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Article

Prospective Life Cycle Assessment: Effect of Electricity Decarbonization in Building Sector

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Abstract: The building sector is responsible for 43% of France's final energy consumption and is strongly associated with a high environmental impact due to its high consumption of energy and natural resources. These impacts are significant in isolated islands. Due to its geographical isolation and an area of 2512 km^2, Reunion Island has a heavily carbon-based economy with a high import rate of raw materials for the building sector. This study aimed to investigate the effect of electricity mix decarbonization on residential house environmental impact. The methodology consists of three parts: (i) evaluating environmental impacts of Single-Family Houses (SFH) using life cyce assessment(LCA), (ii) defining SFH typologies using the K-means clustering algorithm, and (iii) implementing energy scenario in LCA of SFH to assess decarbonization effect. The environmental results were particularly sensitive in the operational phase, with a decrease of 83% between 2020 to 2040 of the global warming potential (GWP). The structural phase highlights the weight of imports in the building sector, as a decrease of only 1% is observed. This study clearly shows the necessary energy transition for Reunion Island. In the structural phase, the study recommends that stakeholders reduce imports and increase the share of recovered materials to achieve a substantial reduction in impacts.

Keywords: decarbonization; LCA; building sector; prospective; electricity scenario; waste energy; biomass; island

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1. Introduction

Since its first assessment report, the Intergovernmental Panel on Climate Change (IPCC) has recognized that small islands are particularly vulnerable to environmental hazards due to climate change effects [1]. Islands appear to rely on international markets and funding due to little capacity to manage and exploit their natural resources and skills in achieving resilience [2,3]. Briguglio [4] investigated the vulnerability of such remote territories by defining an economic index to identify islands and determine their vulnerability level. Oil price volatility has a significant negative impact on electricity production, fundamentally dependent on fossil fuels [5]. Many academic studies have concentrated on mitigating climate change by examining renewable energy potential. Consequently, policy recommendations often recommend the introduction of green energies and an improvement in energy efficiency. People on islands are required to raise and exploit local alternative energies for sustainable electricity provision due to fuel supply scarcity and environmental issues, and most islands are blessed with abundant renewable energy resources [6–8]. Anthropogenic activity is energy-intensive, which, therefore, places energy at the heart of territorial development issues. These challenges are even more crucial in isolated territories because of their heavy dependence on imports.

1.1. Motivation

Energy is, therefore, at the core of transition to green growth. Thus, our work examines the consequences of decarbonization of electricity production in an insular context, focusing particularly on the application to the building construction sector. Beyond reducing greenhouse gas emissions in the electricity mix, our study equally questions the importance of an energy transition at different stages of a building's life cycle to objectivize the environmental policy decisions.

1.2. A Brief Literature Review

The building sector is responsible for the massive impact on the environment due to the consumption of natural resources and associated emissions [9]. This sector consumes about 50% of raw materials, 71% of electricity, 16% of water resources and, consequently, produces 40% of waste going to landfill [10]. Buildings play an important role in maintaining the well-being of humanity and the environment. In particular, they offer great potential for mitigating environmental impacts and much attention has been paid to improving their efficiency and performance [11,12]. They have become a central component of greenhouse gas (GHG) emission reduction initiatives [13]. According to Urge-Vorsats et al. (2012), resolving to current best pratices in energy efficient technologies could potentially halve energy demand for heating and colling by the year 2050 compared to 2005 levels [14]. Energy policies in buildings have been classified as regulatory control mechanisms, economic and market-based instruments, fiscal instruments and incentives, and voluntary action [14]. The influence of environmental impacts on the energy consumption of buildings is a topical issue. In China, a decarbonization study taking into account both technological advances and interregional power transmission for the Chinese power sector has been conceptualized to explore the potential and possible path of decarbonization under the constraint of optimal cost. The results of this study showed that China's power generation is shifting from coal to hydro, nuclear, and wind power, and that coal power generation and carbon emissions may reach their peak by 2030 [15]. Other studies, for instance, by Schwarz et al., have shown that in the case of France, despite the ambitions of the Energy Transition Law for green growth, it is difficult to translate energy targets and commitments into specific policy measures [16]. This study identified five possible ways to reduce energy consumption and carbon emissions in the building sector. These included the increase energy, the increase of renewable energy, considering embodied energy, closing the performance gap, and the acceleration of retrofits. The results of Schwarz et al. [16] could be limited to countries with a similar built environment. Future research should focus on the built environment by comparing compressed earth block(CEB) across countries. This would help policymakers to adapt their future education to their local context [17]. Due to the growing interest of government groups in raising awareness of the impacts of the construction industry, LCA has become more attractive, especially for manufacturers. It allows the estimation of cradle-to-grave environmental impacts caused by all stages of a life cycle phase, even those not included in many traditional assessments, such as the acquisition of raw materials, transportation of materials, and end-of-life disposal [18–20]. In general, LCA is mostly used in the literature to determine the impacts by phase and by building type [21,22], to evaluate strategies for simplifying methods [23], to assess the environmental impacts of buildings [24–26], and to evaluate the impact of environmental factors related to the energy consumption of buildings [9]. Today, the energy demand of buildings accounts for about 31% of the global final energy demand and 23% of global energy-related carbon emissions [27]. As a result, LCA tends to be a useful method for assessing the evolution of the environmental quality of either a system or territory. In this regard, the building and energy industries are especially well suited to this environmental assessment, allowing for the detection of causal links between the two sectors.

1.3. Contribution and Aim of the Work

The literature has highlighted numerous work dealing with life cycle analysis of the buildings from the scale of the material to the neighborhood or city. However, few of them have addressed a prospective approach integrating the evolution of the environment. Thus, the environmental quality of electricity production plays a key role at different building life cycle stages. It seems appropriate to assess the impact of decarbonization scenarios on the mix.

Indeed, the countries in which the built environment is not similar (continental environments), and the choices and decisions of policymakers, as well as the availability of resources, in each country and their capacity to respond to this energy transition is totally different (tropical environments). For this reason, this article proposes the decarbonization of the local electricity mix for the specific case of Reunion Island, given the island is not equipped with similar technologies as in Metropolitan France (70% nuclear). Thus, the implementation of renewable energies in the production of the local electricity mix is used as a driving force for a better energy transition by 2040 on the Reunionese territory.

