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Life Beyond the Grid: A Life-Cycle Sustainability Assessment of Household Energy Demand

Master´s Dissertation in Energy for Sustainability
Specialization in Energy Systems and Policies
Advised by Professor Doctor Fausto Miguel Cereja Seixas Freire & Professor Doctor Luís Cândido Dias

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Life Beyond the Grid: A Life-Cycle Sustainability Assessment of Household Energy Demand

Master´s Dissertation in Energy for Sustainability, developed under the specialization of Energy Systems and Policy, presented to the Faculty of Science and Technology of the University of Coimbra, as part of the requirements for the award of the Master of Science (M.Sc.) degree.

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Cover image, own photo of Benfeita, April 2018

“Off-gridder´s homes are, in many cases, experimental labs for our collective future. The lessons they are learning today about living with renewable energy are the lessons we will all need to learn tomorrow in order to make our lives more sustainable, more respectful towards the environment, and less dependent on non-renewable resources.” Vannini & Taggart, 2015 [1]

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ABSTRACT

This work assesses the sustainability of meeting electricity and heating needs in off-grid homes by performing a combined Life-Cycle Sustainability Assessment (LCSA) and Multi-Criteria Decision Analysis (MCDA) study on two off-grid houses in Benfeita, a small village in Portugal that has attracted an ecologically inclined community. Two homes (Off-Grid House 1 and 2) were selected to serve as case studies because they have unique energy needs as well as distinct resource constraints that require the use of different technologies, making them representative of diverse challenges of off-grid living. Off-Grid House 1 uses the following off-grid electricity systems: photovoltaic panels, a pico-hydro generator, a petrol generator, and lead-acid batteries; Off-Grid House 2 uses: a micro-hydro generator, lead-acid, and lithium-ion batteries. Off-Grid House 1 uses the following off-grid heating systems: a wood burning furnace, a liquefied petroleum gas stove, and a solar cooker; Off-Grid House 2 uses: a wood burning furnace, a butane gas stove, and a solar cooker.

Based on site visits, interviews, and surveys with community members, inventories for these systems were developed and used to build original life-cycle models. Twelve indicators were selected to evaluate life-cycle sustainability performance: six environmental criteria: Global Warming (GW), Non-Renewable Fossil Energy Demand (nREn), Freshwater Aquatic Ecotoxicity (FAE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME); three economic criteria: Investment Cost, Operation & Maintenance Cost, and Levelized Cost of Energy (LCOE); and three health/social criteria: Carcinogenic Toxicity (CT), Non-Carcinogenic Toxicity (NCT), and Local Employment.

The sustainability of meeting energy needs in the off-grid homes, compared to using the grid, was found to be dependent on the criteria under consideration. Off-grid electricity use had lower impacts in GW and nREn, but higher levels of FAE, TA, FE, and ME; while off-grid heating use had lower impacts in GW, nREn, TA, and FE, and higher ones in FAE and ME. The cost of electricity from the grid was found to be 57-65% less expensive than that of off-grid electricity, but 108-288% more expensive than off-grid heating. Off-grid electricity use had higher impacts in CT and NCT, while off-grid heating´s were lower. The results of the USEtox impact categories (FAE, CT, NCT) were significantly different when “recommended” versus “indicative” characterization factors (CFs) were presented, thus the consideration of both is important to improve robustness of results. Both off-grid electricity and heating systems stimulated higher levels of Local Employment in Benfeita.

Baseline results (the current situation) were compared to four energy provisioning scenarios ($\mathbf{A_1}$, $\mathbf{A_2}$, $\mathbf{A_3}$, and $\mathbf{A_4}$) using Multi-Attribute Value Theory (MAVT) to rank alternatives based on their sustainability performance. The scenarios considered the impacts of extending and connecting the grid to the homes to allow for either electricity consumption from the grid, or injection of excess electricity generated to the grid. The resulting ranking of alternatives was mainly dependent on the house´s distance from the grid and whether "recommended" or "indicative" CFs were considered in USEtox calculations. The primary reason for this divergence is the way metals are accounted for in each CF. "Indicative" CFs take into consideration metals in the calculation of toxicity, and because grid extension requires the use of many metals, the impacts from grid extension are much higher compared to when "recommended" CFs are used, which omit metals due to the relatively high uncertainty of addressing the fate of these chemicals within substance groups.

Meeting household electricity and heating needs in a sustainable way requires an analysis of the local context and available resources. For extremely remote homes, off-grid, renewable energy solutions provide a reliable and sustainable form of electricity and heating, required that homeowners have the upfront capital to invest in such systems. Homeowners that live in places with easy access to the grid, or are already connected to the grid, should not consider going off-grid. A consideration of trade-offs is central to understanding the value of alternative possibilities for energy provisioning.

Key words: Off-grid homes; Local energy systems; Life-Cycle Sustainability Assessment; Multi-Criteria Decision Analysis

RESUMO

Este trabalho avalia a sustentabilidade associada à satisfação das necessidades de eletricidade e aquecimento em casas sem acesso às redes de abastecimento convencionais (eletricidade e gás natural), realizando um estudo que combina Avaliação da Sustentabilidade de Ciclo de Vida (LCSA) e Análise de Decisão Multicritério (MCDA) aplicado a duas casas nessas condições em Benfeita, uma pequena vila de Portugal que atraiu uma comunidade com consciência ecológica. Foram selecionadas duas casas (1 e 2) como casos de estudo por possuírem necessidades energéticas e acesso a recursos energéticos endógenos distintos, que exigem o uso de diferentes tecnologias, tornando-as representativas dos diversos desafios de viver sem acesso às redes convencionais. A Casa 1 usa os seguintes sistemas de geração de eletricidade: painéis fotovoltaicos, um gerador pico-hídrico, um gerador a gasolina e baterias de chumbo-ácido; enquanto a Casa 2 usa um micro-gerador hidráulico e baterias de chumbo-ácido e de iões de lítio. Para aquecimento, a Casa 1 usa os seguintes sistemas: um forno a lenha, um fogão a gás de petróleo liquefeito e um fogão solar (para cozinhar); enquanto a Casa 2 usa um forno a lenha, um fogão a gás butano e um fogão solar (para cozinhar).

Com base em visitas ao local, entrevistas e inquéritos a membros da comunidade, foram desenvolvidos inventários desses sistemas que foram utilizados para construir modelos de ciclo de vida. Foram selecionados 12 indicadores para avaliar a sustentabilidade de ciclo de vida: seis critérios ambientais: Aquecimento Global (AG), Requisitos de Energia Fóssil Não Renovável (EF), Ecotoxicidade Aquática de Água Doce (EAAD), Acidificação Terrestre (AT), Eutrofização de Água Doce (EAD) e Eutrofização Marinha (EM); três critérios económicos: custo de investimento, custo de operação e manutenção e Custo Nivelado de Energia (CNE); e três critérios de saúde/sociais: Toxicidade Carcinogénica (TC), Toxicidade Não Carcinogénica (TNC), e Emprego Local.

A sustentabilidade da satisfação das necessidades de energia nas casas desconectadas das redes de abastecimento convencionais quando comparada com o uso das redes mostrou ser dependente dos critérios considerados. O uso de energia elétrica em casas desconectadas da rede teve menores impactes em AG e EF, mas mais altos em EAAD, AT, EAD e EM; enquanto o uso de sistemas de aquecimento desconectados da rede convencional teve menores impactos em AG, EF, AT e EAD, e maiores em EAAD e EM. O custo da eletricidade da rede de abastecimento foi 57-65% mais baixo do que o da eletricidade gerada pelos sistemas desconectados da rede, mas 108-288% mais elevado do que o aquecimento produzido sem recurso às redes convencionais. O consumo de eletricidade com recurso aos sistemas desconectados da rede teve maiores impactos em TC e TNC, enquanto o aquecimento com recurso às redes convencionais foi menor. Os resultados das categorias de impacto do método USEtox (EAAD, TC, TNC) foram significativamente diferentes quando foram considerados os fatores de caracterização (FCs) "recomendados" versus "indicativos", pelo que a consideração de ambos é importante para melhorar a robustez dos resultados. Os sistemas de eletricidade e aquecimento desconectados das redes convencionais estimularam níveis mais altos de Emprego Local em Benfeita.

Os resultados **Base** (situação atual) foram também comparados com quatro cenários de abastecimento de energia ($\mathbf{A_1}$, $\mathbf{A_2}$, $\mathbf{A_3}$, e $\mathbf{A_4}$) usando a Teoria de Valor Multiatributo (TVM) para classificar as alternativas com base no seu desempenho de sustentabilidade. Os cenários consideraram os impactos de estender e conectar a rede a ambas as casas para permitir o consumo de eletricidade da rede ou a injeção do excesso de eletricidade gerada na rede. O *ranking* das alternativas dependeu principalmente da distância da casa à rede e se os FCs "recomendados" ou "indicativos" eram considerados nos cálculos do USEtox. A principal razão para essa divergência é a maneira como os metais são contabilizados em cada tipo de FC. FCs "indicativos" têm em consideração os metais no cálculo do potencial de toxicidade, pelo que, como a extensão da rede requer a utilização de metais, os seus impactes são muito mais altos quando comparados com os FCs "recomendados", que omitem os metais do cálculo devido à sua elevada incerteza.

Atender às necessidades domésticas de eletricidade e aquecimento de maneira sustentável requer uma análise do contexto local e dos recursos energéticos endógenos disponíveis. Para habitações em locais remotos, sistemas com base em energia renovável desconectados da rede fornecem uma forma confiável e sustentável para o fornecimento de eletricidade e aquecimento, exigindo que os proprietários tenham o capital inicial para investir em tais sistemas. Proprietários de casas localizadas em áreas com fácil acesso à rede, ou que já estão conectados à rede, não devem considerar sair da rede. Para compreender o valor das alternativas de abastecimento de energia é fundamental ter em conta estes diversos *trade-offs.*

Palavras-chave: Casas desconectadas da rede; Sistemas locais de geração de energia; Avaliação da Sustentabilidade de Ciclo de Vida; Análise de Decisão Multicritério

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ABBREVIATIONS

AHP – Analytical Hierarchy Process

CAV – Audiovisual Tax (*Contribuição para o Audiovisual*)

CED – Cumulative Energy Demand

CF – Characterization Factor

CHP – Combined Heat and Power

CT – Carcinogenic Toxicity

CTU$_e$ – Comparative Toxic Units for ecosystems

CTU$_h$ – Comparative Toxic Units for humans

DGEG – Directorate General of Energy and Geology (*Direção-Geral de Energia e Geologia*)

DM – Decision Maker

E-LCA – Environmental Life-Cycle Assessment

EC – European Commission

EC-JRC – European Commission-Joint Research Centre

EDP – Energies of Portugal (*Energias de Portugal*)

ETSI – Energy Technology Sustainability Index

FAE – Freshwater Aquatic Ecotoxicity

FE – Freshwater Eutrophication

GHG – Greenhouse Gas

GW – Global Warming

IEC – Special Tax on Electricity Consumption (*Imposto Especial de Consumo de Eletricidade*)

IPCC – Intergovernmental Panel on Climate Change

IRENA – International Renewable Energy Agency

JRC – Joint Research Committee

kW – Kilowatt

kWh – Kilowatt Hour

kWp – Kilowatt Peak

ISO – International Organization for Standardization

LCA – Life-Cycle Assessment

LCC – Life-Cycle Costing

LCI – Life-Cycle Inventory

LCOE – Levelized Cost of Electricity/Energy

LCSA – Life-Cycle Sustainability Assessment

LHV – Lower Heating Value

LPG – Liquefied Petroleum Gas

MAVT – Multi-Attribute Value Theory

MCDA – Multi-Criteria Decision Analysis/Aiding

ME – Marine Eutrophication

MJ – Mega Joules

NCT – Non-Carcinogenic Toxicity

NGO – Non-Governmental Organization

nREn – Non-Renewable Fossil Energy

O&M – Operation & Maintenance

OECD – Organization for Economic Co-Operation and Development

OMIE – Iberian Energy Market Operator

PCA – Principal Component Analysis

PV – Photovoltaic

S-LCA – Social Life-Cycle Assessment

SETAC – Society of Environmental Toxicology and Chemistry

SERUP – Electronic System to Register Production Units (*Sistema Eletrónico de Registro da Unidades de Produção*)

SHS – Solar Home Systems

SMAA – Stochastic Multi-Criteria Acceptability Analysis

TA – Terrestrial Acidification

TH – Time Horizon

UK – United Kingdom

UNEP – United Nations Environment Programme

UPAC – Self-Consumption Units (*Unidade de Produção em Autoconsumo*)

UPP – Small Production Units (*Unidade de Pequena Produção*)

VAT – Value Added Tax

VIP – Variable Interdependent Parameter Analysis

1. INTRODUCTION

Off-grid households are defined as those that are disconnected from electricity and natural gas grids [1]. In many countries, the reason to live off-the-grid is not a choice, an estimated 1.1 billion people worldwide do not have access to electricity [2]. The cost of grid extension in isolated areas, particularly in low-income economies, is extremely high and many residents have few opportunities to access electricity services due to infrastructure or affordability issues [3]. In advanced economies, there has been a recent increase in public and academic interest in "leaving the grid" or "living off-grid," by individuals who have the means to access energy services in a conventional matter, but choose not to [4].

Elaine Forde [5], an ethnographer who spent 15 months researching off-grid communities in rural Wales, describes peoples´ reasons for living off-grid as a challenge against infrastructural inequalities. Van der Schoor & Scholtens [6] studied the impact of the transition towards renewable energy systems on communities, and also came to the conclusion that some citizens, spurred by access to reliable and clean decentralized energy, are starting to voice ideas about self-empowerment and independence from large energy companies. These challenges to the traditional centralized form of energy production address the concept of energy sovereignty, which recognizes energy as a human right and seeks to return the control of energy to its users rather than remote corporations [7]. Achieving energy sovereignty is much more accessible for individuals today due to decreasing costs in renewable energy and storage systems, as well as improvements in microgeneration technology [4]. The use of renewable energy systems to power off-grid homes has become an operationally reliable solution to supply energy to isolated communities [8]. Off-grid homeowners have the ability to harness locally available resources, and make themselves key constituents in the energy infrastructure [5]. Studying off-grid communities, especially those comprised of members who have chosen to live this lifestyle, provides a window to evaluate and explore alternative means of energy provisioning.

Benfeita, a small village situated in the Arganil municipality of Portugal, has attracted a growing population of ecologically inclined foreign immigrants and Portuguese citizens. The village of Benfeita can be described as a natural bowl, enclosed by mountain ridges of 600-1000 meters in all directions except North, creating a natural boundary that isolates it from surrounding villages [9]. Its natural topography makes the use of off-grid systems necessary for some households to meet their needs. Currently, there are 30-40 off-grid households situated within the mountain ridge of Benfeita. After site visits and interviews with community and municipal council members, two off-grid homes were selected as case studies to design a combined Life-Cycle Sustainability Assessment (LCSA) and Multi-Criteria Decision Analysis (MCDA) study evaluating the environmental, economic, and social impacts and trade-offs of meeting electricity and heating needs in an off-grid home. The two homes were selected because they have unique electricity and heating needs as well as distinct resource constraints that require the use of different technologies, making them representative of diverse challenges of off-grid living. The aim of this work is to assess the sustainability of the use of off-grid systems in the attempt to answer the following question: *are off-grid solutions environmentally, socially, and economically viable to meet electricity and heating needs, and if so, under which circumstances?*

1.1. Research Objectives and Areas of Novelty

This research seeks to contribute to LCSA, MCDA, and renewable energy systems literature, while informing homeowners and the general public regarding the sustainability of meeting electricity and heating needs in off-grid homes. To achieve these goals, two off-grid households in Benfeita were selected as case studies to evaluate the life-cycle sustainability impacts of the technologies used to meet household electricity and heating needs compared to conventional sources, i.e. the use of electricity from the Portuguese grid to provide electricity as well as heating (through the use of conventional electric heaters using the Joule effect). Results are presented based on the current scenario and hypothetical alternatives in order to provide the homeowners with recommendations for sustainability improvements.

Within this framework, this research has four main objectives. The first, is to review existing studies and explore stakeholder preferences in order to determine and apply suitable sustainability indicators to perform an LCSA on off-grid homes. The second, is to estimate the life-cycle environmental, economic, and social impacts of the use of off-grid electricity and heating systems to meet household energy demand. The third, is to consider stakeholder preferences and sustainability trade-offs of alternative scenarios through the application of MCDA methods on LCSA results. And the fourth, is to develop conclusions about the sustainability of meeting household energy needs in an off-grid home. By achieving these objectives, this work contributes to the literature in various ways, two of which are particularly noteworthy.

First, the work provides a systematic comparison of the environmental, social, and economic impacts of meeting electricity and heating needs in an off-grid home, a case study which has not yet been evaluated. One of the main attributes of an off-grid household is that it requires the simultaneous functioning of multiple technologies in order to provide reliable energy to the home. While evaluations on renewable energy systems have been well documented, little work in the literature has focused on integrated systems (such as off-grid homes). Rather, most work in the literature has focused on one technology, failing to address the nuances related to integrated systems. This work fills this research gap by developing original life-cycle inventories and models of off-grid electricity and heating technologies based on collected data gathered through interviews and site visits.

Second, the dissertation provides an approach to apply MCDA to LCSA results based on stakeholder preferences and an analysis of the robustness of the conclusions to these preferences. Because the models are based on actual households, we were able to elicit preferences from decision makers, something that is key in MCDA studies but is not often well applied in life-cycle studies that use MCDA methods. Through the successful application of these two methods, the work is able to confirm the complementarity of the use of decision analysis tools to life-cycle studies.

1.2. Thesis Structure

This document is organized through five chapters and is structured as follows. Chapter 1 introduced the topic and defined the research questions. Chapter 2 identifies research gaps through a review of the state of the art regarding evaluations of off-grid energy systems and the application of LCSA and MCDA methods. Chapter 3 describes the applied materials and methods, Chapter 4 presents and discusses results, and Chapter 5 concludes with highlights and key outcomes as well as recommendations for off-grid homeowners.

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2. STATE OF THE ART

Technological innovations in small-scale generation paired with decreasing costs in renewables and storage have sparked public and academic curiosity about the sustainability of living off-grid [4]. As a result, there is an increasing number of publications focused on evaluating off-grid energy systems, with life-cycle and decision analysis tools emerging as common assessment methodologies. This chapter reviews existing literature to identify research gaps, and is organized as follows: Section 2.1 begins with an introduction to life-cycle thinking and the evolution of LCSA, followed by an overview of MCDA methods and their complementarity to life-cycle approaches in Section 2.2. A thorough literature review of evaluations on off-grid energy systems is presented in Section 2.3. The chapter concludes with a summary in Section 2.4.

2.1. The Evolution of LCSA

The consideration of environmental, economic, and social values, otherwise known as the "triple-bottom line" [10], has become increasingly important to citizens around the world. This is highlighted by the growing number of frameworks to assess the sustainability of products [11], [12], companies [13], [14], and even countries [15]–[17]. While there are many methodologies to assess sustainable development, a life-cycle approach ensures that all aspects of sustainability are addressed through the lifetime of the product or system in question, providing a holistic tool for evaluation.

LCSA is a recent development based on Life Cycle Assessment (LCA) methods. LCA is an environmental management tool that evolved from life-cycle thinking, a powerful approach to understand the full impacts of a product or activity from "cradle-to-grave" [18]. LCA is a well-established methodology that dates back to the 1960s, when it was first used to evaluate energy flows [19]. At the Society of Environmental Toxicology and Chemistry (SETAC) symposium in 1991, it was determined that LCA was synonymous with environmental-LCA (or E-LCA), as it specifically provided a method of environmental product assessment; thus, it was clear that additional parameters would be necessary to evaluate the sustainability of a product [20].

Since the early 2000s, there has been an elaboration in LCA, with the development of approaches such as: Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), and Life Cycle Sustainability Assessment (LCSA) [19]. LCC is a tool that emerged from the financial accounting perspective, and enables the estimation of the total costs of a product through its life-cycle [21]. Meanwhile, S-LCA examines the social consequences of a product throughout its life-cycle, by systematically collecting and reporting on social impacts from extraction to end-of-life [22]. LCSA is the newest tool, which has been developed in order to take into consideration all aspects of sustainability. Kloepffer conceptualized LCSA in 2008 as a combination of E-LCA, LCC, and S-LCA so that: LCSA = E-LCA + LCC + S-LCA [20]. Figure 1 presents an illustration of LCSA based on Walter Kloeppfer´s definition.

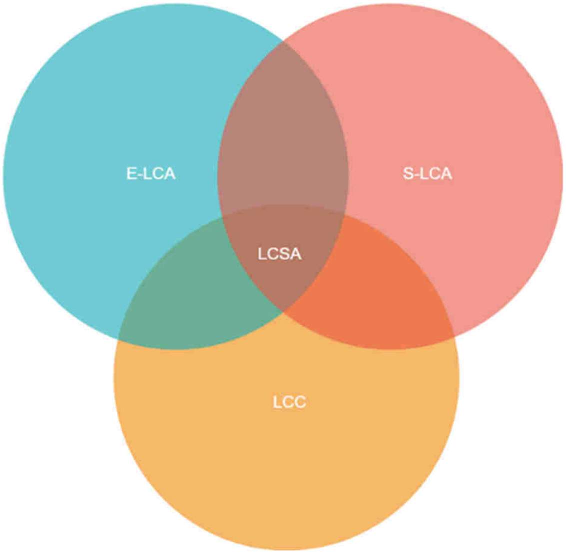

Figure 1. A Conceptualization of LCSA based on Kloepffer [13]

As each method focuses on different externalities and internalities related to the product or good under assessment, LCSA is able to incorporate the three to evaluate all pillars of sustainability together [19], [21]. Although LCSA provides a holistic method to evaluate sustainability impacts, it is difficult to compare alternatives and integrate results. MCDA complements well because it allows for the aggregation of different measures.

2.2. Complementarity of MCDA to LCSA

MCDA is a collection of formalized approaches to account for multiple criteria while evaluating alternatives in the decision-making process [23]. These approaches usually assume the existence of a decision-maker (DM), who can be a single entity or a group that "owns the problem," and whose elicited preferences will affect the overall result and determine recommendations that are as compatible as possible with their values [24]. In this way, the purpose of MCDA is not to get an objective truth, but rather, to derive results that are a function of the DM´s subjective preferences. Other actors involved in the decision-making process include: stakeholders (entities or groups that share impacts arising from the decision), experts (external actors who aid in evaluating the decision), among other actors (e.g. persons, groups or entities taken into account in the decision-process) [24].

There are a variety of MCDA methods available. Dias et al. [25], present a taxonomy of MCDA approaches based on two dimensions: whether the evaluation is dependent of the set of alternatives being evaluated; and on the type of underlying approach used to synthesize performance (by value, distance, or binary relations). Table 1 presents this taxonomy with examples of specific methods in italics[1].

Table 1. Taxonomy of MCDA methods based on Dias et al. [25]

		Does the evaluation of one alternative depend on other alternatives?	
		No	Yes
Underlying approach	Value	I. Global value aggregating individual performances • *Weighted Sum* • *MAVT/MAUT* • *Fuzzy operators*	II. Global value synthesizing comparisons of alternatives • *AHP/ANP* • *PROMETHEE II* • *Borda Score*
	Distance	III. Distance to an externally defined reference • *Manhattan distance* • *Euclidean distance* • *Chebyshev distance*	IV. Distance to a reference defined from the alternative • *Distance to ideal solution* • *TOPSIS*
	Binary Relations	V. Binary relation between alternative and external references • *ELECTRE TRI* • *Rule based methods*	VI. Binary relation on the alternatives evaluated • *Dominance* • *ELECTRE I-IV* • *PROMETHEE I* • *NAIADE*

As demonstrated in Table 1, there exists a range of approaches to assess decision problems. Depending on the method used, the DM can either: select the best alternative; rank or prioritize a list of alternatives; sort or classify alternatives into pre-determined classes; describe options and their consequences; eliminate alternatives; or identify a new action

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[1] This list is not exhaustive, and is merely an overview of commonly used MCDA methods.

[25], [26]. Amidst an assortment of possible approaches, consideration of the decision at hand and the needs or objectives of the DM, help define which method to apply.

MCDA acknowledges that decision-making is a complex process, and provides a rational basis for evaluation [27]. MCDA studies generally follow three main stages: structuring, assessment, and recommendation. The structuring stage defines the problem, alternatives, consequences, and evaluation criteria; the assessment stage evaluates the performance of alternatives against criteria; and the recommendation stage derives recommendations based on the results of the evaluation [28]. This organization provides a logical set of steps that allow for the rational evaluation of alternatives considering both the decision at hand and the preferences of the DM. Although these stages provide a general model of the application of MCDA, in practice, the process is not linear. There is an ability to go back to previous stages to ensure a comprehensive assessment of alternatives, allowing for flexibility in the decision-making process.

The application of MCDA to life-cycle studies has become increasingly popular in recent years, with studies ranging from: choosing alternative biodiesel chains [29], prioritizing bioethanol production pathways [30], choosing renewable energies net-zero energy communities [31], among other general frameworks [32]. LCA and MCDA complement each other well because they provide a clear and transparent way to aggregate complex information to support environmental decisions consistent with DM´s values [28]. The same holds true for the combination of LCSA and MCDA methods, which has been found to be a useful tool to evaluate trade-offs and integrate sustainability results [19]. By being interdisciplinary, participatory, and transparent, MCDA tools supply a powerful framework to evaluate the sustainability of systems [33]. The combination of LCSA and MCDA frameworks provide a holistic and methodological way to assess the impacts of complex systems, which can be readily applied in the case of off-grid homes.

2.3. Evaluation of Off-Grid Homes

The academic and public discourse on off-grid energy is heavily focused on the potential of these systems to provide rural electrification in low-income economies [34], as evidenced by hundreds of publications on their feasibility and sustainability [35]. Consequently, less work centers on evaluating off-grid homes in advanced economies. Yet, technological innovations in micro-generation, decreasing costs of PV prices and battery storage have made off-grid energy solutions more attractive and accessible today [4].

Furthermore, there is a growing trend towards self-empowerment and independence from large energy companies, as some people chose to live off-grid [4], [6]. Thus, there is both an opportunity and space to explore the feasibility of off-grid energy systems in advanced economies. Due to different contexts and challenges related to meeting energy needs, assessing the sustainability of off-grid homes in advanced economies is completely different than performing the same assessment in low-income economies, which is why they should be addressed separately.

Considering feasibility assessments, there are three significant studies focusing on off-grid homes in advanced economies. Two of them concentrate on environmental and economic evaluations of renewable energy systems to power off-grid indigenous populations in Canada, while one study evaluates off-grid solutions in the inner areas of Italy. Thompson & Duggirala [36] assessed the feasibility of renewable energy technologies to power off-grid homes in Canada—focusing specifically on indigenous populations living in isolated regions. They compared the impacts of replacing diesel generators with solar, wind, and biomass technology to see the environmental and economic feasibility of this strategy. They concluded that, biomass combined heat and power (CHP) systems were the most environmentally and economically favorable technology to replace diesel generators. Rahman et al. [37] modeled seven different scenarios of hybrid renewable electricity generation systems for an off-grid community in Canada to evaluate the economic and environmental trade-offs of increasing the fraction of renewable sources. Their analysis showed a correlation between an increase in the fraction of renewable generation systems and a decrease in emissions, coupled with an increase in the cost of electricity. Another approach was taken by Menconi et al. [7], who assessed the optimal renewable energy systems that could be combined with storage to ensure the energy autonomy of rural residential buildings in Italian inner areas. Their findings provided different alternatives to integrate renewable energy systems to create the most efficient stand-alone system. Even though these works focused on evaluating the operational feasibility of these systems, they did not address their full life-cycle impacts.

In terms of life-cycle studies, there are many publications in the academic literature of grid-connected or large scale power systems [38]–[44], but fewer works have focused on smaller-scale energy systems, such as off-grid homes. One notable example is Fleck & Hout [45], who compared the environmental impacts, net-energy impacts, and life-cycle costs of a stand-alone residential wind turbine system with a single-home diesel generator system. Although the residential wind turbine system had lower greenhouse gas

(GHG) and net energy impacts than the diesel generator systems, cost was an issue, as there was a lack of economies of scale in the installation of residential wind turbines. Another example is a technical report by Alsema [46], who compared the life-cycle environmental impacts of Solar Home Systems (SHS) in Indonesia with the use of a diesel generator, battery charging, and kerosene lamps, finding potential GHG emission reductions compared with the alternatives. A third example is from García-Valverde et al. [47], who evaluated a 4.2 kilowatt peak (kWp) stand-alone PV system at the University of Murcia in Spain, finding lower carbon dioxide (CO_2) emission factors per kilowatt hour (kWh) of electricity produced, compared to the use of a diesel generator or the Spanish grid. While these results point to environmental benefits of the stand-alone system, they only consider environmental impacts of CO_2 and embodied energy, and neglect to consider other impact categories which could lead to different conclusions.

Other LCA studies take a more integrated systems perspective, the vast majority of them in the low-income economies. There are a few notable cases that assessed integrated PV and microgrid systems, such as Akinyele et al. [48], who evaluated the economic and environmental performance of solar photovoltaic microgrid systems compared to diesel power plants in Nigeria, providing valuable conclusions about the planning of integrated microgrid systems in remote communities. A later study published by Bilich et al. [49], compared the environmental impacts of three PV and microgrid systems used to generate electricity in rural Kenya, citing PV-battery microgrids as potential long-term energy access solutions. Pascale et al. [50], present an integrated community approach by evaluating community hydroelectric systems in rural Thailand, concluding that although the environmental performance (per kilowatt hour) of small-scale hydro systems is generally worse than larger systems, these impacts may lessen in more isolated communities. Smith et al. [51] evaluated a hybrid wind/microgrid/diesel system to power the village in the island of Koh Jig in Thailand. They found higher environmental benefits regarding the use of the microgrid, especially in the case of more isolated communities (such as the island) but cautioned that the choice of electrification scenario requires the additional consideration of economic and social factors as well. Balcombe et al. [52] present another integrated approach by evaluating the life-cycle environmental impacts of a microgeneration system combining solar PV, CHP, and battery storage. The hybrid system reduced impacts by 35-100% compared to conventional sources of electricity and heat but, there is a trade-off of a 42 times higher level of abiotic resource depletion due to the antimony used for battery manufacture. Finally, a recent study in this area was published by Üçtuğa & Azapagic [53], who assessed the life-cycle impacts of integrated multi-crystalline photovoltaic and lithium-ion battery hybrid systems in Turkey. The authors found that the systems can meet 12.5-18.4% of household annual electricity needs and can generate 4.7-8 times more energy than it consumes. The issue, however, lies in the high cost of batteries, which does not make these systems financially feasible at the moment. Therefore, there is a clear need to explore alternative tools, such as the LCSA, which can take into consideration all aspects of sustainability.

