consumed for the assembly of the materials is **6 kWh $_{el}$/ kWh$_{stored}$** according to the study [42] . The manufacturing impact of an 8 kWh BESS according to SimaPro analysis is **660 kgCO_{2eq}.** As a result, the environmental impact per **kWh stored** is **(**660 kg CO_{2eq}/8 kWh =) **82.5 kg CO_{2eq}/kWh** and per **kg of battery manufactured** is **18.3 kg CO_{2eq}/kg**. Since the materials for the battery installed in Pilot 2 are the same as those of the battery in Pilot 1, the environmental impact per kWh stored is the same. As a result the manufacturing impact for a 24 kWh BESS through SimaPro analysis is (82.5 kg CO_{2eq}/kWh * 24 kWh=) **1980 kgCO_{2eq}.**

The Pilot 5 received a Lithium battery of 80 kWh produced from Lithium Balance. The materials and technical specifications for the manufacturing of the Pilot 5 battery are the same with the materials used for the battery in Pilot 1 and Pilot 2. The SimaPro tool indicates a carbon footprint of 6600 kgCO2eq for the manufacturing of that battery module.

4.2.5.2.2 Operational impact for Pilot 1 and Pilot 2: Greedy, Enhanced and Baseline Scenario

Figure 15 presents the environmental impact of the operation of the UPACs at the pre-SMILE situation (No BESS) and of the examined SMILE scenarios (Greedy and Enhanced). The functional unit was selected to be 1 kWh of electricity generated and delivered to the UPAC consumer and for that reason the operational impact in Figure 15 is expressed in **kg CO_{2eq}/kWh**. The time horizon for the operational impacts in Figure 15 is the **25 years**. Concerning the No BESS scenario, the operational impact represents the collaboration of PV and Grid after 25 years of operation. Moreover, the operational impact of the Greedy and Enhanced scenarios is measured for 25 years of PV and BESS integration alongside the grid contribution. Since BESS lifetime is 15 years, calculations include the installation of a second BESS in the end of 15th year.



	UPAC 2	UPAC 6	UPAC 9	UPAC 12	UPAC 8
No BESS	0,344	0,353	0,314	0,335	0,350
Greedy	0,339	0,257	0,166	0,243	0,359
Enhanced	0,340	0,300	0,230	0,263	0,359

Figure 15: Environmental impact (kg CO_{2eq}/kWh) of each scenario in all Maderira UPACs

The impact of the Madeira electricity fuel generation mix is **0.429 kg CO_{2eq}/kWh.** The findings of Figure 15 indicate that

- Regarding the No BESS scenario (pre-SMILE situation), the use of the PV has positive operational impact for the UPACs leading to lower environmental impact than the impact of Madeira fuel mix (**0.429 kg CO_{2eq}/kWh)**.

- **UPAC 2 and UPAC 8** have the **highest** electricity demand and at the same time low installed PV capacity (compared to their electricity demand). This leads to low curtailment and low battery output because the majority of the PV's produced energy is consumed directly for the UPACs' needs. The fact that these UPACs have high electricity demand with low PV installations, leads to a higher grid contribution, and as a result, the operational impact increases.

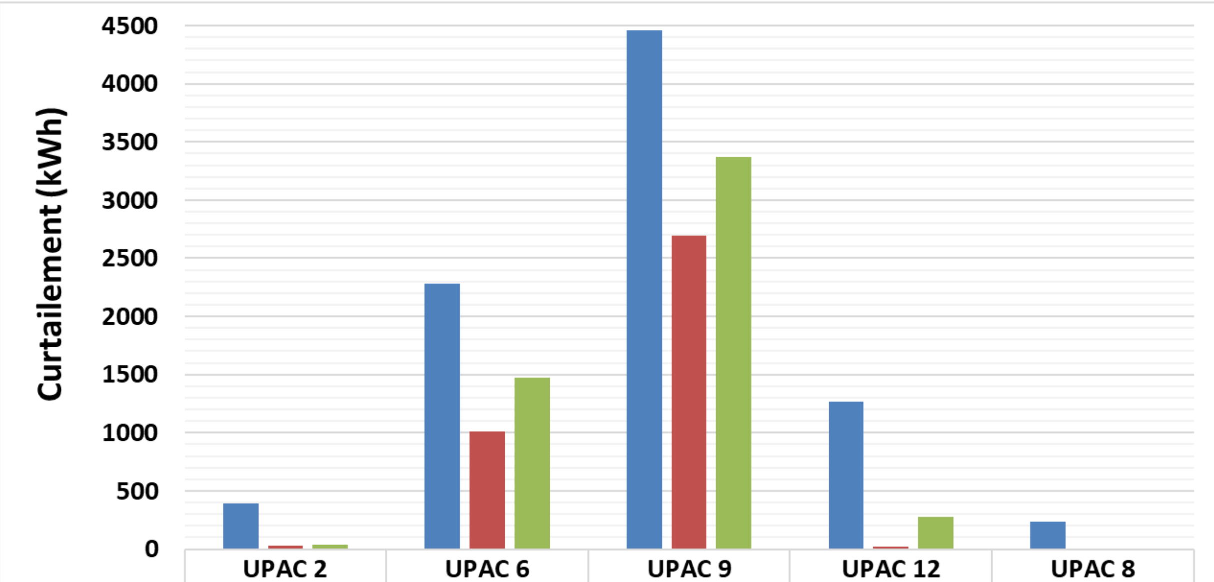
- **UPAC 9** has the **lowest** environmental impact compared to the other UPACs in Enhanced and Greedy scenarios. Moreover, **UPAC 9** is the only UPAC in which the contribution of PV impact in the total impact is higher than the contribution of Grid for Greedy and Enhanced scenario as presented in Table 17. The fact that PV contributes more than the grid in the total impact justifies why UPAC 9 has the lowest operational impact in Greedy and Enhanced scenario. The lowest environmental impact among all UPACs is noticed in **UPAC 9 Greedy scenario** (**0.166 kg CO_{2eq}/kWh**), where the contribution of the grid in covering the demand is the lowest. Table 17 presents the contributions of Grid and PV in the total impact (expressed in %). Taking into consideration the findings of Figure 5 and those of Table 17 concerning all the three presented scenarios, it is clear that, whenever the contribution of the grid is high, the total impact is high, too (e.g. in Greedy scenario UPAC 2 has higher grid contribution than UPAC 12 and, as a result, a higher total impact).

Table 17: Contribution (%) of the Grid, PV and BESS in the total impact for the participated UPACs in the baseline (No BESS) and examined scenarios (Greedy, Enhanced)

	No BESS		Greedy		Enhanced		Grid2BESS	
	PV	GRID	PV	GRID	PV	GRID	PV	GRID
UPAC 2	7%	93%	7%	93%	7%	93%	-	-
UPAC 6	18%	82%	24%	76%	21%	79%	-	-
UPAC 9	31%	69%	62%	38%	45%	55%	-	-
UPAC 12	21%	79%	30%	70%	28%	72%	-	-
UPAC 8	4%	96%	4%	96%	4%	96%	23%	77%

Figure 16 illustrates the curtailment (kWh) for all the UPACs in the three examined scenarios for the first year of operation. UPAC 9 has the **highest** amount of curtailment because it has the **highest** installation of PV capacity in relationship with the low electricity demand. On the other hand, UPAC 2, which has the higher electricity demand together with low installed PV capacity, presents low levels of curtailed energy.

In general, battery storage offers a solution to grid inflexibility and curtailment as presented in Figure 16. UPAC 9, which has the highest levels of curtailment, benefits from the solution of BESS presenting the lowest operational environmental impact.



	UPAC 2	UPAC 6	UPAC 9	UPAC 12	UPAC 8
No BESS	392	2282	4462	1266	240
Greedy	26	1011	2693	19	0
Enhanced	40	1475	3373	275	0

Figure 16: Curtailment (kWh) for the participating UPACs in the three examined scenarios for the 1st year

Figure 17 indicates the operational impact for the integrated operation of PV and BESS throughout the 25 years of operation.

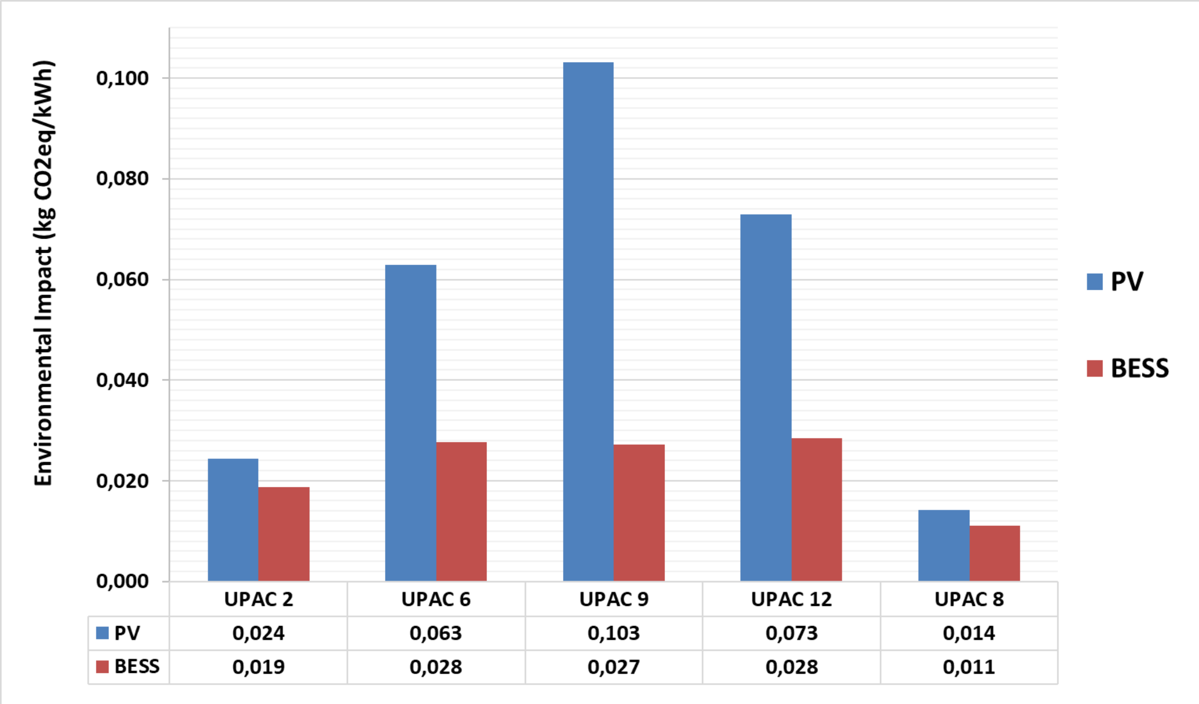


Figure 17: Environmental Impact (kg CO2eq/kWh) for the PV and BESS components for 25 years of integrated operation.

4.2.5.2.3 Operational impact for UPAC 8 in Pilot 2: Grid2BESS model

In this model, BESS charging occurs during the cheap price zones of grid electricity. This stored energy is used for the load satisfaction during the rest (non-cheap) price zones.

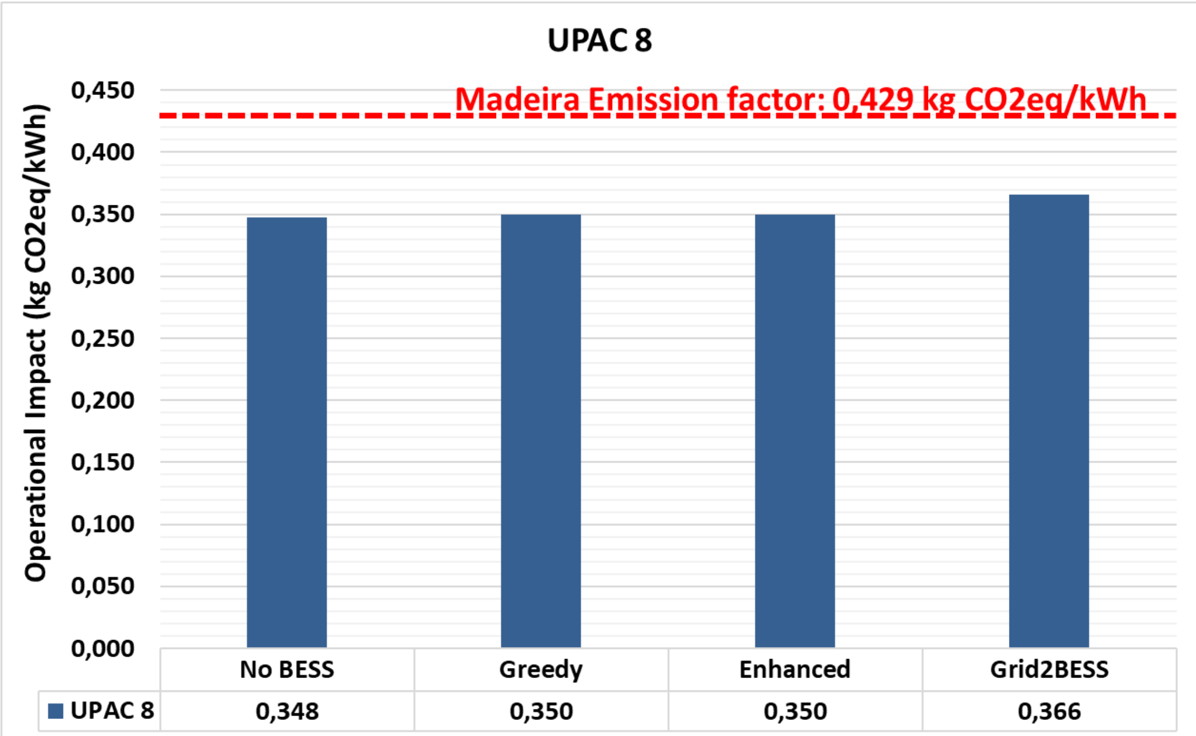


Figure 18. Environmental impact (kg CO_{2eq}/kWh) of all the examined scenarios including GRID2BESS scenario for UPAC 8.

As shown in Table 18 the Grid2BESS scenario requires the highest amount the grid electricity (2.3% higher than Greedy and Enhanced, 1% higher than the No BESS scenario). This is the main reason why the Grid2BESS scenario leads to the highest footprint among the four scenarios during the 25-year period. Generally, the contribution of the grid to the load satisfaction has a major influence to the environmental footprint.

Nevertheless, it should be mentioned that, although the No BESS scenario uses more grid electricity than the Greedy and Enhanced scenario (Table 18), it presents a (slightly) lower environmental footprint (Figure 18). This is explained by the fact that the two BESS scenarios involve the manufacturing environmental cost of the battery.

Table 18: Amount of electricity purchased by the grid in each scenario for the 1st year of study

Year of Operation	Grid El. – No BESS (kWh)	Grid El. – Greedy (kWh)	Grid El. – Enhanced (kWh)	Grid El.- Grid2BESS (kWh)	Diff. percentage Grid2BESS-No BESS	Diff. percentage Grid2BESS-Greedy/Enhanced
1st	18763	18532	18532	18959	+ 1 %	2.3%

4.2.5.3 LCC Calculations

4.2.5.3.1 Purchase and installation costs

The costs in Table 19 represent indicative market prices of the PVs and BESS implemented. The life time of these components also needs to be taken into account, as well as their age at the beginning of the study. The cost data of the PVs was provided by the partners of the Madeira environment, while the BESS data was provided by LIBAL.

Table 19: Presentation of indicative equipment costs used in Pilots 1 and 2 of Madeira

UPAC	Components	Life time (years)	Current age of equipment (years)	Purchase and installation cost (€)
UPAC 2	PV (1.5 kW_p)	25	6	5,000
	BESS (8 kWh)	15		5,667
UPAC 6	PV (2.7 kW_p)	25	0	9,000
	BESS (8 kWh)	15		5,667
UPAC 9	PV (4.5 kW_p)	25	2	15,000
	BESS (8 kWh)	15		5,667
UPAC 12	PV (3 kW_p)	25	2	10,000
	BESS (8 kWh)	15		5,667
UPAC 8	PV (3.92 kW_p)	25	3	13,067
	BESS (24 kWh)	15		17,000

Since the highest life cycle is the PV's, the simulation study is done for this period. During this, a BESS is purchased in the 1st year of study, and another is bought in the 16th. For the purpose of the study's accuracy, in the 25th year the BESS is resold for the 1/3 of its initial price. Moreover, as presented in Table 19, most of the PVs pre-existed of the study, so the acquired PV generation time series have already undergone some years of degradation. The developed simulation calculated the PV generation time series of the years before the acquired time series, in order to reach a whole 25-year simulation. These values are affected by the discount rate, as will be explained in the respective paragraph.