1.4. Organization of the Work

This paper is organized as follows: Section 2 presents the context of the studied territory. Section 3 firstly outlines the LCA approach used to assess environmental impacts of the SFHs and the electricity production. Secondly, it describes the energy scenario modeling. Section 4 reports the results and discusses the effects of decarbonization in the construction sector. Finally, Section 5 provides the main conclusion, the environmental policy implications of this work, and the perspective for future research.

2. The Reunion Island Context

2.1. Geography and Socio-Economic Situation

Reunion Island is a French overseas department located in the south-western Indian Ocean with a mountainous relief and covers an area of 2512 km^2. The island is characterized by a subtropical climate with two seasons: summer (November to April) and winter (May to October). The highly contrasted climate reflects on an uneven distribution of rainfall, that is, the East Windward coast, which is exposed to trade winds and receives abundant rainfall, while the West Leeward coast is sheltered by high reliefs and receives low rainfall [28]. A temperature gradient of about −0.7 °C every 100 m is observable from the coast to the highlands. This shows a significant difference between the two geographical areas. Demographical statistic for 2020 is estimated at 859,959 [29].

The island has all the characteristics of a modern island economy. On the one hand, there is a strong dependence on imports to supply raw materials and products. Tertiary activities represent Reunion's primary source of income, i.e., approximately 87% of the value-added. The weight of industry is minor at 6.1% i.e., half as much as in mainland France. Inequalities are particularly marked in Reunion due to insufficient income from activities and the lack of employment.

In addition, geographical remoteness has a significant impact on the cost of living, which is about 10.6% higher than France [30]. Population growth is more sustained in Reunion Island (1.4%) than in mainland France (0.4%). Recent INSEE projections show the demand for 168,900 housing units to be built by 2035 [31]. Land-use planning, therefore, calls for the anticipation of public policies. Currently, dwellings are concentrated on a coastal band < 400m, which gathers slightly more than 80%. Land pressure is extreme in Reunion Island. Indeed, built-up areas represent 9.9% of the total surface area, and agricultural activity covers 19%. In 2010, the island's national park (40% of the total surface area) was classified as a UNESCO World Heritage Site. These spatial and environmental constraints and development strategies currently place the building construction sector at the heart of the challenges for the next thirty years.

2.2. Overview of the Building Sector

According to the Economic Unit of the Building and Public Works, the construction sector in Reunion Island declined by 5.4% in 2019, after two years of growth (+3.9% in 2018 and +7.9% in 2017) [32]. The aging population of Reunion and the trend of living separately nevertheless implies a strong need for housing, especially small housing [29]. The social housing sector is also a significant economic and social challenge for Reunion Island. It largely contributes to the activity of the construction sector.

2.3. Energy Landscape

A common characteristic of all small islands is a strong dependence on imported fossil resources for electricity generation [33]. Reunion, like most of these island economies, has a high carbon-based electricity production. However, the island has defined for nearly 20 years the willingness to achieve energy self-sufficiency by 2030. In the early 2000s, there was a proactive regional policy targeting the penetration of renewable energies in the electricity mix. This desire for energy autonomy is nothing more or less than the translation of a political intention expressed in the "Immediate Plan for Survival" of 1975, defined by the Reunionese communist party [34]. The PRERURE (Regional Plan for Renewable Energies and Rational Use of Energy), initiated by Paul Vergès, then defined in 2000 a roadmap to reach the objective of energy autonomy in 2025.

The change of governance in the regional council in 2010 has missed absolute immobility in this race for energy autonomy. The share of renewable energies has slightlydecreased from 46.7% in 2000 to 31.2% in 2019, as shown in Figure 1. In 2019, the electricity production delivered to the network is 3046.9 GWh. In comparison to otherislands, Reunion Island's hydroenergy capacity has been thoroughly exploited. Experi-ments with micro hydro-wind power plants were conducted in the island's east due to thecomplementary nature of the two sources. This solution, however, was quickly abandoneddue to its low profitability.

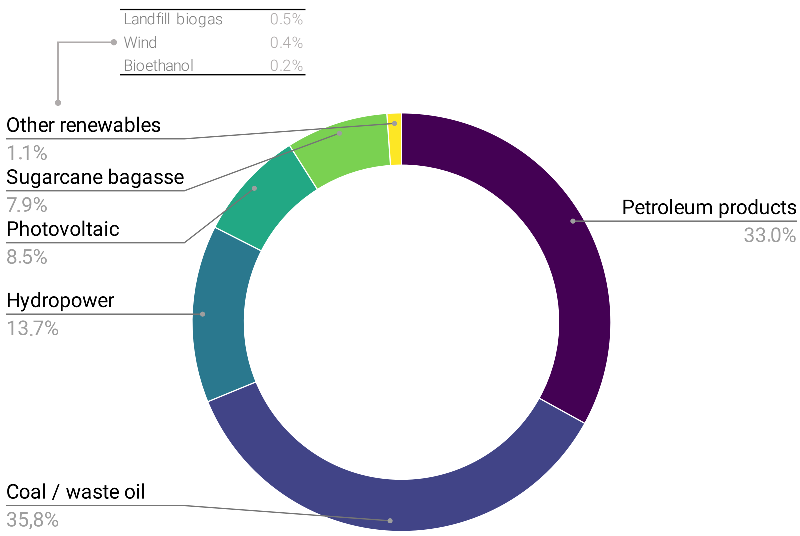

Figure 1. Electricity mix generation of Reunion island by sources, 2019, developed from data from [35].

The change of governance in the regional council in 2010 has missed absolute immobility in this race for energy autonomy. The share of renewable energies has slightly decreased from 46.7% in 2000 to 31.2% in 2019 [36]. In 2019, the electricity production delivered to the network is 3046.9 GWh. In comparison to other islands, Reunion Island's hydroenergy capacity has been thoroughly exploited. Experiments with micro hydro-wind power plants were conducted in the island's east due to the complementary nature of the two sources. This solution, however, was quickly abandoned due to its low profitability.

This low growth in renewable energy is also due to population growth. Indeed, energy intensity has evolved significantly from 1.33 (2010) to 1.41 (2018) MWh/capita. In 20 years, final energy consumption has reached 2724 GWh. Despite this context, Reunion Island has always been part of an energy transition dynamic. The LTCEV (the law relating to the energy transition for green growth) has declined the national objectives for French overseas territories by setting two objectives:

- 50% of RE in final energy consumption in 2020; and
- energy autonomy of territories in 2030.