As it is a newer methodology, there are fewer LCSAs than LCAs focusing on off-grid energy systems, and most of them have concentrated on large scale electricity generation as opposed to off-grid or other types of decentralized forms of energy production. Evaluations of electricity generation technologies have been completed at the country level for various regions including: Mexico [54], Pakistan [55], Portugal [56], Turkey [57], and the UK [58]. One author, Benjamin Greening [59], looked at examples of decentralized energy systems by evaluating microgeneration technologies in the UK using the life-cycle sustainability assessment approach. While there is a growing amount of literature focusing on evaluating energy systems at the country level, only a few studies looked at energy systems at a local level, and none focused specifically on off-grid homes.

A more regional-level approach was conducted by Li et al. [60], who presented a LCSA of grid connected photovoltaic panels in Northern UK, demonstrating how the energy output of the PV system has an effect on their life cycle impacts per kWh of electricity generated. Li et al. [61] also published a conference paper detailing a LCSA of rooftop solar photovoltaic systems to provide electricity for a community energy project in the UK. Even though this work dealt with a fictitious example, the methodology applied provided a straightforward tool to incorporate various sustainability indicators. Moslehi & Arababadi [62] also present a local assessment by conducting an LCSA of two possible electricity generation fuel mixes at the University of Arizona campus in Tempe, Arizona. Based on the results of life-cycle sustainability impacts, the authors developed a Sustainability Index to rate the performance of different mixes. The authors attempted to incorporate decision-making in the assessment, however, they did not use formal MCDA methods which would provide a logical framework to evaluate results.

There are a few notable MCDA studies applied to evaluate the sustainability of off-grid energy systems, and only a small number of combined LCA/LCSA and MCDA approaches. Rojas-Zerpa & Yusta [63], used Analytical Hierarchy Process (AHP) and Compromise Ranking Method (VIKOR) to evaluate solutions for supplying electricity for remote rural locations using technical, economic, environmental and social criteria. In this work, they estimated preference criteria through interviews with four expert groups: academia, energy sector firms, regulators, and non-governmental organizations (NGOs). They found that distributed energy sources, and most specifically renewable hybrid systems with storage, had the highest sustainability performance, and were considered the best option for small rural villages to meet their electricity needs. Another prominent study was completed by Burton & Hubacek [27], who applied the MACBETH method, which involves a series of pairwise comparisons to specify attractiveness between two alternatives, to assess approaches to renewable energy provision in a small borough in the United Kingdom (UK). They elicited preferences from five professionals in the energy sector, as well as council representatives to determine the weights for the assessment. From this study, they concluded that small-scale energy provisioning (compared to large-scale) was the most effective way to meet local energy targets based on their environmental, social, and economic performance.

There are a few cases of combined life-cycle/decision analysis studies focusing on large scale electricity systems, however, these studies often do not have a DM involved, thus recommendations are not based on subjective preferences. Instead, many LCA/MCDA studies try to circumvent subjectivity by deriving weight vectors [24]. A prime example of this is the study by Atiglan & Azapagic [57], who applied Multi-Attribute Value Theory (MAVT) to integrate the results of a LCSA of electricity generation in Turkey. Since there was no DM to elicit preferences from, they assumed equal weights and performed a sensitivity analysis to determine how the rankings would change based on different weightings of sustainability aspects. Ren [64] also presents an MCDA application to LSCA studies without the use of a DM. Instead, the author used a fuzzy two-stage logarithmic goal programming method to determine the weights for a LCSA of electricity generation technologies in the UK. Petrillo et al. [65], combined LCA and AHP to evaluate the sustainability of an air energy storage system for the energy storage of a small PV power plant. These authors also failed to elicit preferences from a DM, and did not propose an explanation on how the weights were derived. Although these works were able to apply decision analysis tools to integrate results, eliciting preferences from a DM would provide for a more realistic and comprehensive assessment.

As demonstrated by the literature review, there exists a wide variety of academic interest in studying off-grid energy systems. However, there has been a lack of focus regarding off-grid homes in advanced economies, with many works focused on the feasibility of these systems in low-income economies. Furthermore, there exists an opportunity to evaluate the sustainability of these homes using a combined LCSA and MCDA approach, to present a comprehensive methodology that integrates sustainability impacts while incorporating DM´s preferences.

2.4. Chapter Summary

This chapter provided an introduction to LCSA and MCDA methods, followed by a brief overview of the academic discourse surrounding evaluations of off-grid energy systems. Given the current state of research, it is clear that there is a gap of knowledge regarding the life-cycle sustainability impacts of off-grid homes. Furthermore, there is an opportunity to incorporate MCDA methods to integrate results and include off-grid homeowner´s preferences and values. By modeling two off-grid households including all required systems to deliver heat and electricity to the home, this work provides a systematic comparison of the environmental, economic, and social impacts of off-grid homes, adding an additional perspective to the academic literature.

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3. MATERIALS AND METHODS

This chapter describes the materials and methods used to evaluate the sustainability of two off-grid households in Benfeita, Portugal. It begins with the assessment framework in Section 3.1 to provide an overview of the materials and methods applied in this study. This is followed by a description of the case study in Section 3.2 to illustrate the context for the application of these methods. Section 3.3 presents the application of LCSA methods and Section 3.4 those of MCDA methods. Section 3.5 concludes with a chapter summary.

3.1. Assessment Framework

Figure 2 presents the assessment framework, which is divided between the application of LCSA and MCDA methods. The LCSA portion of the study includes: the definition of goal and scope, analysis of life cycle inventories (LCIs), impact assessment, and interpretation of life-cycle impacts [66]. The MCDA portion of the study includes: structuring, elicitation, assessment, and recommendation [25].

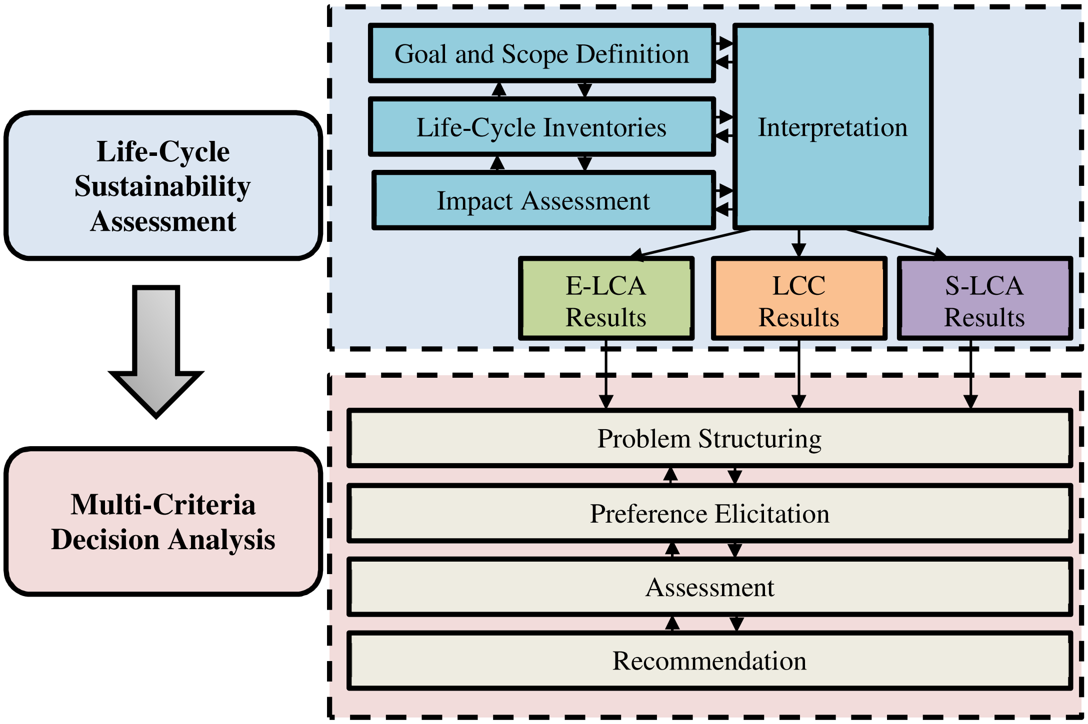

Figure 2. Assessment Framework

The assessment framework provides an overview of the applied materials and methods. Included in the LCSA is the interpretation of results, which is an iterative step, in order to identify, qualify, and check the conclusions based on the assessment, and make any necessary changes. To incorporate a full sustainability assessment, environmental, economic, and social impacts are calculated using E-LCA, LCC, and S-LCA methods, respectively. Baseline results (the current situation) are presented along with alternative energy provisioning scenarios. These results are used as the starting point for the application of MCDA methods to rank alternatives based on their sustainability performance. The following section describes the case studies to which this assessment framework was applied.

3.2. Case Studies

Benfeita is a small parish in the Arganil municipality of Portugal situated between the protected land of the *Serra do Açor* and the town of *Côja* [67]. The parish can be described as a natural bowl, enclosed by mountain ridges of 600-1000 meters in all directions except North, creating a natural boundary that isolates it from surrounding villages [9]. The most recent census data estimates 394 residents in Benfeita [68]. However, from conversations with its residents, the village has attracted a community of about 150 "eco-immigrants", made up of Portuguese nationals and foreigners who are aligned in ecological principals, and are actively involved in the sustainable development of this region [9]. The natural topography of Benfeita makes the use of off-grid energy systems necessary to meet some household´s energy needs. Within the community, there is a central village where many homes are connected to the national grid. However, the 30-40 houses situated on the mountain ridge surrounding the village do not have access to the grid and are dependent on stand-alone, off-grid systems.

After site visits and interviews with community and municipal council members, two off-grid homes were selected to serve as case studies. These homes were selected because they have unique energy needs as well as distinct resource constraints that require the use of different technologies, making them representative of diverse challenges of off-grid living. We interviewed and surveyed members from the two homes to develop LCIs of the technologies used to meet their electricity and heating needs. The completed surveys are presented in Appendix 1 and the detailed inventories are presented in Section

3.3.2. In this study, the houses will be referred to as Off-Grid House 1 and Off-Grid House 2. Figure 3 presents an illustration of the technologies utilized in these two homes.

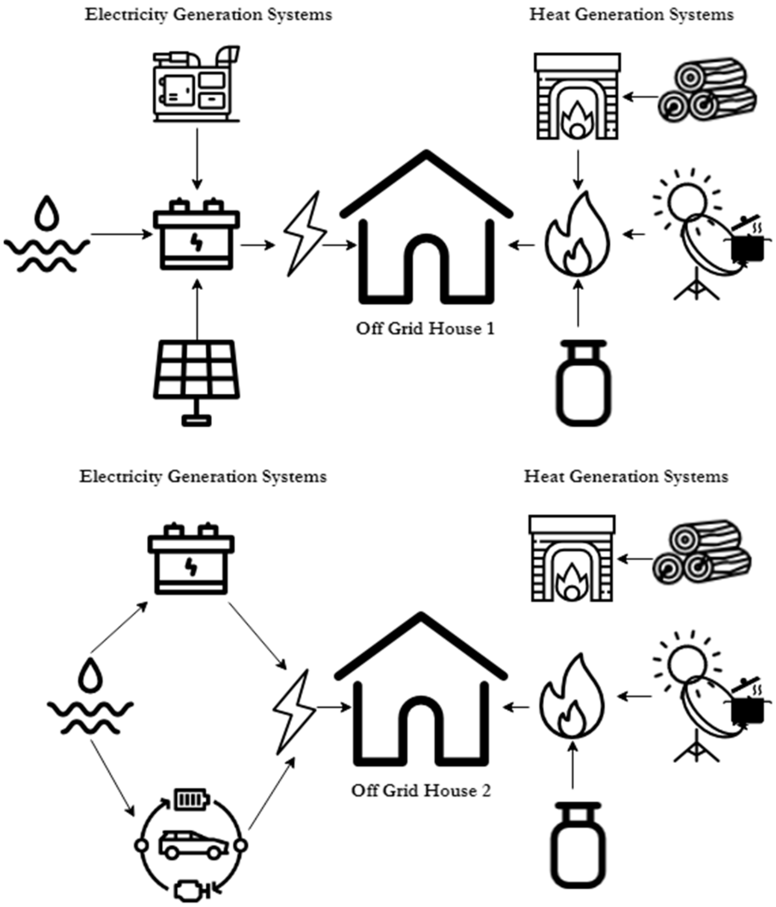

Figure 3. Off-Grid Houses[2]

To meet household electricity needs, Off-Grid House 1 uses the following off-grid electricity systems: 1.59 kWp and 0.56 kWp multi-crystalline silicone photovoltaic (PV) panels, a locally-built 0.3 kW pico-hydro generator, and a 5 kW petrol generator. These systems are connected to two lead-acid battery packs, which are used for storage. The backup generator is used a few times over the winter to charge the batteries when there is not enough generation from the PV panels and hydro generator. Heating needs, which include space and water heating as well as heat for cooking, are met through the use of the following off-grid heating systems: a wood burning furnace, a liquefied petroleum gas (LPG) stove, and a solar cooker. To meet household electricity needs, Off-Grid House 2 uses a 1 kW micro-hydro generator which is connected to two battery packs: one is lead-acid and the other lithium-

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[2] Figure 3 c

ion manganese oxide. The lithium-ion battery pack serves a dual-function, as it is also used to power a small electric vehicle. Heating needs are met through the use of the following off-grid heating systems: a wood burning furnace, a butane gas stove, and a solar cooker. It is important to note that the wood burning furnace represents the majority of heat consumption in both homes as it serves multiple functions: it is used for space heating, heating water for showers and cleaning, as well as heating for cooking. The following section describe how this case study was evaluated applying LCSA methods.

3.3. Life Cycle Sustainability Assessment

The LCSA is performed in a step-wise fashion, but the process is not necessarily linear. The following describe the main steps taken, with the interpretation of results as an iterative step between each phase in order to identify, qualify, and check the conclusions based on the assessment, and make any necessary changes. First, the goal and scope of the assessment is defined (Section 3.3.1). Second, data is collected in order to construct LCIs for each technology evaluated (Section 3.3.2). Third, sustainability indicators are selected to evaluate environmental, economic, and social impacts of the off-grid technologies (Section 3.3.3). Fourth, life-cycle models are developed based on data collected from the LCIs and with the objective to present results for the chosen sustainability indicators. The key assumptions and details regarding the models are presented for the E-LCA (Section 3.3.4), LCC (Section 3.3.5), and S-LCA (Section 3.3.6). The results from these models are then applied for the MCDA (Section 3.4)

3.3.1. Definition of Goal and Scope

The goal of this research is to assess the life-cycle sustainability impacts of meeting electricity and heating needs in an off-grid home, with the purpose to identify the trade-offs of an off-grid home compared to a grid-connected home. The assessment takes a cradle-to-grave approach, with the system boundary including the technologies that provide electricity and heat for an off-grid home. The life-cycle stages are divided into two phases: infrastructure, which includes the extraction, processing, and manufacturing of the systems (or fuels) along with the transportation of parts and final products; and operation and maintenance, which includes the use of the systems in the household and any services rendered throughout the system lifetime. The end-of-life is not considered as an explicit stage in this assessment due to lack of data regarding all systems, and the need to introduce too many assumptions.

Inventory and impact indicators are related to a common functional unit describing the technical and social utility of the product [21]. In this study, the product´s utility is meeting the household´s electricity and heating needs. The functional unit is defined as the electricity (in kilowatt hours (kWh)) and heat (in mega joules (MJ)) consumed by the household in order to satisfy its electricity and heating needs. We present results separately for electricity and heating systems.

To determine each home´s electricity needs, we developed surveys (see Appendix 1) to collect electricity consumption data for the year 2017. With this data, we defined each household´s electricity needs as well as the amount of kWh that were consumed using each system. Table 2 illustrates Off-Grid Houses 1 and 2´s electricity consumption in 2017 and the contribution of each technology to annual electricity use.

Table 2. Household Electricity Consumption, 2017

Household	System	Consumption (kWh)	Contribution to Total (%)
Off-Grid House 1	Petrol Generator	200	10
	PV (0.56 kWp)	300	16
	PV (1.59 kWp)	900	46
	Hydro (0.3 kW)	540	28
Off-Grid House 2	Hydro (1 kW)	1800	100

We calculated the impacts of 1 kWh of electricity consumed in Off-Grid Houses 1 and 2, considering the contribution of each technology to total electricity consumption in each home, respectively. These results are compared to a reference of 1 kWh consumed from the Portuguese electricity mix. We used a model of the Portuguese electricity mix developed by Garcia et al. [39], which takes into consideration the average electricity supply in the country from 2010-2014. These results, which will be referred to as the *Baseline*[3] scenario, represent the technologies in use in the homes today. The *Baseline* scenario is compared to two hypothetical scenarios that explore the impacts of extending the grid to the homes. We calculated each household´s distance from the grid using google maps: Off-Grid House 1 is 300 meters from the grid and Off-Grid House 2 is 900 meters from the grid. The hypothetical scenarios will be referred to as the *Grid Consumption* scenario and the *Grid Injection* scenario.

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[3] Scenarios (*Baseline, Grid Consumption, Grid Injection*) are distinguished in the text using italics.

The *Grid Consumption* scenario evaluates a hypothetical situation where the households do not have any off-grid systems, having decided to connect their homes and consume electricity from the Portuguese grid instead. The *Grid Injection* scenario evaluates a hypothetical situation where the households choose to extend the grid to their homes so they can connect their renewable electricity system(s) to sell excess electricity generated[4]. In the case of Off-Grid House 1, we assumed that there is no petrol generator, and the electricity consumed from this technology is replaced with electricity consumed from the grid. For both homes, we assumed that there are no batteries, as the grid acts as a virtual battery. The impacts from the grid extension are based on a model of one meter of low tension distribution grid in ecoinvent [69].

To determine each home´s heating needs we developed surveys (see Appendix 1) to collect heat consumption data for the year 2017. With this data, we defined each household´s heating needs as well as the amount of MJ that were consumed using each system. Table 3 illustrates Off-Grid House 1 and 2´s heat consumption in 2017 and the contribution of each technology to annual heat use.

Table 3. Household Heat Consumption, 2017

Household	System	Consumption (MJ)	Contribution to Total (%)
Off-Grid House 1	Wood Stove	23450	94.53
	Gas Stove (LPG)	1000	4.03
	Solar Cooker	358	1.44
Off-Grid House 2	Wood Stove	7817	85.2
	Gas Stove (Butane)	1000	10.9
	Solar Cooker	358	3.9

We calculated the impacts of 1 MJ of heat consumed in Off-Grid Houses 1 and 2, considering the contribution of each technology to total heat consumption in each home, respectively. These results are compared to a reference of 1 MJ consumed from the use of conventional electric heaters using electricity from the Portuguese mix. We used a model of the Portuguese electricity mix developed by Garcia et al. [39], which takes into consideration the average electricity supply in the country from 2010-2014. For this reference, it is assumed that the house is heated using conventional electric heaters (1 space heater, 1 water

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[4] This alternative is possible in Portugal according to the Portuguese legislation entitled Decreto-Lei n.º 153/2014 (DL n.º 153/2014), which established two types of possible production units: units for self-consumption, called *unidade de produção em autoconsumo* (UPAC) and small production units, called *unidade de pequena produção*, (UPP) [105]. In this case, we are referring to the UPAC configuration, because the UPP is geared more towards small energy producers, as opposed to individual households.

heater, 1 electric stove) using the Joule effect. The following subsection details the LCIs developed for each technology that were used to build life-cycle models.

3.3.2. Life-Cycle Inventories

Using a combination of household surveys, manufacturing specifications, published research in academic literature, and existing LCA databases, we developed LCIs for the technologies used to provide and store energy in the off-grid households. Table 4, Table 5, and Table 6, present the LCIs for electricity, storage, and heat systems, respectively.

Table 4. LCI of Electricity Systems

	Off-Grid House 1				Off-Grid House 2	Sources[5]
	PV	PV	Hydro	Generator	Hydro	
Power (kW)	1.59	0.56	0.3	5	1	
Energy Source	Sun	Sun	Water	Petrol	Water	
Lifetime (yrs.)	25	25	25	15	10	[41], [70], [71]
Weight (kg)	198	77.6	25	76	25	[71]
Consumption (kWh/yr.)	900	300	540	200	1800	
Investment Cost (€)	10000	3500	1600	750	6100	
O&M Cost (€/year)	50	18	8	75	16	[72]
Fuel Cost (€/year)	0	0	0	188	0	[73]
Local Persons Employed	1	1	1	1	1	

Table 5. LCI of Storage Systems

	Off-Grid House 1	Off-Grid House 2		Sources
	Lead-Acid Batteries	Lead-Acid Batteries	Li-Ion Batteries	
Battery Chemistry	$PbSO_4$	$PbSO_4$	$LiMn_2O_4$	[74]
Capacity (kWh)	25.38	14.88	11.52	
Cycle Life	1200	1200	2000	[74]
Weight (kg)	129	408	200	
Storage (kWh/lifetime)	30456	17856	23040	[74]
Investment Cost (€)	2994	2600	7740	
O&M Cost (€/year)	0	0	0	
Local Persons Employed	1	0	0	

Table 6. LCI of Heating Systems

	Off-Grid House 1			Off-Grid House 2			Sources
	Furnace	Gas-Stove	Solar Cooker	Furnace	Gas-Stove	Solar Cooker	
Lifetime (yrs.)	15	20	20	15	20	20	
Energy Source	Wood	LPG	Sun	Wood	Butane	Sun	
Weight (kg)	180	15	11	180	15	11	
Consumption (MJ/yr.)	23451	1000	358	7817	1000	358	
Investment Cost (€)	2000	100	300	2000	100	300	
O&M Cost (€/year)	0	0	0	0	0	0	
Fuel Cost (€/year)	180	52	0	60	26	0	[73]
Local Persons Employed	1	0	0	1	0	0	

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[5] See Appendix 1 for survey responses, which were used to build the LCIs. Additional sources are listed in this column if the information from the surveys was not enough to build the models.

3.3.3. Selection of Sustainability Indicators

Although there is no one defined standard to select sustainability indicators, the United Nations Environment Programme (UNEP) and SETAC have set recommendations for their selection. These recommendations suggest that all indicators should: be relevant across the life cycle of the product, be considered across multi-dimensional perspectives, and acknowledge stakeholder´s perspectives [21]. We chose indicators based on a combination of top-down and bottom-up approaches to ensure the robustness of assessing relevant issues. The top-down approach involves incorporating the perspective of experts within the field [60], while the bottom-up approach involves the participation of local stakeholders in the indicator selection process, which has been shown in other studies to empower and engage members of the community [75]. To consider the top-down perspective, three literature reviews on sustainability assessments regarding energy systems were compared in order to determine the most frequently cited sustainability indicators, presented in Table 7.

Table 7. Sustainability Indicator Frequency in Renewable Energy Systems Literature[6]

Dimension	Indicator	Unit	Review 1	Review 2	Review 3	Frequency
Environmental	Global Warming	$kgCO_2$ eq./kWh	7	11	31	49
	Land Use	m^2/kWh	5	8	14	27
	Acidification	$kgSO_2$ eq./kWh	1	7	7	15
	NO_x emissions	NO_x./kWh	0	1	11	12
	Biodiversity	Number of Species	1	0	11	12
	Eutrophication	$kgPO_4$ eq./kWh	2	7	0	9
	Lifespan	Years	2	0	6	8
	Ecotoxicity	kgDCB eq./kWh	1	7	0	8
Economic	Capital Costs	€	4	8	35	47
	Operation Costs	€/kWh	4	4	22	30
	Levelized Costs	€/year	2	10	6	18
	Response to demand	Summed Rank	0	5	11	16
	Availability Factor	Percentage (%)	4	5	6	15
	Energy Costs	€/kWh	1	4	8	13
	Installed Capacity	kWh	2	0	8	10
	Payback Period	years	2	0	7	9
Social	Total employment	Person-years/TWh	5	8	34	47
	Social Acceptance	Qualitative	1	3	18	22
	Fatalities	Fatalities/TWh	0	6	6	12
	Workplace Injuries	Injuries/TWh	0	4	6	10
	Human Health	kgDCB eq./kWh	0	7	0	7
	Direct employment	Person-years/TWh	0	7	0	7
	Fuel Supply Diversity	Score (0–1)	0	5	0	5
	Bill Reduction Rate	%	2	0	0	2

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[6] Review 1 corresponds to 7 studies on off-grid or decentralized energy provisioning [27], [37], [60], [62], [63], [116], [117]; Review 2 corresponds to indicators utilized in Akber et al. [55] and those utilized in 11 works reviewed by Kabayo et al. [56] regarding life-cycle sustainability assessments of centralized electricity generation systems; and Review 3 corresponds to the indicators found in the review of 62 LCSA and MCDA studies on energy systems by Gamboa et al. [118].

The reviews illustrated in Table 7 simulates the top down approach of surveying experts in the field by considering indicators used in reputable published and peer-reviewed journals. The bottom-up perspective was considered through conversations with circular economy experts and members of the Benfeita community. They were shown the results from Table 7 and asked to provide their feedback and suggestions for additional indicators if they saw fit. After a comparison of indicators presented in the top down and bottom up approaches, we selected a final group of 12 sustainability indicators considering the relevance of indicators and availability of data. Table 8 shows the selected indicators and the following subsections describe the indicators in detail and the justification for their selection.

Table 8. Sustainability Indicators

Sustainability Issue	Indicator	Unit	Source
Environmental			
Climate Change	Global Warming	g CO_2-eq./kWh or MJ	[76]
Energy Demand	Non-Renewable Fossil Energy	$MJ_{primary}$/kWh or MJ	[77]
Ecotoxicity	Freshwater Aquatic Ecotoxicity	CTU_e/kWh or MJ	[78]
Acidification	Terrestrial Acidification	g SO_2-eq./kWh or MJ	[79]
Eutrophication	Freshwater Eutrophication	g P-eq./kWh or MJ	[79]
	Marine Eutrophication	g N-eq./kWh or MJ	[79]
Economic			
Financial Burden	Investment Costs	€	N.A.
	Operation & Maintenance Costs	€/kWh	N.A.
	Levelized Cost of Energy	€/kWh or MJ	[72]
Social			
Human Health	Carcinogenic Toxicity	$CTU_{h,c}$/kWh or MJ	[78]
	Non-Carcinogenic Toxicity	$CTU_{h,nc}$/kWh or MJ	[78]
Local Employment	Number of local persons employed	#	N.A.

3.3.3.1. Environmental Indicators

Six midpoint indicator categories were chosen to illustrate life-cycle environmental impacts: Global Warming (GW), Non-Renewable Fossil Energy Demand (nREn), Freshwater Aquatic Ecotoxicity (FAE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), and Marine Eutrophication (ME). The methods for calculating these indicators were selected based on the recommendations and guidelines published by the European Commission-Joint Research Centre (EC-JRC) and the UNEP/SETAC Initiative [80], [81]. Although there are other impact categories and other sets of factors that can be considered, these impact categories were chosen because they represent an important mix of impacts to climate, ecosystems, air, and water.

GW is a common indicator used in LCA studies that quantifies the climate change impacts of anthropogenic greenhouse gases emissions by aggregating them into a common unit, carbon-dioxide equivalent (CO_2-eq.) [82]. It is a normalized cumulative metric that "uses the emission´s radiative forcing as an indicator ($W.m^{-2}.kg^{-1}$), integrates it (the absolute GW in $W.yr.m^{-2}. kg^{-1}$), and then divides the value at a specific point in time, the time horizon (TH), by that of CO_2" [81, p. 61]. For the present study, GW was calculated using the characterization factor (CF) by the Intergovernmental Panel for Climate Change (IPCC) 2013 for the time horizon of 100 years (GWP100), and presented in grams of carbon dioxide equivalent (g CO_2-eq) [76]. This method was selected because the JRC classifies it as a recommended CF (level I) for analyses of shorter term climate change, and it provides continuity with LCA practitioners and other studies in the literature [80], [81].

The Cumulative Energy Demand (CED) method quantifies the energy content of all different energy resources: non-renewable, fossil; non-renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; renewable, water [83]. This work considers the impacts of non-renewable fossil energy demand (nREn), as opposed to other forms of energy because of its heightened depletion level. nREn refers to nonrenewable energy extracted from nature in the form of primary energy [84]. nREn is characterized in mega-joules of primary energy using the CED method [77]. This impact category was chosen because gives similar results to GW, and therefore serves as a good point of reference when the results are presented together.

FAE refers to the impacts of toxic substances on aquatic ecotoxicity [82]. FAE is calculated based on the USEtox CF, characterized in Comparative Toxic Units for ecosystems (CTU_e), which relates effects on freshwater ecosystem species to the bioavailable fraction of chemicals in freshwater [85]. This indicator was selected because freshwater is a significant and unique environmental habitat essential for ecosystem biodiversity, thus it is important to reduce levels of toxicity on this source [86]. USEtox was chosen as the calculation method because it is recommended by the UNEP/SETAC regarding the characterization of toxic impacts in life-cycle assessments [78]. The main output of the USEtox model is a database of "recommended" or "indicative" CFs for FAE, based on the modelling of environmental fate, exposure, and effect parameters for the substances [85]. The main difference between the two methods is that the "indicative" CFs calculate the impacts of the metals, dissociating substances, and amphiphilic substances; while the "recommended" does not, due to the relatively high uncertainty of addressing the fate of these chemicals within substance groups [78]. When interpreting results, "indicative" CFs should always be shown together with "recommended" CFs in order to avoid that those substances considered as "indicative" be characterized with zero impact. Therefore, we chose to present both values in order to provide a more complete analysis. However, it is important to consider during the interpretation of the results that, due to deficiencies in the model or the available data, the “indicative” factors have a higher level of uncertainty than the “recommended” factors [85].