4.2.5.3.2 Maintenance costs

The maintenance costs took certain annual values, since it is impossible to foresee any unexpected damage which would require more to be repaired. Thus, the values in Table 20 take into account the actual cost of the annual maintenance services, as well as some extra for unexpected damages. The indicative expected maintenance costs for the Madeira pilots, provided by the Madeira ecosystem of the consortium, are the following:

Table 20: Presentation of the indicative maintenance costs of the equipment used in Pilots 1 and 2 of Madeira

UPAC	Components	Maintenance costs (€/year)
UPAC 2	PV (1.5 kWp)	30
	BESS (8 kWh)	30
UPAC 6	PV (2.7 kWp)	40
	BESS (8 kWh)	30
UPAC 9	PV (4.5 kWp)	70
	BESS (8 kWh)	30
UPAC 12	PV (3 kWp)	50
	BESS (8 kWh)	30
UPAC 8	PV (3.92 kWp)	60
	BESS (24 kWh)	100

As mentioned above and will be described later, these annual costs are affected by the local discount rate.

4.2.5.3.3 Grid electricity costs

The cost of the electricity purchased by the grid represents the operational costs for the 4 scenarios, since the energy derived from PV and battery have zero operational costs. The incremental implementation of PV and BESS decreases the need for grid energy and, thus, its cost. Although it is not studied in the present deliverable, the DR policies can direct the loads to times of the day when the price of electricity is cheaper, in order to further decrease this cost. Table 21 and Table 22 presents indicatively the participation of the grid in each scenario for every UPAC at the 1st year of the simulation model.

Table 21: Presentation of the grid electricity costs for the 1st year of the simulation concerning all UPACs of Pilot 1 of Madeira

UPAC	No-BESS (€)	Enhanced (€)	Greedy (€)
UPAC 2	643	580	585
UPAC 6	355	213	175
UPAC 9	300	103	41
UAPC 12	341	163	151

Table 22: Presentation of the grid electricity costs for the 1st year of the simulation concerning UPAC 8 of Pilot 2 of Madeira

UPAC	No-BESS (€)	Enhanced (€)	Greedy (€)	Grid2BESS (€)
UPAC 8	2820	2774	2779	1620

The annual costs of the grid electricity are affected by the local discount rate, too.

4.2.5.3.4 Externalities

Since they represent external costs of each scenario due to the environmental pollution, it is expected that these costs will be low when the PV penetration is high, because the grid electricity is highly pollutant compared to the manufacturing of PV and BESS. Table 23 and Table 24 shows the participation of the external costs in the final LCC (€/kWh) for each scenario.

Table 23: Presentation of the contribution of external costs concerning all the UPACs tested in Pilot 1 of Madeira

UPAC	No-BESS (€/kWh)	Enhanced (€/kWh)	Greedy (€/kWh)
UPAC 2	0.004	0.005	0.005
UPAC 6	0.004	0.005	0.005
UPAC 9	0.004	0.004	0.004
UAPC 12	0.004	0.005	0.004
UPAC 8	0.005	0.005	0.005

Table 24: Presentation of the contribution of external costs concerning UPAC 8 of Pilot 2 of Madeira

UPAC	No-BESS (€)	Enhanced (€)	Greedy (€)	Grid2BESS (€)
UPAC 8	0.005	0.005	0.005	0.005

4.2.5.3.5 Discount rate

A financial analysis that simulates the cash flows of such a long period has to take into account the discount rate of the local economy. Concerning the local economy of Madeira, the discount rate is defined at **6%** according to the Madeira ecosystem of the consortium. Being higher than the respective Samsø value, it is expected to have a greater impact. This means that high cost paid in the beginning of the study (PV and BESS investment costs) will have an even stronger impact to the final LCC.

4.2.5.3.6 Pilot 1

The LCC calculations concerning the 4 UPACs of Pilot 1 resulted in the values presented in the Figure 19:

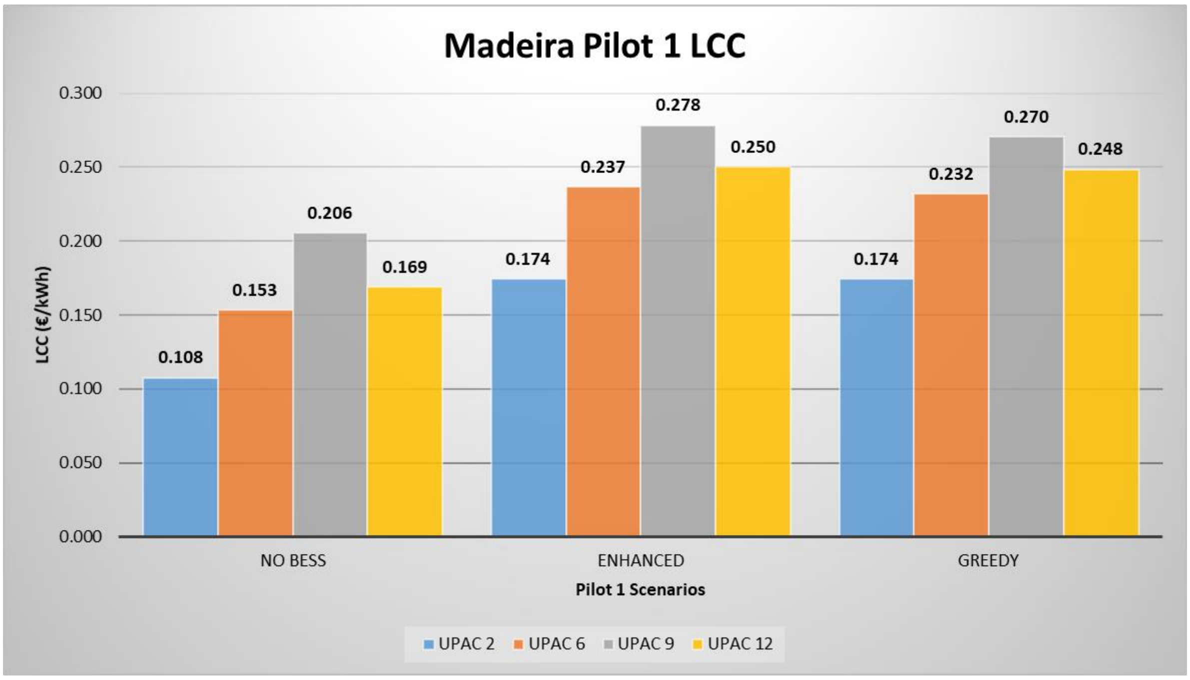


Figure 19: Comparison of scenarios and UPACs based on the LCC results

Indicatively, Figure 20 presents the LCC share of UPAC 2:

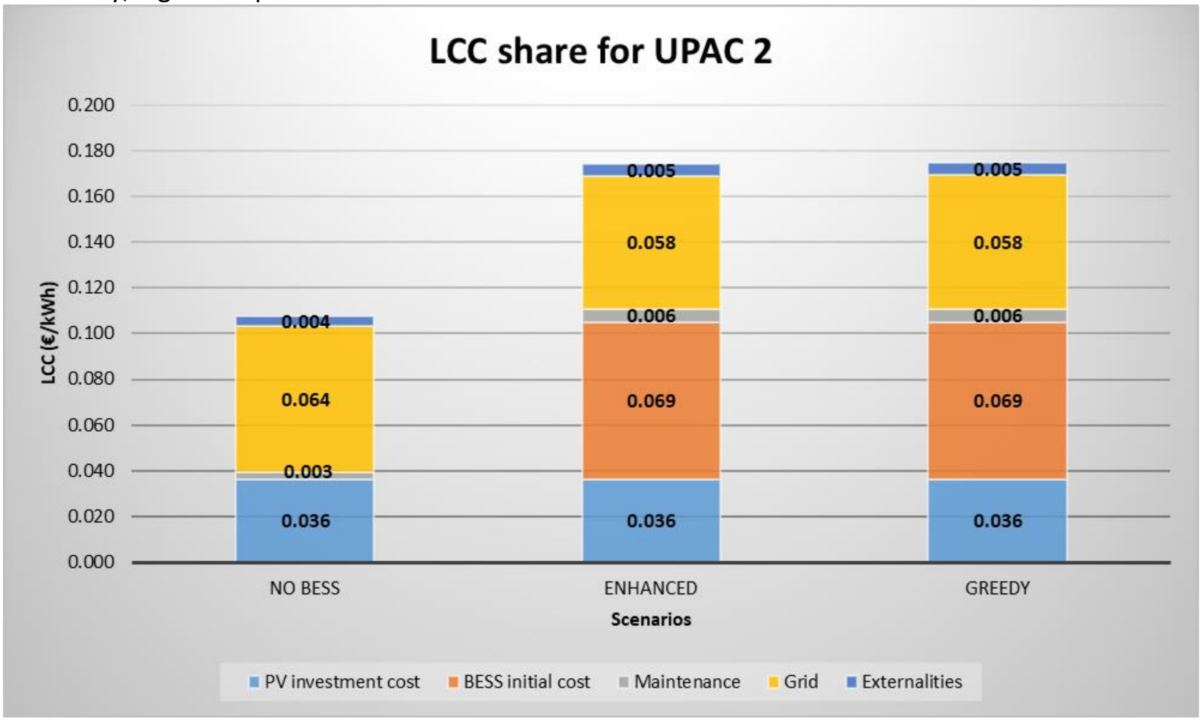


Figure 20: Indicative comparison of LCC share per scenario for UPAC 2 of Madeira

According to the results, the following conclusions were derived:

- The BESS scenarios are significantly more expensive than the no-BESS scenario. This is explained by the fact that the BESS investment cost is really high. This remark was pointed out for the Samsø demo, too. Indicatively, the BESS investment cost is 0.069 €/kWh (about 40% of the final LCC), while on the same time, the reduction of the cost of buying electricity from the grid is only 0.006 €/kWh.

- There is no significant difference in the final LCC among the 2 BESS scenarios (the Greedy is sometimes a little cheaper than the Enhanced, and even then it is less than 3%). The Enhanced scenario provides the advantage of keeping energy reserves for the expensive time zones of the day, while the Greedy provides an all-time exploitation of the battery reserves but with an advanced possibility of being empty during the expensive time zones. The fact that there is no significant difference among them, is probably explained by the specific load curve. Another load curve with other characteristics would probably give a handicap to one of the two scenarios (strategies). For example, a load curve with lower loads compared to the examined load curve during the cheap time zones of the day, would possibly give an extra advantage to the greedy model which would provide more free battery energy to the expensive time zones.
- There are serious differences among the LCC of each UPAC. Indicatively, UPAC 9 presents almost double LCC compared to UPAC 2, even in the no-BESS scenario. This could be explained by the level of exploitation of the PV investment. Figure 21 shows that the curtailment of UPAC 9 is much higher than that of UPAC 2. In other words, it seems that the definition of the PV sizing is more correct in the case of UPAC 2, since almost all the energy generated in the PV is exploited. This shows the importance of a proper sizing definition of such an investment, in order to fully exploit its profits. It seems that the existence of high curtailed PV energy is a serious factor leading to the unfeasibility of a PV investment.

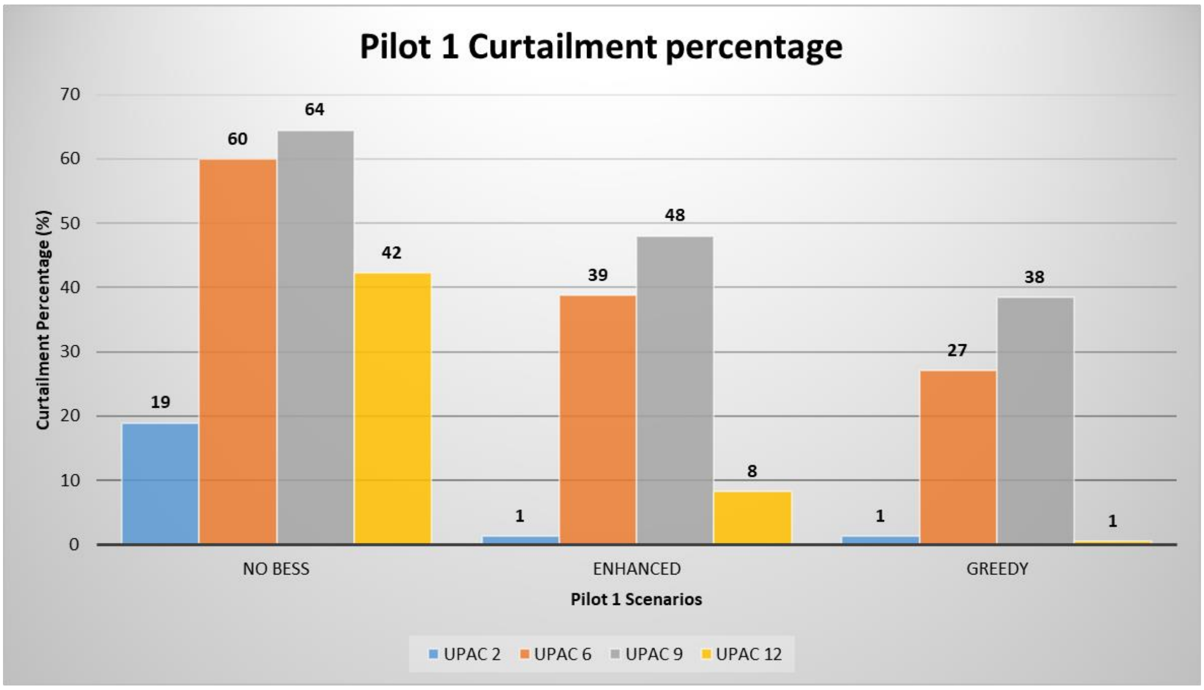


Figure 21: The curtailment percentage of the PV generation in each UPAC for each scenario

4.2.5.3.7 Pilot 2

The LCC calculations concerning the UPAC 8 of Pilot 2 resulted in the values presented in Figure 22 and Figure 23:

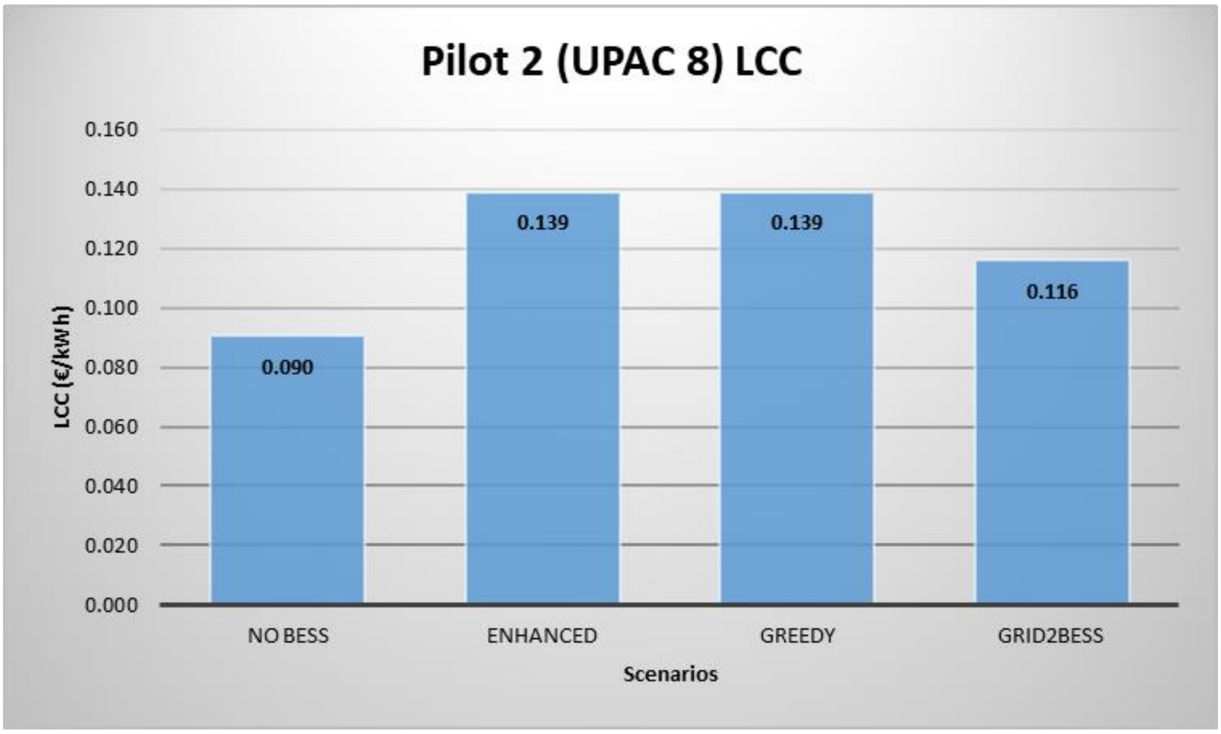


Figure 22: Presentation of LCC results for each scenario of UPAC 8 of Madeira

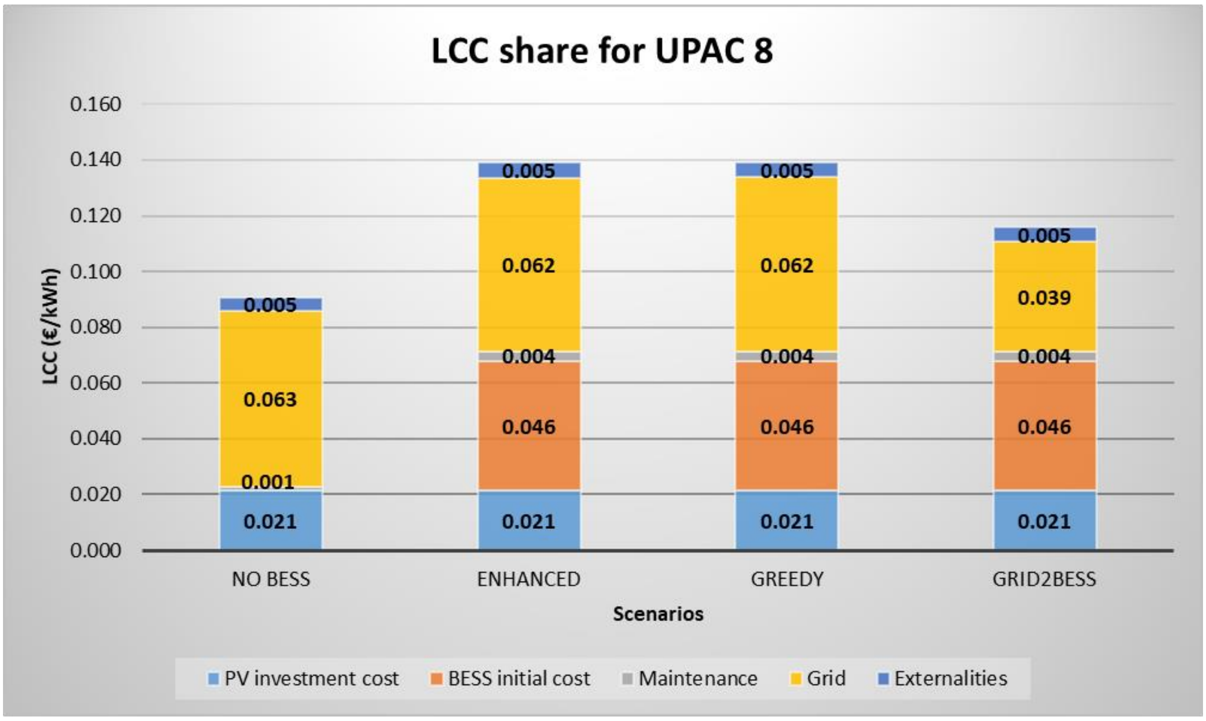


Figure 23: LCC share per each scenario of UPAC 8 of Madeira

According to the results, the following conclusions were derived:

- The BESS scenarios are again significantly more expensive than the no-BESS scenario. This is explained by the fact that the BESS investment cost is really high. This remark was pointed out for the Samsø demo and Madeira Pilot 1, too. Indicatively, the BESS investment cost is 0.046 €/kWh (about 35% of the Enhanced and Greedy models final cost, and about 40% of the

Grid2BESS model final cost), while on the same time, the reduction of the cost of buying electricity by the grid compared to the no-BESS scenario is only 0,001 €/kWh for the Enhanced and Greedy models, and 0,024 €/kWh for the Grid2BESS scenario (this reduction is so high for the Grid2BESS scenario, since much expensive peak power is replaced by the cheaper price zones).

- There is again no significant difference among the Enhanced and Greedy scenarios (they both have an LCC of 0,139€/kWh). The Enhanced scenario provides the advantage of keeping energy reserves for the expensive time zones of the day, while the Greedy provides an all-time exploitation of the free battery energy reserves with the possibility of being empty during the expensive time zones. The fact that there is no significant difference among them, is probably explained by the specific load curve. Another load curve with other characteristics would probably give a handicap to one of the two scenarios (strategies).
- The Grid2BESS scenario provides certainly better results than the other two BESS scenarios, since it achieves a considerable reduction in the cost for grid electricity purchase (-37%), while the rest costs stay the same. Nevertheless, its final LCC is still higher than that of the no-BESS scenario, due to the very high investment cost of BESS.

In fact, in the specific UPAC, the load is so high, that there is practically no curtailment throughout the year, even without the BESS. That is the reason why there is practically no need to apply methods like Greedy and Enhanced in such use cases. A lower BESS investment cost or a different load use case (e.g. a curve with higher loads during cheap times compared to the non-cheap price zone) could lead to Grid2BESS LCC actually competitive to the no BESS scenario.

4.2.6 Pilot 3 and Pilot 4

4.2.6.1 Definition of scenarios and configuration Scheme

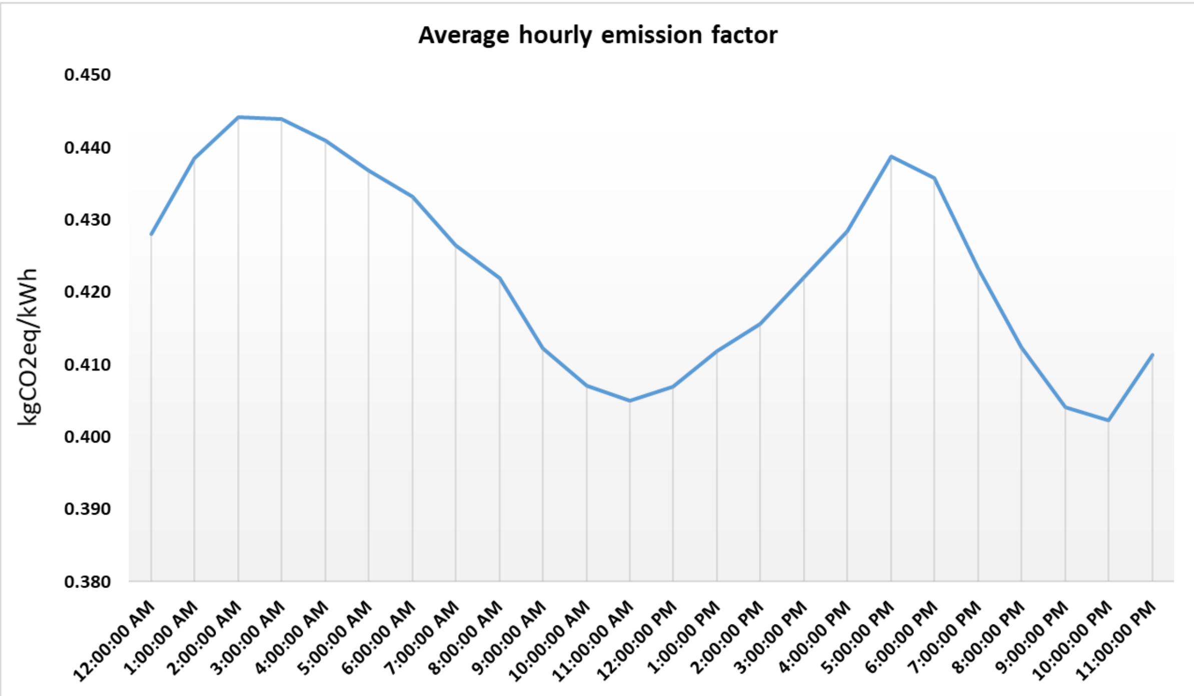


Figure 24: Average hourly emission factor as calculated with feedback by D8.3

The scenarios simulated were defined according to two main parameters, the emissions and the price of the Madeira grid electricity. Moreover, the assumptions taken for granted were the following:

- The emission factor of the grid was calculated in D8.3 (not complete yet) with energy mix data of 2016, which is supposed to be kept the same during the next years (Figure 24). The local mix involved energy generated by solar, wind and hydro RES sources, as well as incineration of solid waste and natural gas;
- The load curve used time series of a year (pilot 3) or less (pilot 4) with more recent data (2018-2019)
- The scenarios had to be simple, so there were no strategy differences throughout the year (e.g. seasonal differences, weekend differences, etc.);
- It is supposed that the vehicles (both pilots) had to be charged twice per day;
- The simulation uses load data of the pilot garages, thus not the charging of each vehicle separately;
- The acquired load time series had a steady background power needed for the system operation. Each time vehicles were being charged, the power was much higher. The background and charging powers were divided. The first was kept steady in all proposed scenarios, while the second was shared in the charging zones proposed by each scenario. The final load had to be kept steady.

The first scenario is before SMILE implementation activities where the charging of EVs occurs at any time throughout the day. The second scenario is a more 'theoretical' and less feasible scenario describing the charging of the EVs twice during the night, which is the reason why that scenario described as 'theoretical'. The third scenario is based on one main pillar of the pilot which is the price-based scheme for the charging of the EVs. This scenario shifts the charging in two pricing zones in which the cost of electricity is the lowest possible. Last but not least, the fourth scenario has been built upon the second main pillar of the pilot approach which is the shifting of charging based on the increase of the RES sharing. Table 25 lists all the implemented scenarios:

Table 25. Definition of scenarios for EVs charging.

Scenarios	Description
(1)	Charging od EVs at any possible time **(Baseline)**
(2)	Charging of EVs during the cheapest electricity price zones (**theoretical-not feasible**)
(3)	Charging of EVs in the pricing zone: 00.00-01.00 and 15.00-16.00 (**price shifting**)
(4)	Charging of EVs in the pricing zone: 12.00-1.00 and 22.00-23.00 (**environmentally friendly**)

Pilots 3 and 4 do not involve the implementation of new equipment, so no life cycle study could be undergone. Instead, the following environmental and economic comparison among the models could provide some conclusions concerning the possible charging strategies to be followed.

4.2.6.2 Environmental Analysis for pilot 3

The environmental analysis took place for scenarios 1,3 and 4, since in scenario 3 (theoretical) it was just supposed that charging was priced with the cheapest price (during night), so no specific emission factor was taken into account. According to Figure 25 and Figure 26, it seems that none of the proposed scenarios can provide a considerable result to the pilot emissions. Although the current energy demands

are such, that the environmental benefit is too low to be considered, an increase in the energy demands will contribute to more serious environmental gains.
The low sensitivity of the scenario emissions by the time zone of the EV charging is based on the fact that the emission factor of the grid electricity throughout the day is quite steady, as presented in Figure 24. In fact, the hourly emission factor moves between 0.408 and 0.442 (less than 10% difference), which means that the changes between the proposed scenarios cause slight changes in the environmental impact.

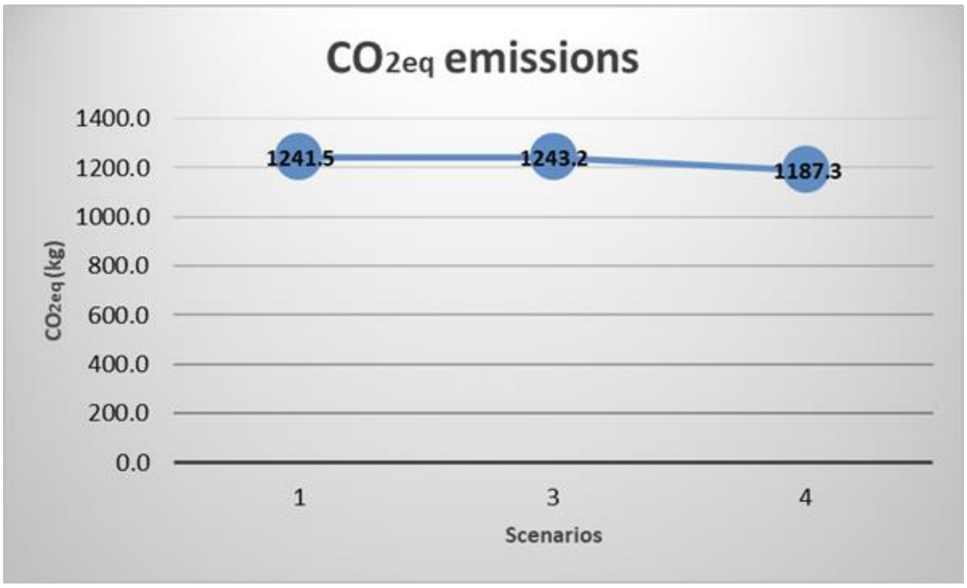


Figure 25: Comparison of CO_2 emissions per each scenario in absolute form

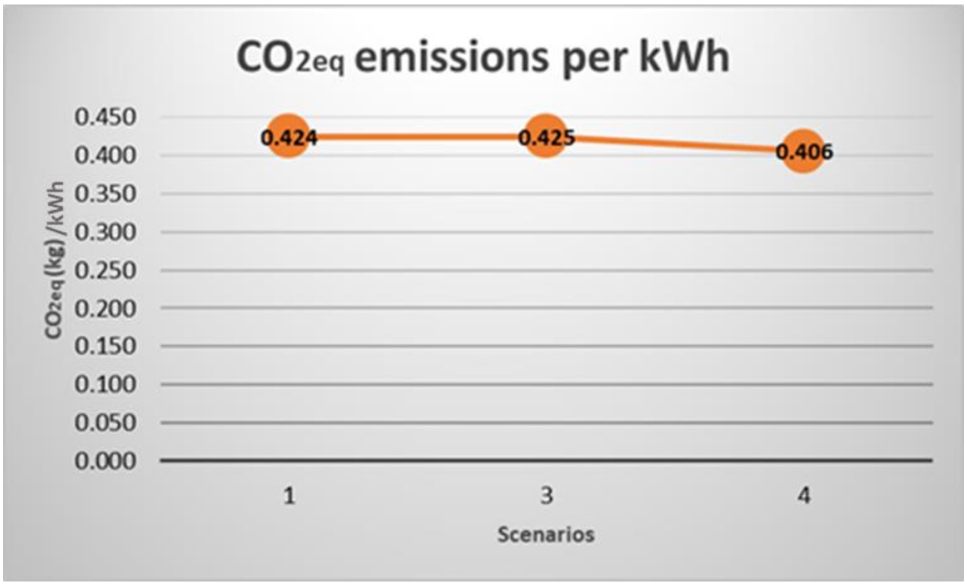


Figure 26: Comparison of CO_2 emissions per each scenario in normalised form

4.2.6.3 Economic Analysis for pilot 3

The results of the economic analysis (Figure 27 and Figure 28) could provide some directions for the pilot. Some remarks are the following:

- The theoretical scenario (Scenario 2) can provide a considerable reduction in the cost compared to the baseline scenario.

- The environmentally-friendly scenario (Scenario 4) still remains a high electricity cost scenario, at the same level as that of the baseline, so it is not proposed as ideal.
- Scenario 3 actually presents a lower cost than that of the baseline scenario. In fact, it presents a reduction of 22,3% compared to the baseline and environmental scenario.

It seems that a direction towards a strategy of charging during the hours proposed in Scenario 3 can result in economic profit. Even though, it is not feasible to be absolutely strict in the charging time zones, a strategy for charging EVs similar to this one that provided in Scenario 3 could contribute in economics savings compared to the current situation (Scenario 1).