The Regional Council has recently acted on revising its multi-year energy program (PPE) targeting carbon neutrality by 2030. The ALBIOMA company, which is the first electricity supplier (45%), signed a decisive agreement with the Region to convert the two bagasse/coal thermal power plants into bagasse/biomass in November 2020 (Green pulp imported from Canada, Brazil). Current energy strategies also includes integrating the Port Est power plant engines' conversion to liquid biomass and substantial deployment of photovoltaics for self-consumption. The objective is to reach 50% renewable energy by 2023. In SIDS, the challenge of developing RE is to expand the population's access to electricity. In the case of Reunion Island, access to the island is already 100%. For the electricity generation sector, a green, innovative, and inclusive recovery system is essential. The 2030 objectives aim for a renewable, ambitious, and inclusive electricity generation sector recovery. The purpose is to eliminate household energy vulnerability and accelerate economic growth in sectors associated with the energy transition.

3. Material and Methods

In the following section, the framework used to model and analyze the decarbonization is described. Based on the several modeling phases described, Figure 2 provides an overview of the overall framework. The three methodological steps are described in Sections 3.1–3.3 accordingly. The process starts with data collection and a life cycle analysis of 34 SFHs. To facilitate the analysis, clustering has defined the typical houses of Reunion Island. At the same time, energy scenarios have been developed to model the electricity mix's decarbonization pathways. Finally, the change in the mix is integrated into the life cycle assessment of the typical houses.

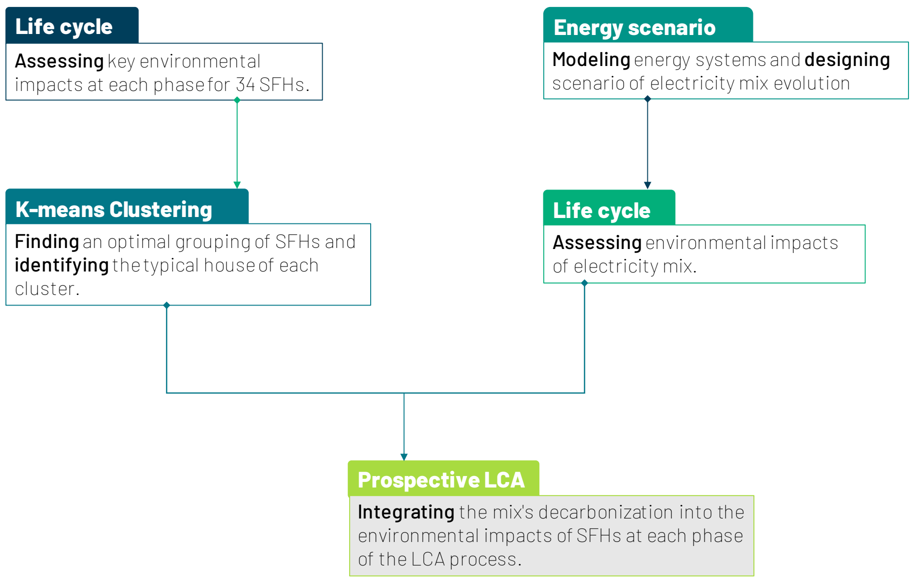

Figure 2. Synoptic of the overall methodology.

3.1. Environmental Assessment

Goal and scope definition—In this article, 34 single-family houses were evaluated. These were built between 2010 and 2020 according to the RTAADOM (Réglementation

Thermique, Acoustique et Aération des Départements d'Outre-Mer) [37]. We first study this sample of 34 houses, and then we reduce it to 3 houses, the most representative in Reunion Island for each of the 3 defined clusters, as shown in the cluster analysis. The surface area of the 3 houses studied are 110.3-106-90 m^2, respectively. The type of houses studied are national representative houses (classic single-family houses in concrete with aluminum joinery). The LCA was carried out taking into account regionalized data based on ISO 14040/14044 [18,38] and EN 15804 [39] standards. In this study, the stages of production (supply of raw materials, transport, manufacturing), construction (transport, construction, installation process), and use (evolution of production and consumption of the local electricity mix over 30 years), as well as the end of life of the houses (deconstruction, energy input, recycling, landfill), were taken into account over a period from 2010 to 2040.

System boundaries—The functional unit for this study is 1 m^2 of the constructed floor area with a life span of 30 years for the houses studied. The environmental impact assessment was carried out on the structural, functional, and end-of-life aspects of the houses. This study, therefore, presents a cradle-to-grave LCA.

Life Cycle Inventory—In this article, LCA based on the whole life cycle was used to first evaluate the single-family houses. It is then used to evaluate the evolution of the production of the Reunionese electricity mix. The environmental impacts were calculated from the processes modified and adapted to the case of Reunion Island, using generic data from the GEMIS (Global Emissions Model for Integrated Systems) tool. The materials and products were imported from several countries (France, Europe, Asia, South Africa, etc.), and the technologies were considered according to the availability of local and imported resources, for example, coal.

Impact categories—Based on the literature review, the impact categories assessed are the most commonly used in LCA building studies, as also suggested by EN 15978:2011 [40] and EN 15804:2013 [41]. The indicators that were used in this paper are mainly:

- Global Warming Potential (GWP)—kg CO_2 eq [42];
- Acidification Potential (AP)-kg SO_2 eq [43];
- Eutrophication (EP)-kg PO_4^{3-} eq;
- Depletion of the ozone layer (ODP)-kg CFC-11 eq;
- Potential of abiotic resources-elements (ADP-E)-kg Sb eq;
- Potential of abiotic resources-fossil fuels (ADP-F)-MJ;
- Secondary Raw Materials(SRM)-kg.

3.2. Clustering

Principal component analysis—The principal component is a widely used statistical method for dimension reduction of a set of data [44]. Thus, PCA is based on the assumption that only some variables are independent; the others can be inferred from each other [45]. For this reason, the first steps of the analysis consist of standardizing all the data to make them comparable, then calculating the correlation matrix to observe possible links. Hence, PCA is applied to the 7 indicators, defined in Section 3.1, in the three phases of LCA assessment counting, a total of 21 variables.