Almost all plant species in the world have an optimal level of acidity, which can be perturbed due to atmospheric deposition of inorganic substances such as phosphates, nitrates, and sulfates [79]. The resulting imbalance of soil acidity causes TA, which is harmful for plant species. TA is calculated in this study based on the midpoint CFs characterized in grams of sulfur dioxide equivalent (g SO_2-eq.) using the ReCiPe method [79]. While the JRC recommends the Accumulated Exceedance as the default method [87], the ReCiPe method is considered to comply on all essential aspects and facilitates comparison with other ReCiPe impact factors. This impact factor was measured in order to provide data regarding anthropogenic soil pollution.

FE covers impacts of high levels of macronutrients (most importantly phosphorous) leading to an elevated production of biomass in aquatic ecosystems, which can result in depressed oxygen levels rendering surface water unacceptable for drinking [82]. Its characterized in grams of phosphorus equivalent (g P-eq.) using ReCiPe [79]. This method was chosen because the JRC recommends it as the default method for FE [80], [88].

ME covers impacts of high levels of macronutrients (most importantly nitrogen) leading to an elevated production of biomass in the photic zone of marine coastal waters [82], [89]. It is characterized in grams of nitrogen equivalent (g N-eq.) using ReCiPe [79]. We chose to separate the eutrophication indicators in order to separate the impacts affecting phosphorous and nitrogen levels to provide a deeper level of detail in our analysis. This method was selected because it is recommended as the default method for ME by the JRC [80], [88].

3.3.3.2. Economic Indicators

The financial feasibility assessment of the energy provisioning systems in the off-grid homes were based on three indicators: Investment Cost, Operation & Maintenance (O&M) Cost, and the Levelized Cost of Energy (LCOE). The Investment Cost refers to the cost of the equipment as well as any installation costs, represented in Euros (€). The O&M costs refer to the annual costs related to maintaining the systems functionally operating, represented in €/year. The LCOE is a more comprehensive indicator that measures the net present value of the energy average unit cost, accounting for the lifetime costs of energy production, which allows for the comparison of different technologies with unequal lifespans, investment costs, and O&M costs.

Results for LCOE are presented considering a 1 to 5% discount rate. A range was considered in order to avoid bias from choosing one discount rate. This specific range was selected because these assets represent low-risk investments. The homeowners are not investors in the stock market, so their alternative to spending the money on these systems would be to keep their savings in the bank, which would only give them a 1 to 2% interest rate annually. Therefore, a range of low discount rates were chosen to reflect this reality. The results are presented based on the functional unit, so in €/kWh or €/MJ, considering electricity and heating, respectively. Equation 1 presents the formula used to calculate LCOE (reproduced from the International Renewable Energy Agency (IRENA) [72]):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{(Eq. 1)}$$

Where:

- LCOE= Levelized Cost of Energy;
- I_t = investment expenditures in year *t*;
- M_t = operation and maintenance expenditures in year *t*;
- F_t = fuel expenditures in year *t*;
- E_t = electricity generation in year *t*;
- r = discount rate; and
- n= economic life of the system

3.3.3.3. Social Indicators

Social impacts were evaluated based on three indicators evaluating impacts to human health and local employment: Carcinogenic Toxicity (CT), Non-Carcinogenic Toxicity (NCT), and Local Employment. Impacts to human health can be evaluated based on the relationship between human health effects to the mass taken in by humans via different exposure pathways, using the USEtox characterization method for human toxicity [85]. USEtox was chosen because it is recommended by the UNEP/SETAC regarding the characterization of toxic impacts in life-cycle assessments [78]. USEtox calculates the CF for human toxicity impacts in Comparative Toxic Units for humans (CTU_h), which estimates the increase in morbidity in the total human population per unit mass of a chemical emitted, divided into carcinogenic ($CTU_{h,c}$) and non-carcinogenic ($CTU_{h,nc}$) toxicity [85]. Like other USEtox characterizations, the model´s output includes both "recommended" and "indicative" CFs: the former are based on chronic or sub-chronic human health effect data, while the latter are based on sub-acute data [85]. As with other USEtox impact categories (e.g. FAE), results from both factors are presented in this study in order to provide a more detailed analysis.

During the selection phase of sustainability indicators, the homeowners made it clear that stimulating the local economy was an important matter for them when they considered how to live sustainably. In order to capture this idea, we developed a novel indicator to calculate local employment. The homeowners were asked to report the number of local persons involved during the building, installation, or maintenance of each system. Local Employment refers explicitly to hiring people within the community of Benfeita. Both homeowners stressed that one of the major reasons for going off-grid was to gain independence from large energy companies. So, we considered that the use of electricity from the grid does not result in the hiring of any local persons because it is managed by large energy companies. Even if a local person worked for an energy company and was hired for maintenance work, it was considered that that specific person hired was working as a representative of that energy company, and not of the local economy.

It is important to note that there exists an informal local economy in Benfeita as well. While some members use currency to exchange goods and services, others choose to trade working hours with each other. For example, one person may work a day in another community members farm in exchange for help in another project later. Our indicator considers the number of local persons employed during the lifetime of each system. Implicitly, this indicator says that the homeowners are happy if they are able to provide labor to many local persons (no matter how many hours or money). Therefore, it was found to be an adequate indicator to use in this informal economy also justified by a lack of data regarding the money or work hours exchanged.

3.3.4. E-LCA Model and Assumptions

Models were developed in order to calculate environmental-life cycle results for six indicators: Global Warming (GW), Non-Renewable Fossil Energy Demand (nREn), Freshwater Aquatic Ecotoxicity (FAE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME). The following subsections provide key details regarding the E-LCA models and assumptions for the electricity (Section 3.3.4.1) and heating (Section 3.3.4.2) systems.

3.3.4.1. Electricity Systems

The 1.59 and 0.56 kWp multi-crystalline silicon PV panels in Off-Grid House 1 are based on a model of multi-crystalline silicon PV systems from ecoinvent [70]. Within the infrastructure stage, we considered the transportation of parts to build the panels, the production of the inverter, and the transportation of the PV systems from the distribution center to the final consumer. Within the operation and maintenance phase, we consider the operation of the panels to produce electricity and the use of water to clean the panels.

The 0.3 kW hydro generator in Off-Grid House 1 and 1 kW hydro generator in Off-Grid House 2 are modeled based on an LCA study of a Powerspout[7] [71]. We considered the materials used in the manufacturing of a Powerspout, with some adaptations. For the 0.3 kW hydro system, which was built locally, we assumed that any power tools were operated using the electricity mix of Portugal, and that all of the parts used to build the system were produced within Portugal (so any transportation would be by van within the country). For the 1 kW hydro system, which is an actual Powerspout, we considered that the hydro system was manufactured in New Zealand and transported to Benfeita (by boat to Lisbon, and then van to Benfeita). We also included in the infrastructure life-cycle stage of the 1 kW hydro system the manufacturing, transportation, and installation of 450 meters of polyethylene pipe, which were installed by the homeowner in order to divert water from the stream to the hydro system. The operation and maintenance stage for both hydro systems included the use of the hydro system to produce electricity and the use of lubrication oil for maintenance. These values were based on ecoinvent [90], and scaled down to fit a 0.3 kW and 1 kW system, respectively.

The petrol generator was modeled based on a small internal combustion engine for a car from ecoinvent [91], because the components are similar to a small generator. The operation and maintenance life-cycle stage include the emissions of the petrol generator along with the use and waste of lubrication oil. We added petrol emissions to the model by considering a model for a passenger petrol car from ecoinvent [91], with all of the emissions not related to the petrol emissions omitted (such as brake, road, or tire degradation).

The lead-acid batteries were modeled based on an inventory of materials by Spanos et al. [74]. The manufacturing specification for the lithium-ion batteries did not

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[7] Powerspout is a brand for a micro-hydro generator developed in New Zealand.

disclose the exact battery chemistry, however, as the cycle life of the battery was cited as 2000 cycles per lifetime, we assumed that the battery chemistry was that of a lithium ion manganese oxide battery and based our inventory of materials on Notter et al. [92].

The models for grid extension were based on each household´s respective distance from the grid; Off-Grid House 1 is 300 meters from the grid and Off-Grid House 2 is 900 meters from the grid. The impacts from the grid extension are based on a model of one meter of low tension distribution grid in ecoinvent [69].

3.3.4.2. Heating Systems

We modeled the wood burning furnaces based on an inventory from Bauer et al. [93], and the impacts associated with the cultivation of wood based on a study from Dias & Arroja [94]. In order to calculate the amount of heat generated by the burning of wood, we used the weight of the dry wood considering that 40% of the total weight of the wood collected is made up of moisture [94]. According to the surveys (see Appendix 1), Off-Grid House 1 uses 1800 kg of dry wood and Off-Grid House 2 uses 600 kg of dry wood over one year. We considered 18.612 MJ/kg as the LHV of the wood burned, which is based on an average LHV of hardwood from a study conducted by Peduzzi et al. [95].

The gas stoves were modeled based on an inventory for gas stoves by Jungbluth [96]. We included in the infrastructure stage the transportation of the gas stove from Lisbon to Benfeita. The impacts from transporting the LPG tank and the butane tank over the lifetime of the stoves were also considered in this stage. We considered that the LPG or butane gas tanks would be refilled from the closest gas station to Benfeita in Tábua (24 km away). We modeled the tank being refilled when the energy content of the tank was empty, or once it has generated 548.9 MJ (for LPG) and 554.4 MJ (for butane). We assumed that the gas tanks had a capacity of 11 kg, and the energy content of butane to be 50.4 MJ/kg and of LPG to be 49.9 MJ/kg. The operation and maintenance stage considered gas emissions during combustion. We based the inventory of the emissions of LPG from Afrane & Ntiamoah [97], and the emissions from butane from ecoinvent [98].

Since there is no existing model for a solar cooker available in the literature or in ecoinvent database, the solar cookers in this study were modeled based on specifications by the manufacturer [99], which provided the main materials and approximate weights that make up the solar cooker: solar glass, cork, and aluminum. The model considers that the solar cooker was produced in Portugal and that the end-product was transported from Lisbon to Benfeita. The operation and maintenance stage considered the use of the solar energy to cook food.

3.3.5. LCC Model and Assumptions

The economic indicators evaluated the Investment Cost, O&M Costs, and LCOE. The following subsections provide key details regarding the LCC models and assumptions for the electricity (Section 3.3.5.1) and heating (Section 3.3.5.2) systems.

3.3.5.1. Electricity Systems

Investment Cost data was collected from surveys. The homeowners did not have specific data regarding O&M costs, so some assumptions were made. For typical electricity generation systems, annual O&M costs are often quoted as a percentage of the investment cost per kW per year, where values range from 1% to 4% for renewable energy systems [72]. Because the systems in the off-grid households are operated at a very small scale and the homeowners do most of the maintenance work for themselves, it was assumed that the O&M costs represented 0.5% of the investment cost of the system per kW. For the micro-hydro system in Off-Grid House 2, we considered that this calculated maintenance cost came from the investment cost of the hydro system (€1600), not the total cost of the system, which includes the cost of the polyethylene pipes (€4500). Since the maintenance cost of generators can be highly variable, a 10% of investment cost per kW per year was applied. The fuel cost for the petrol generator was calculated based on the average cost of petrol in Portugal in 2017, €1.6/L [73], and 40 L of petrol use per year based on the homeowner´s response in the survey (see Appendix 1). We assumed no cost for the maintenance of the batteries, since these types of batteries require no maintenance.

The LCOE of off-grid electricity were compared the cost of obtaining electricity from the grid. The cost of electricity from the grid was calculated based on the simple tariff employed by electricity distribution companies in Portugal. Energias de Portugal (EDP) is the market leader in terms of electricity distribution. In 2018 they served 82% of Portuguese clients, followed by Galp (5.2% of clients), Endesa (5.1%), and Iberdrola (3.8%) [100]. We considered the average simple tariff quoted by these four companies in order to provide a reference that reflects how market players are pricing electricity for their customers. For a system of 3.45 kVA, the average simple tariff was found to be 0.168 €/kWh + 23% value added tax (VAT) per kWh of electricity consumption, plus a fixed cost of 0.181 € per day of electricity use. We included the three taxes that are added to all electricity bills in Portugal:

tax on electricity consumption (*Imposto Especial de Consumo de Eletricidade* (IEC)) fixed at 0.001 €/kWh + 23% VAT [101], exploration taxes (*Taxa de Exploração da Direção-Geral de Energia e Geologia* (DGEG)) fixed at 0.07 €/month + 23% VAT [102], and audiovisual taxes (*Contribuição para o Audiovisual* (CAV)) fixed at 2.85 €/month + 6% VAT [103].

The cost of grid extension was based on the standards published by EDP, who provide an online tool that quotes grid extension costs based on the distance from the grid [104]. Using the cost calculator, we estimated the costs based on 300 and 900 meters of grid extension to be €2169 and €6724 in Off-Grid Houses 1 & 2, respectively. For the *Grid Injection* scenario, we included the savings from injecting excess electricity to the grid. Savings were calculated based on Equation 2, as stated in the DL n.º 153/2014 [105]:

$$RUPAC_m = E_{supplied,m} * OMIE_m * 0.9 \qquad \text{(Eq. 2)}$$

Where:

- $RUPAC_m$ is the remuneration in month *m* in €;
- $E_{supplied,m}$ is the energy supplied in month *m* in kWh;
- $OMIE_m$ is the simple arithmetic average of the closing price of the Iberian Energy Market Operator (OMIE) for Portugal in month *m* in €/kWh.

Based on Eq. 2 and considering the average annual OMIE value in Portugal from 2007-2017, savings were calculated as 0.047 €/kWh [106]. We also embedded the registration and inspection costs for each systems based on the regulations stipulated by the DL n.º 153/2014 [105], which states that systems between 200W and 1.5 kW must be registered with the DGEG through the Production Unit Registration Electronic System, called *Sistema Eletrónico de Registo da Unidade de Produção* (SERUP) and pay a registration fee. Systems up to 1.5 kW have a €30 fee, and systems from 1.5 kW to 5 kW have a €100 fee [107]. Systems with installed power above 1.5 kW or with power supply to the grid, are subject to inspections every 10 years, with a fee of 20% of the rate applicable to their respective registration [105], [108].

3.3.5.2. Heating Systems

Investment Cost data was collected from surveys (see Appendix 1). O&M costs took into consideration fuel costs, which were derived based on the quotes provided by the homeowners, with the cost of eucalyptus wood quoted at €30/m^3 and the cost of refilling a butane or LPG tank quoted at €26 per tank. The LCOE of off-grid heating were compared the cost of heating with electric joule heaters using electricity from the Portuguese grid. The cost of heating was based on the cost of electricity from the grid stipulated in Section 3.3.5.1 and converted to €/MJ. It was assumed that all the electric heaters (1 space heater, 1 water heater, 1 electric stove) in the house cost €200.

3.3.6. S-LCA Model and Assumptions

The social impacts evaluated were related to human health (carcinogenic and non-carcinogenic toxicity) and local employment. Human health impacts were calculated using the models created for the E-LCA (see Section 3.3.4). Local employment indicators were collected during the inventory reporting stage (see Appendix 1).

3.4. Multi-Criteria Decision Analysis

From the LCSA, we identify the life-cycle environmental, economic, and social impacts of meeting energy demands in the off-grid homes. The second part of the analysis involves the incorporation of MCDA methods in order to aggregate results and present homeowner preferences. Section 3.4.1 defines the decision problem we address, followed by a description of the applied MCDA methods in Section 3.4.2.

3.4.1. Decision Problem

As they currently stand, both off-grid households meet electricity and heating needs through stand-alone and completely off-grid systems. The results of the LCSA provide the environmental, economic, and social impacts of these stand-alone systems. However, they do not answer the question of whether these systems, or other alternatives, are the most sustainable means of meeting energy needs for these homes. In order to see if the stand-alone systems are the most sustainable option, we consider four hypothetical combinations of electricity and heating systems to meet the energy needs of each home. These combinations are presented in Table 9.

Table 9. Hypothetical Alternatives to Meet Energy Needs

Alternative	Off-Grid House 1		Off-Grid House 2	
	Electricity	Heating	Electricity	Heating
Baseline	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone
A_1	Grid Consumption	Stand-Alone	Grid Consumption	Stand-Alone
A_2	Grid Consumption	Grid Consumption	Grid Consumption	Grid Consumption
A_3	Grid Injection	Stand-Alone	Grid Injection	Stand-Alone
A_4	Grid Injection	Grid Consumption	Grid Injection	Grid Consumption

The **Baseline**[8] refers to the systems currently in place, which are stand-alone off-grid electricity and heating systems. Different combinations of electricity and heating systems are listed as new alternatives. **A_1** describes a scenario where the grid is extended and connected to the home so that all electricity is consumed from the grid, and heating needs are met by off-grid heating systems. **A_2** describes a scenario where the grid is extended and connected to the home so that all electricity and heating needs are met by consuming electricity from the grid. **A_3** describes a scenario where the grid is extended and connected to the home to allow for excess electricity, not consumed from off-grid technologies, to be sold back to the grid, and where heating needs are met by off-grid heating systems. Finally, **A_4** describes a scenario where the grid is extended and connected to the home to allow for excess electricity, not consumed from off-grid technologies to be sold back to the grid, and where heating needs are met by consuming electricity from the grid.

Each homeowner is presented a performance table listing the alternatives (A), and the criteria (j) by which they were evaluated. The criteria were chosen from the list of sustainability indicators selected for the LCSA (Table 8). Of the original, nine were selected to apply the MCDA. The values from nREn were excluded from the environmental assessment, because the results of this indicator follow the same trends as GW, so including both criteria would be redundant. The Energy Cost indicator was calculated based on the LCOE of the technologies (considering a 1% discount rate[9]). The Energy Cost Indicator internalizes the results of the Investment Cost and O&M Cost indicators, so the latter two were excluded from the MCDA. The MCDA methods are applied twice, once considering

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[8] MCDA alternatives (**Baseline**, **A_1**, **A_2**, **A_3**, and **A_4**) are distinguished in the text using boldface.

[9] A 1% discount rate was chosen here because of the range of values we presented prior (1-5%), 1% is closer to the actual interest rate that the homeowners would get if their money was in a bank.

the “recommended” CFs for FAE, CT, and NCT, and another presenting “indicative” factors. This allows for comparison of results considering both CFs.

In order to present the values of electricity and heating systems together, values for each indicator are calculated based on annual energy consumption. Then, the homeowners are presented a performance table that shows the percent change from the **Baseline** in each alternative. Table 10 provides an example of the performance table presented to each homeowner with the results of the assessment considering their home.

Table 10. Example of Performance Table

Criteria	Indicator	Baseline	A_1	A_2	A_3	A_4
j_1	Global Warming	$j_1(B)$	$j_1(a_1)$	$j_1(a_2)$	$j_1(a_3)$	$j_1(a_4)$
j_2	Freshwater Ecotoxicity	$j_2(B)$	$j_2(a_1)$	$j_2(a_2)$	$j_2(a_3)$	$j_2(a_4)$
j_3	Terrestrial Acidification	$j_3(B)$	$j_3(a_1)$	$j_3(a_2)$	$j_3(a_3)$	$j_3(a_4)$
j_4	Freshwater Eutrophication	$j_4(B)$	$j_4(a_1)$	$j_4(a_2)$	$j_4(a_3)$	$j_4(a_4)$
j_5	Marine Eutrophication	$j_5(B)$	$j_5(a_1)$	$j_5(a_2)$	$j_5(a_3)$	$j_5(a_4)$
j_6	Energy Cost	$j_6(B)$	$j_6(a_1)$	$j_6(a_2)$	$j_6(a_3)$	$j_6(a_4)$
j_7	Carcinogenic Toxicity	$j_7(B)$	$j_7(a_1)$	$j_7(a_2)$	$j_7(a_3)$	$j_7(a_4)$
j_8	Non-Carcinogenic Toxicity	$j_8(B)$	$j_8(a_1)$	$j_8(a_2)$	$j_8(a_3)$	$j_8(a_4)$
j_9	Local Employment	$j_9(B)$	$j_9(a_1)$	$j_9(a_2)$	$j_9(a_3)$	$j_9(a_4)$

For the first 8 criteria, j_1-j_8, results are presented to the homeowners in terms of impact minimization, meaning that negative percentages are favorable and positive percentages are unfavorable (e.g. -20% means a 20% decrease in emissions compared to the baseline). For criteria j_9 (local employment), results are presented in terms of impacts maximization, so a percent increase is favorable (meaning more jobs created), and a percent decrease is unfavorable (meaning less jobs created). As the decision is specific to each homeowner, the homeowner is presented with alternatives only for their own home.

3.4.2. Application of MCDA Methods

For the purposes of this study, Multi-Attribute Value Theory (MAVT) is applied and the robustness of results is tested using Stochastic Multi-Criteria Acceptability Analysis (SMAA) and Variable Interdependent Parameter Analysis (VIP). MAVT is a rigorous framework that allows for the computation of an overall score for different alternatives, utilizing weights for each criterion elicited from the DM [25]. Using this framework, the obtained result presents options that acknowledge the DM´s preference. SMAA and VIP are two methods that can be applied to evaluate the robustness of results. SMAA allows for the analysis of which kind of valuations would make each alternative the preferred one, without the use of preferences from a DM [109], while VIP allows for a greater degree of tolerance in analyzing results, providing a greater degree of flexibility for the DM [110].

MAVT is broken down into two main steps: building a value function for each criterion, and then computing a global value for each alternative so they can be ranked [111]. We built value functions and computed the global values using JSMAA software, an open-source software that allows for MAVT (along with other MCDA) computations [112]. Value functions reflect the subjective preferences of the DM over each criterion, by measuring how much value the DM places on its performance. The value function should reflect the performance of one alternative compared to another based on each criterion evaluated, and the difference between each alternative should reflect how much value the DM places on its performance. Furthermore, the DM needs to comply with two rules: transitivity of preferences and transitivity of indifference. The transitivity of preference says that if alternative *x* is preferred to alternative *y*, and *y* is preferred to *z*, then *x* must be preferred to *z*. Similarly if alternative *x* is indifferent to alternative *y*, and *y* is indifferent to *z*, then *x* must be indifferent to *z* [25].

There are various elicitation techniques available to determine preferences from a DM in order to build a value function. The choice of elicitation method is based on which method will better help the DM define their preferences. We chose to apply the bisection method [113], because it is easy to communicate and visualize, and therefore facilitates the elicitation process. Utilizing this method, we ask our DM to indicate the performance level that splits the interval of the value function of each indicator in two in terms of value such that, changing from 0 value to 0.5 changes just as much from going from 0.5 value to 1. We applied this technique to bisect the intervals of value in quarters for each of the criteria listed in order to build a utility value function for each criterion.

After developing value functions for each criterion, we ask our DM to determine the scaling coefficients (k-value) for each criterion using the swings method [113]. To do this, we ask our DM to compare improvements in one criterion to another and allocate points to express the relative added value of each swing so that the best swing was assigned 100 points. From there, the DM is asked to use this as an anchor to set point values for the rest of the criteria. Once points are determined for each criterion, they are summed, and scaling coefficients are assigned to each criterion by dividing K_i by the sum of total points. These values are then used to help determine scaling coefficients to determine weights for the global value. Finally, using the k-values determined in the swings method and the value functions elicited for each criterion, we compute a global value v(a_i) for each alternative a_i using the additive model, whose equation is defined below (Eq. 3) [25], [111]:

$$v(a_i) = \sum_{j=1}^{n} k_j v_j(a_i) = k_1 v_1(a_i) + k_2 v_2(a_i) \dots k_n v_n(a_i) \qquad \text{(Eq. 3)}$$

A global value is then computed for each of the alternatives, with the highest value corresponding to the most sustainable alternative. Once the global value was computed, a ranking was given from 1-5 on the sustainability of each alternative, with 1 being the most sustainable and 5 being the least sustainable option.

Robustness of results is tested using SMAA and VIP. SMAA allows for the computation of results for additive models (such as MAVT), without specifying a weights vector [29]. Using rank acceptability indices and weights supporting a potential winning alternative, SMAA presents results by generating k-values considering probabilistic distributions [109]. Using the JSMAA software, we evaluate the performance of each alternative to obtain a probability distribution for each alternative being placed in each rank. VIP analysis also allows for the computation of results for additive models (such as MAVT), through the use of linear programming to find the most extreme results that correspond to extreme weight vectors [29]. Using the VIP software [110], we evaluate the performance of each alternative to obtain a range of possible global values for each alternative.

3.5. Chapter Summary

This chapter described the combination of life-cycle and decision analysis materials and methods used to evaluate two off-grid households in Benfeita, Portugal. The chapter provided a detailed overview of the assessment framework in Section 3.1, followed by a description of the case study in Section 3.2. The application of LCSA and MCDA methods were presented in Section 3.3 and Section 3.4, respectively. Chapter 4 presents and discusses the results from the application of these methods.

4. RESULTS AND DISCUSSION

This chapter presents and discusses results. The outcomes of the E-LCA are discussed first in Section 4.1, followed by the LCC in Section 4.2, and the S-LCA in Section 4.3. The MCDA results are presented in Section 4.4, and Section 4.5 concludes with a chapter summary.

4.1. Environmental Life-Cycle Assessment

This section provides results for six indicators: Global Warming (GW), Non-Renewable Fossil Energy Demand (nREn), Freshwater Aquatic Ecotoxicity (FAE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME). Results for the electricity systems are presented first in Section 4.1.1, comparing the environmental life-cycle impacts of the consumption of 1 kWh of electricity in Off-Grid Houses 1 and 2 to a reference of 1 kWh consumed from the Portuguese electricity mix. This is followed Section 4.1.1.1., which provides a comparison of the *Baseline* scenario to two alternatives that take into consideration the added environmental burdens of extending the grid to the homes (*Grid Consumption* and *Grid Injection*). Results for the heating systems are discussed in Section 4.1.2., which illustrate environmental life-cycle impacts of 1 MJ of heat consumed in Off-Grid Houses 1 and 2 compared to a reference of 1 MJ consumed from electric joule heaters using the Portuguese electricity mix.

4.1.1. Electricity

Figure 4 illustrates the life-cycle impacts of consuming of 1 kWh of electricity in Off-Grid Houses 1 and 2 compared to the reference of 1 kWh consumed from the Portuguese electricity mix. Looking at all indicators together, the off-grid electricity systems outperform the reference in the categories of GW and nREn, but have higher impacts in FAE, TA, and ME. FE depletion levels are higher for Off-Grid House 2 compared to the reference due to the presence of lithium-ion batteries, where the use of phosphates in the production process lead to FE.

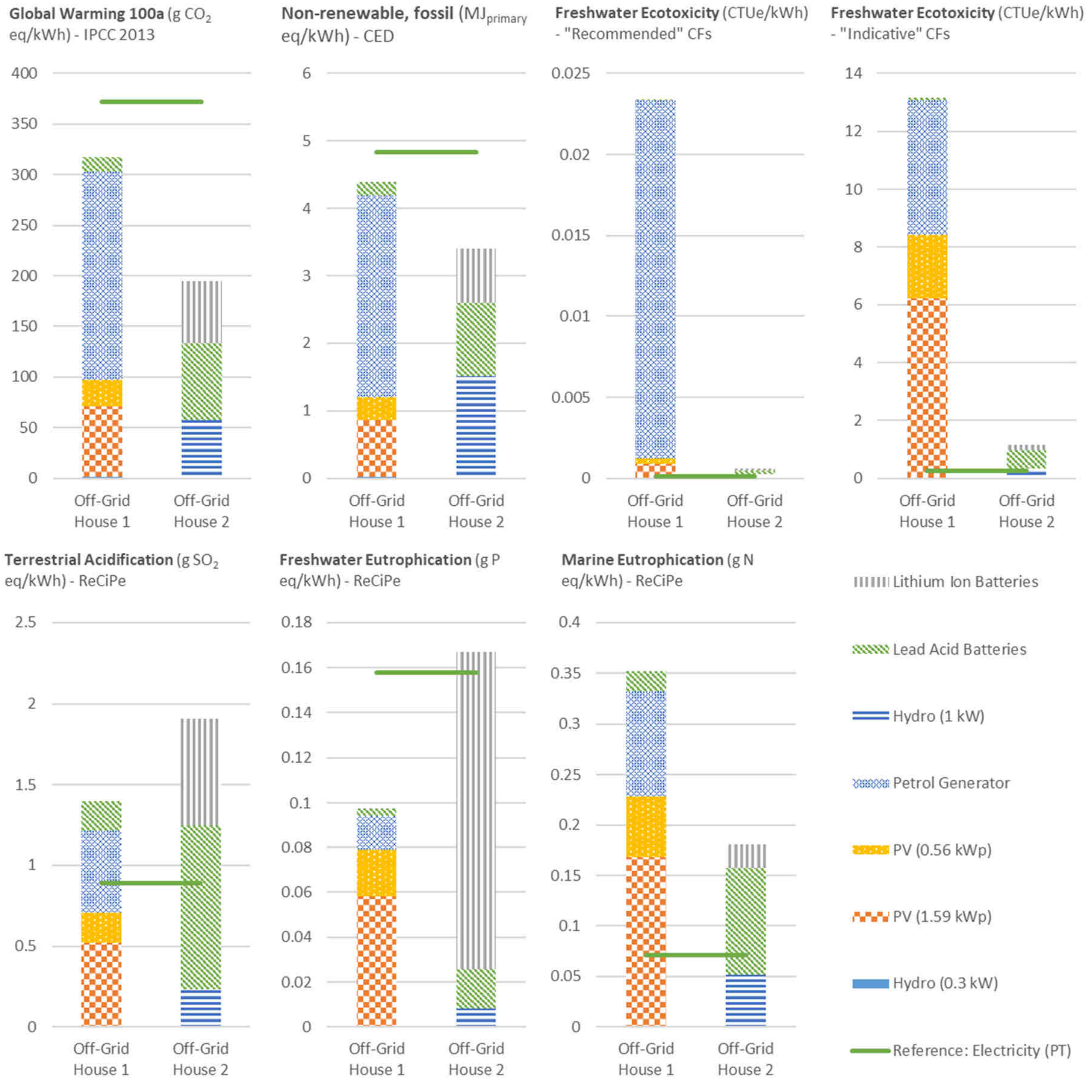

Figure 4. Environmental Impacts, Electricity

The environmental performance of the off-grid electricity systems compared to the reference varies depending on the impact category considered. Results for GW and nREn indicators show similar trends. The use of off-grid electricity has lower levels of GW and nREn because the majority of impacts, with the exception of the ones that come from the petrol generator, are realized during the systems' manufacturing stages and not their use; whereas consuming electricity from the Portuguese mix has high impacts in both the infrastructure and operation life-cycle stages because the mix includes the use of technologies (i.e. coal and natural gas plants) with high GHGs emissions and non-renewable energy content. Because of its reliance on the petrol generator for backup power, Off-Grid House 1 has greater impacts in GW and nREn than Off-Grid House 2. Although the petrol generator only accounts for 10% of electricity consumption, it makes up 64% of GW emissions (due to releases of CO_2 during the combustion of petrol), and 68% of nREn (due to the oil, gas, and coal that make up the energy content of the fuel). For Off-Grid House 2, upstream processes make up the majority of impacts in these two categories: lead-acid batteries are the highest contributors to GW (due to CO_2 released during the manufacturing process) and the 1 kW hydro system accounts for 81% of total nREn (due to the polyethylene pipe, whose production process uses high amounts of oil and natural gas). In contrast, consuming electricity from the off-grid systems results in higher impacts of FAE, TA, ME, and FE (for Off-Grid House 2). FE depletion levels are high for Off-Grid House 2 as a consequence of its use of lithium-ion batteries, whose production process releases phosphorous in the water. Table 14 in Appendix 2 provides a breakdown of results per life-cycle stage, which shows that most impacts are realized during the infrastructure stage, detailed further in the following paragraphs.