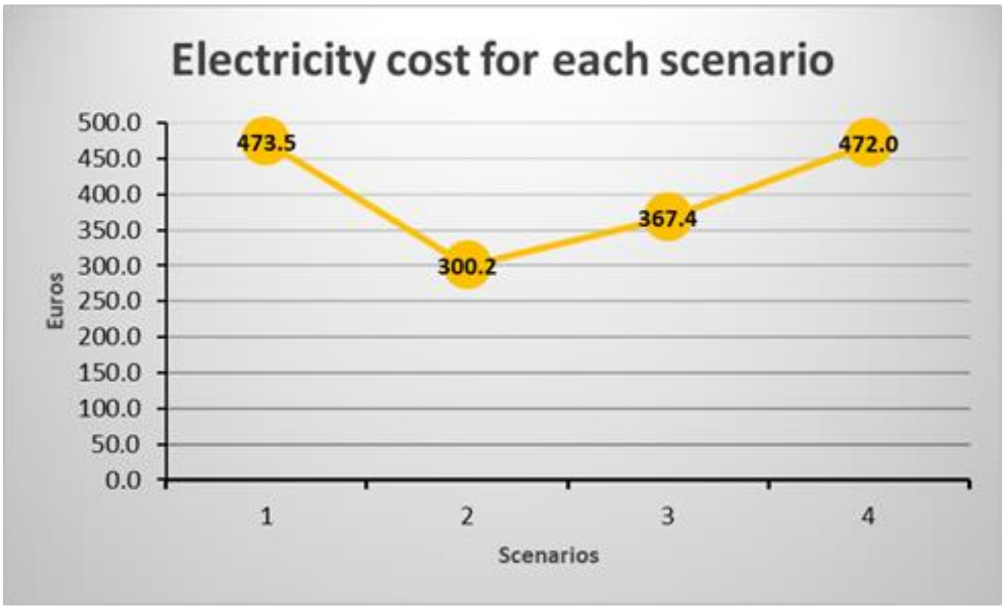


Figure 27: Comparison of cost per each scenario

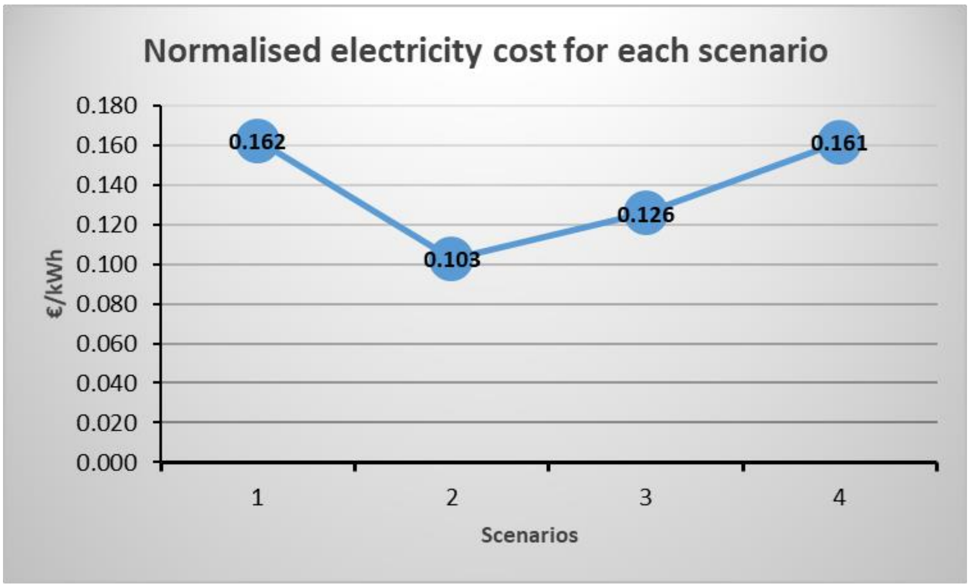


Figure 28: Comparison of normalised costs for each scenario

4.2.6.4 Environmental Analysis for pilot 4

The environmental analysis in pilot 4 does not provide meaningful conclusions or directions for the charging strategy of the EVs (Figure 29 and Figure 30). The 3 tested scenarios lead to practically the same

amount of emissions. Even the 4th scenario (the environmentally friendly) has only 1% less emissions compared to the 3rd (price-shifting) scenario, so there is no solid motivation for its proposal and application.
As in pilot 3, the low sensitivity of the scenario emissions by the time zone of the EV charging is based on the fact that the emission factor of the grid electricity throughout the day is quite steady, as presented in Figure 24. So, this scenario has a more meaningful character in case that the grid is based on solar energy, so the hourly emission factors is significantly different in throughout the day. However, the results become more meaningful in cases with a large fleet of EVs, when the load is increasing significantly.

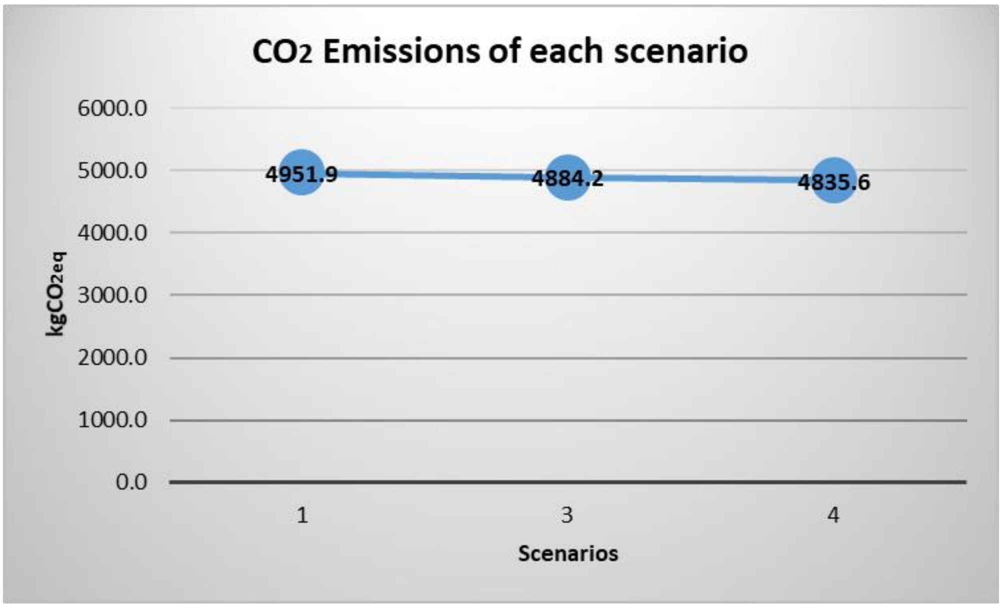


Figure 29: Comparison of CO_2 emissions for each scenario

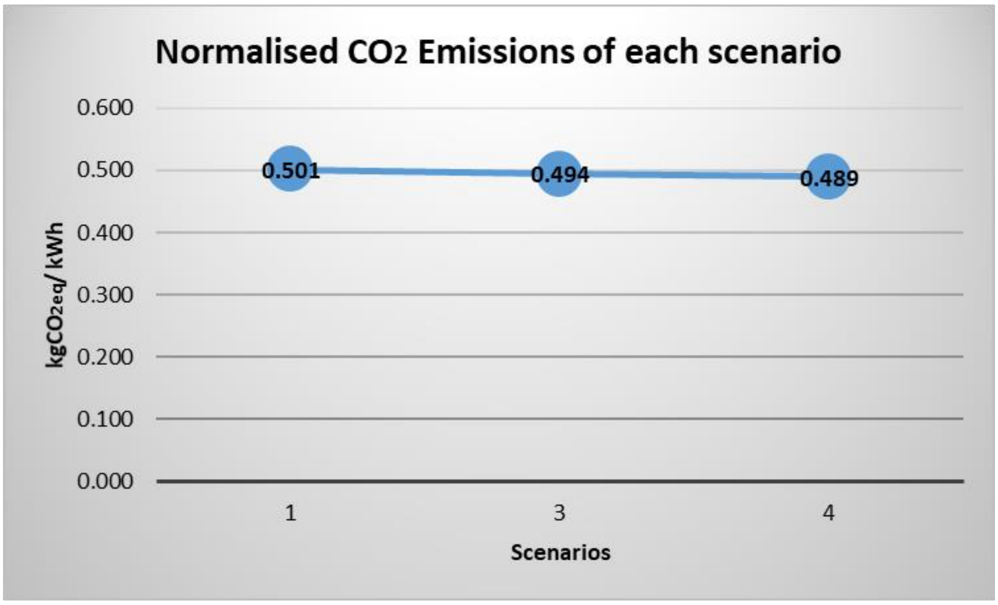


Figure 30: Comparison of normalised CO_2 emissions for each scenario

4.2.6.5 Economic analysis for Pilot 4

As in pilot 3, the results of the economic analysis could provide some directions for the pilot. Some remarks are the following:

- The theoretical scenario (Scenario 2) can provide a considerable reduction in the cost compared to the baseline scenario.
- The environmentally-friendly scenario (Scenario 4) leads to a considerable cost reduction of about 26% compared to the baseline.
- Scenario 3 presents a cost reduction of about 27% compared to the baseline, being at the same level as scenario 4.

It seems that a direction towards a strategy of charging during the hours proposed in Scenario 3 can result in the best economic profit, although, the differences between scenarios 3 and 4 are too slight to be considered as important as presented in Figure 31 and Figure 32. Moreover, it is not feasible to be absolutely strict in the charging time zones, so this simulation can only provide general directions and not a solid strategy to be followed.

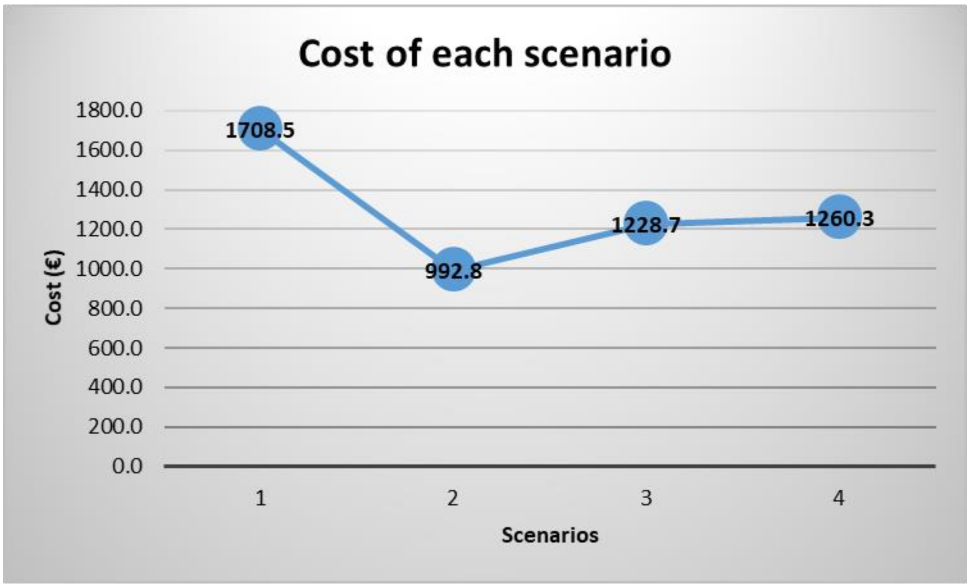


Figure 31: Comparison of cost per each scenario of Pilot 4

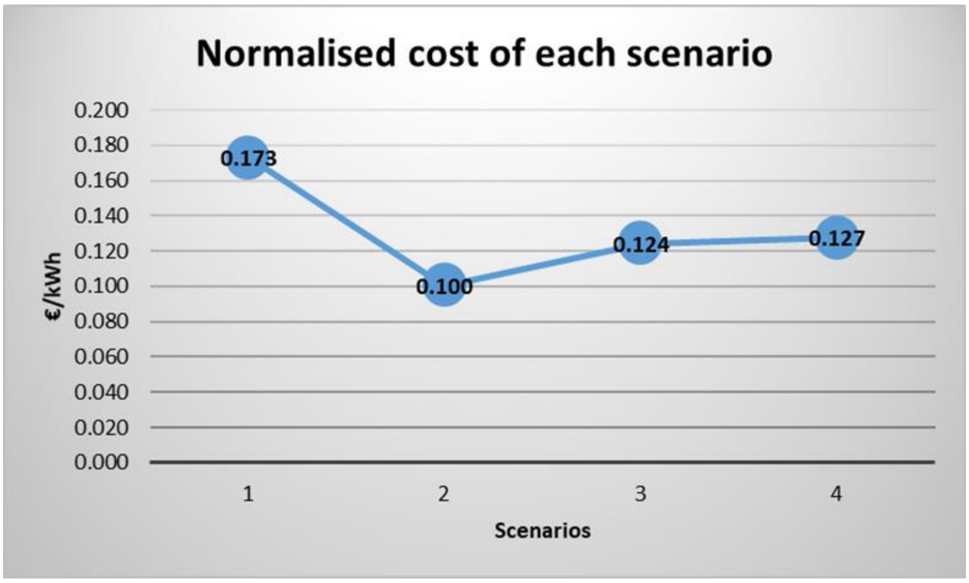


Figure 32: Comparison of normalised cost per each scenario of Pilot 4

4.3 Orkneys demo site

4.3.1 Description of the pilot

In the 1st pilot, domestic heat storage is implemented in order to exploit RES grid energy that would otherwise be curtailed. The domestic heat installations consist of approximately 45 properties, contacted with the help of the in-house developed Contact Relationship Management (CRM) tool of CES, with a variety of different type of technologies implemented, including: 1) flow boilers, 2) heat pumps, 3) Sunamp Phase Change Material (PCM) heat battery thermal store, 4) hot water tanks, and 5) batteries combined with VCharge/OVO dynamos. As analyzed below VCharge/OVO dynamos included consist of:

- 15 x 5.6 kW internally heated Sunamp PCM heat battery thermal store, VCharge/OVO controls
- 15 x 5 kW air to water heat pump (ASHP), Sunamp PCM heat battery thermal store, VCharge/OVO controls
- 10 x 5 kW ASHP, hot water thermal store VCharge/OVO controls
- 5 x 5 kW ASHP, hot water thermal store, BESS, VCharge/OVO controls

4.3.2 System Boundaries

The analysis is conducted indicatively for a domestic property coded as “CRM 21”, which represents a Type 3 domestic property where the oil boiler is replaced by an air-sourced heat pump (ASHP) and a hot water cylinder (Figure 33). The purpose is to store heating energy (hot water) in a hot water buffer tank during the curtailment events that take place in the island due to the high RES penetration in the local electricity grid. The annual space heating needs were calculated 32,428 kWh, while the water heating needs are estimated 2,200 kWh annually.

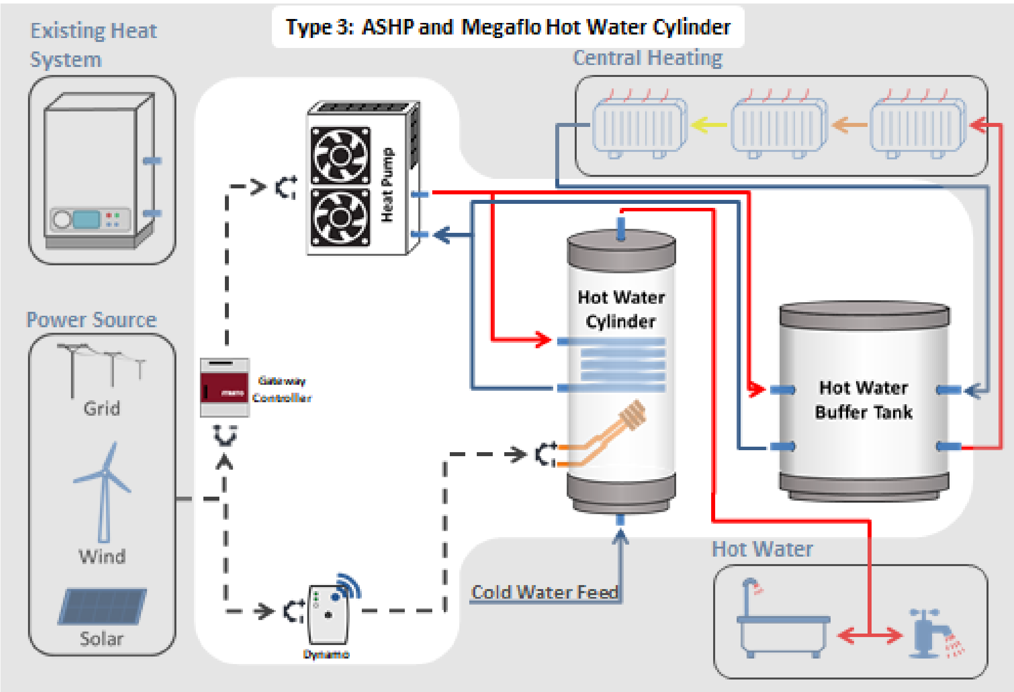


Figure 33: The SMILE heating implementations of CRM 21, a typical example of a Type 3 domestic property

The ASHP is the main source of heat generation in the SMILE scenarios examined, while the immersion element of the hot water cylinder, which has considerably lower efficiency than the ASHP, has a supportive role. During the curtailment events, the ASHP is supposed to operate at full-power in order

to store heat power in the buffer tank. Since the ASHP requires around 10 minutes to begin providing heat energy when turned on, the immersion element will be operating during these 10 minutes, as it can provide heat power instantly.
Due to the fact of high penetration of wind energy in the electricity mix in Orkney during certain times in year, the produced energy is significantly higher compared to the demand. For the purposes of the study, it is supposed that a 2-hour curtailment event happens every day. The electricity price has a fixed value at 0.20 €/kWh, concerning the CRM 21. In order to promote heating-storage methodology during curtailment events, a new energy pricing scheme is proposed. A fixed pricing mechanism that drops electricity price to 0.05€/kWh is introduced. This specific pricing plan is adapted only during curtailment event periods. A lower charging pricing model could motivate users to invest in heating storage equipment, in order to avoid high energy peaks and assist 'smoothening' the overall energy system demands.
The analysis provides estimations for a 15 year ahead period, in order to take into consideration both equipment parameters (e.g. degradation), as well as financial parameters (e.g. discount rate).
The LCA methodology is performed for both the manufacturing and the operational phase. The environmental impact of the manufacturing phase is estimated through the use of relevant modules found in Ecoinvent database. The implementation methods used for the estimation of the environmental footprint is the Impact 2002+, a standardized method found in Sima pro tool. During the operational phase, CO_{2eq} emissions are considered for two reasons: 1) due to oil combustion process (pre-SMILE scenario) and 2) because of the heat pumps electricity needs throughout the life time of the equipment.
The LCC methodology takes into consideration: 1) the investment cost of the equipment, 2) the maintenance cost, 3) the operational costs and 4) the external costs derived by the CO_{2eq} values of the grid electricity generation and the oil combustion for each examined scenario.