K-means clustering—The HCPC function from the FactoMineR package was used to perform hierarchical clustering. Inertia is used as a measure of inter and intra-class variability in this function. The K-means method, one of the most widely used clustering algorithms, is used to partition the data. The cluster is represented by its center of gravity in this method. The principal goal of this technique to reduce total within-cluster variation [46] according to Equation (1).

$$\mathrm{I_a} + \mathrm{I_b} = \mathrm{I_{a\cup b}} - \frac{\mathrm{m_a m_b}}{\mathrm{m_a} + \mathrm{m_b}}\mathrm{d}^2(\mathrm{a},\mathrm{b}), \tag{1}$$

where I is the inertia; $\mathrm{m_a}$ and $\mathrm{m_b}$ are the numbers of SFHs (called individuals) in clusters a and b, respectively, and $\mathrm{d}^2(\mathrm{a},\mathrm{b})$ is the squared distance between their centers of gravity. Inertia is reduced when the two clusters are grouped by a value proportional to the clusters' distance. The number of individuals in each class is the weight. All the statistical analysis and clustering were carried out using the FactomineR package [47]. Optimization of the number of clusters was carried out using the gap statistical method, which uses a statistical solution rather than a global metric, such as the elbow or the average silhouette method [48].

3.3. Energy Scenario Design

The SARI model—In this work, the energy modeling tool OSEMOSYS is used to design energy scenarios for Reunion Island to determine the evolution of RE in electricity generation. The OSEMOSYS modeling method has been implemented in many regions to shape the future energy grid. In South America, Moura et al. [49] built the South America Model Base (SAMBA), concluding that investment in massive hydropower plants and trading between countries can be a viable alternative to reducing the cost of emissions and power generation. In The Electricity Model Base for Africa (TEMBA), Taliotis et al. [50] modeled a total of 47 continental countries, including transmission links between them, where the conclusions suggest that investing in transboundary transmission links could theoretically alter the African energy environment and reduce energy production costs. OSeMOSYS is a highly adaptable and scalable architecture for optimizing energy systems. It is designed as a linear program that determines the optimum technology power investments and dispatch schedules to optimize costs. In contrast to many other energy modeling platforms, OSeMOSYS is open source to promote its use. An OSeMOSYS implementation is composed of distinct "blocks" of functionality that correspond to the various components of the modeled structure.

Before the prospective exercise, it is first necessary to define the reference energy system. The objective is to represent the different sources of production for the reference year 2018. Figure 3 presents the details of the processes and resources implemented in OSeMOSYS for the open Source model bAse for Reunion Island called SARI.

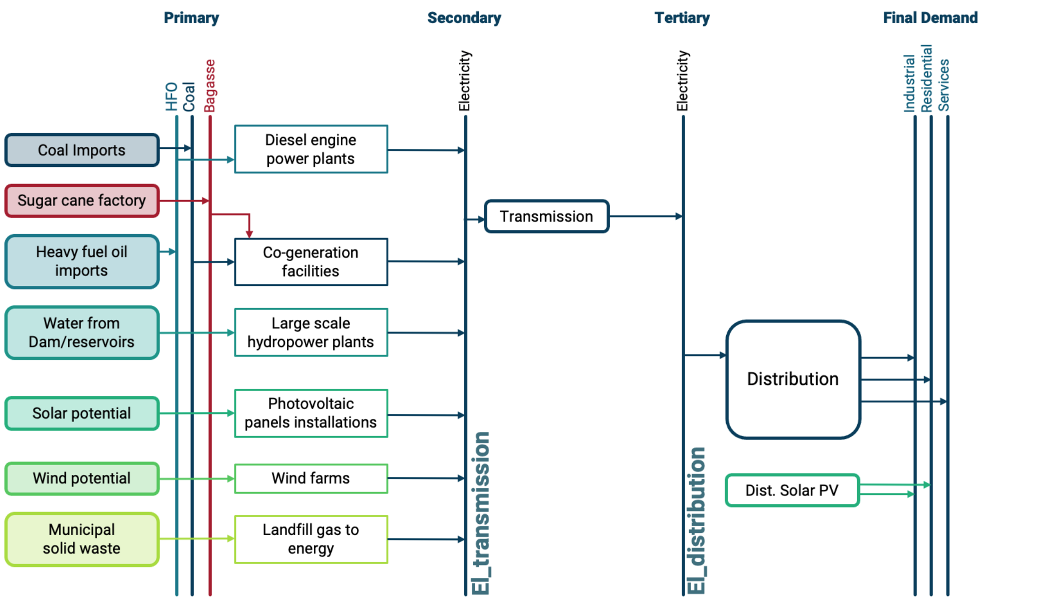

Figure 3. SARI reference energy system (RES).

Scenario setting—The model structure was developed considering the demand pattern, the power generation technologies, and their associated economic, technical, and environmental aspects. Thus, the following scenarios have been created:

- BAU—This scenario illustrates the current situation of the territory. There is no increase in the share of renewable energy in the mix. The production of hydro, PV, and wind power are left constant.
- Scenarios—Firstly, coal is abandoned in favor of green pulp, and a progressive decrease of HFO plants is modeled until 2029. One of the significant points is the integration of waste recovery in several forms. The first existing aspect that will

be developed will be biogas from landfills, despite the low availability of land for new landfills. A second aspect concerns the incineration of Municipal solid waste (MSW) and gasification, which, at the moment, is still in the experimental phase on the island [51,52]. Finally, geothermal energy, which had been neglected for a long time, is again discussed in the plans. Geothermal technology has been integrated into the scenario according to the possibility of a first installation.

An optimum electricity generation model with a virtual renewable source is modeled. The method is based on a sequential search for backstop energy technology with zero environmental impact and zero costs. The optimization process will favor the backstop as its environmental impact and costs are zero to meet the electricity demand. Then, in a second step, the mix of this backstop is defined by renewable production potential. Within the framework of its energy planning, Reunion Island initially prioritized PV/wind and waste treatment energy (WTE). Thus, we established the complementary energy generated via the backstop and then detailed how this mix would be implemented in future planned installations. This includes integrating two incineration plants, Ocean thermal energy conversion (OTEC), gasification systems, geothermal energy, and, finally, the use of green pulp in place of coal by 2025. These resources represent potentials that have been barely, or not at all, exploited until now.