FAE results vary depending on the CF applied. As “indicative” CFs calculate the impacts of the metals and “recommended” CFs do not, there is a multiple orders of magnitude difference in results and each presents a different system as the principal contributor to FAE. Considering “recommended” CFs, the generator has the highest impacts, which is due to effluents released during its manufacturing process. However, acknowledging “indicative” CFs highlights the PV systems as the worst-performers, which is associated with the use of copper in the production of the panels. Although the generator still has an impact on FAE when “indicative” CFs are considered, its contribution gets surpassed by the PV systems. These discrepancies are important to note because they demonstrate how the consideration of metals in the calculation of toxicity affects results. While the consideration of “indicative” CFs are attributed to a higher level of uncertainty, not considering them would mean not acknowledging that the manufacturing process of the PV panels have an impact on FAE. Thus, it is important to consider the results of both analyses side by side, to be able to have a more holistic perspective of the impacts to this environmental indicator.

The infrastructure life-cycle stage of the off-grid systems is responsible for the majority of impacts that lead to TA, FE, and ME (see Table 14 in Appendix 2). The two PV systems account for almost 50% of TA in Off-Grid House 1. Manufacturing of the PV cells play a primary role, due to releases of N_2O and S_2O during this process. The use of the petrol generator is the next biggest contributor of TA, where 50% of these impacts are a result of emissions of S_2O from the combustion of petrol. In Off-Grid House 2, the batteries contribute the most to TA because their manufacturing results in S_2O and N_2O air emissions. In terms of FE, the lithium-ion batteries in Off-Grid House 2 and the PV panels in Off-Grid House 1 have the highest impacts due to releases of phosphates in their respective manufacturing processes. In terms of ME, the manufacturing of PV panels, the petrol generator, and batteries results in the release of nitrates in water. Emissions from the petrol generator during combustion also contribute to ME.

4.1.1.1. Alternative Scenarios

Figure 5 presents the percent variation from the *Baseline* to two alternatives: *Grid Consumption*, and *Grid Injection*. Positive numbers represent an increase in impacts, and negative values a decrease. A detailed breakdown of the contribution of each technology to these impacts is provided in Figures 20-26 in Appendix 3.

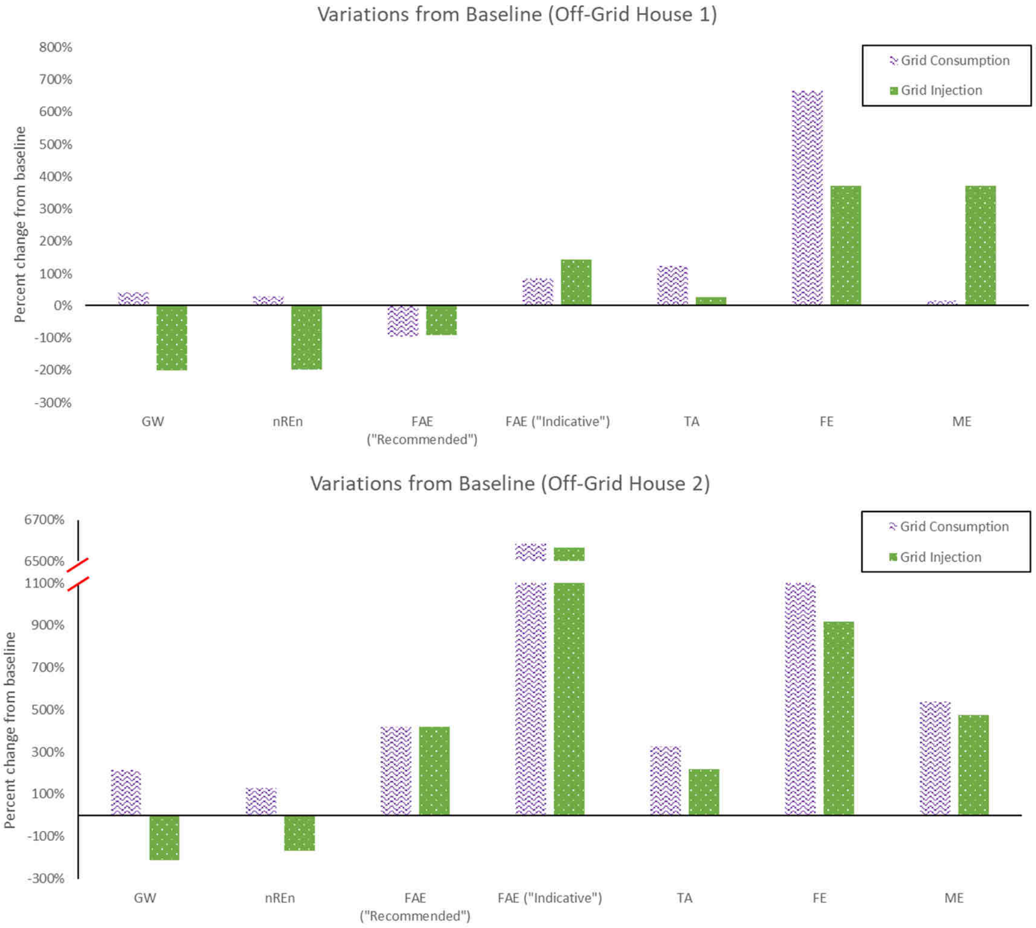

Figure 5. Environmental Impact Variations from Baseline

For the majority of indicators, both households have higher environmental impacts in the hypothetical scenarios compared to the *Baseline*. Depending on whether “indicative” or “recommended” CFs are applied in the calculation of FAE, the results are dramatically different. Grid construction requires the use of various metals, which result in releases of zinc and copper in the water (contributors to FAE). When FAE is calculated using “recommend” CFs, impacts from the use of metals during the construction of the grid are not taken into consideration; while when using “indicative” CFs, these impacts are considered, thus FAE results are higher.

For Off-Grid House 1, the *Grid Consumption* scenario increases emissions in all impact categories except for FAE when considering “recommended” CFs. This is due mainly to the use of the petrol generator in the *Baseline* scenario, which is the largest contributor to FAE in the home. Since the alternative scenarios result in the omission of this technology, impacts decrease dramatically. However, when “indicative” CFs are considered, the *Baseline* outperforms the alternatives in FAE because the impacts from extending the grid far outweigh the impacts from the use of a petrol generator. The *Grid Injection* scenario allows for 200% reductions in GW, 197% reductions in nREn, and a 91% reduction in FAE (“recommended” CFs). Yet, the *Baseline* outperforms the two alternatives in FAE (“indicative” CFs), TA, FE, and ME. For Off-Grid House 2, the *Grid Consumption* scenario increases emissions in all impact categories, making it a clearly undesirable alternative for this household. Although the *Grid Injection* scenario reduces GW by 211% and nREn by 166% from the *Baseline*, there is a massive trade-off when considering other impact categories. These impacts increase from a range of over 200% in TA to over 6000% in FAE.

The largest environmental contributor to all impact categories in the alternative scenarios, except when considering GW and nREn, is related to the physical extension of the grid. These impacts are especially dramatic for Off-Grid House 2 because of its larger distance from the grid (900 meters versus 300 meters for Off-Grid House 1). While there are a few environmental gains in the *Grid Injection* scenario, there is clearly a trade-off when considering other impact categories. The results of this analysis show that the benefits of being off-grid are dependent on context. When comparing the off-grid homes to the original reference (consuming electricity from the Portuguese grid), they had higher impacts in most of the categories considered. However, in this particular case, acknowledging the added burdens of extending the grid demonstrates the benefits of a stand-alone system, thus stressing the importance of context in determining the environmental viability of these energy provisioning services.

4.1.2. Heating

Figure 6 illustrates the life-cycle impacts of consuming of 1 MJ of heat in an off-grid household compared to the reference of 1 MJ of heat produced from electrical heaters with electricity obtained from the grid. The off-grid systems outperform the reference considering the indicators of GW, nREn, TA, and FE. Meanwhile, they contribute to higher levels of FAE (considering "indicative" CFs) and ME than using electricity from the grid. Off-Grid House 1 slightly outperforms the reference in terms of FAE (considering "recommended" CFs), while Off-Grid House 2 underperforms the reference in this category.

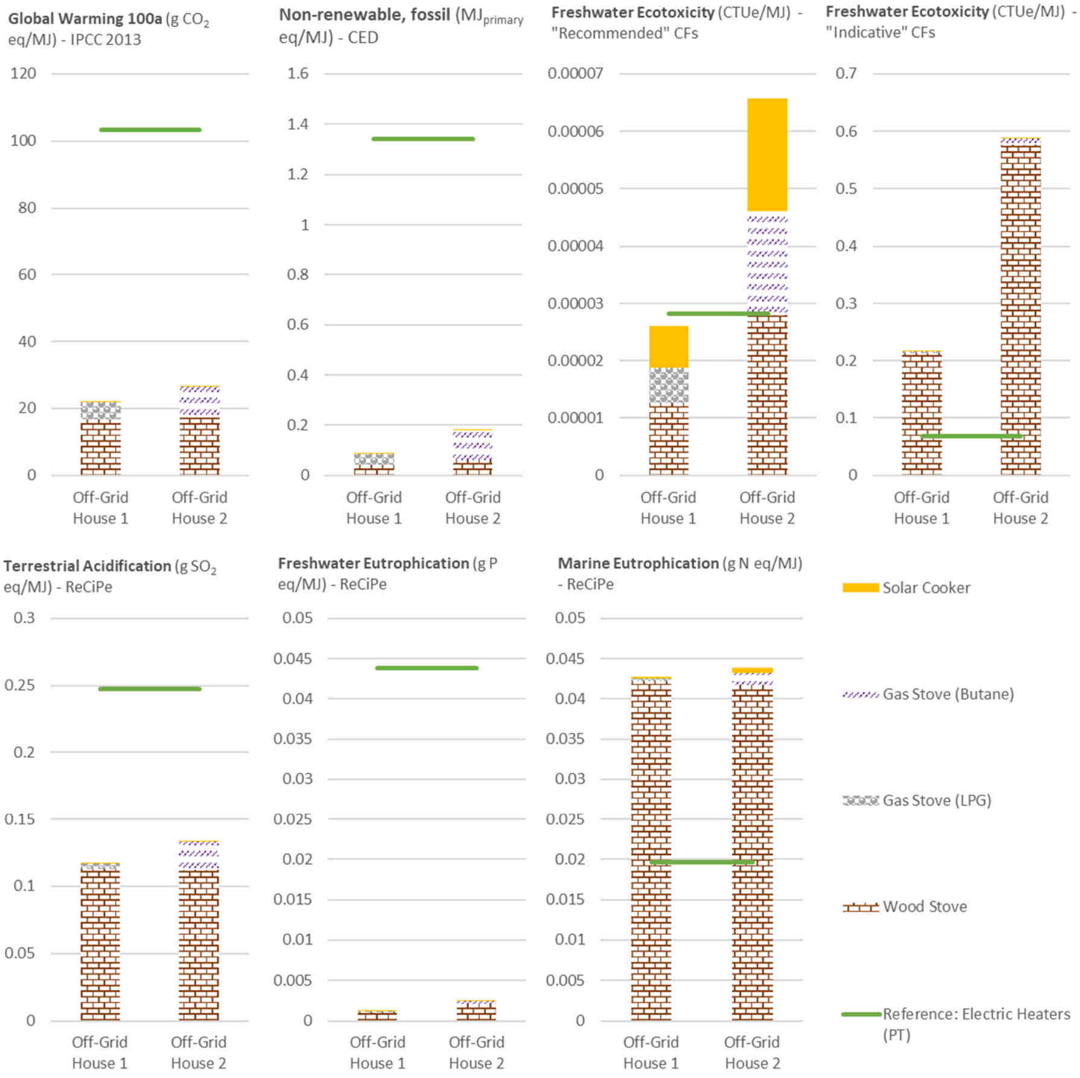

Figure 6. Environmental Impacts, Heating

The environmental performance of the off-grid heating systems varies depending on the impact category considered. Since they use similar technologies, the results for Off-Grid Houses 1 and 2 follow similar trends, except that the former has slightly lower impacts than the latter. This is the case because Off-Grid House 1 consumes more heat than Off-Grid House 2. Although it seems counterintuitive that a home that consumes more emits less, this is the case because the majority of heat consumption comes from the use of the furnace, a technology where most impacts are concentrated in its manufacturing processes (see Appendix 2, Table 15). Thus, more heat consumed by the household results in lower impacts when results are presented per MJ of heat consumed.

Unlike the results from the electricity systems, GW and nREn impacts do not follow similar trends. While off-grid systems have 74-78% lower GW emissions compared to the reference, the difference in nREn is more dramatic (86-93% lower impacts than the reference). These results differ because nREn does not consider any emissions from the burning of biomass, while over 70% of the furnaces´ GW emissions are attributable to the release of methane from burning biomass. It is also important to note that the IPCC 2013 method of calculating GW does not consider CO_2 released from the burning of biomass as a contribution to global warming, which would make results for GW slightly higher. CO_2 is not accounted for because the calculation considers emissions from burning biomass as carbon neutral, based on the principle that they are offset by a sequestration credit from the tree´s lifetime. A more comprehensive calculation considering the rate of carbon sequestration and atmospheric decay to calculate biomass derived CO_2 emissions, such as the one presented in Cherubini et al. [114], would provide more exact results in this impact category. However, the results from this analysis would still render the off-grid home´s impacts in this category as significantly lower than any conventional counterpart, therefore we considered this simplification in this CF´s calculation as satisfactory. The gas-stoves are the second highest contributors to these two impact categories, due to CO_2 emissions from the combustion of LPG and propane and their high fossil energy content. It is important to note, while the use of the gas stove represent only 4% and 10% of heat consumption, they make up 24% and 34% of total GW emissions in Off-Grid Houses 1 and 2, respectively.

The off-grid households result in higher levels of FAE, except for the case of Off-Grid House 1 when “recommended” CFs are acknowledged. Each method stresses a different hotspot for FAE. The consideration of “recommended” CFs highlights the solar cooker as a big contributor, due to the presence of cork, whose production process results in releases of cumene in the water. Meanwhile, the consideration of “indicative” CFs shows the furnace to be responsible for over 97% of all FAE impacts in both households, which is primarily due to the use of chromium in the manufacturing of the furnace. The disparity between the FAE impacts in both methods is due to the consideration of metals. The "recommended" method does not take metals into consideration in calculating the CFs, and only highlights other impacts, such as the use of insecticides in the cultivation of wood. Thus, the level of impacts is significantly higher when "indicative" CFs are considered.

The use of off-grid heating has significantly lower impacts in TA and FE than the reference. The use of off-grid heating systems reduces impacts on TA by 45-52% and on FE by 94-97% in the off-grid houses. Only the furnace plays a significant contribution to TA and FE in the off-grid households. The cultivation of eucalyptus is responsible for the majority of these impacts, because it considers the application of nitrogen-containing fertilizers, which accounts for releases in ammonia resulting in TA [94], and phosphates to the ground resulting in FE. This level of depletion, however, is significantly lower than the level attributed from the use of electricity from the grid. The presence of coal in the Portuguese electricity mix is the highest contributor to TA and FE impacts. In contrast, the use of the off-grid heating systems results in a 112-117% increase in ME compared to the use of electrical systems from the Portuguese grid. The use of eucalyptus wood in the furnace contributes the most to this impact category, due to the application of nitrogen-containing fertilizers, which accounts for releases in nitrates which contribute to impacts in ME.

4.2. Life-Cycle Costing

This section presents the results of the LCC for three indicators: Investment Cost, Operation & Maintenance Cost (O&M), and Levelized Cost of Energy (LCOE). Results for the electricity systems are detailed in Section 4.2.1, comparing the economic impacts of the consumption of 1 kWh of electricity in Off-Grid Houses 1 and 2 to a reference of 1 kWh consumed from the Portuguese electricity mix. This is followed Section 4.2.1.1., which provides a comparison of the *Baseline* scenario to two alternatives that take into consideration the added economic burdens of extending the grid to the homes (*Grid Consumption* and *Grid Injection*). Results for the heating systems are presented in Section 4.2.2, which illustrate economic impacts of consuming 1 MJ of heat in Off-Grid House 1 and 2 compared to a reference of 1 MJ consumed from the use of electric joule heaters using the Portuguese electricity mix.

4.2.1. Electricity

Figure 7 presents the Investment and O&M Costs for the electricity systems. The technologies installed in the off-grid homes require a high initial investment but have low operation and maintenance costs throughout their lifetimes. In order to be completely off-grid, homeowners must be willing to invest a large sum of money initially upfront. However, the marginal cost of producing electricity after the initial purchase is essentially zero because the systems are inexpensive to operate and maintain. Yet, because of the high initial investment of the assets, they have high total lifetime costs.

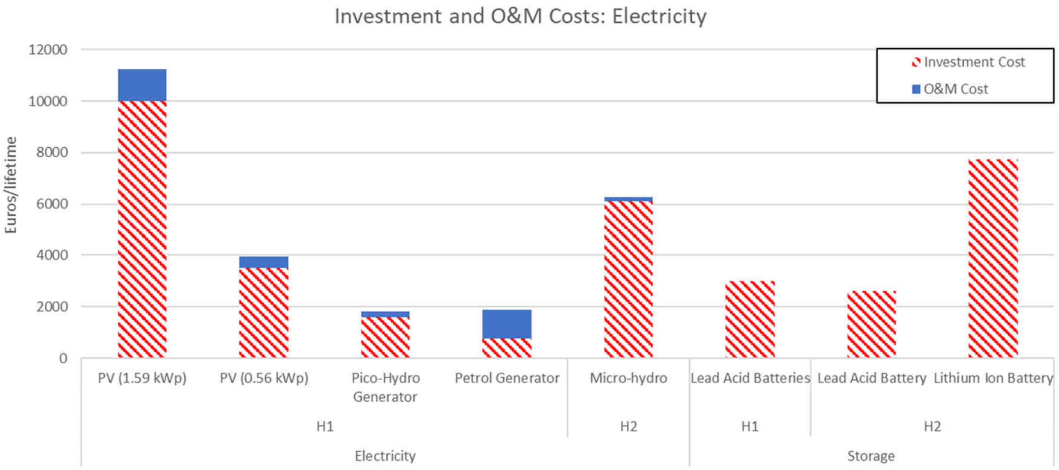

Figure 7. Investment and O&M Costs, Electricity

The LCOE of the electricity and storage systems compared to the cost of electricity in Portugal are presented in Figure 8. A sensitivity analysis considering different discount rates is included and presented with the use of error bars. The higher bar represents the LCOE considering a 5% discount rate, and the lower bar represents the LCOE considering a 1% discount rate.

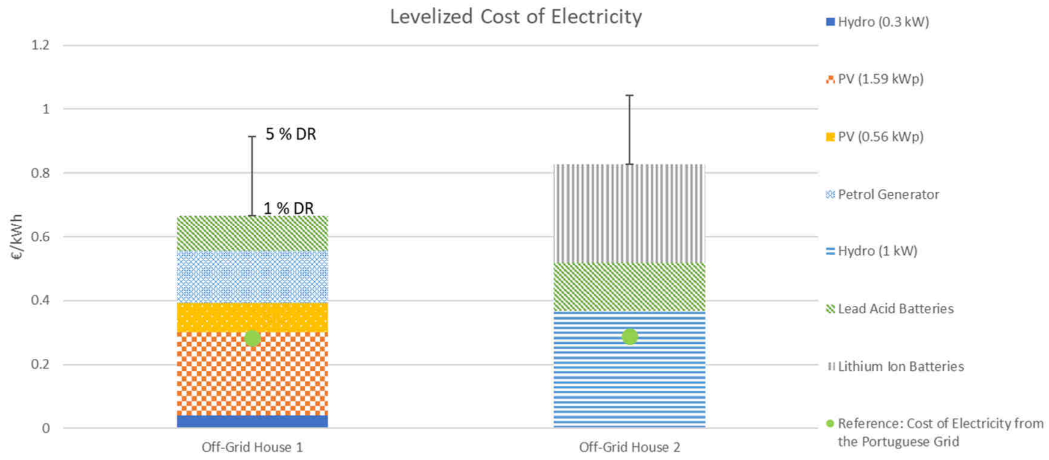

Figure 8. Levelized Cost of Electricity

This analysis shows the economic trade-offs of having a completely stand-alone and off-grid system. The off-grid homes have higher electricity costs than the cost of electricity from the grid. Considering a 1% discount rate, the cost of electricity from the grid is 57% lower than the LCOE of Off-Grid House 1, and 65% lower than the LCOE of Off-Grid House 2. This is due to the fact that there is a high investment cost to installing these systems, and the homes do not have high levels of consumption. If the systems were installed for a household that had a higher level of consumption, or if the systems were shared with various households, the LCOE would decrease, because there is a zero-marginal cost of producing additional energy by the systems. Thus, any additional consumption would be essentially “free” because the high costs come from the investment of the systems as opposed to their operation. However, because the households are completely independent, they have to incur a large upfront cost for systems that are over dimensioned for their use.

4.2.1.1. Alternative Scenarios

Figure 9 presents the variation from the *Baseline* to two alternatives: *Grid Consumption*, and *Grid Injection*. Positive numbers represent an increase in cost and negative numbers represent a decrease in cost compared to the baseline. A detailed breakdown of the contribution of each technology to these costs is presented in Appendix 3, Figure 27.

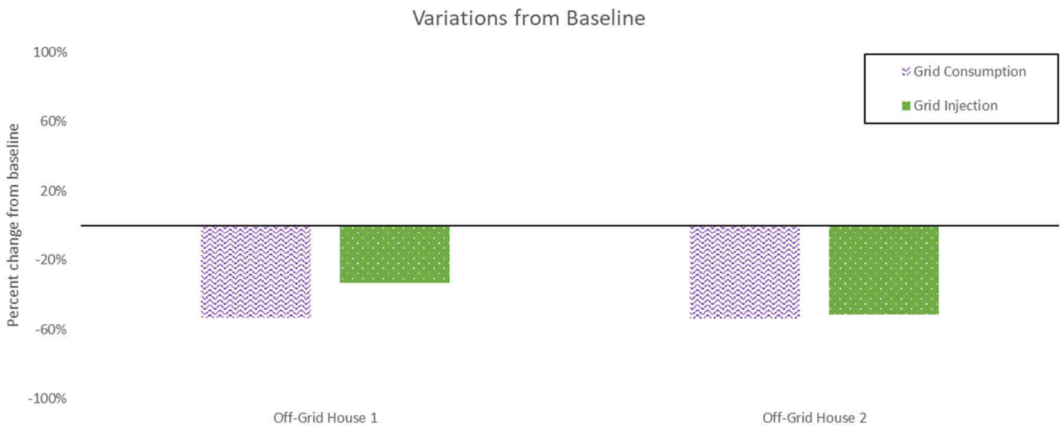

Figure 9. Economic Impact Variations from Baseline

Even taking into consideration the additional costs of extending and paying for electricity from the grid, the LCOE of the *Grid Consumption* scenario is lower than the *Baseline*, reducing costs by 52% in Off-Grid House 1 and by 53% in Off-Grid House 2. While extending the grid represents a high initial investment, it is offset by the fact that the grid has a lifetime of 40 years and will be used to provide all electricity needs. Although the *Grid Injection* scenario provides savings compared to the *Baseline*, it is still more expensive than the *Grid Consumption* scenario, which does not require investing in renewable energy systems. This is mainly due to the low returns from selling electricity back to the grid compared to the high costs of the renewable energy systems. Under the UPAC configuration, homeowners are only remunerated at 90% of the closing price set by the OMIE, which on average has been 0.04 €/kWh [105]. Because of this, the households are not able to recuperate many savings from the *Grid Injection* scenario. The real benefit that they get from connecting renewable energy systems to the grid is that it serves as a virtual storage system. By injecting all generation into the grid, energy systems are not limited to the storage capacity available and are able to generate electricity to their maximum potential. However, because the households have to first use the electricity they generate to power the home, they can only sell back excess generation at a low price.

4.2.2. Heating

Figure 10 presents the Investment and O&M Costs for the heating systems. Compared with the electricity and storage systems, heating systems have more significant O&M costs than Investment Costs. In the case of the furnace, these costs are associated with the purchasing of wood, and in the case of the gas stoves, they are associated with the purchase of LPG and butane.

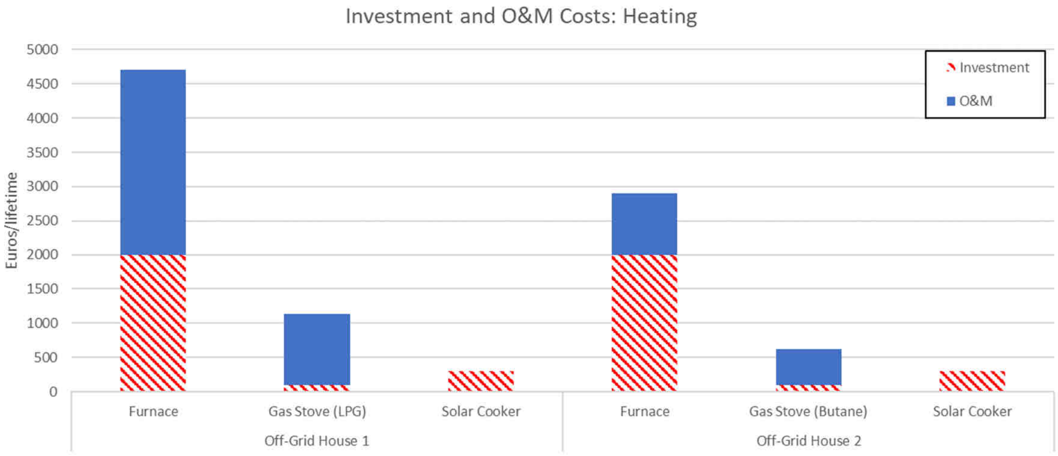

Figure 10. Investment and O&M Costs, Heating

Figure 11 presents the LCOE of the off-grid heating systems compared to the cost of heating with electric heaters from the use of electricity in Portugal (converted to €/MJ). A sensitivity analysis considering different discount rates is included and presented with the use of error bars. The higher bar represents the LCOE considering a 5% discount rate, and the lower bar represents the LCOE considering a 1% discount rate.

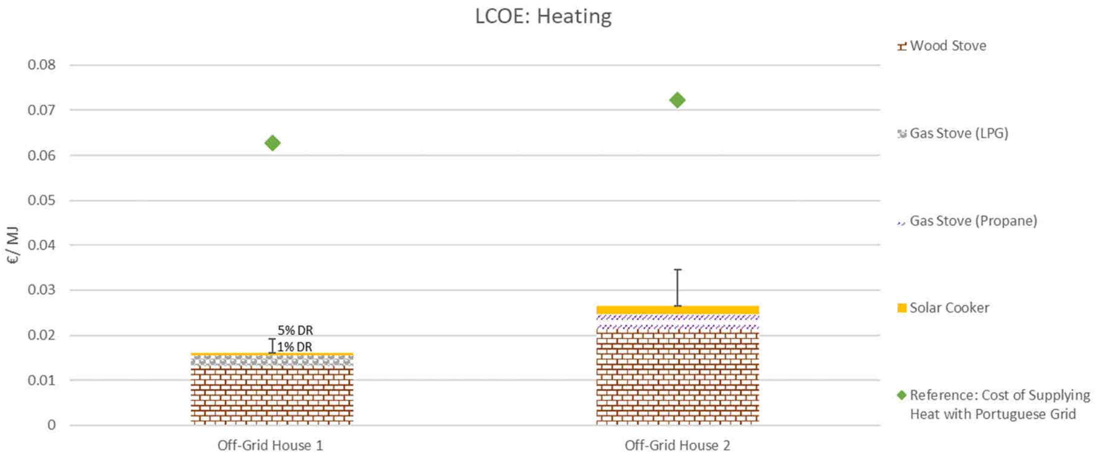

Figure 11. Levelized Cost of Heating

The cost of heating with the off-grid systems is 52-74% lower than heating with electricity from the grid. Because the households use inexpensive systems and consume little heat, they have lower costs than the reference. In this case, it is to the household's advantage to invest in off-grid heat generation systems as opposed to conventional systems.

4.3. Social Life-Cycle Assessment

This section presents social-life cycle results for three indicators: Carcinogenic Toxicity (CT), Non-Carcinogenic Toxicity (NCT), and Local Employment. Results for the electricity systems are detailed in Section 4.3.1, comparing the social life-cycle impacts of the consumption of 1 kWh of electricity in Off-Grid Houses 1 and 2 to a reference of 1 kWh consumed from the Portuguese electricity mix. This is followed by Section 4.3.1.1, which presents a comparison of the *Baseline* scenario to two alternatives that take into consideration the added social burdens of extending the grid to the homes (*Grid Consumption* and *Grid Injection*). Results for the heating systems are presented in Section 4.3.2 which illustrate social life-cycle impacts of consuming 1 MJ of in Off-Grid Houses 1 and 2 compared to a reference of 1 MJ consumed from the use of electric joule heaters using the Portuguese electricity mix.