4.3.3 Life Cycle Inventory for Orkneys

The Life Cycle Inventory analysis involves the technical specification of the components, the investment costs, and the energy prices. In order to model and evaluate the pilots cases, primary data derived by the Orkneys ecosystem and secondary data derived by literature and market are used. The annual space heating needs as provided by the Orkneys ecosystem are 32,428 kWh, while the annual hot water needs are calculated to be at 2,200 kWh. Table 26-Table 29 summarize the dataset detail description and values as used for the LCA/LCC modelling process.

Table 26: The dataset of the boiler of CRM 21

Dataset	Status	Value
Efficiency (%)	Assumed	92
Capacity(kW)	Assumed	27
Oil price (€/L)	Assumed	0.6
Life time (years)	Assumed	12
Investment cost (€)	Assumed	4000
Annual maintenance costs (€/year)	Assumed	70
End-of-life cost (€)	Assumed	0
Annual degradation rate of efficiency (%)	Assumed	0.5

Table 27: The dataset of the heat pump of CRM 21

Dataset	Status	Value
Type/model	Provided	Daikin ERSQ011AAV1

Heating Capacity (kW)	Provided	11
CoP	Provided	2.92
Purchase and installation (€)	Assumed	6000
Annual maintenance costs (€/year)	Assumed	70
Life time (years)	Assumed	15
End-of-life cost (€)	Assumed	0
Annual degradation rate of efficiency (%)	Assumed	0.5

Table 28: The dataset of the hot water cylinder of CRM 21

Dataset	Status	Value
Type/Model	Provided	Megaflo Heatrae
Capacity (L)	Provided	100
Power of immersion element (kW)	Provided	2.8
Heating Efficiency of immersion element	Provided	1
Life time (years)	Assumed	30
Purchase and installation (€)	Assumed	700
Annual maintenance costs (€/year)	Assumed	10
End-of-life cost (€)	Assumed	0

Table 29: The dataset of the hot water buffer tank of CRM 21

Dataset	Status	Value
Capacity (L)	Provided	250
Life time (years)	Assumed	20
Purchase and installation (€)	Assumed	500
Annual maintenance costs (€/year)	Assumed	0
End-of-life cost (€)	Assumed	0

4.3.4 Definition of scenarios

Table 30 presents the examined scenarios for the Orkney demo case. In a detailed analysis, the Scenario 1 describes the baseline case where an oil boiler provides the required space and water heating. In the Scenario 2 the oil boiler is replaced by an efficient ASHP and hot water cylinder. In this case the necessary space and water heating is provided by ASHP and hot water cylinder infrastructure. During the Scenario 3 an additional hot water buffer tank is added, extending by this way the Scenario 2 for modelling energy curtailment operation events.

Table 30: The defined scenarios of heating the CRM 21 in Orkneys' 1st pilot

Scenario	Description
Scenario 1	Baseline/reference scenario. The heating system of CRM 21 utilizes an oil boiler. All the required space and water heating is provided by the oil boiler operation. The estimated operation time was 4 hours on a daily basis.
Scenario 2	The oil boiler is replaced by an ASHP and a hot water cylinder. In this scenario, all the required space and water heating is provided by the

	ASHP, since it has considerably higher efficiency than the immersion element of the hot water cylinder. The estimated operation time was 9 hours on a daily basis
Scenario 3	In the heating system of scenario 2, a hot water buffer tank is added in order to store heating energy provided during the curtailment events. The immersion element operates for 10 minutes at the beginning of the curtailment event, in order for the ASHP to reach high levels of efficiency. The electricity supplier is supposed to provide cheaper (at 1/4 of the normal) electricity during the period of the curtailment events. In this model, it is supposed that there is a 2-hour curtailment event every day, so the ASHP operates for 2 hours daily being fed with low-cost electricity, and so does the immersion element for 10 minutes.

4.3.5 LCA calculations

4.3.5.1 Environmental manufacturing impact

The manufacturing impact of the scenarios corresponds to the emissions generated during manufacturing phase for each equipment component used in the defined scenarios. In Scenario 1, the boiler is the main component to be considered. Since the analysis is performed for a 15 year duration, the replacement of the boiler on 12th years is taken into consideration accordingly. In Scenario 2, the ASHP and the hot water cylinder are considered, while in Scenario 3, an additional buffer tank in the infrastructure of Scenario 2 is considered. All used equipment in scenarios 2 and 3 have life time duration more than the 15 years.
Therefore the relevant emissions of each scenario are presented in Table 31, taking into consideration the life time of each component used in each scenario. The modelling for the manufacturing impact was carried out in SimaPro by using components with similar specifications found in the Ecoivent database.

Table 31: Environmental manufacturing impact of each scenario (kgCO2eq/years of life time)

Scenarios	Infrastructure impact ($kgCO_{2eq}$/years of life time)
Scenario 1	73.17
Scenario 2	70.67
Scenario 3	85.87

For the calculation of manufacturing impact per KWh, the normalization was carried out by using the energy produced in a year for each scenario. Therefore, the total manufacturing impact was measured in $kgCO_{2eq}$ per kWh produced in one year operation (Table 32).

Table 32: Environmental manufacturing impact of each scenario (kgCO2eq/kWh/year)

Scenarios	Manufacturing impact ($kgCO_{2eq}$/kWh/year)
Scenario 1	0.0020
Scenario 2	0.0020
Scenario 3	0.0024

Based on the above results, the replacement of the oil boiler with an ASHP seems to not achieve any further reduction in the manufacturing impact. In Scenario 3, the manufacturing impact increases the level of the impact by 20% compared to Scenario 2 due to the added infrastructure of the tank.

4.3.5.2 Environmental Operational impact

The operational impact of the scenarios corresponds to the emissions generated by the oil combustion in the Scenario 1 and by the grid electricity generation Scenario 2 and Scenario 3. The emission factor of the heating oil combustion is 0.245 $kgCO_2/kWh$[7], while the emission factor of the UK electricity grid was taken as 0.254 $kgCO_{2eq}/kWh$[8]. For the Scenario 3 it was supposed that the emission factor during the 2-hour curtailment events is zero since it refers to RES energy that would otherwise be curtailed. The operational impact of each scenario is presented in the Table 33.

Table 33: Environmental operational impact of each scenario (kgCO2/kWh)

Scenarios	Operational impact ($kgCO_2/kWh$)
Scenario 1	0.273
Scenario 2	0.090
Scenario 3	0.069

A significant reduction of around 67% in the operational impact due to the replacement of the oil boiler with an ASHP is achieved. The exploitation of the curtailed energy in Scenario 3 could further decrease the environmental impact by 23% compared to Scenario 2. The environmental benefits would be even more in case that the specific emission factor of the Orkney's grid is taken instead of that of the whole UK's grid. This happens since the RES penetration in the Orkney grid is even higher compared to UK's grid.

4.3.5.3 Sensitivity analysis

In this paragraph, a sensitivity analysis on CoP of the ASHP and the annual degradation rate of ASHP is carried out.

4.3.5.3.1 CoP of the ASHP

Table 34: Environmental operational impact depending on CoP of the ASHP (kgCO2/kWh)

Scenarios	Operational impact ($kgCO_2/kWh$) CoP: 2.00	Operational impact ($kgCO_2/kWh$) CoP: 2.50	Operational impact ($kgCO_2/kWh$) CoP: 2.92
Scenario 1	0.273	0.273	0.273
Scenario 2	0.132	0.105	0.090
Scenario 3	0.101	0.081	0.069

Lower values of the ASHP's CoP were examined. According to Table 34, it is observed that different values of the ASHP's CoP certainly change the operational environmental impact of the two scenarios,

[7] http://www.nef.org.uk/knowledge-hub/view/oil-central-heating
[8]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/812146/Local_authority_C02_technical_report_2017.pdf

since the grid electricity required for the same heat load satisfaction is higher. Even though, in the worst case (CoP: 2) the emissions remain lower compared to the oil boiler scenario.

4.3.5.3.2 ASHP degradation ratio

Table 35: Environmental operational impact depending on ASHP annual degradation ratio (kgCO2/kWh)

Scenarios	Operational impact ($kgCO_2/kWh$) Annual degradation: 0.0%	Operational impact ($kgCO_2/kWh$) Annual degradation: 0.5%	Operational impact ($kgCO_2/kWh$) Annual degradation: 1.0%	Operational impact ($kgCO_2/kWh$) Annual degradation: 2.0%
Scenario 1	0.273	0.273	0.273	0.273
Scenario 2	0.087	0.090	0.093	0.101
Scenario 3	0.066	0.069	0.073	0.080

According to the results provided in Table 35, it seems that the degradation of the ASHP does not affect significantly the emissions of the two scenarios, especially when compared to the emissions of the oil boiler. Even in the worst case scenario where the annual degradation is defined at 2%, the environmental impact of the heat pump in both Scenario 2 and Scenario 3 is less than 63% compared to Scenario 1. In each case, the heat pump has a significantly lower environmental impact compared to the oil boiler, while the exploitation of the curtailment events can further reduce this impact by around 20-25%.

4.3.5.3.3 Daily curtailment period

Table 36: Environmental operational impact depending on the daily curtailment period (kgCO2/kWh)

Scenarios	Operational impact ($kgCO_2/kWh$) Daily curtailment: 1 hour	Operational impact ($kgCO_2/kWh$) Daily curtailment: 2 hours	Operational impact ($kgCO_2/kWh$) Daily curtailment: 3 hours	Operational impact ($kgCO_2/kWh$) Daily curtailment: 4 hours
Scenario 3	0.080	0.069	0.059	0.049

In Table 36 , the environmental operational impact of Scenario 3 depending on the curtailment event daily periods (1-4 hours) is provided. Obviously, the impact decreases considerably when the curtailment event period rises since the electricity price is lower during this period. It should be mentioned that the storage of the heat energy during the curtailment events is depending on the heating storage capacity of the water buffer tank.

4.3.5.4 Overview of Environmental impacts

The overall environmental impact of each scenario is presented in Table 37

Table 37: An overview of environmental impacts (kgCO2eq/kWh)

Impact categories ($kgCO_{2eq}/kWh$)	Scenario 1	Scenario 2	Scenario 3
Manufacturing impact	0.0020	0.0020	0.0024
Operational impact	0.2730	0.0900	0.0690
Total impact	**0.275**	**0.0920**	**0.0714**

In all examined scenarios, the operational impact has the major share of the total impact. It seems that the replacement of the oil boiler with an ASHP have a significant reduction of around 66.5% and 74% in the total impact compared to Scenario 2 and Scenario 3, respectively. The exploitation of the curtailed energy in Scenario 3 further decrease the level of the impact by 22.4% compared to Scenario 2.

4.3.6 LCC calculations

4.3.6.1 Purchase and installation costs

Table 38 presents the indicative equipment market prices provided by the Orkneys ecosystem. For each of the presented components a lifetime period (in years) is also included, in order to be able to measure the Life Cycle Costs in an accurate and efficient way.

Table 38: Investment costs of the heating equipment of CRM 21

Equipment	Life time (years)	Price (€)
Boiler	12	4000
Heat pump	15	6000
Hot water cylinder	30	700
Hot water buffer tank	20	500

The LCC analysis is performed for a 15 year duration. This results to the replacement of the equipment with shorter lifetime. Hence, the relevant costs for the purchase of the new equipment is examined in the analysis. During the final year (15th), the new equipment, as well the other equipment components are consider to have a residual value. The residual value is computed based on the time of use of the equipment and its remaining functional working years.

4.3.6.2 Maintenance costs

Table 39 presents the annual maintenance cost for each of the equipment components. Two main factors are taken into consideration, in order to compute the maintenance costs: 1) the actual expected costs provided by Orkneys pilot and 2) the estimation of unexpected costs, due to equipment parts failures. These values are affected by the discount rate, as will be explained in the respective paragraph.

Table 39: Annual maintenance costs of the heating equipment of CRM 21

Equipment	Annual maintenance cost (€/year)
Boiler	70
Heat pump	70
Hot water cylinder	10
Hot water buffer tank	0

4.3.6.3 Oil and grid electricity costs

The operational cost computations based on the purchase price of oil per litre, exploited during the Scenario 1. For Scenario 2 and Scenario 3, the operational costs are based on the electricity purchase price per kWh, needed to cover the energy grid requirements. Table 40 and Table 41 present indicatively the cost of the energy resources (oil and electricity) needed for the heating in each scenario[9]. The grid electricity price during the curtailment events is considered significantly lower compared to the grid electricity. This involuntary curtailment is more problematics for the individual RES operator than from a system point of view since the value of the generation and the market price is low with excess generation. It is also assumed the generators are not receiving production-dependent market support for voluntary curtailment.

Table 40: The prices of the types of energy used for heating in each scenario of CRM 21

Type of energy resource	Price
Oil	0.6 €/L
Grid electricity	0.20 €/kWh
Grid electricity during curtailment events (assumed)	0.05 €/kWh

Table 41: The 1st year's operational cost for heating in each scenario of CRM 21

Scenarios	Annual cost of energy resource
Scenario 1 (oil)	2069
Scenario 2 (electricity)	2372
Scenario 3 (electricity)	1956

4.3.6.4 Externalities

Table 42 presents the participation of the external costs in the final LCC (€/kWh) methodology for each scenario examined. The externalities are directly connected with the grid electricity mix (electricity consumed by the heat pumps). Environmentally friendly externalities accompanied with curtailment events lead to considerably lower external costs. Values presented are affected by the discount rate, as it will be explained in the respective paragraph.

Table 42: The external cost per kWh for each scenario of CRM 21

Scenarios	External cost (€/kWh)
Scenario 1	0.015
Scenario 2	0.003
Scenario 3	0.003

4.3.6.5 Discount rate

In order to simulate and analyse budgeting in financial terms, discount rate of the local Orkneys economy needs to be addressed in each of the proposed scenarios. Discount rate expresses the interest rate used

[9] the oil and electricity prices correspond to the prices in Orkney before the COVD-19 crisis

to determine the present value of future cash flows. Discount rate determine if the future cash flows of the investment will be worth more than the capital outlay needed to fund the investment in the present. Investment funds in Orkneys case studies are covered through the equipment purchase of boiler, heat-pumps etc. Concerning the local economy of Orkneys, the discount rate is assumed at the value of **5%**.

4.3.6.6 LCC results

Table 43 presents the LCC analysis results of the three scenarios examined in a 15-year time horizon.

Table 43: The LCC results of the scenarios tested in CRM 21

Scenarios	LCC (€/kWh)
Scenario 1	0.071
Scenario 2	0.069
Scenario 3	0.060

As presented in Figure 34 SMILE scenarios (Scenario 2 and Scenario 3) achieve lower LCC values for the given parameters compared to baseline scenario (Scenario 1).

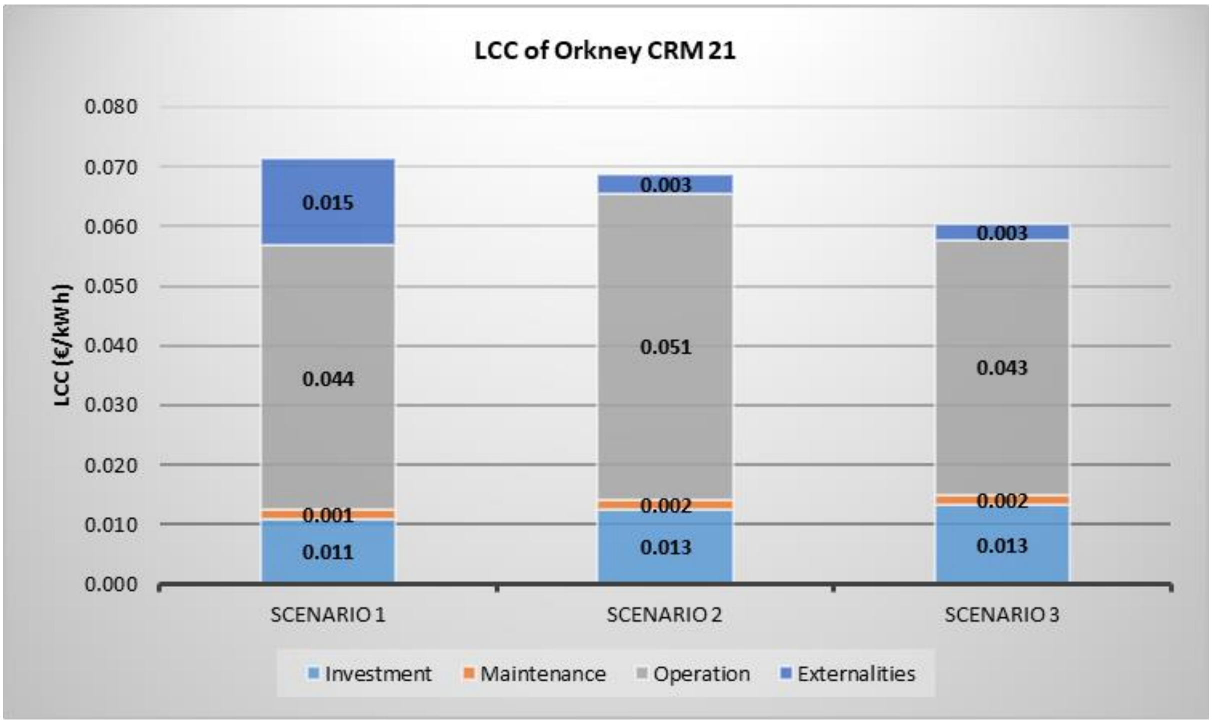


Figure 34: The LCC share of CRM 21

As it is observed the investment and maintenance cost remain at the same level in each of the examined cases. On the other hand, operational cost achieves the lowest values in Scenario 3 where SMILE techniques were applied. It should be mentioned that the operational cost represent more than 60% of the total LCC costs. The application of the heating storages able to reduce these costs, since the consumed electricity was purchased during the energy low price hours. In addition, by taking into consideration the externalities factor, this indicates that the high RES penetration in the Orkneys case is able to provide low environmental harm compared to non-RES Scenario 1. As a result, the application of the ASHP and the hot water cylinder in Scenario 2 and the extended solution with hot water buffer in Scenario 3 become the prevailing solutions.