4. Results and Discussion

4.1. Environmental Assessment of 34 SFHs

The first results showed that the environmental impact of single-family houses built in Reunion Island varies between 2064.3 and 2874.7 kg CO_2eq/m^2. The repartition of the ratios shows a relatively concentrated distribution of the environmental impacts. These results reflect the homogeneity of the construction techniques in Reunion Island. The most impacting houses obtain a total ratio higher than 2500 kg CO_2eq/m^2. However, the results underline that most houses in Reunion Island have a total ratio between 2000 and 2500 kg CO_2eq/m^2. The least impacting houses reach less than 2000 kg CO_2eq/m^2. As shown in the studies of Endrit Hoxha et al. and Ahmad Faiz Abd Rashid et al. [53,54], when assessing the environmental impact of residential houses, it is the functional phase that impacts the most. In our study, assessing the environmental impacts of the 34 single-family houses also highlighted that it is mainly the functional phase that impacts the most over the entire life cycle. A more in-depth analysis was carried out for each phase to explain the impacts. When we take a closer look, we see that the structural phase ranges from 517 to 1240 kg CO_2eq/m^2, the functional phase from 1170 to 1210 kg CO_2eq/m^2, and the end of life impact of the houses ranges from 371.2 to 434.7 kg CO_2eq/m^2; see Figure 4.

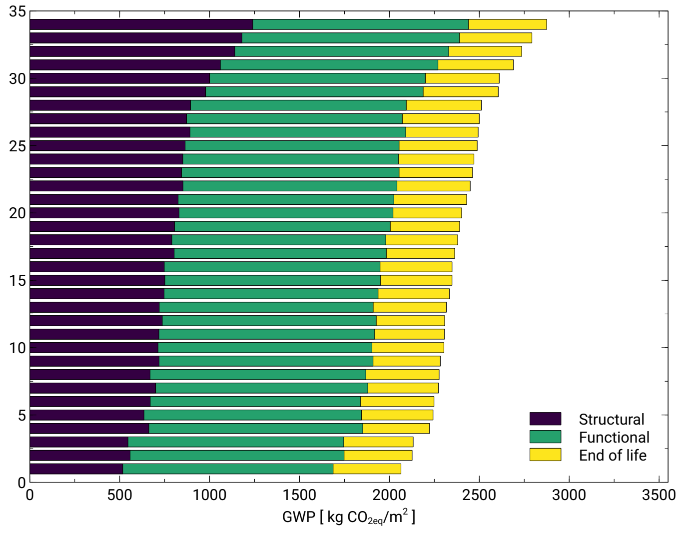

Figure 4. GWP ratio in CO_2eq/m^2 of the 34 SFHs by life cycle phase.

4.2. Typology of the Reunion Houses

A PCA is performed on a matrix of 34 SFHs defined by 21 LCA indicators, using the methodology outlined in Section 3.2. The factorial axes inertia suggests that the PCA's first two axes express 46.3% of the data set's total inertia. This value is higher than the reference value of 26.81%, indicating that this first projection plan explains a large amount of variability. This reference inertia is the quantile 0.95 of the distribution of inertia percentages obtained by simulating a random data set of comparable dimensions of the normal distribution. Clustering is performed on either the raw data table or on selected objects. Our process begins by performing a PCA and then clustering using the individuals' coordinates (SFH). The PCA can hold only the most significant dimensions for study. Thus, the points denoting the houses are initially projected onto the plane defined by the PCA's first two dimensions. They are then clustered. Since the distances between the points from the main plane vary, the two points projected close together are not inherently close. Thus, the superposition of the clusters' projections does not imply that these clusters overlap. Because their projections on the main plane overlap, this does not imply that an individual may belong to more than one class. The K-means partitioning principle requires that a person belongs to only one class.

Figure 5 shows the clustering results projected on the first two principal components. The results revealed three distinct clusters with different features. The cluster analysis is carried out in two stages: first for variables, then for individuals (SFHs). The categorical variables associated with each cluster characterize them. A relevant p-value of 0.05 is used to classify these variables. Our classification's objective was not to characterize each according to the variables but to define construction typologies according to environmental quality.

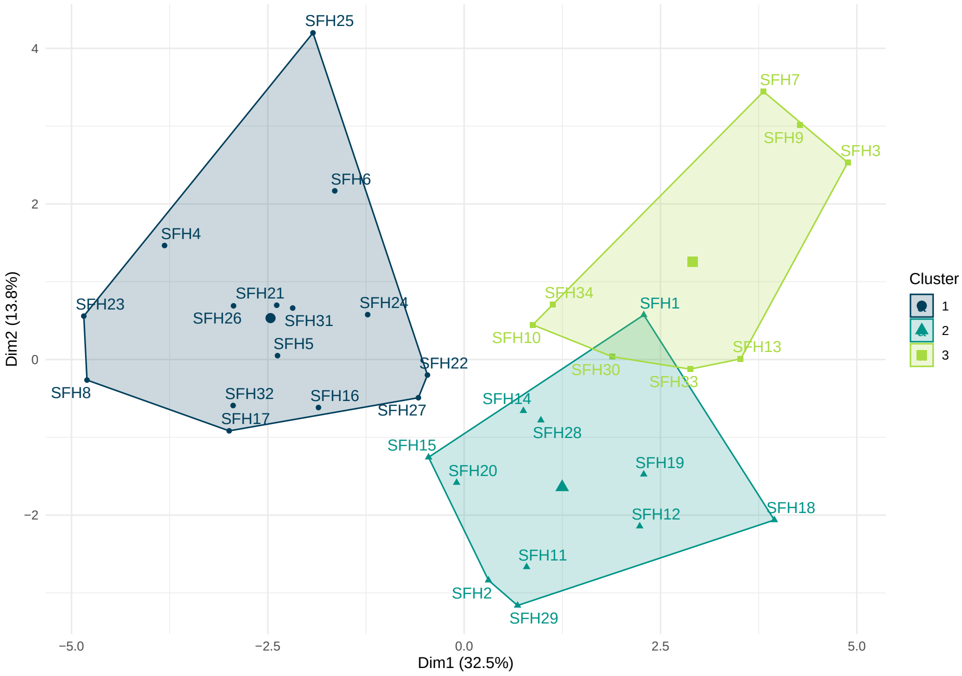

Figure 5. Clustering results for houses typology definition projected on the first two principal components.