4.3.1. Electricity

Figure 12 illustrates the social life-cycle impacts of consuming of 1 kWh of electricity in an off-grid household compared to the reference of 1 kWh obtained from the grid. In general, off-grid electricity consumption has greater health impacts than the use of electricity from the grid. Consuming off-grid electricity resulted in higher impacts in CT and NCT for both houses, with the exception of Off-Grid House 2, which had lower levels of NCT when "recommended" CFs are taken into consideration. It is important to note that health impacts are mostly related to upstream processes during the manufacturing processes of all systems. The only exception are the impacts related to the emission of petrol with the use of the generator in Off-Grid House 1. This means that while off-grid systems contribute more to CT and NCT, these health impacts do not directly affect the local community. Meanwhile, the use of off-grid electricity stimulates higher level of Local Employment in Benfeita.

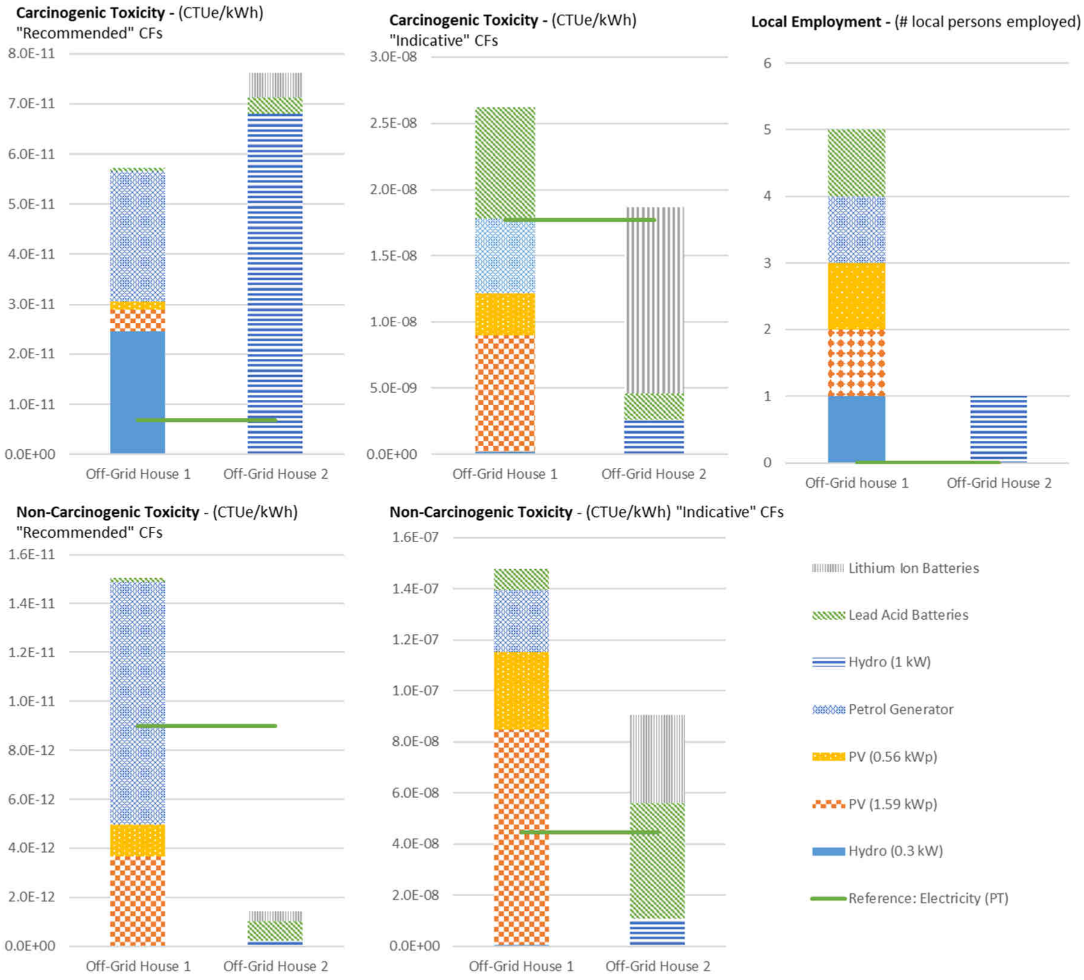

Figure 12. Social Impacts, Electricity

The off-grid homes have higher levels of CT compared to the reference considering both CFs, however, each stresses a different technology as the main contributor. When "recommended" CFs are considered, the hydro systems and the petrol generator seem to have the biggest impact on CT. For the hydro systems, this is due to the use of PVC, which in its manufacturing process releases tetrachlorodibenzo-p in the water. For the petrol generator, 51% of impacts are related to the manufacturing process which have prominent releases of benzene in the air and water, and 48% of impacts come from emissions of the petrol generator which have high releases of formaldehyde in the air. Meanwhile, the acknowledgement of "indicative" factors highlights the PV systems and the lead-acid battery in Off-Grid House 1 and the lithium-ion battery in Off-Grid House 2 as the main causes of CT. The PV systems and lithium-ion batteries show high levels of toxicity because chromium is a material used to produce these systems, which leads to chromium in the air, water, and soil. The lead in the lead-acid battery results in the release of formaldehyde in the air during the production process.

In terms of NCT, the performances of the households vary depending on the CF acknowledged. Off-Grid House 1 has higher levels of NCT than the reference for both CFs, while Off-Grid House 2 has higher levels only when "indicative" factors are considered. "Recommended" CFs highlight the petrol generator and the PV systems as having the highest effects on NCT. For the petrol generator, this is due to emissions of zinc in the water and air during its use, as well as various upstream processes during its manufacture. For the PV systems, this is due to results in methane in the air, propylene oxide in the air and water, and Aldrin in the soil during the manufacturing of the panels. The acknowledgement of "indicative" result in the PV systems in Off-Grid House 1, and the lead-acid battery in Off-Grid House 2 having the highest impact in NCT. For the PV systems, this is primarily due to the treatment of sulfidic tailings during the mining processes, which results in arsenic and zinc in the water. For the lead-acid batteries, the use of lead as a primary material results in the release of zinc in the air and lead in the air.

In contrast to the health impacts, the use of the off-grid systems has a positive benefit on Local Employment. In the case of Off-Grid House 1, all of the electricity and storage systems required the employment of local persons. The hydro system was completely built by the homeowner with the help of a local electrician, using materials that were purchased within Portugal and manufactured in Benfeita. Each PV system required the hiring of one local person to install when it was purchased, and the batteries required the hiring of a local person to connect to all of the electricity systems. The homeowner tends to hire one local person to do routine maintenance on the petrol generator. In the case of Off-Grid House 2, the homeowner hired a local electrician for the installation of his hydro system. In comparison, consuming electricity from the grid does not contribute to local employment because members of the Benfeita community would not be hired to either install or perform maintenance on the grid. Rather, the person hired would be a representative of the energy company that manages electricity services in the neighborhood. As the homeowners are adamant about being independent from large energy companies, they prefer to service their off-grid electricity systems with the help from people from the community. This would not be possible if they were dependent on receiving services from a specific energy company.

4.3.1.1. Alternative Scenarios

Figure 13 presents the variation from the *Baseline* to the two alternative scenarios: *Grid Consumption* and *Grid Injection*. Positive values for CT and NCT are considered unfavorable, and negative values favorable (as they represent an increase and decrease of emissions, respectively). In contrast, for Local Employment, positive values are favorable and negative values are unfavorable because they represent an increase or decrease in persons employed, respectively. A detailed breakdown of the contribution of each technology to these social impacts are provided in Figures 28-30 in Appendix 3.

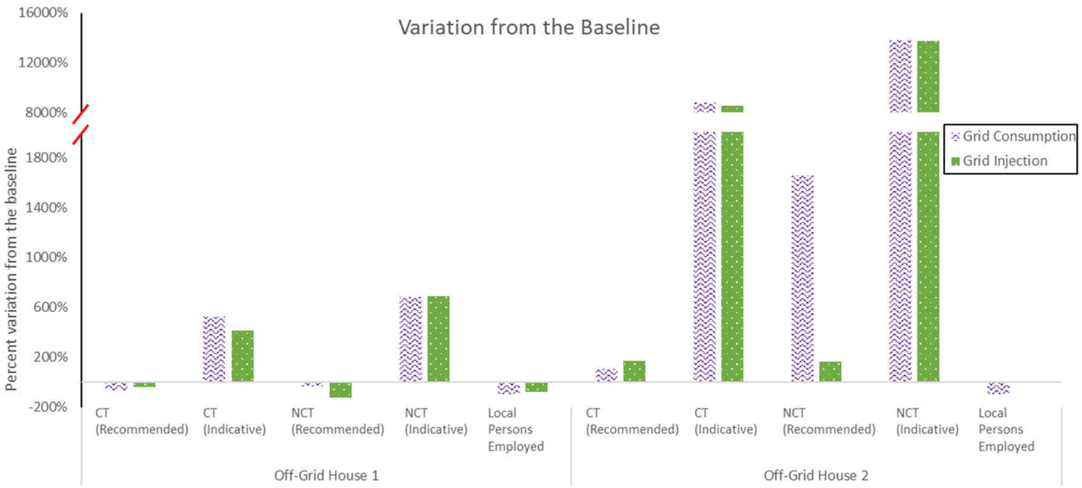

Figure 13. Social Impact Variations from the Baseline

For Off-Grid House 1, the performance of the alternative scenarios compared to the *Baseline* is dependent on the CFs considered. Considering "recommended" CFs, both alternatives result in a decrease in CT and NCT. However, if "indicative" CFs are considered, the metals related to the extension of the grid cause the total impacts to increase drastically compared to the baseline. In terms of Local Employment, the *Baseline* results in the most local persons employed. In contrast, for Off-Grid House 2, the *Baseline* is preferable to the alternatives considering all impact categories. CT and NCT increase in both scenarios considering both calculation methods. The only difference is that the increase is significantly higher when "indicative" CFs are considered. Local Employment decreases in the *Grid Consumption* scenario and stays the same for the *Grid Injection* scenario.

4.3.2. Heating

Figure 14 illustrates the social life-cycle impacts of consuming of 1 MJ of heat in an off-grid household compared to the reference of 1 MJ of heat produced from electrical heaters with electricity obtained from the grid. Compared to heating from the grid, off-grid heating use had lower impacts in CT and NCT considering both “recommended” and “indicative” CFs, and stimulated higher levels of Local Employment in Benfeita.

Figure 14. Social Impacts, Heating

The use of off-grid heating systems outperformed the reference in all indicators considered. From a health perspective, off-grid heating use had lower impacts in CT and NCT considering both CFs. When considering “recommended” factors, Off-Grid House 1 has 84% lower levels of CT than the reference and Off-Grid House 2 has 40% lower. Butane is a big contributor in Off-Grid House 2 due to the release of formaldehyde to the air during its burning. One of the main attributes of the solar cooker is that it is made out of cork, which, in its production process releases some formaldehyde which accounts for the majority of impacts towards CT from this system. When considering “indicative” factors, the furnace is the only system with a significant impact. This is mostly due to the use of chromium in the building process, which is depleted into the air, soil and water. Considering both CFs, the off-grid heating systems have significantly lower levels of NCT than using electricity for heating. When acknowledging “recommended” CFs, impacts from off-grid heating are over 97% less than those from the grid. Meanwhile, while considering “indicative” factors, the impacts are higher because of the consideration of metals in the production of the furnace, which accounts for zinc released into the water. The use of the off-grid heating technologies stimulated higher levels of Local Employment in Benfeita, because the homeowners contract a local person to deliver them wood at the beginning of the winter season. The other systems in the household do not contribute to local employment.

4.4. Multi-Criteria Decision Analysis

The LCSA results provide life-cycle environmental, economic, and social impacts of meeting energy needs in an off-grid home. In order to integrate these values, total impacts of the **Baseline** and four alternative options (**A_1**, **A_2**, **A_3**, and **A_4**) were calculated based on annual electricity consumption. Figure 15 presents a graphical representation of the percent variations from the **Baseline** for the four alternatives considering all sustainability indicators for Off-Grid Houses 1 and 2.[10]

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[10] Figure 15 was designed by the author using icons from [119].

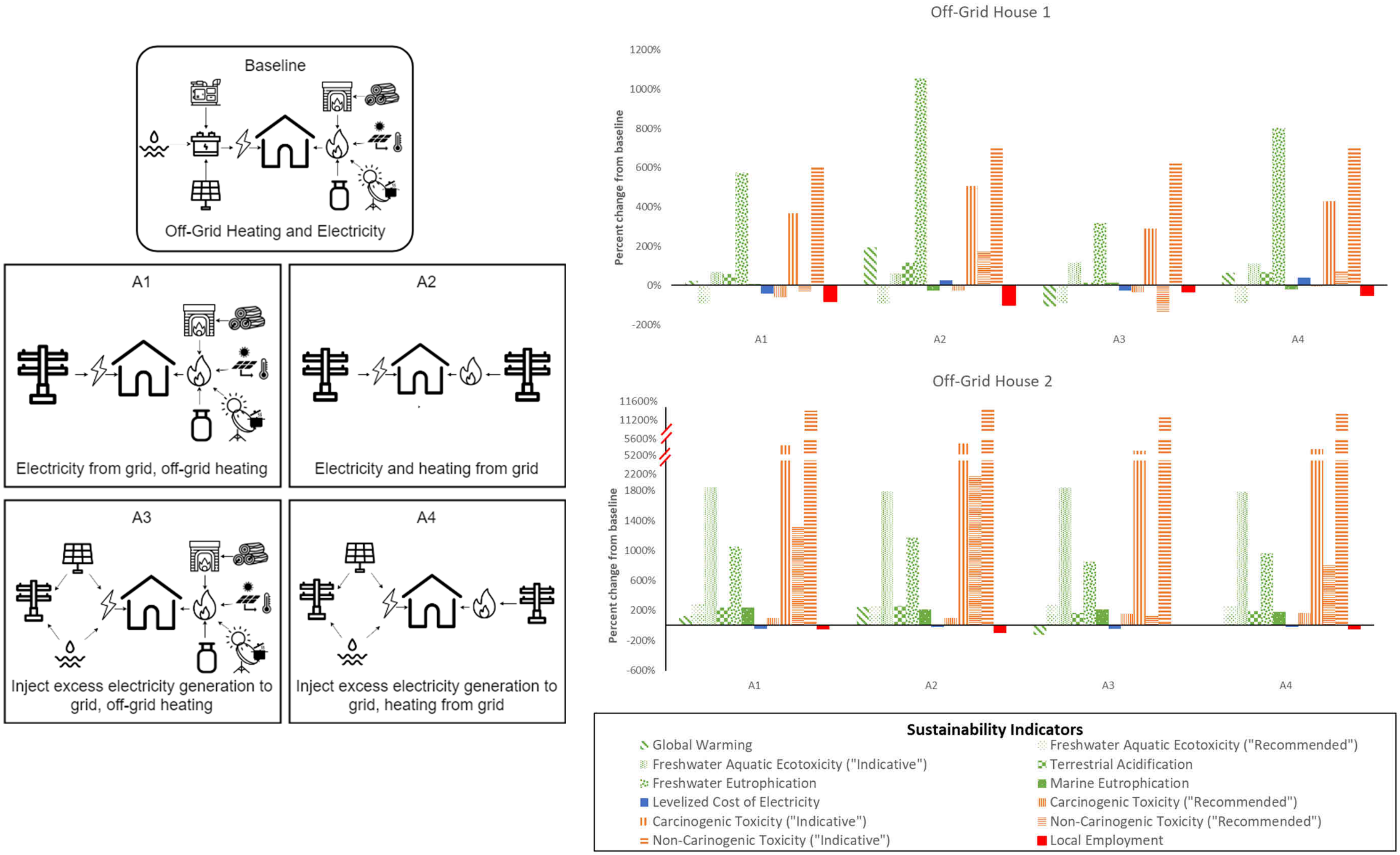

Figure 15. Sustainability Impact Variations from the Baseline

There is not one alternative that clearly dominates the others. Because of this, we applied MAVT in order to elicit preferences from the homeowners to understand whether the systems they currently have in place, or other alternatives, are the most sustainable means of meeting energy needs. The homeowners were presented a performance table (Table 11) showing the percent difference from the **Baseline** for the four alternative scenarios considering 9 sustainability indicators: GW (j1), FAE (j2 and j2*[11]) TA (j3), FE (j4), ME (j5), Energy Cost (j6), CT (j7 and j7*), NCT (j8 and j8*), and Local Employment (j9). The goal for criteria j1-j8 is impact minimization, while for criterion j9, higher values are better.

Table 11. Performance Table of Variations from Baseline for Alternative Scenarios

	Off-Grid House 1				Off-Grid House 2			
Criteria	A_1 (%)	A_2 (%)	A_3 (%)	A_4 (%)	A_1 (%)	A_2 (%)	A_3 (%)	A_4 (%)
j_1	22	195	-106	67	127	245	-124	-6
j_2	-94	-94	-90	-90	274	254	274	254
j_{2*}	70	62	119	111	1846	1788	1840	1782
j_3	60	117	13	70	240	263	167	190
j_4	574	1056	320	802	1056	1174	851	968
j_5	6	-27	13	-20	240	209	211	180
j_6	-41	27	-25	42	-47	-23	-44	-21
j_7	-61	-28	-37	-4	97	101	160	164
j_{7*}	368	508	290	430	5422	5467	5290	5335
j_8	-30	175	-133	72	1311	1997	132	817
j_{8*}	613	700	620	706	11535	11576	11446	11488
j_9	-83	-100	-33	-50	-50	-100	0	-50

We elicited homeowner´s preferences in order to build value functions for each criterion, which indicate how performances are valued by the DMs. Figure 31 and Figure 32 in Appendix 4, illustrate the resulting value functions for the owners of Off-Grid Houses 1 and 2, respectively. Once the value functions were determined, we elicited weights from the DMs for each criterion using the swings method. Table 16 and Table 17 in Appendix 4 provide the weights elicited from each DM.

The elicitation process revealed how different DM´s can perceive sustainability. Off-Grid House 1´s DM found it difficult to evaluate the utility of the environmental criteria, because this DM considers that all environmental criteria are important when discussing sustainability, and that it is not possible to consider one measure of environmental impact as more significant than another. This point of view is reflected by the DM´s assignment of similar weights and a linear value function for these criteria. Cost was another important indicator, because the decision to go off-grid was made in order to avoid energy costs in the

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[11] Both "recommended" and "indicative" factors are presented for FAE, CT, and NCT, with the criteria with a * referring to results based on "indicative" CFs and the other to "recommended".

future. This is reflected by the DM attributing the same weight for Cost of Energy as the environmental impact categories. The resulting value function for Cost of Energy shows that the DM is relatively content with the current financial scenario, and any cost increase would lower utility dramatically, while any cost decrease would slightly increase utility. Local Employment was also important, as going off-grid allowed the DM to hire local people from the community for the installation and maintenance of the systems. However, this criterion was not as significant as environmental and economic criteria, so it was assigned a slightly lower weight. CT and NCT were assigned low weights, because the DM did not find them to be as critical as the other categories.

Off-Grid House 2´s DM believes that impacts to the environment are the most important and is especially concerned with water issues. Thus, FAE was given the highest weight. The indicators related to water (FAE, FE, and ME) were all assigned steep value functions, with dramatic drops in utility for any increase of emissions. This DM considered CT and NCT to be the next most important indicators after the environmental criteria, followed by the Cost of Energy, and Local Employment. Local Employment was seen to be the least important because the DM saw it as an additional benefit of living off-grid, but not as a primary reason to go off-grid. The following subsections present both the stochastic and preference-based rankings for each alternative. The analysis was run twice, once considering "recommended" factors and another considering "indicative" factors.

4.4.1. Off-Grid House 1

Figure 16 presents the stochastic and preference-based rankings of alternatives in Off-Grid House 1 considering "recommended" CFs for FAE, CT, and NCT. The stochastic rankings are based on probabilistic distribution of weight vectors using SMAA. The preference-based rankings present the global value attained by the alternatives based on the results of the MAVT (shown in white) and the range of possible global values by each alternative based on the results of the VIP analysis, which uses linear programming to estimate results based on extreme weights (illustrated by the blue bar graphs).

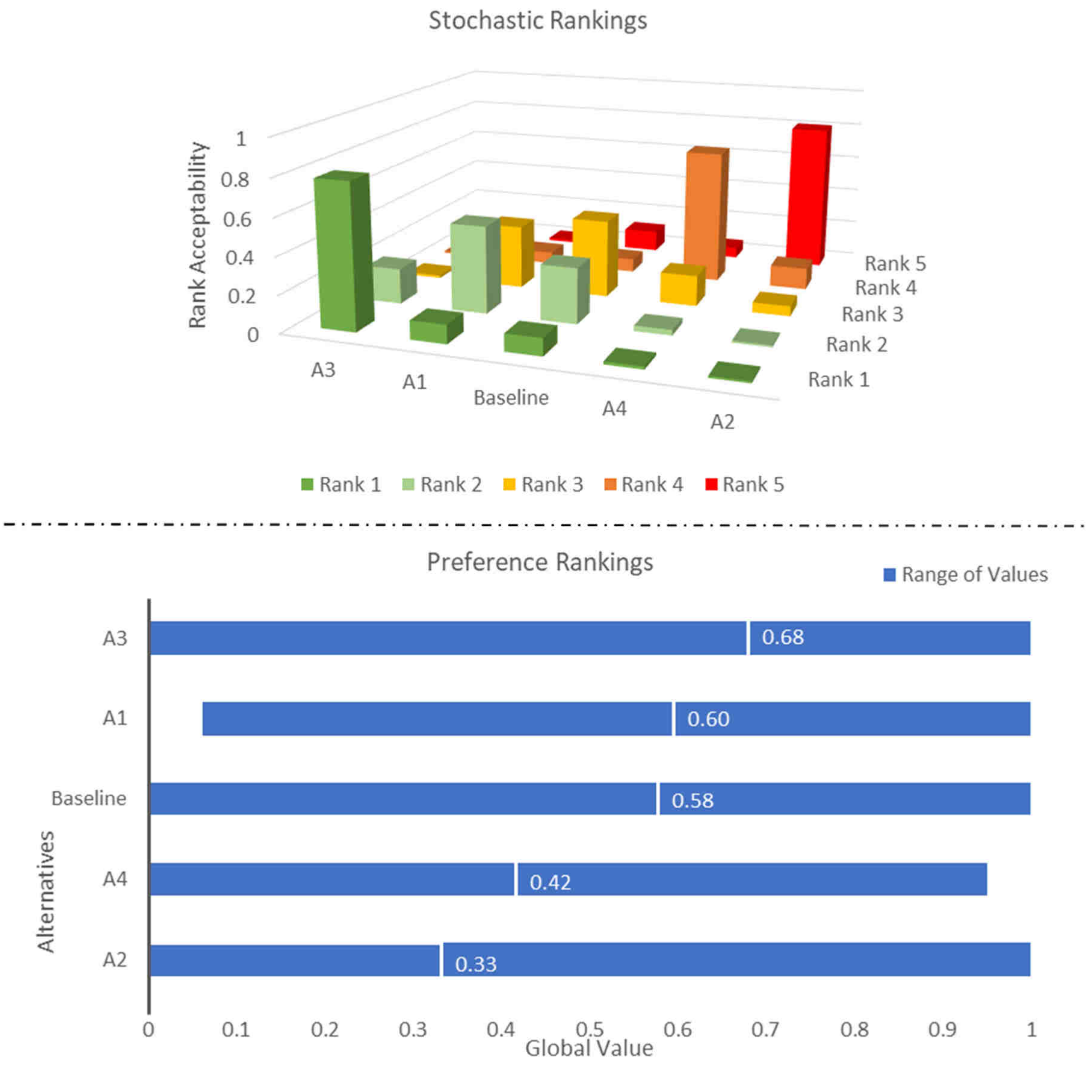

Figure 16. Off-Grid House 1, "Recommended" CFs

A3 (the scenario where the grid is extended to the home to allow for grid injection of excess electricity, while maintaining the use of off-grid heating systems) has a 78% chance of ranking first considering a probabilistic distribution of weights for the sustainability criteria. Therefore, this alternative will most likely be ranked first, regardless of the DM, which is consistent with the results using preference-based weights, where the alternative obtained the highest global value (0.68). The alternatives that could rank second and third are not as clear cut. **A1** (the scenario where the grid is extended to the home to allow for grid consumption of electricity, while maintaining the use of off-grid heating systems) and the **Baseline** (the current scenario) compete for Ranks 2 and 3, with **A1** having a higher probability of classifying as second and the baseline as third. Global values obtained based on the DM´s preferences were very close, **A_1** outranked the baseline by a mere 0.02 points. A different combination of weights could easily change this result. The lower ranking alternatives were more consistent. Based on DM preferences, **A_4** (the scenario where the grid is extended to the home to allow for grid injection of excess electricity, and use of electricity from the grid for heating) ranked fourth with a global value of 0.42 and **A_2** (the scenario where the grid is extended to the home to allow for grid consumption for electricity and heating) ranked fifth with a global value of 0.33. The stochastic rankings for these alternatives provide robustness to these results, 73% of weight distributions rank **A_4** in fourth and 80% rank **A_2** in fifth.

While the stochastic rankings of alternatives are quite constant, results from the VIP analysis show that under extreme weight considerations, almost all alternatives could score within the range of global values between 0 and 1, with the exception of **A_4**, whose maximum possible score is 0.95, and **A_1**, whose minimum possible score is 0.06. The VIP analysis also confirms that no alternative is clearly dominated by another, meaning that no alternative can be completely discarded.

When "recommended" factors are considered, **A_3** has a high probability of ranking first compared to other alternatives due to better performance of its electricity and heating systems in many of the evaluated criteria. From the point of view of the electricity systems, the ability to inject excess electricity to the grid offsets many of the environmental and health burdens from grid extension, and also results in lower overall costs than the baseline due to savings from selling back to the grid. The overall household performance is also strengthened by the use of off-grid heating systems, which outperforms the use of electricity from the grid for the majority of the impact categories evaluated. Part of the reason why **A_1** and the **Baseline** are ranked second and third, while **A_2** and **A_4** are ranked fourth and fifth can be attributed to the former using stand-alone heating and the latter using electricity from the grid to heat their homes. In contrast, the consideration of "indicative" CFs results in different rankings, as illustrated by Figure 17.

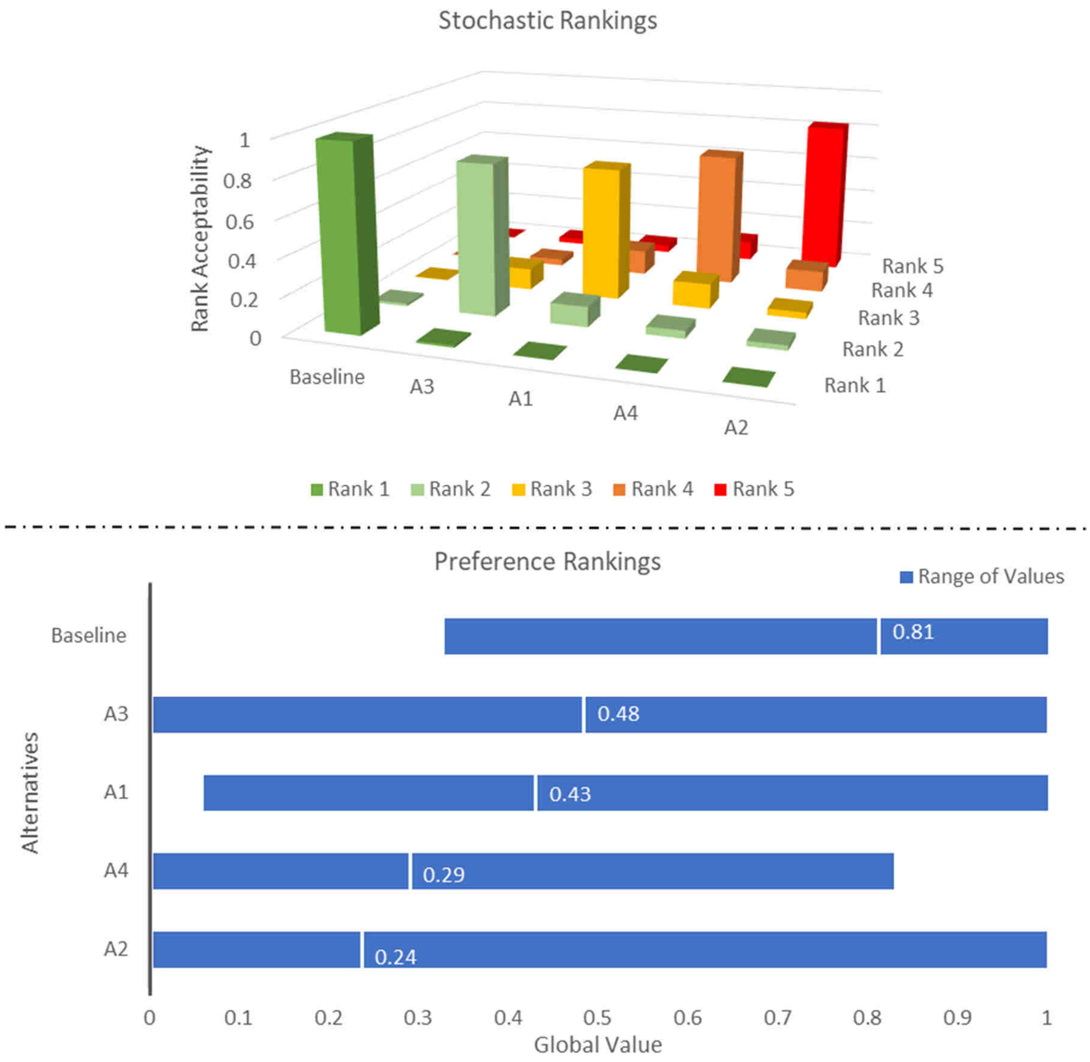

Figure 17. Off-Grid House 1, "Indicative" CFs

Considering "indicative" CFs for FAE, CT, and NCT, the **Baseline** secures Rank 1, achieving a global value of 0.81 based on the DM´s preferences. The SMAA verified the robustness of this result, as the **Baseline** will rank first 98% of the time based on a probabilistic distribution of weights. The results of the VIP analysis confirm that even under extreme weighting conditions, the **Baseline** could never achieve a lower global value than 0.33, while **A$_1$** has the possibility to score a global value of 0.06 and **A$_2$**-**A$_4$** a global value of 0. Based on the DM´s preferences, **A$_3$** was ranked second with a global value of 0.48, followed closely by **A$_1$** with a global value of 0.43. This is consistent with the stochastic rankings, which place **A$_3$** in Rank 2 over 80% of the time and **A$_1$** in Rank 3 over 70% of the time. Based on the DM´s preferences, **A4** was ranked fourth and **A2** ranked fifth, which is consistent with stochastic rankings which place **A4** in fourth place over 70% of the time and **A2** in fifth place over 82% of the time.