4.3.6.6.1 CoP of the ASHP

Figure 35: The LCC of CRM 21 for various CoP of the ASHP

In Figure 35 a sensitivity analysis concerning the parameter CoP of the ASHP is examined. Although the initial value of CoP provided by the manufacturer was 2.92 the actual CoP values variates according to the difference between the ambient and the desired temperature. Three different scenarios were examined based on different values of CoP=[2.0, 2.5, 2.92]. Results indicate high effect to the computed operational expenses for the different CoP values. In detail, setting CoP value at 2.0 seems to negatively affect the life cycle costs for both Scenario 2 and Scenario 3 solutions. On the other hand, Scenario 1 solution is favoured when CoP remains in low values. As the CoP parameter increases, the ASHP and the hot water cylinder solutions (Scenario 2 and Scenario 3) rapidly recover the estimated costs per kWh.

4.3.6.6.2 Oil price

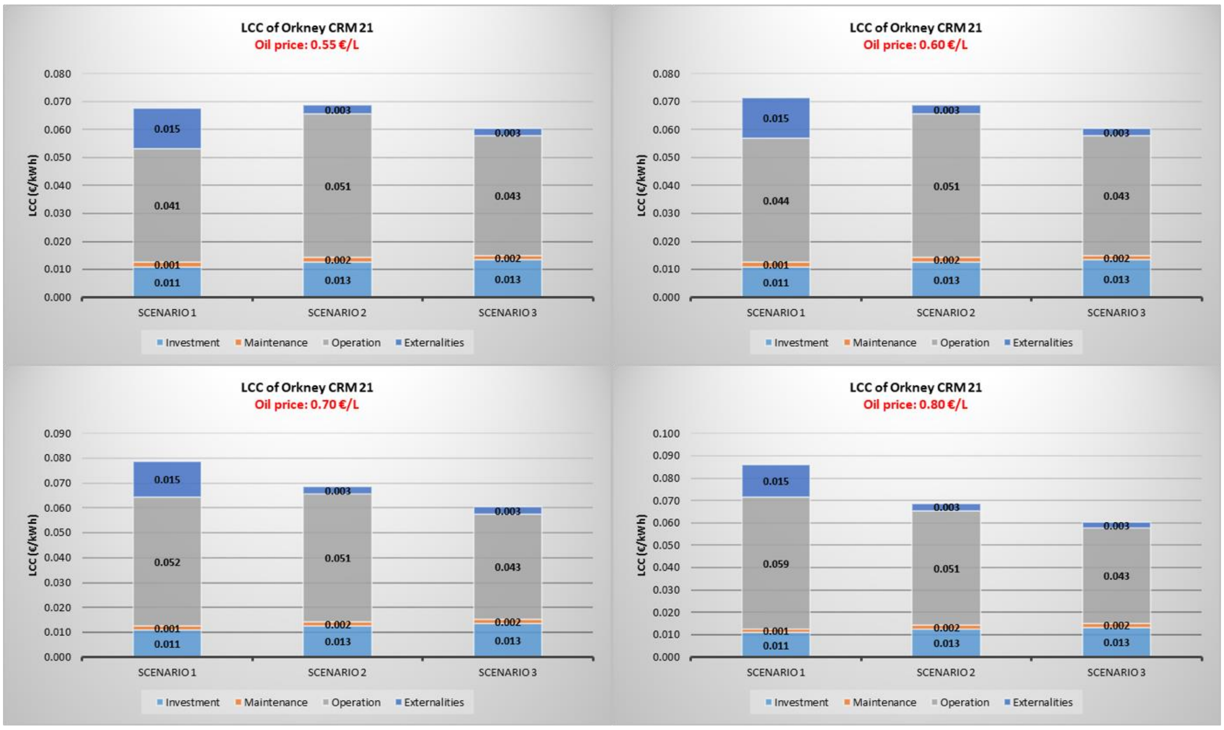


Figure 36: The LCC of CRM 21 for various oil prices

In Figure 36, oil price of Orkneys demo case is applied as sensitivity parameter to the LCC analysis. Different values of oil price = [0.55, 0.60, 0.70, 0.80 €/L] were examined. As the oil price increases, Scenario 1 case fails to recover costs, as it is totally connected to oil product. On the other hand, ASHP and a hot water cylinder technologies in Scenario 2 and Scenario 3 aim to decrease the estimated costs as the oil price increases. In specific, Scenario 3 energy storage technologies provide an additional rapid cost minimization compared to other examined cases.

4.3.6.6.3 Price of the grid electricity

In Figure 37, multiple electricity prices =[0.18, 0.20, 0.22, 0.24 €/kWh] are examined as a factor to the final LCC analysis result. In this case, the amount of curtailed energy achieved in Scenario 3 has the ¼ of the non-curtailed electricity price. As previously mentioned, the price of the grid electricity has a serious impact on the LCC, since the operational cost has the largest share in the final LCC. It is observed that low electricity price affect positively the Scenario 2 and Scenario 3, since the ASHP system is able to perform efficiently. On the other hand, oil based Scenario 1 maintains high LCC values. As it is obvious, as energy price increases, Scenario 2 case fails to maintain in low LCC values because of no-storage options. Even in high electricity price of 0.24 €/kWh, LCC cost remains at lower levels compared to other Scenarios.

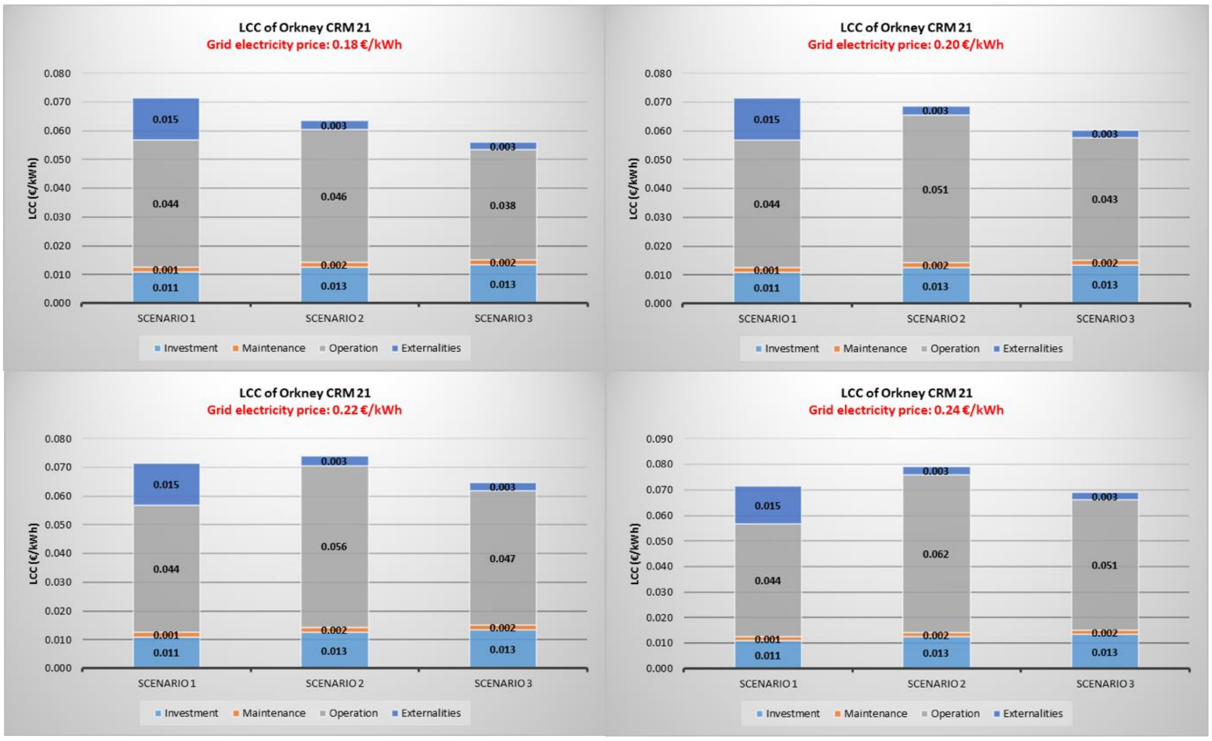


Figure 37: The LCC of CRM 21 for various grid electricity prices

4.3.6.6.4 Curtailed energy grid price

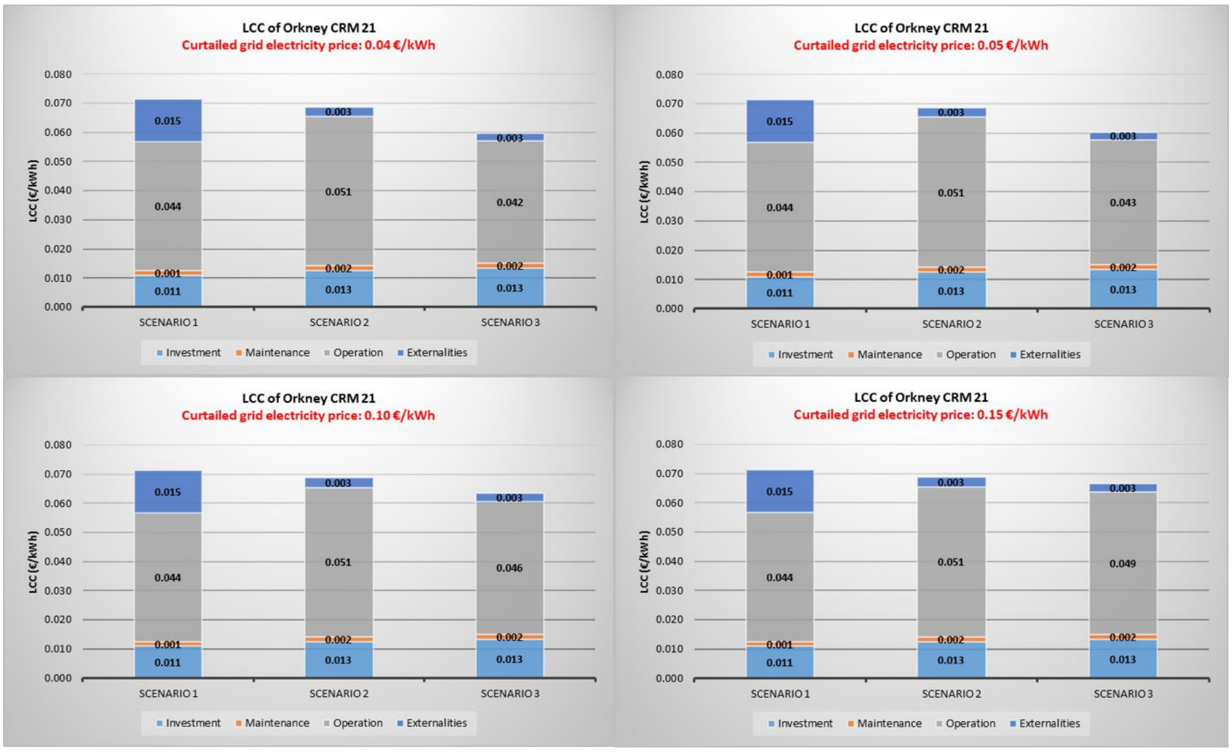


Figure 38: The LCC of CRM 21 for various curtailed grid electricity prices

Figure 38 compares the impact of the multiple curtailed electricity prices =[0.04, 0.05, 0.10, 0.15 €/kWh]. As it is observed low curtailment prices favor the solution that enables energy storage. In this case

Scenario 1 and Scenario 2 costs are not affected by the energy price cost. As it is obvious, Scenario 3 is incentivized by the energy price as it is shown in Figure 38

4.3.6.6.5 Daily curtailment period

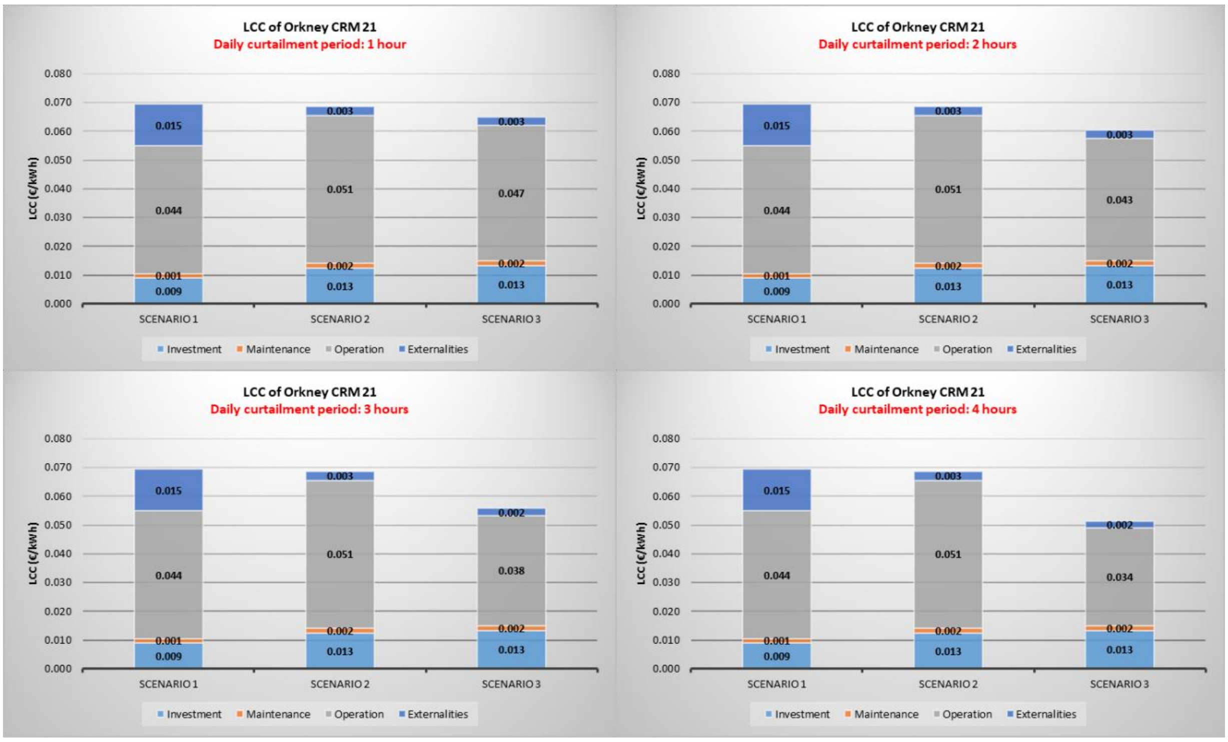


Figure 39: The LCC of CRM 21 for various daily curtailment periods

In Figure 39, the LCC of Scenario 3 depending on the curtailment event daily periods (1-4 hours) is provided. Obviously, the LCC decreases when the curtailment event period rises, as the electricity price during this period is lower. For the case of 4-hour daily curtailment events, the LCC of Scenario 3 is 25% lower compared to the LCC of Scenario 2. It should be mentioned that the storage of the heat energy during the curtailment events is depending on the heating storage capacity of the water buffer tank.