The process of clustering entails the identification of paragons. The individual whose coordinates are nearest to the barycenter for each group is known as the parangon, and its profile better characterizes the cluster to which the individual belongs. These parangons, therefore, avoid treating all 34 houses in our analysis but focus on three of them that are representative of the entire database. The parangons are SFH16 (cluster 1), SFH12 (cluster

2), and SFH13 (cluster 3). The SFH16 house represents a cluster with low environmental impact in all phases of the life cycle, while SFH12 has the characteristics of a low impact group in terms of ozone depletion but high values on secondary raw materials and ADPE in the structural and end-of-life phases. Finally, SFH13 synthesizes a cluster's characteristics strongly marked by a GWP in the structural phase and a high acidification potential throughout the life cycle.

4.3. Environmental Impact of Materials

The high proportion of concrete in some single-family homes explains the major structural effect (foundations, slab, screed, frame, and facades), as well as the widespread use, of aluminum joinery (doors, windows, jalousies, frame, bay window, roller shutter). For a concrete slab and an aluminum motorized roller shutter, the regionalized emission factor is 187 and 623 kg CO_2 eq, respectively. Because of the island's geographical position, which is heavily reliant on significant imports, regionalization of the data was required. According to Reference [55], regionalizing and adapting data to remote territories, which do not have the same requirements and restrictions as continental territories using standardized data, is crucial. As pointed out by Ayagapin [56], an environmental overcost between a French overseas island and France of 37% is mainly explained by shipping due to remoteness of the island. On the other hand, for the functional phase, the production of the local electricity mix, as well as the impact of the consumption of the inhabitants, was taken into account in order to determine the average production ratio, i.e., 0.657 kg CO_2eq/kWh, and the impact of the consumption of the users in Reunion Island, i.e., 4.1 kg CO_2eq/capita. These figures allowed us to obtain an average ratio in the functional phase for each of the houses studied. Finally, after examining the components of the houses with the lowest impacting ratios, we discover the presence of interior partitions and false ceilings made of plasterboard, as well as hinges in the exterior facade coverings, as shown in Figure 6.

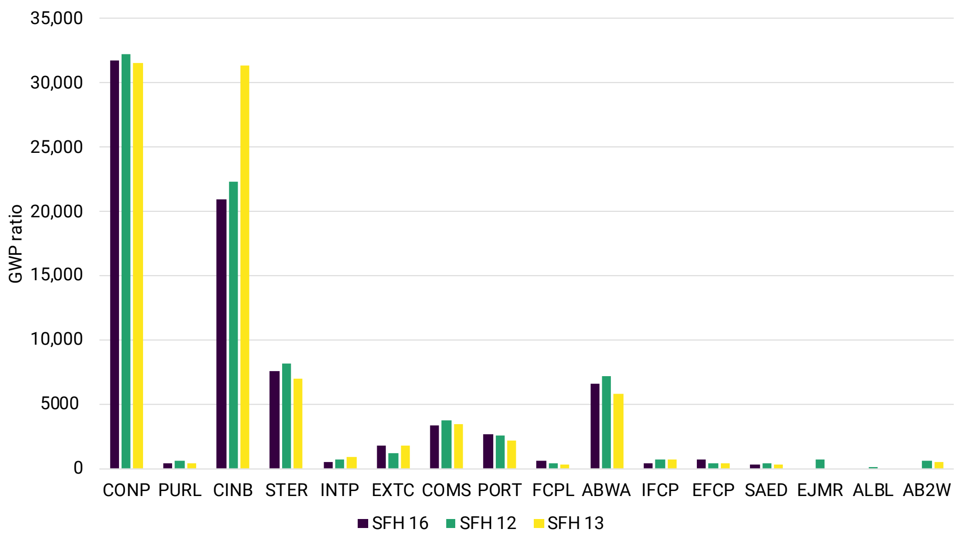

Figure 6. Main building materials constituting three typical houses: CONP—Concrete paving, PURL—Purlins, CINB—Cinder block, STER—Steel roofing, INTP—Interior plastering, EXTC—External coating, COMS—Concrete mortar screed, PORT—Porcelain tile, FCPL—False celing in plasterboard, ABWA—American block wall, IFCP—Interior facade coating type paint, EFCP—External facade coating type paint, SAED—Solid aluminium entrance door, EJMR—Exterior joinery type motorized roller shutter, ALBL—Aluminium blinds, AB2W—Aluminium bay window.

The details of the nomenclature of the products and materials composing the house are specified in the Abbreviations section on page 15.

4.4. Overall Indicators Results

Previous research has primarily used the GWP as a significant measure. The other indicators studied in this paper have been carried out to a more in-depth analysis. The environmental impact of the indicators on SFH 16–12 and 13 are quite similar overall but differ slightly from one house to the next, as shown in Figure 7.

SRM and ADP-F's effects impact the SFH16 on the structural and functional phases. However, the functional phase has a much more significant impact on other indicators, such as ADP-E, GWP, and ODP. The end-of-life phase remains the least impactful phase, despite its more significant proportion for the AP, ADP-E, and SRM.

For SFH12, we can see that indicators, such as ADP-F, SRM, AP, and GWP, have a relatively significant environmental impact on the structural aspect. Instead of the ADP-F, the GWP, especially the ODP, has a consequent environmental impact on the functional aspect. Finally, it is mainly the AP, the SRM, and the EP that obtain a more consequent impact for the end-of-life phase. Finally, for the SFH13, the structural phase's environmental impact is more critical for the ADP-F, the SRM, and the GWP. The functional phase has a more significant impact for the ODP, the GWP, the ADP-F, and the SRM. We observe that the ADP-F, GWP, and AP have notable impacts in the functional phase. For the GWP, coal is the worst choice. Three additional indicators, namely ADP, EP, and MAETP, appear to have major effects such as GWP. The combustion of the fuels explains the majority of the impacts from coal and oil power plants. The ADP, which is almost entirely due to fuel extraction, is an exception. The effect of bagasse electricity generation on the AP and EP is primarily due to the slag and ash remaining after bagasse combustion [57]. Hydropower, on the other hand, has only one impact: the building of the plants.