As demonstrated by the contrasting rankings illustrated in Figure 16 and Figure 17, the consideration of “recommended” or “indicative” CFs presents different alternatives as the most sustainable. While the consideration of “recommended” factors highlights **A3** as the best alternative, acknowledgement of “indicative” factors ranks the **Baseline**, an option that would rank third previously, as first. The primary reason for this divergence is due in large part to how each CF considers the environmental burdens in extending the grid.

The acknowledgement of “indicative” factors takes into consideration the use of metals during grid extension in the calculation of toxicity factors. Because of this, alternatives that include the extension of the grid perform dramatically worse than when “recommended” factors are considered, which do not account for the use of metals in the calculation. This explains the drop in the ranking of **A3** when “indicative” CFs are considered. Considering “recommended” CFs, the grid injection scenario for electricity and use of stand-alone heating systems presents the most benefits for this household. However, if the added burden of the metals used during the grid extension are acknowledged, this alternative is no longer the most attractive, and the benefits of a completely stand-alone system are greater. Even though “indicative” factors are accompanied by higher uncertainty, it is important to consider them because not acknowledging these impacts can lead to a skewed result. Thus, presenting results considering both CFs is beneficial because it provides a more comprehensive assessment of environmental impacts.

4.4.2. Off-Grid House 2

The results for Off-Grid House 2 differ greatly from Off-Grid House 1, primarily due to the location of the home and the types of systems utilized. Figure 18 presents the stochastic and preference-based rankings of alternatives in Off-Grid House 2 considering “recommended” CFs for FAE, CT, and NCT. The stochastic rankings are based on probabilistic distribution of weight vectors using SMAA. The preference-based rankings present the global value attained by the alternatives based on the results of the MAVT (shown in white) and the range of possible global values by each alternative based on the results of the VIP analysis, which uses linear programming to estimate results based on extreme weights (illustrated by the blue bar graphs).

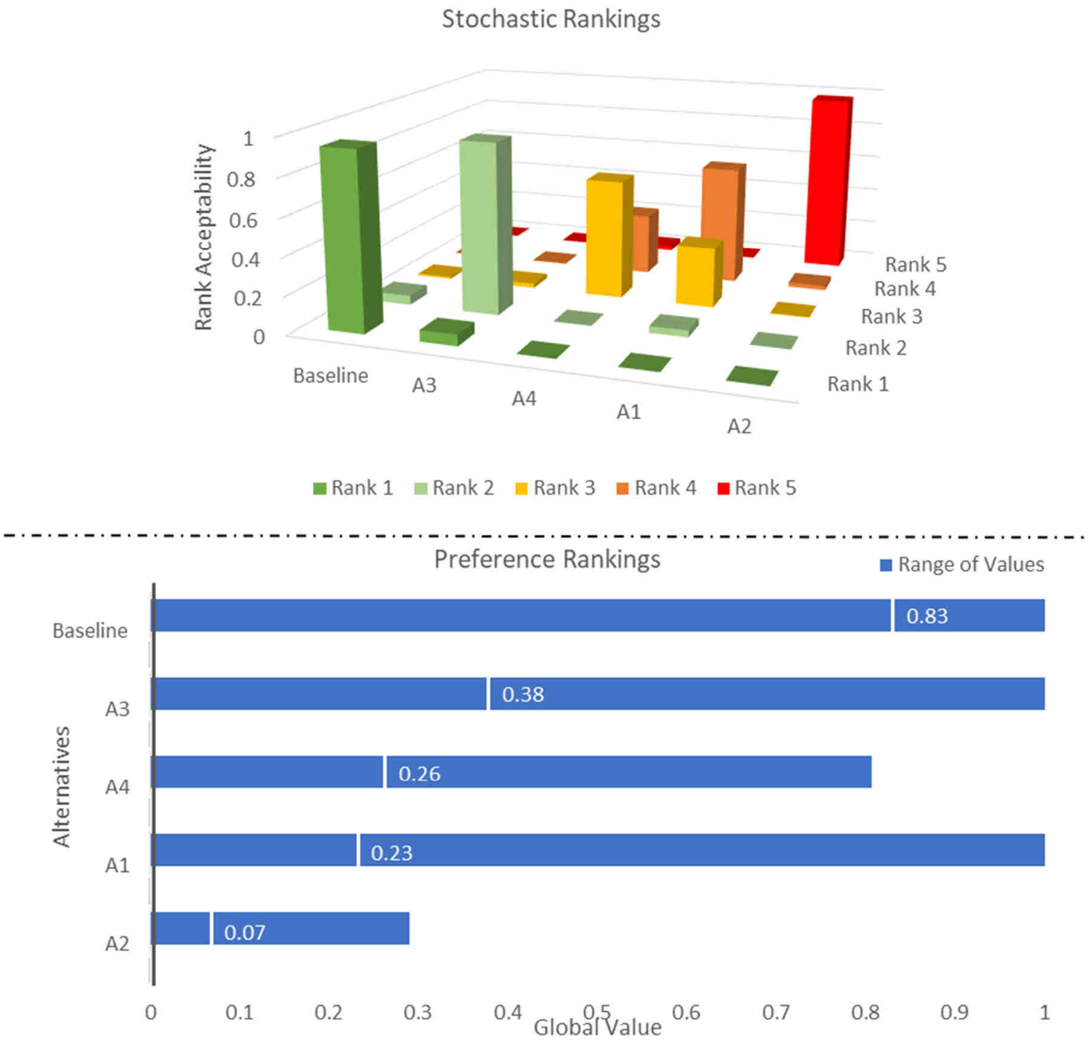

Figure 18. Off-Grid House 2, "Recommended" CFs

The **Baseline** has a 93% chance to be ranked first considering a probabilistic distribution of weights for the sustainability criteria. This is consistent with the results using preference-based weights, where the alternative obtained the highest global value (0.83). **A3** is ranked second 91% of the time, **A4** has a higher probability to be ranked third and **A1** ranked fourth. **A2** is securely ranked fifth considering both calculation methods, with a 97% probability. The results of the VIP analysis confirm that no alternative is clearly dominated by another, however, **A2** only has the possibility of achieving a maximum global value of 0.29 and **A4** of 0.80, while the other alternatives can achieve any value from 0-1 considering extreme weights. When "indicative" CFs are used instead, the results are quite similar, as illustrated in Figure 19.

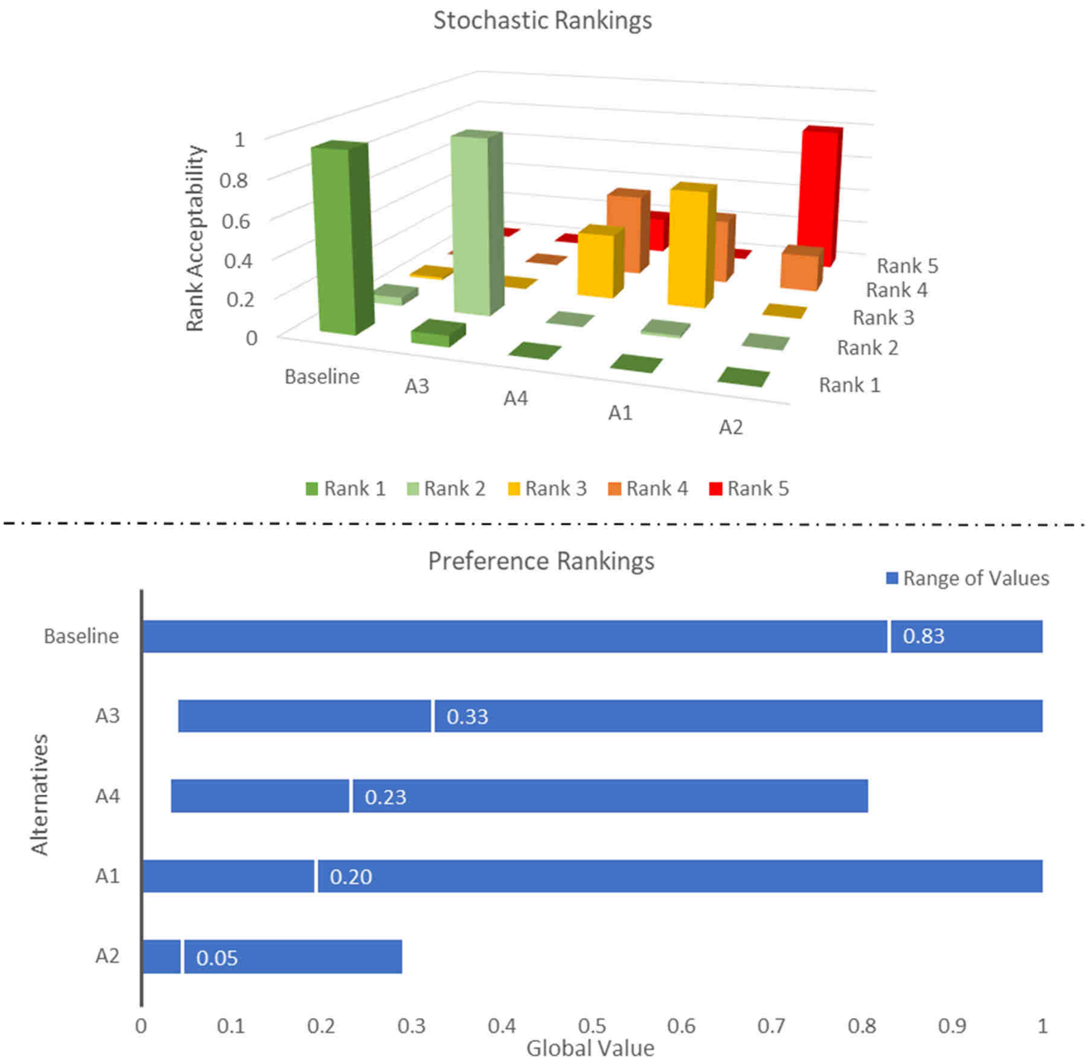

Figure 19. Off-Grid House 2, "Indicative" CFs

Considering "indicative" CFs, the **Baseline** is ranked first, with a global value of 0.83 based on elicited preferences. These results are robust, as the alternative has a 94% likelihood of being ranked first considering a probabilistic distribution of weight vectors. **A$_3$** is ranked second 93% of the time, with a global value of 0.33 based on this DM´s preferences. Compared to the results when "recommended" factors are considered, the distance between Rank 1 and Rank 2 in this scenario is slightly larger (0.50 versus 0.45). Based on elicited preferences, **A$_4$** is ranked third and **A$_1$** is ranked fourth. However, according to stochastic rankings, **A$_4$** has a higher probability to be ranked fourth than third (44% versus 35%), and **A$_1$** has a higher probability to be ranked third than fourth (63% versus

35%). Finally, $\mathbf{A_2}$ is securely ranked fifth, with a global value of 0.05 based on the DM´s preferences and an 80% chance of achieving that rank.

Both calculation methods rank the **Baseline** as the best alternative by a large margin. This is primarily due to the level of isolation of Off-Grid House 2, which is 900 meters away from the grid and isolated from the community. Because of this, the burdens from extending the grid to only one household are quite large. Considering "recommended" factors, at least five households that require grid connection would need to exist in this area to sufficiently lower the impacts from the grid extension so that the **Baseline** would no longer be ranked first.[12] However, when "indicative" factors are considered, eight households in the area would have to be connected. The main difference between the two is that consideration of "indicative" CFs increases the distance between the alternative ranked first and the other alternatives. As "indicative" factors consider metals in their calculation of toxicity, impacts will be larger than when "recommended" factors are considered. In this case, the burdens from grid extension (which uses a lot of heavy metals) are important to the overall impacts of the system, thus whether or not metals are considered in the calculation has a drastic effect on the results.

4.5. Chapter Summary

This chapter discussed the results of the combined LCSA-MCDA study evaluating two off-grid households in Benfeita, Portugal. The results for the environmental assessment were presented first, followed by the economic assessment, and the social assessment. Results were presented separately for electricity and heating systems. Alternative scenarios (*Grid Consumption* and *Grid Injection*) evaluated the additional burdens of extending the grid to the homes to explore other forms of energy provisioning. To integrate results, four alternatives ($\mathbf{A_1}$, $\mathbf{A_2}$, $\mathbf{A_3}$, and $\mathbf{A_4}$) were assessed against the **Baseline** using MCDA methods, ranking them based on their sustainability.

The results of this analysis show that a consideration of trade-offs is essential to understanding the value of alternative possibilities for household energy provisioning. This is especially important in the case of off-grid households because of the relevance of the

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[12] This analysis was performed by calculating total impacts considering additional households connected to the grid. In the alternative scenarios, the impacts for grid extension are all attributable to Off-Grid House 2. However, if there were two households in the area, only half of the impacts would be attributable to Off-Grid House 2, and if there were three, one-third, etc. We calculated total impacts of one additional household until the results of the MCDA considering the DM´s preferences would no longer rank the **Baseline** alternative first.

distance from the grid. When off-grid electricity systems were compared to a conventional home using electricity from the grid, the off-grid systems had higher environmental impacts in most impact categories, and higher costs. However, when the impacts from grid extension were taken into consideration, these results varied. A longer distance from the grid, such as in Off-Grid House 2, results in high impacts related to grid extension, making the choice to go off-grid more sustainable than extending the grid. In contrast, for a household that is closer to the grid, such as Off-Grid House 1, the impacts from grid extension do not necessarily make going off-grid more sustainable than extending the grid. In these cases, results vary dramatically depending whether "recommended" or "indicative" CFs are considered. Because "recommended" CFs do not take into consideration the impact from metals in toxicity calculations, the full impacts from grid extension are not reflected. Meanwhile, the consideration of "indicative" CFs made the grid extension scenarios appear as less sustainable because the impacts from metals are considered. Thus, it is important to present results acknowledging both "indicative" and "recommended" CFs to increase robustness of results. While one alternative cannot be definitively labeled as the "most sustainable," the results of this analysis illustrate how the use of multiple decision-analysis methods is useful to evaluate trade-offs. Furthermore, the use of MCDA helps to inform decision-making by adding an increased level of transparency and integration to the results.

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5. CONCLUSION

Decreasing costs of renewable energy technologies paired with innovations in small scale generation have driven new possibilities for energy production. One such alternative is to live off-the-grid, relying on independent energy generation disconnected from regional electricity or gas distribution grids. Off-grid homeowners have the ability to harness locally available and renewable resources in order to meet daily electricity and heating needs. Studying off-grid households, especially those comprised of members who have chosen to live this lifestyle, provides a window to evaluate and explore alternative means of energy provisioning.

This work assessed the sustainability of meeting energy needs in off-grid households by performing a combined Life-Cycle Sustainability Assessment (LCSA) and Multi-Criteria Decision Analysis (MCDA) study on two off-grid homes within Benfeita, a small village in Portugal that has attracted an ecologically inclined community. After site visits and interviews with community and municipal council members, two homes (Off-Grid House 1 and 2) were selected to serve as case studies. These homes were chosen because they have unique energy needs as well as distinct resource constraints that require the use of different technologies, making them representative of diverse challenges of off-grid living. Off-Grid House 1 uses the following off-grid electricity systems: photovoltaic panels, a pico-hydro generator, a petrol generator, and lead-acid batteries; Off-Grid House 2 uses: a micro-hydro generator, lead-acid, and lithium-ion batteries. Off-Grid House 1 uses the following off-grid heating systems: a wood burning furnace, a liquefied petroleum gas stove, and a solar cooker; Off-Grid House 2 uses: a wood burning furnace, a butane gas stove, and a solar cooker.

Based on site visits, interviews, and surveys with community members, inventories for these systems were developed and used to build original life-cycle models. Twelve indicators were selected to evaluate life-cycle sustainability performance: six environmental criteria: Global Warming (GW), Non-Renewable Fossil Energy Demand (nREn), Freshwater Aquatic Ecotoxicity (FAE), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME); three economic criteria: Investment Cost, Operation & Maintenance (O&M) Cost, and Levelized Cost of Energy (LCOE); and three health/social criteria: Carcinogenic Toxicity (CT), Non-Carcinogenic Toxicity (NCT), and Local Employment.

Results of the LCSA demonstrate that the sustainability of meeting energy needs in an off-grid home, compared to the use of electricity from the grid and the use of electrical heaters with electricity obtained from the grid, is dependent on the criteria and the dimension under consideration. From an environmental perspective, the use of off-grid electricity had lower impacts in GW and nREn than consuming electricity from the grid. Impacts from the systems´ manufacturing process resulted in higher levels of FAE, TA, FE, and ME; while off-grid heating systems show lower impacts in GW, nREn, TA, and FE compared to the reference, and higher ones for FAE and ME. From an economic perspective, the cost of electricity from the grid was found to be 57-65% less expensive than that of off-grid homes. Although the use of off-grid electricity systems has low O&M Costs, there is a large initial Investment Cost, and multiple systems need to be purchased to ensure reliability and independence. The combination of these factors makes meeting electricity needs in an off-grid home expensive. In contrast, the use of off-grid heating is 52-74% cheaper than the reference due to low consumption and the use of inexpensive solutions by the homeowners. Finally, from a social perspective, consuming off-grid electricity resulted in higher impacts in CT and NCT, which are mainly attributed to the manufacturing of the systems. Meanwhile, using off-grid heating resulted in lower health impacts than the reference. This is due to the fact that the majority of heat consumed by the homes comes from the use of the wood burning furnace, whose impacts to toxicity are primarily due to the presence of chromium in the manufacturing of the furnace. Both off-grid electricity and heating systems stimulated higher levels of Local Employment in Benfeita, because they allowed for the hiring of local people in the installation and maintenance of the systems.

Baseline results (the current situation) were compared to four energy provisioning scenarios (**A_1**, **A_2**, **A_3**, and **A_4**) using MAVT to rank alternatives based on their sustainability performance. The alternative scenarios consider the impacts of extending and connecting the grid to the homes to allow for energy consumption from the grid or injection of excess electricity generated to the grid. Besides eliciting the homeowner´s preferences, SMAA and VIP were used to evaluate robustness of results.

The resulting ranking of alternatives was dependent on two main factors: (1) the house´s distance from the grid and (2) whether "recommended" or "indicative" CFs were considered in USEtox calculations. For Off-Grid House 1, which is 300 meters away from the grid, the consideration of "recommended" or "indicative" CFs in toxicity indicators (FAE, CT, and NCT) present different alternatives as the most sustainable. The consideration of "recommended" CFs highlights **A_3** (the scenario where the grid is extended to the home to allow for grid injection of excess electricity, while maintaining the use of off-grid heating systems) as the best alternative, but, acknowledgement of "indicative" CFs ranks the **Baseline**, an option that would rank third previously, as first. The primary reason for this divergence is due in large part to the fact that "indicative" CFs take into consideration metals in the calculation of toxicity, while "recommended" CFs do not. For Off-Grid House 2, which is 900 meters away from the grid, the use of either CF results in the **Baseline** being ranked first, because the home is farther away from the existing grid, and the impacts from extending the grid are captured regardless of the factor considered. In this case, the distance from the grid is a determining factor because the rankings are the same regardless of the CF considered for the USEtox categories.

There are a few key takeaways that can be taken from this study. First, consideration of trade-offs is essential to understanding the value of alternative possibilities for household energy provisioning. While one alternative cannot be definitively labeled as the "most sustainable," the use of multiple decision-analysis methods facilitates decision-making by adding an increased level of transparency and integration to the results. Second, it is important to consider the local context as well as resource constraints. In the case of Off-Grid House 2 for example, its level of isolation plays a big role on the sustainability of having an off-grid system compared to other alternatives. Yet, when off-grid homes are compared to reference scenarios (the use of the Portuguese grid to provide electricity and heating), they are not always the best option. Third, when employing USEtox methods, both CFs should be presented for toxicity calculations. Even though "indicative" factors are accompanied by higher uncertainty, it is essential to consider them alongside "recommended" factors because not acknowledging them can lead to a skewed result. Finally, LCSA and MCDA methodologies complement each other well because they allow for the consideration of DM´s values and trade-offs to build more comprehensive sustainability assessments.

5.1. Limitations and Future Work

While this analysis provides an in-depth exploration of the different technologies employed to generate heat and electricity in two off-grid homes, it is important to acknowledge the methodological and practical limitations associated with this study. First, the conclusions are bound to the current time. As grid electricity becomes greener and as off-grid technologies evolve, new studies should reappraise trade-offs. Studies can also be more detailed considering time dynamics, for example, by considering the change of the grid mix and off-grid mix during the year and even during the day (e.g. it might result that the grid is better in the winter and the contrary in the summer). Second, the work only considered two households in the context of one small village in Portugal. Due to topographical limitations, not all types of off-grid systems are used in this village (such as residential wind turbines, for example). Also, local resources (e.g. wood, water) and local needs (heating in the winter, cooling in the summer) might be different. Further studies could replicate this methodology and apply it to other off-grid communities across different locations to evaluate how the sustainability performance of these homes varies across contexts. Third, there was a lack of detailed data available on Local Employment because the homeowners did not maintain records of such information. The collection of data, such as the number of hours worked by local employees, would provide a stronger indicator as opposed to the number of local persons employed.

Future research can be based on methodological or practical aspects of this work. From a methodological perspective, this work presents a comprehensive way to apply a combined LCSA and MCDA study to evaluate off-grid homes. This methodology can be applied to any other type of case study, even if it is unrelated to energy systems. From a practical perspective, this study could be expanded to evaluate an energy community. Because there are 30-40 off-grid homes in Benfeita, there exists the potential to connect renewable energy systems to a community microgrid. A future research project could assess the life-cycle sustainability impacts of an integrated community energy system in Benfeita. This line of research is very relevant to current discussions on the feasibility and sustainability of distributed renewable energy systems at the community level [115].

5.2. Recommendations

Homeowners should consider the distance they are from the grid when deciding whether or not they should be fully off-grid. For extremely remote homes, off-grid, renewable energy solutions provide a reliable and sustainable form of electricity and heating, required that homeowners have the upfront capital to invest in such systems. The selection of technologies utilized should be dependent on the context and local resources in order to maximize the efficiency of the systems. Homes that are close to the grid should evaluate the trade-offs between going completely off-grid and the potential to connect their renewable energy systems to the grid to sell excess generation. For groups of households that are close together, sharing renewable energy systems (i.e. a community solar/wind/hydro system) is an interesting option to consider. These type of synergies would avoid the over-dimensioning of individual stand-alone systems, allowing the systems to be used more efficiently. Furthermore, if the homes are interested in extending the grid, the burden of the grid extension would be divided amongst multiple homes as opposed to one home. Finally, homeowners that live in places with easy access to the grid, or are already connected to the grid, should not go off-grid. If they are looking to increase the sustainability of their energy consumption, they may consider the addition of renewable energy systems to their homes to lower their electricity consumption from the grid, save on their utility bill, and have an increased level of energy independence. Meeting household energy needs in a sustainable way requires an analysis of the local context and available resources. A consideration of each household´s sustainability trade-offs is central to understanding the value of alternative possibilities for energy provisioning.

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REFERENCES

[1] P. Vannini and J. Taggart, *Off the Grid: Re-Assembling Domestic Life*. New York: Routledge, 2015.

[2] International Energy Agency, “Energy access,” 2018. [Online]. Available: https://www.iea.org/energyaccess/. [Accessed: 29-May-2018].

[3] A. Yadoo, A. Gormally, and H. Cruickshank, “Low-carbon off-grid electrification for rural areas in the United Kingdom: Lessons from the developing world,” *Energy Policy*, vol. 39, no. 10, pp. 6400–6407, Oct. 2011.

[4] R. Khalilpour and A. Vassallo, “Leaving the grid: An ambition or a real choice?,” *Energy Policy*, vol. 82, pp. 207–221, Jul. 2015.

[5] E. Forde, “The ethics of energy provisioning: Living off-grid in rural Wales,” *Energy Res. Soc. Sci.*, vol. 30, pp. 82–93, Aug. 2017.

[6] T. van der Schoor and B. Scholtens, “Power to the people: Local community initiatives and the transition to sustainable energy,” *Renew. Sustain. Energy Rev.*, vol. 43, pp. 666–675, Mar. 2015.

[7] M. E. Menconi, S. dell’Anna, A. Scarlato, and D. Grohmann, “Energy sovereignty in Italian inner areas: Off-grid renewable solutions for isolated systems and rural buildings,” *Renew. Energy*, vol. 93, pp. 14–26, Aug. 2016.

[8] M. Ranaboldo, L. Ferrer-Martí, A. García-Villoria, and R. Pastor Moreno, “Heuristic indicators for the design of community off-grid electrification systems based on multiple renewable energies,” *Energy*, vol. 50, pp. 501–512, Feb. 2013.

[9] W. Howard, “Benfeita Autonomous Ecozone: A Proposal,” 2017. [Online]. Available: www.permacelturinginportugal.net/blog/wp-content/.../03/ecozone-arganil-EN.pptx. [Accessed: 30-May-2018].

[10] J. Elkington, “Accounting for the Triple Bottom Line,” *Meas. Bus. Excell.*, vol. 2, no. 3, pp. 18–22, Mar. 1998.

[11] International Organization for Standards and International Electrotechnical Commission., “ISO 14024:2018 - Environmental labels and declarations - Type I environmental labelling - Principles and procedures,” *International Organization for Standards*, 2018. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:14024:ed-1:v1:en. [Accessed: 04-Dec-2018].

[12] S. Spillemaeckers and G. Vanhoutte, “A Product Sustainability Assessment,” in *Management Models for Corporate Social Responsibility*, de W. M. Jonker J., Ed. Berlin, Heidelberg: Springer, 2006, pp. 257–264.

[13] CDP, “A List 2017,” 2017. [Online]. Available: https://b8f65cb373b1b7b15feb-c70d8ead6ced550b4d987d7c03fcdd1d.ssl.cf3.rackcdn.com/comfy/cms/files/files/000/001/290/original/A_list.pdf. [Accessed: 04-Dec-2018].

[14] L. Chen, O. Tang, and A. Feldmann, “Applying GRI reports for the investigation of environmental management practices and company performance in Sweden, China and India,” *J. Clean. Prod.*, vol. 98, pp. 36–46, Jul. 2015.

[15] Robeco Institutional Asset Managment B.V., “Country Sustainability Ranking,” 2018. [Online]. Available: https://www.robecosam.com/en/key-strengths/country-sustainability-ranking.html. [Accessed: 04-Dec-2018].

[16] E. Grigoroudis, V. S. Kouikoglou, and Y. A. Phillis, “SAFE 2013: Sustainability of countries updated,” *Ecol. Indic.*, vol. 38, pp. 61–66, Mar. 2014.

[17] C. Xiao, Q. Wang, T. van der Vaart, and D. P. van Donk, “When Does Corporate Sustainability Performance Pay off? The Impact of Country-Level Sustainability Performance,” *Ecol. Econ.*, vol. 146, pp. 325–333, Apr. 2018.

[18] A. Azapagic, "Appendix: Life Cycle Thinking and Life Cycle Assessment (LCA)," in *Sustainable Development in Practice*, Chichester, UK: John Wiley & Sons, Ltd, 2005, pp. 426–437.

[19] T. Guinée, Jeroen B, Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., and Rydberg, "Life cycle assessment: past, present and future," *Environ. Sci. Technol.*, vol. 45, no. 1, pp. 90–96, 2011.

[20] W. Kloepffer, "Life Cycle Sustainability Assessment of Products," *Int. J. Life Cycle Assess.*, vol. 13, no. 2, pp. 89–95, 2008.

[21] UNEP/SETAC Life Cycle Initiative, "Towards a Life Cycle Sustainability A ssessment: Making informed choices on products," UNEP/SETAC Life Cycle Initiative, 2011.

[22] C. Benoît *et al.*, "The guidelines for social life cycle assessment of products: just in time!," *Int. J. Life Cycle Assess.*, vol. 15, no. 2, pp. 156–163, Feb. 2010.

[23] V. Belton and T. J. Stewart, *Multiple Criteria Decision Analysis: An Integrated Approach*. Norwell, Massachussetts: Kluwer Academic Publishers, 2002.

[24] L. C. Dias, F. Freire, and J. Geldermann, "Perspectives on Multi-Criteria Decision Analysis and Life-Cycle Assessment," in *New Perspectives in Multiple Criteria Decision Making*, M. Doumpos, J. R. Figueira, S. Greco, and C. Zopounidis, Eds. Springer, 2019, pp. 1–14.

[25] L. C. Dias, S. Silva, and L. Alçada-Almeida, "Multi-criteria environmental performance assessmetn with an additive model," in *Handbook of Research Methods and Applications in Environmental Studies*, M. Ruth, Ed. Cheltenham: Edward Elgar Publishing Limited, 2015, pp. 450–472.

[26] A. Ishizaka and P. Nemery, *Multi-criteria Decision Analysis: Methods and Software*. West Sussex: John Wiley & Sons, 2013.

[27] J. Burton and K. Hubacek, "Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments," *Energy Policy*, vol. 35, no. 12, pp. 6402–6412, Dec. 2007.

[28] A. R. Domingues, P. Marques, R. Garcia, F. Freire, and L. C. Dias, "Applying Multi-Criteria Decision Analysis to the Life-Cycle Assessment of vehicles," *J. Clean. Prod.*, vol. 107, pp. 749–759, Nov. 2015.