5 Conclusions

The aim of the present deliverable is to investigate the environmental and economic impact of the implemented SMILE solutions. This could be achieved through the development of dynamic multi-parameter simulations for the pre-SMILE situation, as well as for the optimal SMILE solutions. The main remarks derived by the simulations are:

- The implementation of a sensibly sized PV has a positive impact both in environmental and economic terms. The decrease in the operational costs is certainly high, which makes the PV implementation a feasible solution in all cases.
- While the implementation of BESS has a positive environmental impact due to the reduction in the use of the grid electricity, it also causes an obvious increase in the LCC due to its high investment cost, which represents around 40-50% of the overall LCC.
- A heating system using an ASHP has lower environmental costs compared to an oil boiler heating system due the fact that the emissions of the oil combustion are significantly higher than the emissions of the grid electricity generation. For Orkney demo, the relevant saving emissions are over 65%. The environmental profits increase even more with the implementation of the heat storage, especially in use cases where there is curtailed RES energy.
- In Orkney demo, a heating system using ASHP has similar LCC to an oil boiler heating system due to the fact of the low oil prices received. In case of higher oil price, the option of the ASHP application presents lower LCC compared to the oil boiler heating system. Depending on the pricing strategy of the grid electricity, it can provide economic benefits, too. These benefits can rise even more in cases where heat storage is implemented, since the investment cost of heat storage is very low (around 5% of the overall LCC), while the benefits in the operational cost can be much higher as long as the curtailed energy is supplied in lower prices.
- The handling of the charging time zones of the EVs can provide profits mostly financial and less environmental. This conclusion is not applicable in all sorts of use cases, as it seems to be based on both the price model applied as well as the mixture of the related grid.

The two main conditions that should be taken into consideration in the building of the LCA/LCC models with BESS implementation are:

- the high increase in the investment cost (both environmental and economic) due to the implementation of the BESS equipment;
- the decrease in the operational costs (both environmental and economic) due to the reduction in the need for grid electricity, especially during the peak expensive time zones of the day.

As mentioned, in the use cases tested, the BESS implementation reduced the LCA, while its high investment cost resulted in the overall increase of the LCC. Nevertheless, a number of factors should be taken into consideration to make the BESS implementation feasible, such as the reduction of cost in the manufacturing materials, a reduced interest rate, the expansion of its life time, an increased grid electricity price, a load curve with heavy evening and night loads etc. Two concepts are selected for the battery use a) the battery use for the load satisfaction during the expensive time-zones of the day and b) the battery use for the load satisfaction any time the PV generation is not enough. The selection of the concept for the targeted cases depends on the characteristics of the load curve. The analysis on the environmental and economic impact of the domestic heating storage proved that the most contributional factors are the efficiency of the system and the prices of oil and electricity. A high-performance ASHP has significantly lower emissions than the oil boiler, and can provide economic benefits, too, as long as it has high performance (probably a CoP higher than 2.5 which represents use cases with a difference of less than 60°C between ambient and output temperature). The corresponding prices and price models of oil and electricity play a decisive role, as well, in the overall LCC comparison for the two heating systems. The heating storage can certainly decrease the system emissions, especially if the local grid has high RES penetration during certain periods of the day. It can also decrease the LCC of the system if the pricing strategy of the local grid supports with incentives the consumption during some periods of the day, in which the heat can be stored for use later within the day when the grid electricity price is higher. In the use case examined, the heat storage provided a 7-20% decrease in the overall LCC.

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ANNEX I KPIs Calculation

The ANNEX includes the calculation of all the environmental and economic KPIs tracked in deliverable D6.1[10] for the evaluation of SMILE solutions.

1. Energy Return On Energy Investment

The ratio of the amount of usable energy (the exergy) delivered from a particular energy resource to the amount of exergy used to obtain that energy resource during its lifetime

$$EROI = E_{out}/E_{in}$$

Where E_{out}= Energy delivered (kWh) and E_{in}= Primary energy required for the delivery of the energy above (kWh)

Based on the study [43], the primary energy needed to produce a 1 kWh of LMO-graphite BESS is **1030 kWh.** From this amount of electricity 33% is the energy embedded in the battery materials, 66% is the energy consumed in the battery cell production and the energy used in the final battery pack manual assembly. Based on study [44] and report *(Independent Energy Partners)* the energy consumption for manufacturing of 1 kW_p PV module ranges between 5500 - 7000 kWh.

Table 44: Calculation of Energy Return of Investment (EROI) for the Samsø Pilot

	Scenarios	EROI SAMSØ (years)
Model 1	Scenario 2 (No BESS)	2.1
	Scenario 3 (SMILE scenario)	1.7
	Scenario 4 (Scale up scenario)	1.5
Model 2	Scenario 2 (No BESS)	2.1
	Scenario 3 (SMILE scenario)	2
	Scenario 4 (Scale up scenario)	1.7
Model 3	Scenario 2 (No BESS)	2.1
	Scenario 3 (SMILE scenario)	1.8
	Scenario 4 (Scale up scenario)	1.5

MODEL 1 Scenario 2

This scenario includes only the 60 kW_p PV with no BESS installation. The AC delivered energy through 25 years of operation is **738,631 kWh**. The primary energy for the construction of a 60 kW_p PV is **360,000** kWh if we assume that an average of 6000 kWh is required to produce 1 kW_p of PV. **As a result, the EROI=738,631 kWh/360,000 kWh = 2.1 years.**

MODEL 1 Scenario 3

This scenario includes the 60 kW_p Photovoltaic integrated with 240 kWh BESS installation. The AC delivered energy through 25 years of operation is **1,078,651 kWh**. The primary energy for the construction of a 60 kW_p PV is **360,000** kWh and for the manufacturing of a 240 kWh BESS is 247,000 kWh. **As a result, the EROI=1,078,651/ (360,000+247,000) kWh = 1.7 years.**

MODEL 1 Scenario 4

This scenario includes the 120 kW_p PV integrated with 240 kWh BESS installation. The AC delivered energy through 25 years of operation is **1,444,931 kWh**. The primary energy for the construction of a 120 kW_p PV is **720,000** kWh and for the manufacturing of a 240 kWh BESS is **247 000 kWh**. **As a result, the EROI=1,078,651/ (720,000+247,000) kWh = 1.5 years.**

[10] D6.1 "Report on selected evaluation indicators" (https://cordis.europa.eu/project/id/731249/results)

MODEL 2 Scenario 2

This scenario includes only the 60 kW_p PV with no BESS installation. The AC delivered energy through 25 years of operation is **738,631 kWh**. The primary energy for the construction of a 60 kW_p PV is **360,000** kWh. **As a result, the EROI=738,631 kWh/360,000 kWh = 2.1 years.**

MODEL 2 Scenario 3

This scenario includes the 60 kW_p Photovoltaic integrated with 240 kWh BESS installation. The AC delivered energy through 25 years of operation is **1,197,102 kWh**. The primary energy for the construction of a 60 kWp PV is **360,000** kWh and for the manufacturing of a 240 kWh BESS is **247,000 kWh. As a result, the EROI=1,197,102/ (360,000+247,000) kWh = 2 years.**

MODEL 2 Scenario 4

This scenario includes the 120 kW_p Photovoltaic integrated with 240 kWh BESS installation. The AC delivered energy through 25 years of operation is **1,643,897 kWh**. The primary energy for the construction of a 120 kWp PV is **720,000** kWh and for the manufacturing of a 240 kWh BESS is **247 000 kWh**. **As a result the EROI=1,643,897/ (720,000+247,000) kWh = 1.7 years.**

MODEL 3 Scenario 2

This scenario includes only the 60 kWp PV with no BESS installation. The AC delivered energy through 25 years of operation is **738,631 kWh**. The primary energy for the construction of a 60 kW_p PV is **360,000** kWh. **As a result, the EROI=738,631 kWh/360,000 kWh = 2.1 years.**

MODEL 3 Scenario 3

This scenario includes the 60 kW_p Photovoltaic integrated with 240 kWh BESS installation. The AC delivered energy through 25 years of operation is **1,091,917 kWh**. The primary energy for the construction of a 60 kW_p PV is **360,000** kWh and for the manufacturing of a 240 kWh BESS is **247 000 kWh. As a result, the EROI=1,091,917/ (360,000+247,000) kWh = 1.8 years**

MODEL 3 Scenario 4

This scenario includes the 120 kWp Photovoltaic integrated with 240 kWh BESS installation. The AC delivered energy through 25 years of operation is **1,472,403 kWh**. The primary energy for the construction of a 120 kWp PV is **720,000** kWh and for the manufacturing of a 240 kWh BESS is **247,000 kWh**. **As a result, the EROI=1,472,403/ (720,000+247,000) kWh = 1.5 years.**

Discussion of the Samsø EROI results

The parameter affecting most the calculation of EROI is the amount of AC delivered electricity during the operation of Photovoltaic.

For all examined models it is clear from Figure 44 that scenario 2 which has no BESS support (no BESS implementation leads to higher amount of curtailment) present the higher EROI value. On the contrary, scenario 3 has the implementation of 240 kWh BESS reducing the amount of curtailment. The reduction of curtailment signifies that higher proportion of PV generation is not 'wasted' and delivered to the Marina of Ballen in order to meet the electricity demand. For scenario 4 there is a scale up of installed PV power output (increase in energy consumption to manufacture a bigger PV) alongside with the same BESS capacity. This leads to an increase of the curtailment because BESS cannot store the excess PV energy. Despite the increase in the curtailment, PV delivers more AC electricity annually which offsets the increase in curtailment leading to lower value of EROI.

Table 45: Calculation of Energy Return of Investment (EROI) for Pilot 1 and Pilot 2 of Madeira demo site

	Scenarios	EROI Madeira (years)
UPAC 2	No BESS	4.01
	Enhanced	2.5
	Greedy	2.5
UPAC 6	No BESS	1.9
	Enhanced	2
	Greedy	2.4
UPAC 9	No BESS	1.88
	Enhanced	2.2
	Greedy	2.6
UPAC 12	No BESS	2
	Enhanced	2.2
	Greedy	2.4
UPAC 8	No BESS	5.8
	Enhanced	2.9
	Greedy	2.9
	GRID2BESS	2.9

Discussion of the Madeira EROI results

The EROI values in the Madeira pilots are not as concrete as in Samsø. Especially for the No-BESS scenarios, the differences among their values are considerable. For instance, UPAC 2 has a high EROI value, higher than the other two BESS scenarios, in contrast to UPAC 6 which presents a lower No-BESS EROI compared to the BESS scenarios. As described in the context of the deliverable, the installed capacity in UPAC 2 is chosen wisely in order to have low levels of curtailment. This means that the PV in UPAC 2 delivers most of the energy generated, which increases the value of EROI. UPAC 8 has zero levels of curtailment, so the No-BESS scenarios has certainly the highest value, in contrast to the BESS scenarios which include the manufacturing energy of BESS.

2. CO_2 Payback time

An important environmental indicator for evaluation of RES and storage systems is "CO_2 equivalent Payback Time (CO_2PBT)". It calculates the time (years) required for the RES, BESS system (e.g. PV) to save the exact amount of CO_{2eq} emitted during its entire life time (starting from its manufacturing). The CO_{2eq} PBT is mainly dependent on the amount of kWh produced/delivered by the system, and the grid CO_{2eq}/kWh emission factor.

$$\mathrm{CO_2\ PBT} = \frac{\text{Indirect emissions}}{\text{Emissions Factor} \cdot \text{Annually Produced Energy}}$$

Regarding the operational profile of the PV and BESS the for the examined scenarios in the UPACs (i.e. the produced and stored energy) the CO_{2eq} Payback Time is presented in Table 46.

Table 46: CO_2 Payback Time (years) for the PV and BESS installed in the Ballen Marina of Samsø

Models	Scenarios	Carbon Footprint Payback Time (years)
Model 1	Scenario 2 (No BESS)	**13.9**
	Scenario 3 (SMILE scenario)	**10.9**
	Scenario 4 (Scale up scenario)	**15.5**
Model 2	Scenario 2 (No BESS)	**13.9**
	Scenario 3 (SMILE scenario)	**9.8**

	Scenario 4 (Scale up scenario)	**13.1**
Model 3	Scenario 2 (No BESS)	**13.9**
	Scenario 3 (SMILE scenario)	**10.8**
	Scenario 4 (Scale up scenario)	**14.9**

Discussion of the Samsø CO_2PBT results

Scenario 3 presents the lowest curtailment, and therefore, the highest annual AC delivered energy by the PV. This is the reason why scenario 3 provides the lowest CO_2PBT.

Scenario 4 presents in all models the highest values of CO_2PBT which is based on the increase of the manufacturing emissions (double PV capacity), which is not overcome by the increase in the annual delivered energy (PV of 60 kWp emits 136000 kg CO_{2eq} and delivers 45000 kWh AC annually, PV of 120 kWp emits 272000 kg CO_{2eq} and delivers 59000 kWh AC annually). The delivered energy of scenario 4 is lowered by the fact that the curtailment is high, losing a high amount of the generated energy, and thus, requiring more electricity by the grid.

Table 47: CO_2 Payback Time (years) for the UPACs participated in Madeira demo site

	Scenarios	Carbon Footprint Payback Time (years)
UPAC 2	No BESS	**5.4**
	Enhanced	**5.2**
	Greedy	**5.2**
UPAC 6	No BESS	**11.1**
	Enhanced	**7.7**
	Greedy	**6.3**
UPAC 9	No BESS	**11.7**
	Enhanced	**8.2**
	Greedy	**6.8**
UPAC 12	No BESS	**10.8**
	Enhanced	**7.2**
	Greedy	**6.5**
UPAC 8	No BESS	**3.7**
	Enhanced	**4.3**
	Greedy	**4.3**
	GRID2BESS	**4.4**

Discussion of the Madeira CO_2PBT results

- Generally, the Greedy model in all UPACs presents the lowest CO_2PBT since it involves the lowest levels of curtailment, and therefore, more PV energy is delivered for the load satisfaction.
- On the other hand, it seems that the No-BESS scenarios present the highest values of CO_2PBT. Even though these models are not burdened by the manufacturing emission of the batteries, they present high levels of curtailment, which result in low delivered PV energy, and therefore, high CO_2PBT values.

3. Life-cycle cost of energy generation

LCC of energy generation includes the private costs (investment C_{inv}, operational and maintenance $C_{O\&M}$, and end of life C_{dis}), as well as the external cost C_{ext} corresponding to the environmental impact, when it is applied. The costs are divided by the whole *load* satisfied throughout the *life* time of the equipment (the time period of the scenario being tested) in order to be normalized to €/kWh.

$$LCC = \frac{C_{inv} + C_{O\&M} + C_{dis} + C_{ext}}{Life \cdot Load}$$

Following are the tables presenting all the final LCCs of the Samsø and Madeira pilots.

Table 48: Presentation of the Samsø pilot LCC

€/kWh	Model 1	Model 2	Model 3
Scenario 1	0.164	0.164	0.164
Scenario 2	0.134	0.134	0.134
Scenario 3	0.201	0.202	0.198
Scenario 4	0.183	0.186	0.185

Table 49: Presentation of the Madeira pilot 1 LCC

€/kWh	No BESS	Enhanced	Greedy
UPAC 2	0.108	0.174	0.174
UPAC 6	0.153	0.237	0.232
UPAC 9	0.206	0.278	0.270
UPAC 12	0.169	0.250	0.248

Table 50. Presentation of the Madeira pilot 2 LCC

€/kWh	No BESS	Enhanced	Greedy	Grid2BESS
UPAC 8	0.090	0.139	0.139	0.116

Table 51: Presentation of the Orkneys CRM 21 LCC

Scenarios	LCC (€/kWh)
Scenario 1	0.071
Scenario 2	0.069
Scenario 3	0.060

The presented LCCs show (as explained in Chapter 4) that the BESS scenarios include significantly higher costs than the No-BESS scenarios. This is explained by the fact that the purchase cost of the battery is much higher than the annual profit due to the reduction in the electricity costs by the grid.
Among the BESS scenarios, the Grid2BESS (pilot 2 of Madeira) reaches to the most competitive LCC results compared to the respective No-BESS (about 30% higher). This means that the utilization of BESS for the purpose of cheap grid electricity exploitation seems to be the most sensible choice among the various BESS scenarios.
Moreover, according to the Samsø pilot (Table 48), it seems that the implementation (scenario 2) provides much lower LCC compared to the only-grid scenario (scenario 1). The investment cost along with the maintenance costs of PV are too low to be compared with the gains due to the reduction in the need for grid electricity.
In addition, the two proposed BESS scenarios of the Madeira pilots (Greedy and Enhanced scenarios in Tables Table 49 and Table 50) do not present any significant difference in the LCC. Their different approaches are explained in 4.2.5.1. No safe conclusions concerning the selection of the Greedy or the Enhanced scenario can be derived, since it seems that the characteristics of the load curve of each use

case may provide different results (whether the majority of loads appears during the cheap or the expensive price zones of the grid).