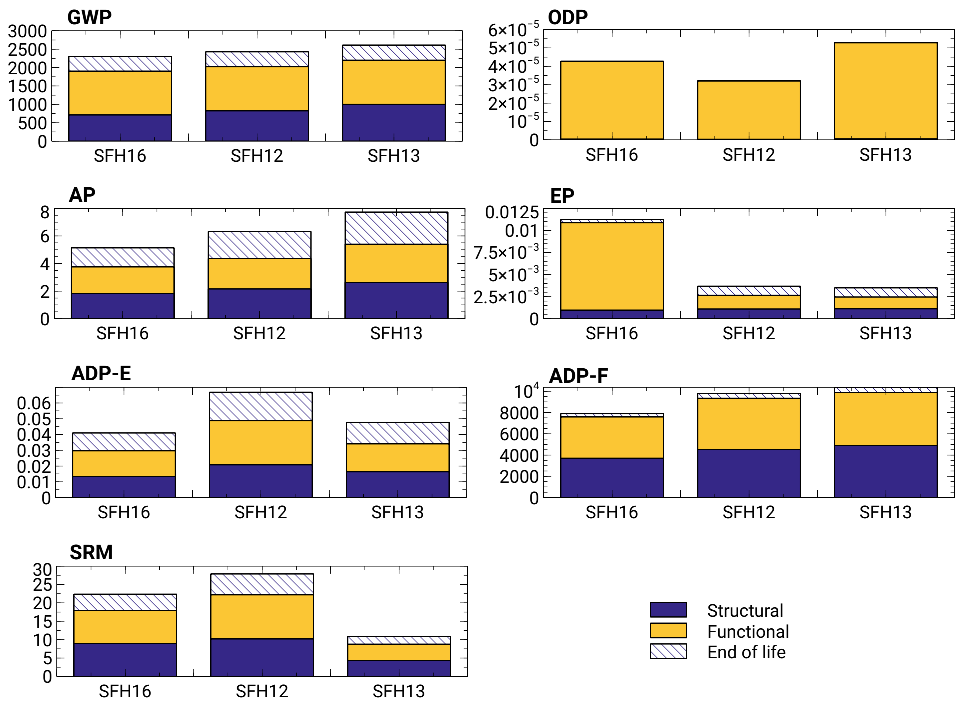

Figure 7. Overall life cycle results.

4.5. Energy Scenario

This section discussed the results of the scenarios assessed using the technological optimization parameters. Our approach was to consider in the scenario the technologies available according to the 2018 reference year. Then, we integrated the ambitions of the policies for the decarbonization of electricity production. The strategy focuses on the intention to develop a diverse energy mix capable of securing energy production. Thus, the goals are to reduce the territory's energy vulnerability and, secondly, to contain the volatility of electricity prices by limiting the island's dependency on exogenous resources. Three main axes are considered:

- removal of coal in the short term;
- increase in historically available renewable facilities; and
- development of new technologies ("Backstop" approach).

To favor the integration of new installations, we have created a virtual energy resource with zero economic and environmental impact. In this way, it is possible to force this backstop technology to meet the electricity demand. Once this demand was identified, we referred to the guidelines of Reunion Island's multi-year energy plan to propose a new electricity mix.

In this case, coal-fired electricity generation will reach 1233 GWh from 2018 to 2024, after which coal-fired power plants will be phased out starting in 2025, see Figure 8. Green pulp will be used in the energy system beginning in 2025, taking coal as an alternative fuel source. For the years 2025 to 2040, green pulp generates a constant amount of 1233 GWh. HFO, on the other hand, shows a decreasing trend in energy generation from 2018 to 2025, accounting for 880 GWh in 2029, owing to a steady capacity decline. HFO-fired power plants will be phased out by 2025. Energy output from bagasse, hydropower, biogas, and wind resources maintains the same pattern as in the BAU scenario since no new facilities are planned.

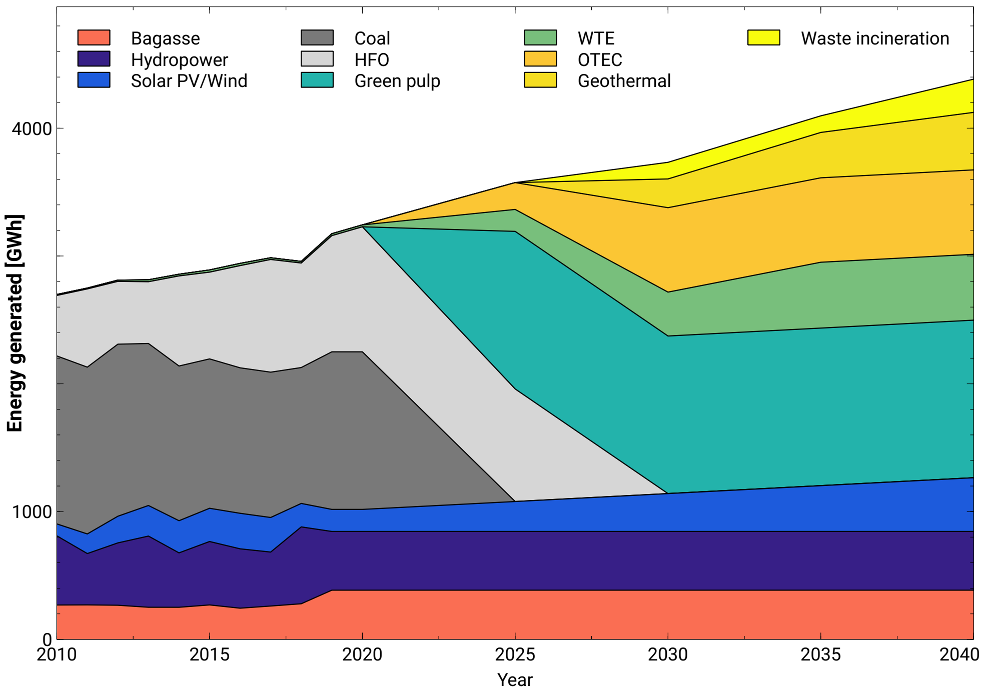

Figure 8. Electricity generation evolution of Reunion island from 2010 to 2040.

In 2040, the share of the backstop represents 61.39% of the overall mix. This new renewable energy contribution in GWh is distributed as follows: Green Pulp (1233)-OTEC(660)-Geothermal(450)-Gasification (227)-Waste incineration(260). Projections show a 63.6% reduction in GHG emissions for the electricity mix, from 0.657 in 2020 CO_2eq/kWh to 0.239 in 2040.