[29] L. C. Dias, C. Passeira, J. Malça, and F. Freire, "Integrating life-cycle assessment and multi-criteria decision analysis to compare alternative biodiesel chains," *Ann. Oper. Res.*, pp. 1–16, Sep. 2016.

[30] J. Ren, A. Manzardo, A. Mazzi, F. Zuliani, and A. Scipioni, "Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making," *Int. J. Life Cycle Assess.*, vol. 20, no. 6, pp. 842–853, Jun. 2015.

[31] H. Karunathilake, K. Hewage, W. Mérida, and R. Sadiq, "Renewable energy selection for net-zero energy communities: Life cycle based decision making under uncertainty," *Renew. Energy*, vol. 130, pp. 558–573, Jan. 2019.

[32] J. Seppälä, L. Basson, and G. A. Norris, "Decision Analysis Frameworks for Life-Cycle Impact Assessment," *J. Ind. Ecol.*, vol. 5, no. 4, pp. 45–68, Sep. 2001.

[33] G. Munda, "Multiple Criteria Decision Analysis and Sustainable Development," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, J. Figueira, S. Greco, and M. Ehrgott, Eds. Boston: Springer Science + Business Media, Inc., 2005, pp. 953–986.

[34] World Bank Group, "Reliable and Affordable Off-Grid Electricity Services for the Poor: Lessons from the World Bank Group Experience," 2016. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/25391. [Accessed: 04-Dec-

2018].

[35] S. Mandelli, J. Barbieri, R. Mereu, and E. Colombo, “Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review,” *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1621–1646, May 2016.

[36] S. Thompson and B. Duggirala, “The feasibility of renewable energies at an off-grid community in Canada,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2740–2745, Dec. 2009.

[37] M. M. Rahman, M. M.-U.-H. Khan, M. A. Ullah, X. Zhang, and A. Kumar, “A hybrid renewable energy system for a North American off-grid community,” *Energy*, vol. 97, pp. 151–160, Feb. 2016.

[38] E. Mallia and G. Lewis, “Life cycle greenhouse gas emissions of electricity generation in the province of Ontario, Canada,” *Int. J. Life Cycle Assess.*, vol. 18, no. 2, pp. 377–391, Feb. 2013.

[39] R. Garcia, P. Marques, and F. Freire, “Life-cycle assessment of electricity in Portugal,” *Appl. Energy*, vol. 134, pp. 563–572, Dec. 2014.

[40] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013.

[41] D. D. Hsu *et al.*, “Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation,” *J. Ind. Ecol.*, vol. 16, pp. S122–S135, Apr. 2012.

[42] E. Santoyo-Castelazo, H. Gujba, and A. Azapagic, “Life cycle assessment of electricity generation in Mexico,” *Energy*, vol. 36, no. 3, pp. 1488–1499, Mar. 2011.

[43] D. Weisser, “A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies,” *Energy*, vol. 32, no. 9, pp. 1543–1559, Sep. 2007.

[44] E. Martínez, E. Jiménez, J. Blanco, and F. Sanz, “LCA sensitivity analysis of a multi-megawatt wind turbine,” *Appl. Energy*, vol. 87, no. 7, pp. 2293–2303, Jul. 2010.

[45] B. Fleck and M. Huot, “Comparative life-cycle assessment of a small wind turbine for residential off-grid use,” *Renew. Energy*, vol. 34, no. 12, pp. 2688–2696, Dec. 2009.

[46] E. A. Alsema, “Environmental life cycle assessment of solar home systems,” *Tech. rep. NWS-E-2000-15*, 2000. [Online]. Available: https://www.researchgate.net/publication/266339822_Environmental_Life_Cycle_Assessment_of_Solar_Home_Systems.

[47] R. García-Valverde, C. Miguel, R. Martínez-Béjar, and A. Urbina, “Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system,” *Sol. Energy*, vol. 83, no. 9, pp. 1434–1445, Sep. 2009.

[48] D. O. Akinyele and R. K. Rayudu, “Techno-economic and life cycle environmental performance analyses of a solar photovoltaic microgrid system for developing countries,” *Energy*, vol. 109, pp. 160–179, Aug. 2016.

[49] A. Bilich *et al.*, “Life Cycle Assessment of Solar Photovoltaic Microgrid Systems in Off-Grid Communities,” *Environ. Sci. Technol.*, vol. 51, no. 2, pp. 1043–1052, Jan. 2017.

[50] A. Pascale, T. Urmee, and A. Moore, “Life cycle assessment of a community hydroelectric power system in rural Thailand,” *Renew. Energy*, vol. 36, no. 11, pp. 2799–2808, 2011.

[51] C. Smith *et al.*, “Comparative Life Cycle Assessment of a Thai Island’s diesel/PV/wind hybrid microgrid,” *Renew. Energy*, vol. 80, pp. 85–100, Aug. 2015.

[52] P. Balcombe, D. Rigby, and A. Azapagic, “Environmental impacts of microgeneration: Integrating solar PV, Stirling engine CHP and battery storage,” *Appl. Energy*, vol. 139, pp. 245–259, Feb. 2015.

[53] F. G. Üçtuğ and A. Azapagic, “Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries,” *Sci. Total Environ.*, vol. 643, pp. 1579–1589, Dec. 2018.

[54] B. A. Benedict, “Understanding Full Life-cycle Sustainability Impacts of Energy Alternatives,” *Energy Procedia*, vol. 107, no. September 2016, pp. 309–313, 2017.

[55] M. Z. Akber, M. J. Thaheem, and H. Arshad, “Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix,” *Energy Policy*, vol. 111, no. September, pp. 111–126, 2017.

[56] J. Kabayo, F. Freire, and P. Marques, “Life Cycle Sustainability Assessment of Key Electricity Generation Technologies in Portugal,” M.Sc. Thesis, University of Coimbra, 2017.

[57] B. Atilgan and A. Azapagic, “An integrated life cycle sustainability assessment of electricity generation in Turkey,” *Energy Policy*, vol. 93, pp. 168–186, 2016.

[58] L. Stamford and A. Azapagic, “Life cycle sustainability assessment of UK electricity scenarios to 2070,” *Energy Sustain. Dev.*, vol. 23, pp. 194–211, Dec. 2014.

[59] B. P. Greening, “Life cycle environmental and economic sustainability assessment of micro- generation technologies in the UK domestic sector,” Doctoral Thesis, University of Manchester, 2013.

[60] T. Li, A. P. Roskilly, and Y. Wang, “Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England,” *Appl. Energy*, Aug. 2017.

[61] T. Li, A. P. Roskilly, and Y. Wang, “A Regional Life Cycle Sustainability Assessment Approach and its Application on Solar Photovoltaic,” *Energy Procedia*, vol. 105, no. 0, pp. 3320–3325, 2017.

[62] S. Moslehi and R. Arababadi, “Sustainability Assessment of Complex Energy Systems Using Life Cycle Approach-Case Study: Arizona State University Tempe Campus,” *Procedia Eng.*, vol. 145, pp. 1096–1103, Jan. 2016.

[63] J. C. Rojas-Zerpa and J. M. Yusta, “Application of multicriteria decision methods for electric supply planning in rural and remote areas,” *Renew. Sustain. Energy Rev.*, vol. 52, pp. 557–571, Dec. 2015.

[64] J. Ren, “Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment,” *Sustain. Prod. Consum.*, vol. 16, pp. 45–57, Oct. 2018.

[65] A. Petrillo, F. De Felice, E. Jannelli, C. Autorino, M. Minutillo, and A. L. Lavadera, “Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system,” *Renew. Energy*, vol. 95, pp. 337–355, Sep. 2016.

[66] International Organization for Standards, “ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework,” 2006. [Online]. Available: https://www.iso.org/standard/37456.html. [Accessed: 15-Feb-2018].

[67] Rede das Aldeias do Xisto, “Benfeita,” 2013. [Online]. Available: https://aldeiasdoxisto.pt/aldeia/benfeita. [Accessed: 30-May-2018].

[68] Instituto Nacional de Estatística, “Censos 2011,” 2011. [Online]. Available: http://censos.ine.pt/xportal/xmain?xpid=CENSOS&xpgid=censos_ficheirosintese. [Accessed: 30-May-2018].

[69] R. A. Dones, R., Bauer C., Burger B., Faist Emmenegger M., Fischknecht R., Heck

T., Jungbluth N., “Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen,” in *Ökobilanzen für die Schweiz. Final report ecoinvent data v2.0, No. 6.*, vol. 6, Dübendorf, CH: Swiss Centre for Life Cycle Inventories, 2007.

[70] N. Jungbluth, M. Stucki, R. Frischknecht, and S. Büsser, “Photovoltaics,” in *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, vol. 6–IV, no. 6, Roberto and Dones, Eds. Uster: ESU-services Ltd, 2010, p. v2.0.

[71] Cataylyst R&D Ltd., “Assessing the carbon footprint of a PowerSpout,” *Report for EcoInnovation*, 2009. [Online]. Available: http://catalystnz.co.nz/uploads/PowerSpout-footprint-Report-Nov09.pdf. [Accessed: 20-Jun-2018].

[72] International Renewable Energy Agency, “Hydropower,” *Renewable Energy Technologies: Cost Analysis Series*, 2012. [Online]. Available: http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf. [Accessed: 18-Dec-2018].

[73] Global Petrol Prices, “Portugal gasoline prices,” 2018. [Online]. Available: https://www.globalpetrolprices.com/Portugal/gasoline_prices/. [Accessed: 03-Sep-2018].

[74] C. Spanos, D. E. Turney, and V. Fthenakis, “Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead-acid batteries designed for demand-charge reduction,” *Renew. Sustain. Energy Rev.*, vol. 43, pp. 478–494, Mar. 2015.

[75] E. D. G. Fraser, A. J. Dougill, W. E. Mabee, M. Reed, and P. McAlpine, “Bottom up and top down: Analysis of participatory processes for sustainability indicator identification as a pathway to community empowerment and sustainable environmental management,” *J. Environ. Manage.*, vol. 78, no. 2, pp. 114–127, 2006.

[76] IPCC, *Climate Change 2013 - The Physical Science Basis*. Cambridge: Cambridge University Press, 2013.

[77] R. Frischknecht *et al.*, “Implementation of Life Cycle Impact Assessment Methods,” Final report ecoinvent v2.2 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH., 2007.

[78] R. K. Rosenbaum *et al.*, “USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment,” *Int. J. Life Cycle Assess.*, vol. 13, no. 7, pp. 532–546, Nov. 2008.

[79] M. A. J. Huijbregts *et al.*, “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level,” *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138–147, Feb. 2017.

[80] M. Hauschild *et al.*, “Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors (International Reference Life Cycle Data System - ILCD handbook),” 2011. [Online]. Available: http://publications.jrc.ec.europa.eu/repository/handle/JRC61049. [Accessed: 18-Dec-2018].

[81] UNEP/SETAC Life Cycle Initiative, “Global guidance for life cycle impact assessment indicators,” 2016. [Online]. Available: https://www.lifecycleinitiative.org/training-resources/global-guidance-lcia-

indicators-v-1/. [Accessed: 18-Dec-2018].

[82] J. B. Guinée, *Handbook on life cycle assessment-operational guide to the ISO Standards*. Dodrecht: Kluwer Academic Publishers, 2002.

[83] R. Frischknecht, F. Wyss, S. Büsser Knöpfel, T. Lützkendorf, and M. Balouktsi, "Cumulative energy demand in LCA: the energy harvested approach," *Int. J. Life Cycle Assess.*, vol. 20, no. 7, pp. 957–969, Jul. 2015.

[84] R. Arvidsson and M. Svanström, "A framework for energy use indicators and their reporting in life cycle assessment," *Integr. Environ. Assess. Manag.*, vol. 12, no. 3, pp. 429–436, Jul. 2016.

[85] M. Bijster *et al.*, "USEtox® 2.0 Documentation (Version 1.1)," 2017. [Online]. Available: https://www.usetox.org/sites/default/files/assets/USEtox_Documentation.pdf.

[86] European Centre for Ecotoxicology and Toxicology of Chemicals, "Technical Report no.127 - Freshwater ecotoxicity as an impact category in life cycle assessment - Ecetoc," 2016. [Online]. Available: http://www.ecetoc.org/publication/technical-report-no-127-freshwater-ecotoxicity-impact-category-life-cycle-assessment/. [Accessed: 16-Aug-2018].

[87] J. Seppälä, M. Posch, M. Johansson, and J.-P. Hettelingh, "Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator," *Int. J. Life Cycle Assess.*, vol. 11, no. 6, pp. 403–416, Nov. 2006.

[88] M. Z. Hauschild *et al.*, "Identifying best existing practice for characterization modeling in life cycle impact assessment," *Int. J. Life Cycle Assess.*, vol. 18, no. 3, pp. 683–697, Mar. 2013.

[89] N. Cosme, H. F. Larsen, and M. Z. Hauschild, "Endpoint characterisation modelling for marine eutrophication in LCIA Marine Eutrophication," *SETAC Eur. 23rd Annu. Meet.*, no. Figure 1, pp. 1–20, 2013.

[90] R. Bollinger and C. Bauer, "Wasserkraft," in *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, R. Dones, Ed. Dübendorf, CH: Swiss Centre for Life Cycle Inventories, 2007.

[91] M. Spielmann, C. Bauer, R. Dones, and M. Tuchschmid, "Life Cycle Inventories Transport Services," Final report ecoinvent v2.0 No. 14., Swiss Centre for Life Cycle Inventories, Dübendorf, CH., 2007.

[92] D. A. Notter *et al.*, "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles," *Environ. Sci. Technol.*, vol. 44, no. 17, pp. 6550–6556, Sep. 2010.

[93] C. Bauer, "Holzenergie," in *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, D. R., Ed. Dübendorf, CH: Swiss Centre for Life Cycle Inventories, 2007.

[94] A. C. Dias and L. Arroja, "Environmental impacts of eucalypt and maritime pine wood production in Portugal," *J. Clean. Prod.*, vol. 37, pp. 368–376, Dec. 2012.

[95] E. Peduzzi, G. Boissonnet, and F. Maréchal, "Biomass modelling: Estimating thermodynamic properties from the elemental composition," *Fuel*, vol. 181, pp. 207–217, Oct. 2016.

[96] N. Jungbluth, "Life-Cycle-Assessment for Stoves and Ovens," Zürich, CH, UNS Working Paper No. 16, 1997.

[97] G. Afrane and A. Ntiamoah, "Comparative Life Cycle Assessment of Charcoal, Biogas, and Liquefied Petroleum Gas as Cooking Fuels in Ghana," *J. Ind. Ecol.*, vol.

15, no. 4, pp. 539–549, Aug. 2011.

[98] H.-J. Althaus, R. Hischier, M. Osses EMPA, S. Gallen Alex Primas, S. Hellweg ETH Zürich Niels Jungbluth, and M. Chudacoff Chudacoff Ökoscience, "Life Cycle Inventories of Chemicals," Final report ecoinvent data v2.0 No. 8. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, 2007.

[99] Suntaste, "SunOK solar cookers," 2018. [Online]. Available: http://www.sunok.eu/home/products/suntaste. [Accessed: 25-Jul-2018].

[100] Entidade Reguladora dos Serviços Energéticos, "Liberalização do Mercado Elétrico," 2018. [Online]. Available: http://www.erse.pt/pt/perguntasfrequentes/liberalizacao/paginas/liberalizacao.aspx. [Accessed: 07-Sep-2018].

[101] Entidade Reguladora dos Serviços Energéticos, "Recomendação N. 1/2012: Informação do Imposto Especial de Consumo na Fatura de Eletricidade," 2012. [Online]. Available: http://www.erse.pt/pt/electricidade/regulamentos/relacoescomerciais/Documents/Recomendações/Recomendação_IEC_6jan2012.pdf. [Accessed: 07-Sep-2018].

[102] Ministério da Indústria e Energia, *Decreto-Lei n.º 4/93*. Diário da República, 1993, pp. 59–61.

[103] Assembleia da República, *Lei n.º 30/2003*. Diário da República, 2003, pp. 5312–5313.

[104] EDP Distribuição, "Guia de Boas Práticas Para a Integração Paisagística de Infrastruturas Elétricas," 2011. [Online]. Available: https://www.edpdistribuicao.pt/pt/ambiente/desempenhoambiental/Documentos/Guia de boas práticas para integração paisagística de infraestruturas elétricas - Anexos (vol. 2).pdf. [Accessed: 13-Aug-2018].

[105] Ministério do Ambiente Ordenamento do Território e Energia, *Decreto-Lei n.º 153/2014*. Ministry of Environment, Spatial Planning and Energy, 2014, pp. 5298–5311.

[106] OMIE - Mercado Grossista de Eletricidade - PORTUGAL, "OMIE - Mercado Grossista de Eletricidade - PORTUGAL," 2017. [Online]. Available: http://www.sctconsulting.pt/wp-content/uploads/2017/09/OMIE-MERCADO-DIÁRIO-201708.pdf. [Accessed: 23-Oct-2018].

[107] Miguel Prado, "Taxas de registo para produzir energia solar caem para 30 euros," *Jornal de Negócios*, 2015. [Online]. Available: https://www.jornaldenegocios.pt/empresas/energia/detalhe/taxas_de_registo_para_produzir_energia_solar_caem_para_30_euros. [Accessed: 06-Sep-2018].

[108] FF Solar, "Self consumption," 2018. [Online]. Available: http://www.ffsolar.com/index.php?lang=EN&page=selfconsumption. [Accessed: 23-Oct-2018].

[109] R. Lahdelma, J. Hokkanen, and P. Salminen, "SMAA - Stochastic multiobjective acceptability analysis," *Eur. J. Oper. Res.*, vol. 106, no. 1, pp. 137–143, Apr. 1998.

[110] L. C. Dias and J. N. Clímaco, "Additive aggregation with variable interdependent parameters: the VIP analysis software," *J. Oper. Res. Soc.*, vol. 51, no. 9, pp. 1070–1082, Sep. 2000.

[111] R. L. Keeney, "Using preferences for multi-attributed alternatives," *J. Multi-Criteria Decis. Anal.*, vol. 14, no. 4–6, pp. 169–174, Jul. 2006.

[112] T. Tervonen, "JSMAA: open source software for SMAA computations," *Int. J. Syst. Sci.*, vol. 45, no. 1, pp. 69–81, Jan. 2014.

[113] P. Goodwin and G. Wright, *Decision analysis for management judgment*, Fifth Edit. Wiley, 2014.

[114] F. Cherubini, G. P. Peters, T. Berntsten, A. H. Stromman, and E. Hertwich, "CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming," *GCB Bioenergy*, vol. 3, no. 5, pp. 413–426, Oct. 2011.

[115] B. P. Koirala, E. Koliou, J. Friege, R. A. Hakvoort, and P. M. Herder, "Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 722–744, Apr. 2016.

[116] T. Li, "A Life Cycle Approach to Sustainability Assessment on Community Energy Projects in the UK," in *ACEEE Summer Study on Energy Efficiency in Buildings*, 2016, no. August, pp. 1–12.

[117] B. Mainali and S. Silveira, "Using a sustainability index to assess energy technologies for rural electrification," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 1351–1365, Jan. 2015.

[118] M. Martín-Gamboa, D. Iribarren, D. García-Gusano, and J. Dufour, "A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems," *J. Clean. Prod.*, vol. 150, pp. 164–174, 2017.

[119] Freepik, "Ecology 50 premium icons," 2018. [Online]. Available: https://www.flaticon.com/packs/ecology-112. [Accessed: 27-Aug-2018].

APPENDIX 1

Table 12 and Table 13 present the responses to the household surveys. Only the sections that were answered by the homeowners are presented here. The survey has additional sections that could be filled out if the homeowners had those systems installed.

Table 12. Survey Responses - Off-Grid House 1

Name: Wendy Howard		**Date:** 3-Apr-18
A - Select the technologies used to provide electricity to your home (mark "X", where appropriate)	**Select Here**	**Sections to Fill Out**
Solar PV (specify if on roof or ground)	X (Rotating/tilting metal frames)	E1
Micro-Wind Turbines		E2
Pico-Hydroelectric Power Generator (under 5 kW)	X	E3
Micro-Hydroelectric Power Generator (5-100 kW)		E3
Internal Combustion Generator (i.e. diesel generator)	X	E4
Electricity from the grid		E5
Other (please list and insert additional rows if necessary)		E6
B- Select the technologies used for heat (including hot water, space heating, cooking) (mark "X", where appropriate)	**Select Here**	**Sections to Fill Out**
Heat/Space Heating		
Biomass (i.e. wood)	X	F1
Solar Thermal	X	F2
Other (please list and insert additional rows if necessary)		F3
Liquid Cooking Fuels		
Kerosene		F4
Liquefied Petroleum Gas (LPG)	X	F4
Other (please list and insert additional rows if necessary)		F4
Solid Cooking Fuels		
Firewood	X	F5
Coal		F5
Other Cooking Fuels		
Biogas		F6
Electricity		F6
Other (please list and insert additional rows if necessary)	X (Solar)	F6
C- Select the technologies used for storage (mark "X", where appropriate)	**Select Here**	**Sections to Fill Out**

Electric Vehicle		G1
Batteries	X	G2
Other (please list and insert additional rows if necessary)		G3

E- Main characteristics of the electricity generation technologies

(please fill in the data for the technologies previously selected in A)	Solar PV	Solar PV
E1 - Solar	24V system	12V system
Power Output total system (kW)	1.59kW	0.56kW
Annual energy output per system (kWh/year)	c ±900kWh	c ±300kWh
Cell Material	Poly	Poly
Size of each PV Panel (m2)	1.65	1.94
Number of Panels in System	6	2
Name of System (Brand) Panels	REC	Schutten
Inverter	Outback FX2024E	Studer C1600-12
Charge controller	Outback FlexMax 80	Morningstar Tristar TS-45
Batteries	Rolls	TAB
Lifetime of System (years referenced from brand)	10-25 years	10-25 years
System Cost (€/system)	c. 10,000€	c. 3,500€
Cost of Installation (€/system)	Didn't keep records	Didn't keep records
Operation and Maintenance Cost (€/year)	10	5
Number of operation/maintenance times per year (average)	6	6
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes, 1 installation	Yes, 1 installation
E3- Hydro	Pico-Hydro	
Annual energy output (kWh/year)	c ±500kWh	
Total Installed Capacity (kW)	5	
Hydraulic head (m)	30	
Surface of reservoir/river (m2)	n/a	
Volume of reservoir/river (m3)	n/a	
Type of System (run-of-river, reservoir, etc.)	Hybrid water wheel/impulse turbine	
Name of System (Brand)	Home built	
Lifetime of System (years referenced from brand)	25	
System Cost (€/system)	Around €1600	
Cost of Installation (€/system)	Didn't keep records	
Operation and Maintenance Cost (€/year)	20	
Number of operation/maintenance times per year (average)	2	
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes - local person built it	
E4- Internal Combustion Generator	**Petrol**	

Generator Power (kW)	5
Fuel Consumption at full load (L/hour or m3/hour)	No idea
Estimated use per year (hours/year)	40
Please describe how you use your generator (at full load, half load, etc.), for which purposes, and how often you use it.	Battery charging during winter bad weather when not enough water for hydro. Use of power tools >2000W
Name of System (Brand)	Daewoo
Lifetime of System (years referenced from brand)	15 years
System Cost (€/system)	€750.00
Cost of Installation (€/system)	n/a
Operation and Maintenance Cost (€/year)	Highly variable
Number of operation/maintenance times per year (average)	Don't keep records
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes – maintenance/checks
F- Main characteristics used for heat (including hot water, space heating, cooking)	
(please fill in the data for the columns of the technologies previously selected in B)	
F1- Biomass	
Annual Weight of Biomass used for heat (kg/year) (*if you have multiple years, please include)	I use about 6m³/year
Type of Wood Used	Whatever is available
Please describe how often you use biomass for heat, what kind of technology you use to heat the house with biomass (i.e. fireplace, stove, etc.)	Woodstove used nightly in winter, wood-burning water heater twice weekly in winter
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes – collect wood
F3-Liquid Cooking Fuels	Liquefied Petroleum Gas
Annual Volume of Fuel used for heat (L/year or m3/year) (*if you have multiple years, please include)	Gas is supplied by weight. I use around 26kg/year
Please describe what you use these fuels for and how often you use them	Cooking
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	No
F4- Solid Cooking Fuels	Firewood
Annual Weight of Fuel used for heat (kg/year) (*if you have multiple years, please include)	Included in firewood total
Please describe what you use these fuels for and how often you use them	cooking and baking
F5- Other Cooking Fuels	Solar
Annual Volume of Fuel used for heat (kg/year)	Not measurable
Please describe what you use these fuels for and how often you use them	cooking in summer

Please describe what technology you use to cook (i.e. stove, burner, etc.)	parabolic solar reflector
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	No

G- Main characteristics of Storage Technologies

(please fill in the data for the columns of the technologies previously selected in C)

G2-Batteries	Batteries - 24V system	Batteries - 12V system
Type of battery (i.e. lithium-ion, lead, etc.)	lead acid deep cycle	lead acid deep cycle
Number of batteries	4	6
Cost of battery (€/battery)	525	149
Battery Lifetime (years)	12	10
Weight (kg)	100	29
Nominal Voltage (V)	6V	2V
Capacity (Ah)	770Ah	575Ah
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes - installation	Yes - installation

Table 13. Survey Responses - Off-Grid House 2

Name: Haico Laeven		**Date:** 15-Apr-18
A - Select the technologies used to provide electricity to your home (mark "X", where appropriate)	**Select Here**	**Sections to Fill Out**
Solar PV (specify if on roof or ground)		E1
Micro-Wind Turbines		E2
Pico-Hydroelectric Power Generator (under 5 kW)		E3
Micro-Hydroelectric Power Generator (5-100 kW)	X	E3
Internal Combustion Generator (i.e. diesel generator)		E4
Electricity from the grid		E5
Other (please list and insert additional rows if necessary)		E6
B- Select the technologies used for heat (including hot water, space heating, cooking) (mark "X", where appropriate)	**Select Here**	**Sections to Fill Out**
Heat/Space Heating		
Biomass (i.e. wood)	X	F1
Solar Thermal		F2
Other (please list and insert additional rows if necessary)		F3
Liquid Cooking Fuels		
Kerosene		F4

Liquefied Petroleum Gas (LPG)		F4
Other (please list and insert additional rows if necessary)	X (Butane)	F4
Solid Cooking Fuels		
Firewood	X	F5
Coal		F5
Other Cooking Fuels		
Biogas		F6
Electricity		F6
Other (please list and insert additional rows if necessary)	X (Solar)	F6
C- Select the technologies used for storage (mark "X", where appropriate)	**Select Here**	**Sections to Fill Out**
Electric Vehicle	X	G1
Batteries	X	G2
Other (please list and insert additional rows if necessary)		G3
E- Main characteristics of the electricity generation technologies		
(please fill in the data for the technologies previously selected in A)		

E3- Hydro	Micro-Hydro
Annual energy output (kWh/year)	4380
Total Installed Capacity (kW)	12KW a day
Hydraulic head (m)	55
Surface of reservoir/river (m2)	?
Volume of reservoir/river (m3)	> 3 liters a second
Type of System (run-of-river, reservoir, etc.)	Run-of-river
Name of System (Brand)	Powerspout
Lifetime of System (years referenced from brand)	10
System Cost (€/system)	6000
Cost of Installation (€/system)	(included in system cost)
Operation and Maintenance Cost (€/year)	Didn't keep records
Number of operation/maintenance times per year (average)	Do most maintenance myself, don't keep records
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes - installation/maintenance
F- Main characteristics used for heat (including hot water, space heating, cooking)	
(please fill in the data for the columns of the technologies previously selected in B)	
F1- Biomass	
Annual Weight of Biomass used for heat (kg/year)	2 m^3
Type of Wood Used	Pine, eucalyptus, mimosa

Please describe how often you use biomass for heat, what kind of technology you use to heat the house with biomass (i.e. fireplace, stove, etc.)	A woodstove. Used: in wintertime every day and in cold spring, summer and autumn days/evenings.	
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	Yes – collect wood	
F3-Liquid Cooking Fuels	Butane	
Annual Volume of Fuel used for heat (L/year or m3/year)	2 cans	
Please describe what you use these fuels for and how often you use them	Cooking	
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	No	
F4- Solid Cooking Fuels	Firewood	
Annual Weight of Fuel used for heat (kg/year)	Included in firewood total	
Please describe what you use these fuels for and how often you use them	When the woodstove is on we cook water and heat up food on top of the stove.	
F5- Other Cooking Fuels	Solar	
Annual Volume of Fuel used for heat (kg/year)	Not measurable	
Please describe what you use these fuels for and how often you use them	We bought a solar cooker from SunOk. We use it when the sun shines.	
Please describe what technology you use to cook (i.e. stove, burner, etc.)	The SunTaste, they are made in Portugal and mainly out of cork. :-) http://www.sunok.eu/home/products/suntaste	
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	No	
G- Main characteristics of Storage Technologies		
(please fill in the data for the columns of the technologies previously selected in C)		
G1- Electric Vehicle	Electric Car	
Vehicle Storage Capacity (kW)	14	
Vehicle Name (Brand)	Frisian Motors https://www.frisianmotors.com/leffert-fm-50-elektrische-transporter/	
Lifetime of Vehicle (years referenced from brand)	?	
Vehicle Cost (€/system)	New: 15000 including IVA	
Operation and Maintenance Cost (€/year)	750	
Number of operation/maintenance times per year (average)	1	
Please describe how you use your electric vehicle for storage reasons, and how often you use it.	When we don’t have hydro available, we charge these car batteries from the normal grid. We use it for electricity in the house: light, charging phone and laptop, music player. When building we use it to power the electric saw and drill and other tools.	
Other details:	Very handy because everywhere we go with the car, we will have 220/230V power.	
G2-Batteries	Battery	Battery

Type of battery (i.e. lithium-ion, lead, etc.)	OPxS Lead acid	Lithium Ion
Number of batteries	12	4
Cost of battery (€/battery)	2600	7740
Battery Lifetime (years)	20	?
Weight (kg)	A piece: 23,5 kg dry, 34 kg wet	200
Nominal Voltage (V)	2	5-10 kW at 70 V
Capacity (Ah)	620	160
Did you hire a local person for the building, installation, or maintenance of this system during its lifetime?	No	No

APPENDIX 2

Table 14 and Table 15 present a breakdown of the percentage of impacts that come from each life-cycle stage and the total environmental impacts per kWh of MJ consumed.