Finally, concerning the heating storage of the Orkneys pilot, it seems that the replacement of a domestic heating system based on the oil combustion in a boiler with an ASHP using the grid electricity, can reduce the LCC. This is mostly based on the relative prices of oil and electricity, as well as to the equivalent efficiency of each heating system. There is a strong difference in the external costs because the oil has much more emissions than the electricity production. The 3rd scenario, in which the heating storage is implemented, provides considerably lower LCC results. This is based on the fact that the corresponding pricing strategy of the local electricity grid is supposed to sell cheaper electricity during the time periods when there are curtailment events on the grid due to the high RES penetration.

4. Annuity Gain

It gives an impression of how much money can be saved or must be paid annually when implementing energy efficiency or renewable energy measures.

$$AG = \frac{\text{ECSG-ECBl}}{ECBl} \, 100$$

where:

ECSG=Annual Cost of the Energy (€) to the Operator in a Smart Grid case study, and

ECBl=Current Annual Cost (€) of the Energy to the Operator Unit

Table 52: Annuity Gain (%) for the Samsø demo site

Models/ Scenarios	Electricity Demand (kWh)	Average Annual Cost (€) of the Energy to the Operator in Baseline	Average Annual Cost (€) of the Energy to the Operator in SMILE case study	Annuity Gain (AG)
Model 1				
Scenario 2	104550	23739.03	17017.05	-28%
Scenario 3		23739.03	12317.30	-48%
Scenario 4		23739.03	8962.65	-62%
Model 2				
Scenario 2	104550	23739.03	17017.05	-28%
Scenario 3		23739.03	12395.40	-48%
Scenario 4		23739.03	9346.57	-61%
Model 3				
Scenario 2	104550	23739.03	17017.05	-28%
Scenario 3		23739.03	12166.62	-49%
Scenario 4		23739.03	8086.69	-66%

Table 53: Annuity Gain (%) for the Pilot 1 and 2 of Madeira demo site

Madeira	Electricity Demand (kWh)	Average Annual Cost (€) of the Energy to the Operator in Baseline	Average Annual Cost (€) of the Energy to the Operator in SMILE case study	Annuity Gain (AG)
UPAC 2				
Enhanced	5504	650.4	592.2	-9%
Greedy		650.4	596.6	-8%
UPAC 6				
Enhanced	3861	357.5	222.7	-38%
Greedy		357.5	188.3	-47%
UPAC 9				

Enhanced	3978	302.9	106.5	-65%
Greedy		302.9	50.6	-83%
UPAC 12				
Enhanced	3723	343.6	173.1	-49%
Greedy		343.6	164.3	-52%
UPAC 8				
Enhanced	24397	2847.8	2811	-1%
Greedy		2847.8	2815.2	-1%
GRID2BESS		2847.9	1786.6	-37%

Table 54: Annuity Gain (%) for the Orkneys CRM 21

Scenarios	Annual heating demand (kWh)	Average Annual Cost (€) of the oil supply to the baseline scenario	Average Annual Cost (€) of the electricity in the other case studies	Annuity Gain (AG)
Scenario 2	34,628	2,117	2,457	+16%
Scenario 3			2,041	-4%

The results of the annuity gain calculations do not provide overall conclusions on the economic feasibility of the various scenarios. They only refer to the reduction in the cost for buying electricity by the grid, leaving aside the investment costs of buying the equipment for each scenario (PV and BESS).
In Samsø, it seems that the implementation of both PV and BESS actually reduces the operational grid costs. Among the 3 tested models, it seems that there is a slight advantage of the 3rd model which provides a slightly higher reduction in the grid costs.
In Madeira, the Greedy model provides a slightly higher reduction in the operational costs due to the grid compared to the Enhanced model. The Grid2BESS model provides the highest reduction of this cost. These results, again, do not provide compact conclusions on the evaluation of the examined models, since the shape of the use case's load curve can give the advantage to the one model or the other.
In the Orkneys pilot, the annual cost for the oil needed in the 1st scenario is lower than the annual electricity cost in the 2nd scenario. This is mainly due to the oil price in Orkneys, which is quite low (0.60 €/L). The cost of electricity in the 3rd scenario is considerable lower due to the assumption that the grid electricity price should be lower during the curtailment events (at ¼ of the normal grid electricity price).

5. Total Capital Cost per kW installed

Measures the total capital cost of an energy investment per kW installed (per kWh when we examine storage)

$$TCC = \sum \text{(CAPEX)/IC, i=1-N}$$

Where i= pointer of CAPEX sources CAPEX= Capital cost IC= Installed capacity
In all cases the CAPEC includes the capital costs for 25 years. This means it is 1 PV (25 years life cycle) and 5/3 units of BESS (15 years of life cycle)

Table 55: Presentation of Samsø CAPEX (25 years period)

€/kWh	Installed capacity (kW_p)	PV (€)	BESS (€)	CAPEX (€/kW_p)
Scenario 1	0	0	0	0
Scenario 2	60	28,000	0	467
Scenario 3	60	28,000	283,333	5,188
Scenario 4	120	56,000	283,333	2,828

Table 56: Presentation of the Madeira demo CAPEX (25 years period)

€/kWh	Installed capacity (kW_p)	PV (€)	BESS (€)	Sum (€)
UPAC 2	1.5	5,000	9,445	9,630
UPAC 6	2.7	9,000	9,445	6,831
UPAC 9	4.5	15,000	9,445	5,432
UPAC 12	3	10,000	9,445	6,482
UPAC 8	3.92	13,067	28,333	10,561

Table 57: Presentation of the Orkney CRM 21 CAPEX

Scenarios	Oil Boiler (€)	ASHP (€)	Hot water cylinder (€)	Hot water buffer tank (€)	CAPEX (€/kW_p)
Scenario 1	5,000				5,000
Scenario 2		6,000	350		6,350
Scenario 3		6,000	350	375	6,725

As mentioned, the BESS investment cost is too high to be overcome by the reduction in the operational costs (purchase of electricity by the grid).
Moreover, the CAPEX of the heating system equipment in the Orkneys pilot does not play a vital role in the total LCC as it represents only a 20% of the total LCC. Moreover, the prices used are quite common in most markets, and they do not alter often.

ANNEX II Literature review for batteries

All reviewed studies, which include the battery use phase, find battery production to contribute a significant share to the environmental impact over lifetime. This share depends on the amount of charge-discharge cycles provided by the battery, which is therefore important for the overall environmental performance. The majority of all LCA studies that take charge-discharge efficiency into account assume an average battery efficiency of 90%. For a charge-discharge efficiency of 90%, the CED for storing 1 kWh of electricity caused by internal inefficiencies is about 0.3 kWh and the corresponding GWP **46.7 g CO_{2eq}**. Thus, the impacts of internal losses on CED and GWP over battery lifetime are in the same order of magnitude as those of the production of the battery itself. In consequence, the differences in internal efficiency between different battery technologies can have significant impacts and should not be neglected when assessing their environmental impacts.

Table 58: GHG emissions (kg CO_{2eq}/kWh) of different Battery technologies

Battery Typology	GHG emissions ($kgCO_{2,eq}$/kg of battery)	GHG emissions (kgCO2,eq/kWh)	Reference
$LiFePO_4$ Manufacturing	22	-	
$LiMnO_4$ Manufacturing and end-of-life	6	-	[45]
$LiFePO_4$ (NMP solvent) Manufacturing and end-of-life	41.04	-	[46]
$LiFePO_4$ (water solvent) Manufacturing and end of-life	31.71	-	[46]
Li-ion Manufacturing, operation and end-of-life	40.5	-	[47]
Lithium-ion (NMP solvent) Manufacturing	12.5	61-97.1	[48]
Li-ion Manufacturing	12		[49]
LIB chemistries Manufacturing	-	110	[50]
LFP battery manufacturing	-	18.15	[51]
Li-ion Manufacturing	-	150-200	[52]
Samsø BESS	**18.5**	**65.8**	**SMILE**

ANNEX III Literature review for PV

Several studies during the 70's debate about the energy required producing a PV system and if that amount of energy is greater than the whole energy generated by the system over its lifetime. Most of the components of the PV systems are manufactured using fossil fuel intensive materials and processes, which indicate that significant energy amounts are consumed during the various life stages of a PV system. A PV system is sustainable only if the energy produced during its operating life compensates the total energy costs that can be estimated through the life cycle assessment (LCA) methodology. The PV power generation system consists of multiple components like cells, mechanical and electrical connections, mountings, and means of regulating and/or modifying the electrical output. These systems are rated in peak kilowatts (kW_p), which is an amount of electrical power that a system is expected to deliver when the sun is directly overhead on a clear day. The most commonly used materials from which PV panels are manufactured are mono-crystalline and poly-crystalline silicon [53]. Crystalline silicon modules are the most extensively studied PV types, since they are the most largely used. Mono-crystalline silicon or single-crystalline silicon type of PVs represent the most energy intensive and efficient PV technology. Poly-crystalline photovoltaic cells/panels have an efficiency of 15% and Silicon crystalline modules exhibit lifetimes in the range of 20–30 years. Commercial PV materials commonly used for photovoltaic systems include monocrystalline, polycrystalline and amorphous silicon and thin film technologies [54] and [55]. Because different PV technologies have different energy conversion efficiencies, the choice of a specific PV technology affects the results of their environmental assessment. Thin film-amorphous silicon technology as examined from [56] in the stage of materials construction has the highest energy requirements and thus the highest resulting emissions (measured in kg CO_{2eq}.) among all. The study of [57] determines parameters, such as a) the level of solar radiation, b) the position of the modules, c) the modules manufacturing energy intensity followed by its corresponding fuel mix, and d) the solar radiation conversion efficiency of the module, which play a role in the estimation of the environmental performance of PV technologies, especially for the case of multi-crystalline and thin film (amorphous) modules.

Table 59: GHG emissions (kg CO2eq/kWh) of mono-Si PV systems

Location	Irradiation (kW h/m^2/yr)	Module Efficiency (%)	Lifetime (years)	GHG emissions (kg $CO_{2,eq}$/kWh)	Reference
UK	1253	12	20	-	[58]
Japan	1427	12.2	20	61	[59]
South-European	1700	13.7	30	41	[60]
Switzerland	1117	14	30	-	[61]
South-European	1700	14	30	30	[62]
China	1702	-	-	50	[63]
Lebanon	1867	13.1	25	89	[64]

Table 60: GHG emissions (kg CO_{2eq}/kWh) of mono-Si and multi-Si PV systems

Reference	GHG emissions (kg CO_{2eq}/kWh)	Irradiation (kWh/m²/yr)	Module Efficiency (%)	System Lifetime (years)	Mounting type
[65]	60	1700	13	30	Ground-mounted
	30	1700	15	30	Ground-mounted
	20	1700	17	30	Ground-mounted
[66]	35	1700	13.2	30	Ground-mounted
[67]	82	900	13	25	Ground-mounted
	44	1800	13	25	Ground-mounted
	93	900	13	25	Rooftop
	50	1800	13	25	Rooftop
	88	900	13	25	Rooftop
	47	1800	13	25	Rooftop
	85	900	13	25	Rooftop
	46	1800	13	25	Rooftop
[68]	36	1700	13.2	30	Rooftop
[69]	53	1314	14	30	Rooftop
	44	1314	14	30	Rooftop
[70]	57	1117	13.2	30	Rooftop
	62	2060	13.2	30	Rooftop
[71]	106	2060	13	25	Rooftop
	217	2060	12	20	Rooftop
	53	1359	14	30	Rooftop
[57]	72	950	12.9	30	Rooftop
[57]	102	1700	13.4	25	Rooftop
	57	1100	13.4	25	Rooftop
[72]	104	1100	13.4	25	Rooftop
[73]	20	1697	16	28	Ground-mounted
[74]	55	1644	12.4	30	Rooftop
	51	1644	12.4	30	Rooftop
	62	1644	12.4	30	Rooftop

ANNEX IV Literature review for Heat Pump

Since space heating creates a significant amount of GHG emissions, a key target of climate-change policy is to improve this application's carbon footprint.

Based on IPCC Fourth Assessment Report IN 2007 the Global Warming Potential for air-source heat pump is 2088 kg CO_{2eq}/kg.

- Cradle to grave analysis air-source heat pump: *Air-source heat pump carbon footprints: HFC impacts and comparison to other heat sources*

The most common design of a heat pump involves four main components

- Condenser
- expansion valve
- evaporator
- compressor

ANNEX V LCA Literature Review

LCA is an instrument to quantify all environmental impacts of the entire energy supply chain of a product or a service, considering the cumulative energy demand (CED) of a) its production phase, b) its operation phase, during its whole life cycle up to its decommissioning. The whole product or service is split up into components and subcomponents and all energy and material flows through it are examined. The life cycle impact of typical renewable energy systems is important compared to conventional fuel-based systems for rational choice of energy sources. Since fossil fuels are used in the conventional fuel based system, it is obvious that emissions savings are considered using the renewable energy sources. In addition, in what concerns the economics, several stark differences are considered in all impact areas, which strongly favour the renewable energy solutions, especially in case that feed in tariff are in force according to the relevant national legislative framework. The LCA can be applied to assess the impact on the environment of electricity generation and allow producers to make better decisions pertaining to environmental protection. Typical quantifiable examples of comparison between renewable electricity generation Technogym and any conventional electricity generation sources are shown in Table 61.

Table 61: Comparison of LCEs (gCO_2/kWh) of conventional electricity generation with renewable electricity generation sources

Conventional systems		Renewable systems	
System	**gCO_2/kWh**	**System**	**$g\ CO_2/kWh$**
Coal fired	975.3	Wind	9.7-123.7
Oil fired	742.1	Solar PV	53.4-250
Gas fired	607.6	Biomass	35-178
Nuclear	24.2	Solar Thermal	13.6-202
		Hydro	3.7-237

This section offers guidance on what to include or exclude from the life-cycle inventory analysis for a PV system [75].

Product stage:

- Raw material and energy supply
- Manufacture of the panels
- Manufacture of the mounting system
- Manufacture of the cabling
- Manufacture of the inverters
- Manufacture of all further components needed to produce electricity and supply it to the grid (e.g., transformers for utility-scale PV)

Manufacturing in the product stage of the LCI should cover the following: energy and material flows caused by manufacturing and storage, climate control, ventilation, lighting for production halls, onsite emissions and their abatement, and onsite waste treatments. PV manufacturing equipment may be included if data are available.

Construction process stage:

- Transports to the power plant site (where the plant is operated)
- Construction and installation, including foundation, supporting structures and fencing

Use stage:

- Auxiliary electricity demand
- Cleaning of panels
- Maintenance
- Repair and replacements, if any

End-of-life stage:

- Deconstruction, dismantling
- Transports
- Waste processing
- Recycling and reuse
- Disposal

The following parts should be excluded:

- Commuting (transportation to and from work)
- Administration, marketing, and research and development (R&D) activities.

The functional unit allows consistent comparisons to be made of various PV systems and of other electricity-generating systems that can provide the same function.
The following functional unit for PV systems:

- for grid-connected systems, use the kWh of alternate current electricity fed into the grid. For PV systems with dedicated transformers (e.g., utility solar farms), use the electricity-output downstream of the transformer.
- m^2 module is used for quantifying the environmental impacts of a particular building, or of supporting structures (excluding PV modules and inverters). Square metre is not suited for comparisons of PV technologies because of differences in module and inverter efficiencies.
- kW_p is used for quantifying the environmental impacts of electrical parts, including inverter, transformer, wire, grid connection, and grounding devices. The kW_p may also serve as the reference flow in quantifying the environmental impacts of an individual module technology. However, the comparisons of module technologies shall not be based on nominal power (kW_p) because the amount of kWh fed to the grid may differ between the systems analysed.

The LCA should come along with information about key parameters and other important aspects characterizing the PV system(s) analyzed. Key parameters to be documented are

1. PV technology (e.g., single and multi-crystalline silicon, CdTe, CIS, amorphous silicon, micromorphous silicon)
2. Type of system (e.g., roof-top, ground-mount, fixed-tilt, or tracker)
3. Module-rated efficiency and degradation rate
4. Lifetime of PV and BOS
5. Location of installation
6. Annual irradiation, and expected annual electricity production with the given orientation and inclination or system's performance ratio

Table 62: Key parameters for LCA phases of a Photovoltaic module

Manufacturing	Operative conditions	End of Life
Includes the supply of raw materials, production / assembly and maintenance /	PV module efficiency	Wastes disposal- Metals recycling

substitution of the main components of the plant.		
Manufacturing of PV cell: silicon production, fabrication of PV modules	Solar radiation and ambient temperature-Electricity consumption	Treatment of waste from the plant components
Production of Materials: steel, glass, aluminium, cement etc	Life cycle of the energy sources (electricity and natural gas) consumed (from the grid) during the useful life of the plant	
Energy consumption for manufacturing of solar PV modules varied between 11 -18 MWh th/kWp.	Primary energy requirement-Electricity and Natural gas consumption	
	Useful lifetime of the solar PV is about 25 years	
	Two typologies of PV assisted systems: grid connected and stand-alone systems. PV Stand-alone (full load) or PV Stand Alone (partial load)	