Table 14. Environmental Impacts of Electricity and Storage Systems

		Ref.	Off-Grid House 1					Off-Grid House 2		
		Grid	Generator	0.3 kW Hydro	1.59 kW PV	0.56 kW PV	Lead-Acid	1 kW Hydro	Lead-Acid	Li-Ion
GW	Infrastructure (%)		10	99.94	100	100	100	99.99	100	100
	O&M (%)		90	0.06	0	0	0	0.01	0	0
	g CO_2eq/kWh	371.5	1991	5.3	150	174	14	57	75.92	61.99
nREn	Infrastructure (%)		8	99.93	100	100	100	100	100	100
	O&M (%)		92	0.07	0	0	0	0	0	0
	MJ/kWh	4.8	29	0.08	1.8	2.2	0.2	1.5	1.08	0.816
FAE (Rec.)	Infrastructure (%)		98	99.97	100	100	100	100	100	100
	O&M (%)		2	0.03	0	0	0	0	0	0
	CTUe/kWh	0.0001	0.2	3.1E-05	0.001	0.002	4.6E-05	2E-05	2E-04	1E-4
FAE (Indic.)	Infrastructure (%)		98	99.98	100	100	100	100	100	100
	O&M (%)		2	0.02	0	0	0	0	0	0
	CTUe/kWh	0.2	45	0.04	13.4	14.2	0.1	0.33	0.6	0.2
TA	Infrastructure (%)		33	99.97	100	100	100	100	100	100
	O&M (%)		67	0.03	0	0	0	0	0	0
	g SO_2eq/kWh	0.9	4.9	0.02	1.1	1.2	0.2	0.23	1	0.6
FE	Infrastructure (%)		72	99.97	100	100	100	100	100	100
	O&M (%)		28	0.03	0	0	0	0	0	0
	g P.eq/kWh	0.2	0.14	0.001	0.1	0.1	0.003	0.008	0.01	0.1
ME	Infrastructure (%)		66	99.95	99.99	100	100	100	100	100
	O&M (%)		34	0.05	0.01	0	0	0	0	0
	g N.eq/kWh	0.07	1.01	0.001	0.4	0.4	0.01	0.051	0.1	0.02

Table 15. Environmental Impacts of Heating Systems

		Ref.	Off-Grid House 1			Off-Grid House 2		
		Grid	Furnace	Stove (LPG)	Solar Cooker	Furnace	Stove (Butane)	Solar Cooker
GW	Infrastructure (%)		20	3	100	30	6	100
	O&M (%)		80	97	0	70	94	0
	g CO2eq/MJ	103	17.6	133	4.7	20.1	84.8	4.7
nREn	Infrastructure (%)		100	4	100	100	6	100
	O&M (%)		0	96	0	0	94	0
	MJ/MJ	1.3	0.04	1.05	0.06	0.07	1.08	0.06
FAE (Rec.)	Infrastructure (%)		100	26	100	100	29	100
	O&M (%)		0	74	0	0	71	0
	CTUe/MJ	2.8E-05	1.3E-05	1E-04	5E-04	3.3E-05	2E-04	0.0005
FAE (Indic.)	Infrastructure (%)		100	67	100	100	63	100
	O&M (%)		0	33	0	0	37	0
	CTUe/MJ	0.07	0.2	0.08	0.05	0.7	0.1	0.05
TA	Infrastructure (%)		49.2	13	100	54	9	100
	O&M (%)		50.8	87	0	46	91	0
	g SO_2eq/MJ	0.2	0.1	0.09	0.03	0.1	0.2	0.03
FE	Infrastructure (%)		100	64	100	100	52	100
	O&M (%)		0	36	0	0	48	0
	g P.eq/MJ	0.04	0.001	0.002	0.002	0.002	0.003	0.002
ME	Infrastructure (%)		93	26	100	94	20	100
	O&M (%)		7	74	0	6	80	0
	g N.eq/&MJ	0.02	0.04	0.008	0.02	0.05	0.01	0.02

APPENDIX 3

Figure 20 to Figure 30 present a detailed breakdown of the environmental, economic, and social impacts of the alternative scenarios defined for the electricity and storage systems. The baseline refers to the current scenario, grid consumption refers to a scenario where the renewable energy systems are replaced by consumption of electricity from the grid, and grid injection refers to a scenario where the renewable energy systems are used for self-consumption and excess electricity is sold to the grid. The blue dots show the total impacts in each scenario.

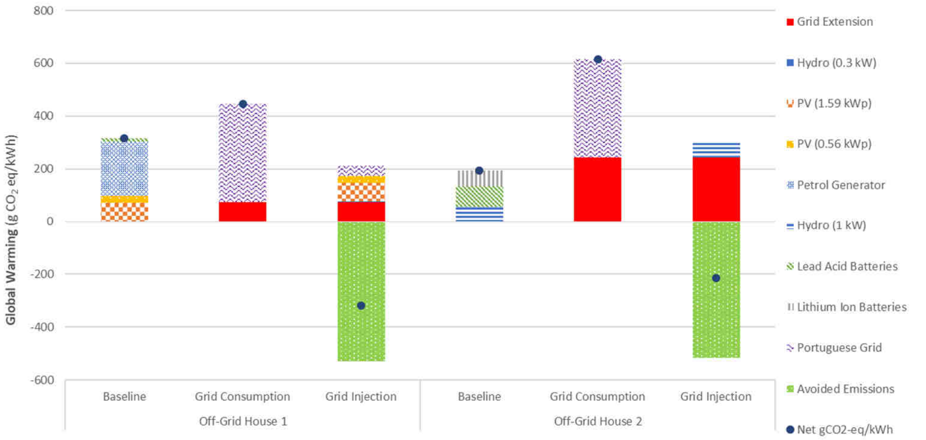

Figure 20. Alternative Scenarios – Global Warming Impacts

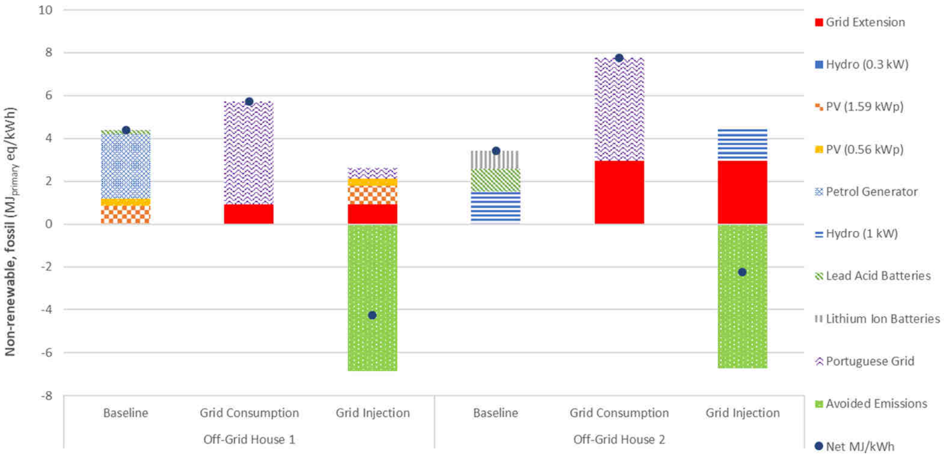

Figure 21. Alternative Scenarios – Non-Renewable Fossil Energy

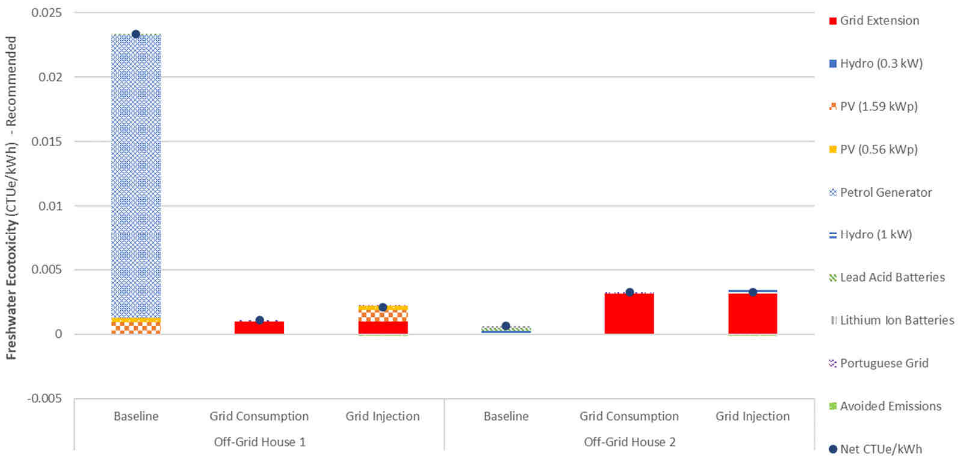

Figure 22. Alternative Scenarios – Freshwater Ecotoxicity ("Recommended" CFs)

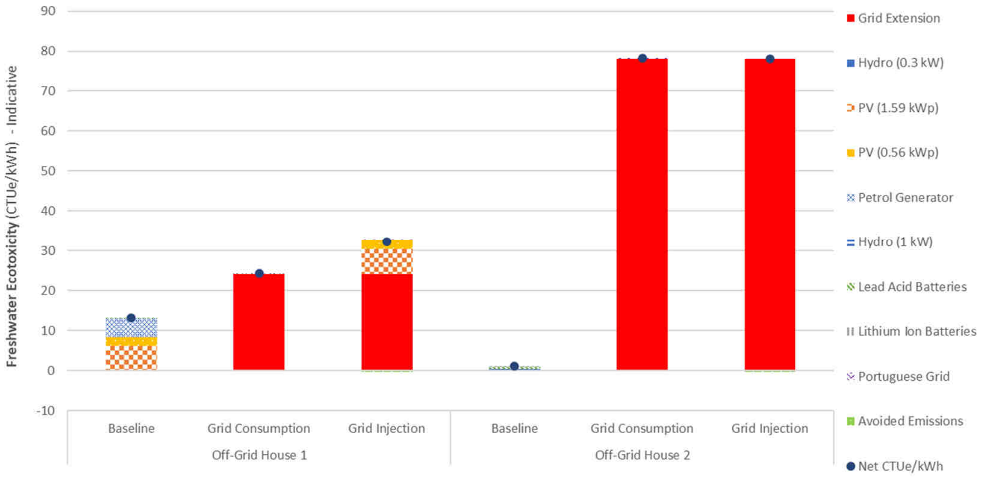

Figure 23. Alternative Scenarios – Freshwater Ecotoxicity ("Indicative" CFs)

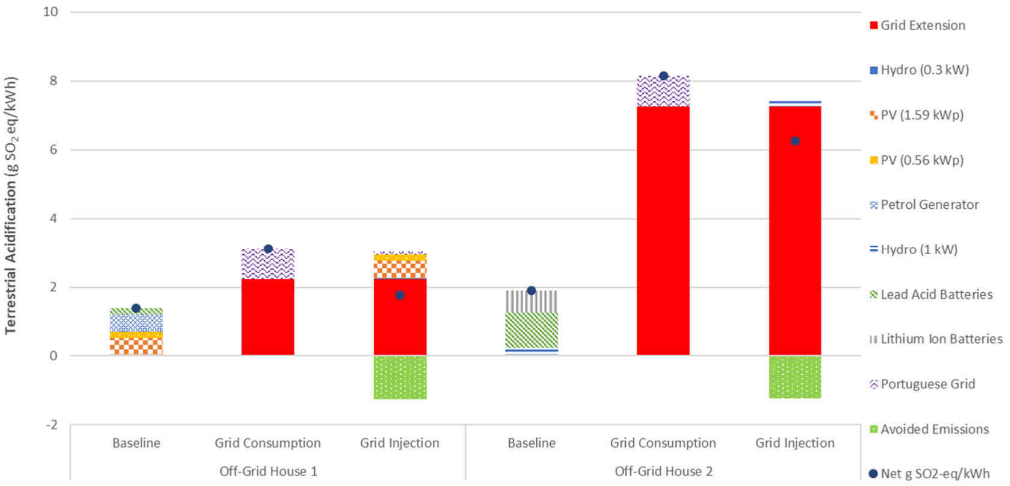

Figure 24. Alternative Scenarios – Terrestrial Acidification

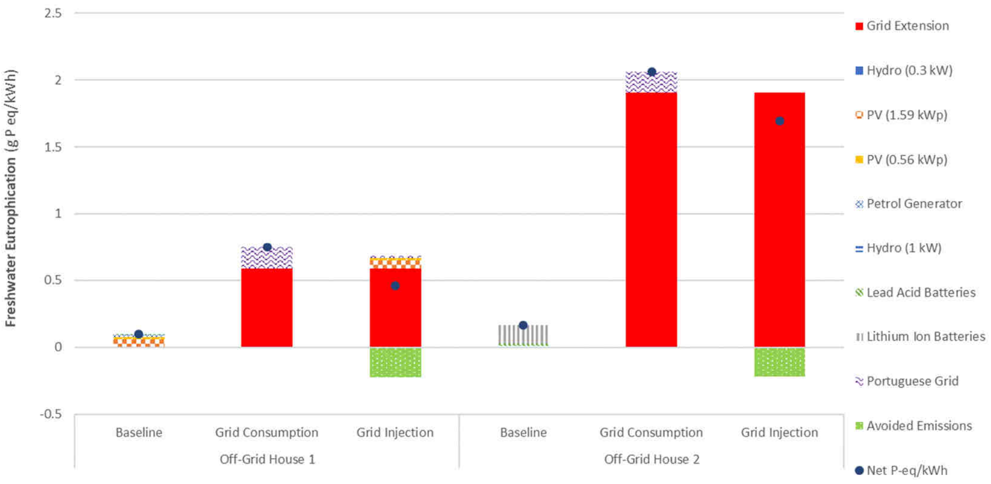

Figure 25. Alternative Scenarios – Freshwater Eutrophication

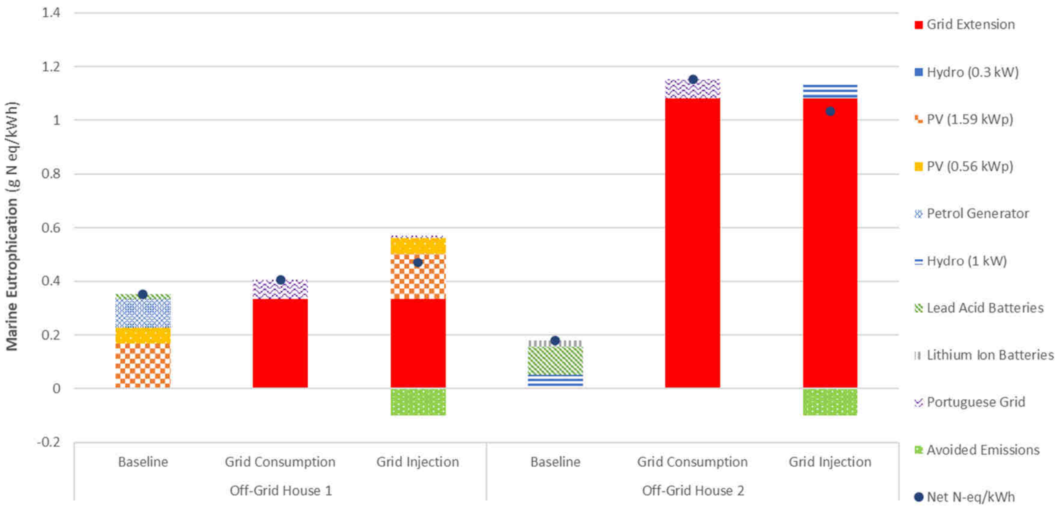

Figure 26. Alternative Scenarios – Marine Eutrophication

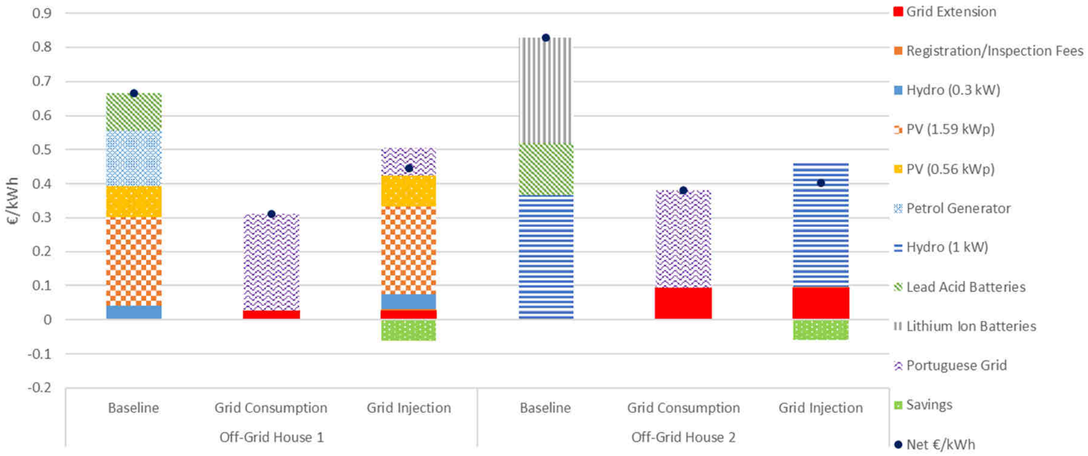

Figure 27. Alternative Scenarios – Levelized Cost of Electricity

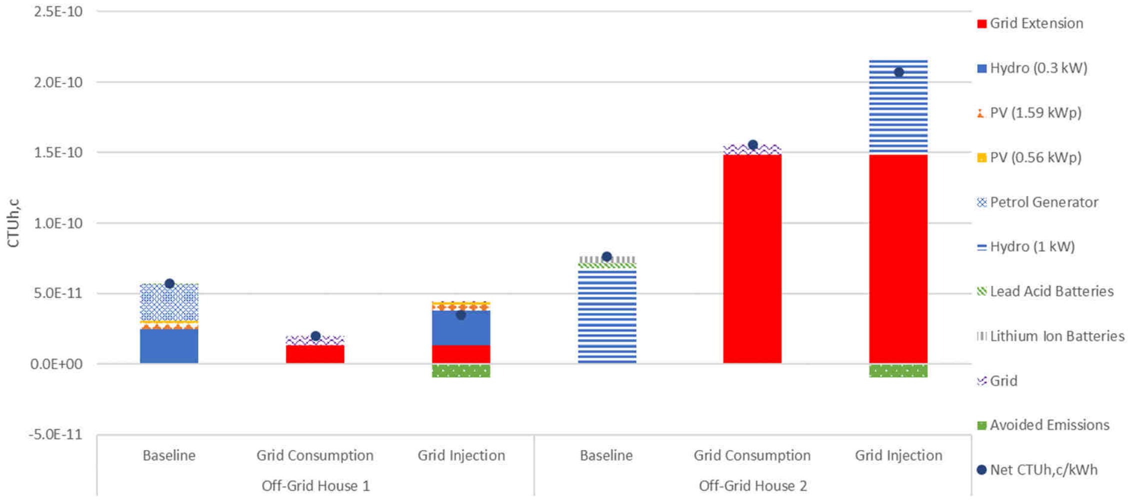

Figure 28. Alternative Scenarios – Carcinogenic Toxicity

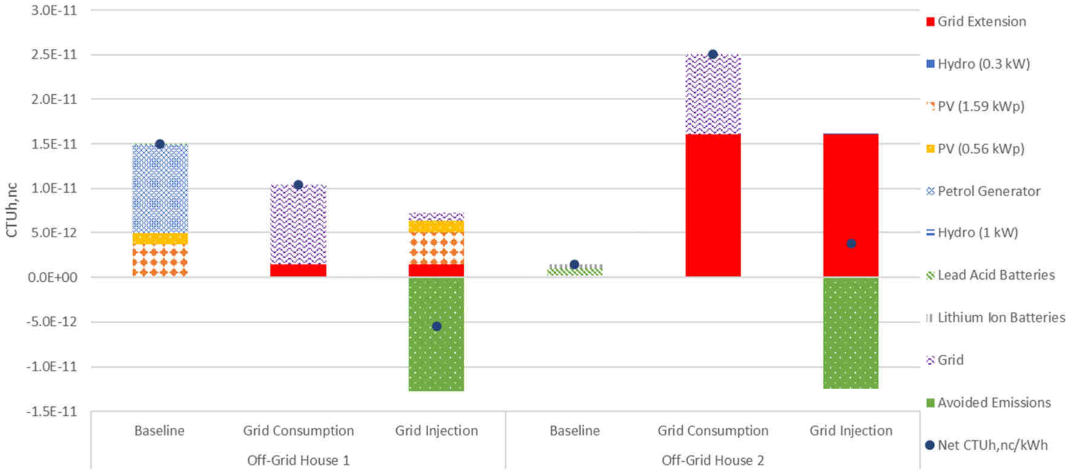

Figure 29. Alternative Scenarios – Non-Carcinogenic Toxicity

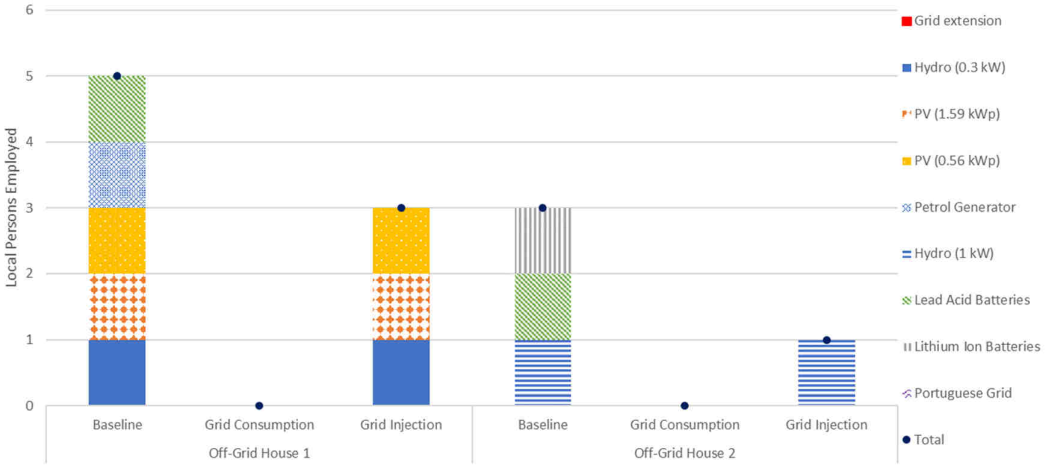

Figure 30. Alternative Scenarios – Local Employment

APPENDIX 4

Figure 31 illustrates the value functions of the utility of each indicator, elicited based on the preferences of the homeowner of Off-Grid House 1. The elicited weights are presented in Table 16. The k-value represents the weight based on the sum of all of the points.

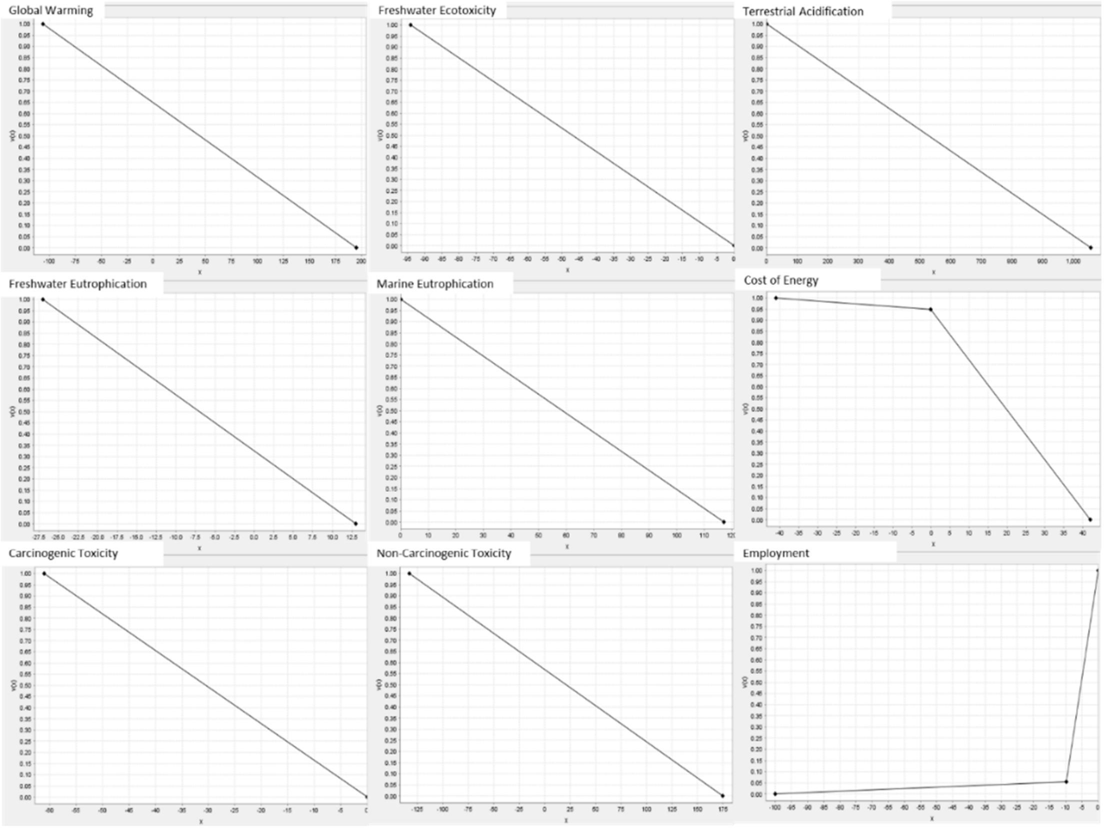

Figure 31. Elicited Value Functions for Indicators (Off-Grid House 1)

Table 16. Elicited Weights for Off-Grid House 1

Criteria	Indicator	0 (worst)	1 (best)	Points	k-value
j_1	Global Warming	195	-106	100	0.125
j_2	Freshwater Ecotoxicity	0	-94	100	0.125
j_3	Terrestrial Acidification	117	0	100	0.125
j_4	Freshwater Eutrophication	1056	0	100	0.125
j_5	Marine Eutrophication	13	-27	100	0.125
j_6	Cost of Energy	42	-41	100	0.125
j_7	Carcinogenic Toxicity	0	-61	60	0.075
j_8	Non-Carcinogenic Toxicity	175	-133	60	0.075
j_9	Local Employment	-100	0	80	0.10

Figure 32 illustrates the value functions of the utility of each indicator, elicited based on the preferences of the homeowner of Off-Grid House 2. The elicited weights are presented in Table 17. The k-value represents the weight based on the sum of all of the points.

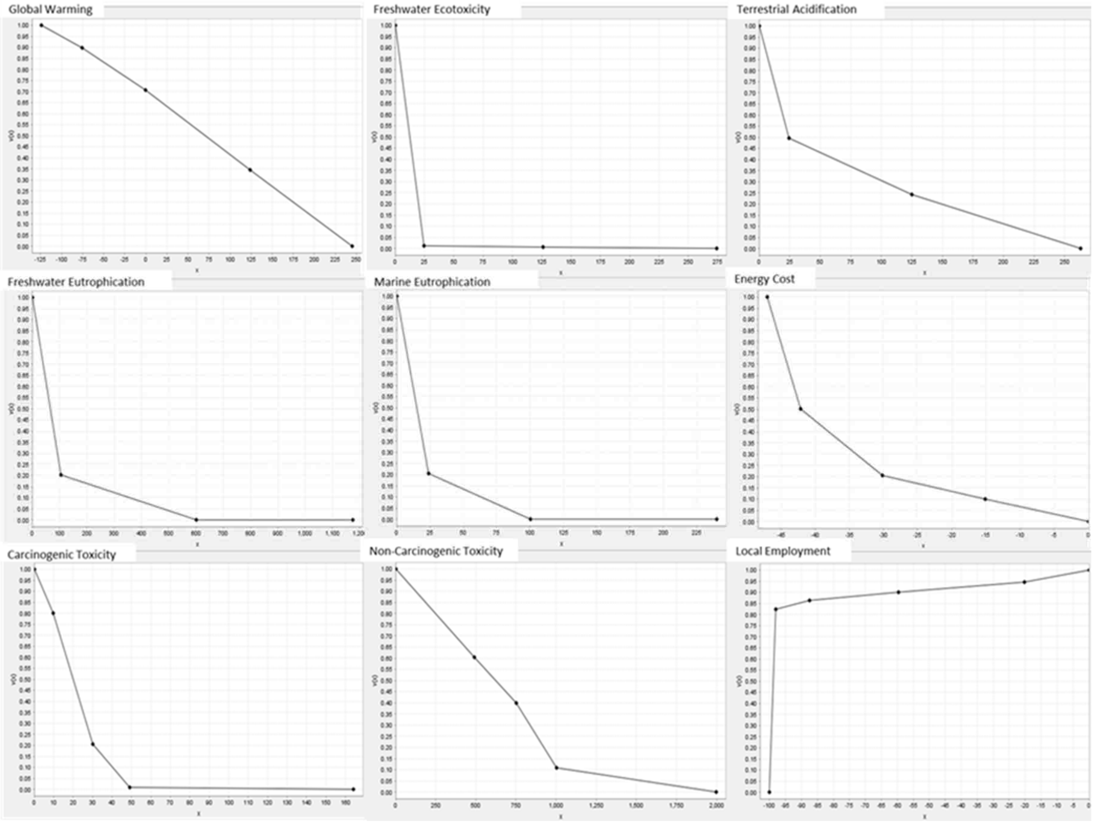

Figure 32. Elicited Value Functions for Indicators (Off-Grid House 2)

Table 17. Elicited Weights for Off-Grid House 2

Criteria	Indicator	0 (worst)	1 (best)	Points	k-value
j_1	Global Warming	245	-124	80	0.12
j_2	Freshwater Ecotoxicity	274	0	100	0.15
j_3	Terrestrial Acidification	263	0	90	0.13
j_4	Freshwater Eutrophication	1174	0	80	0.12
j_5	Marine Eutrophication	240	0	80	0.12
j_6	Cost of Energy	0	-47	60	0.09
j_7	Carcinogenic Toxicity	164	0	70	0.10
j_8	Non-Carcinogenic Toxicity	1997	0	70	0.10
j_9	Local Employment	-100	0	50	0.07