4.6. Effect of Decarbonization of the Electricity Mix

The decarbonization effect was performed on the 3 houses selected when defining the typology of the 34 single-family houses presented in this paper. The decarbonization effect allowed to highlight the evolution of the environmental impact of the single-family houses over 30 years, taking into account the use of the local electricity mix for the structural, functional, and end-of-life phases. Further decarbonization of the energy system is essential for achieving the 2030 and 2050 climate targets. Thus, the EU's green deal [58] commits to developing the electricity sector primarily through renewable energy sources. However, there is a lack of international consensus about how to decarbonize the sector. Over the next three decades, electricity production will experience a significant structural change in Europe, where stringent carbon limits are likely to be adopted [59]. As an outermost area of Europe, these ambitions even concern Reunion. The initial situation is not the same in all regions of Europe. Indeed, the Eastern European countries have a development system heavily dependent on coal and natural gas. The situation of Reunion Island is peculiar because coal constitutes 24.1 percent of its generated electricity. Similarly to Eastern European countries, the preference for a stable energy mix at low cost has led to the penetration of coal in the mix [60]. Now that the energy debate is also taking place on the ecological stage, the "coal question" is not sustainable because its effects impact other sectors.

In Reunion, thermal power plants run on sugarcane bagasse during the sugar season (July to December). Outside of this period, coal takes priority. To achieve its decarbonization target, it intends to substitute coal with imported green pulp from South America. Thus, the environmental impact will be significantly decreased but not eliminated due to transportation. Additionally, the territory's energy vulnerability remains unchanged as we continue to rely on imports. This supply could jeopardize electricity production in the event of a global crisis (energy, health, economic). As a result, this decarbonization represents a significant opportunity to reduce emissions in the building sector, especially during the operational phase of the building's life cycle.

The impact of the production of the local electricity mix was considered in 2010 with an electricity environmental impact that was evaluated at 0.699 kg CO_2eq/kWh in 2010, at 0.657 kg CO_2eq/kWh in 2020, at 0.195 kg CO_2eq/kWh in 2030, at 0.239 kg CO_2eq/kWh in 2040. Figure 5 shows the evolution of SFH 16–12 and 13 from 2010 to 2040. The decarbonization effect started in 2020, but becomes more pronounced in 2025, thanks to the use of new technologies available on the territory of Reunion (see Figure 9).

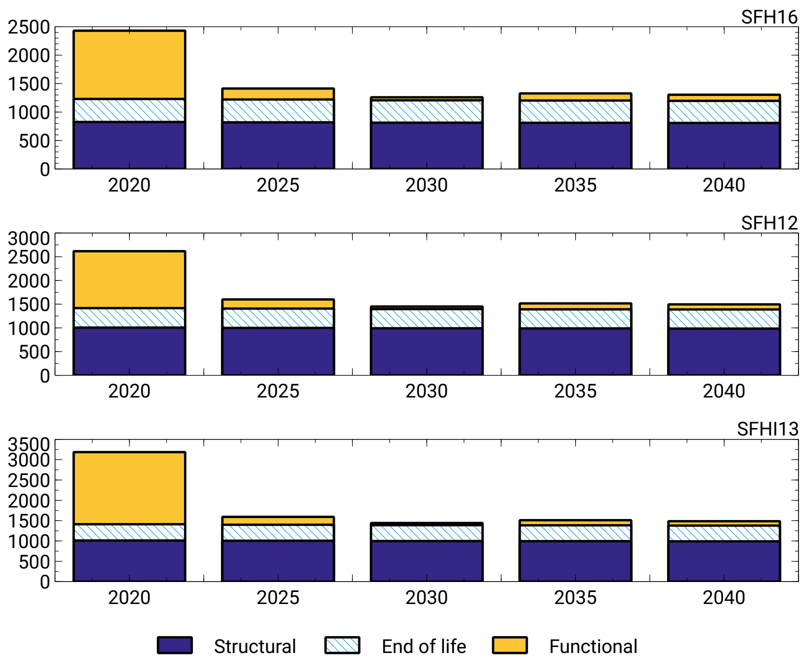

Figure 9. Effect of electricity decarbonization on the three typical SFHs through the GWP in kg CO_2eq/m^2.

Decarbonizing the local electricity mix decreased the total environmental impact of the 3 houses studied by 45%. Looking more closely, this decarbonization decreased the structural impact by 2%, the functional impact by 80% and the end-of-life impact by 1%. The use of the local electricity mix in the structural and end-of-life phases remains very minimal.

5. Conclusions and Policy Implications

This paper discusses the consequence of decarbonizing power generation in the construction sector under an insular context. Since the islands have few raw materials and infrastructure, they are heavily reliant on imports. There are no exceptions in the construction and electricity industries.

Materials and goods are extracted and manufactured in foreign countries using their local electricity mix. The local electricity mix is only used in the structural process for semi-finished items that must be assembled before being deposited on the installation site. Few products (less than 37%) are recycled locally at the end of their lives. The rest is either exported for treatment and recycling abroad or considered as final waste in a landfill. This impact reduction is due to the decarbonization of the local electricity mix, which has the most significant impact on the impact of the use of materials/products, water quality, and household waste. However, to reduce the environmental impacts of the houses, several solutions for the island are possible depending on the phases. On a local scale, less massive importation of materials and products can be considered in the structural phase. Reusing secondary raw materials and limiting raw material extraction in countries will be prudent. This practice will also have environmental (less CO_2), social (local job creation), and economic (supply/demand on the island market for environmental aspects) benefits. On the island, specific materials and goods can be directly transformed. It will also be essential to reconsider content and product supply chains by importing from neighboring countries. For the functional aspect, it will be essential to operate primarily at the local level: since Reunion's electricity mix is high in carbon (currently 64% fossil energy), decarbonization considerations are vital. The decarbonization scenarios presented in this paper show that by 2040, the use of emerging technology would enable Reunion's houses to have a significantly lower functional effect. Indeed, one promising prospect locally is the residual household waste (RHW) valorization. Methanization and gasification have been investigated in a scenario to generate electricity from household waste. Finally, a third lever that can be considered locally for reducing impacts on the functional phase is to try to minimize electricity consumption by energy side management while taking into account the evolution of electricity consumption: the Business-As-Usual (BAU).

Finally, in terms of the houses' end-of-life process, deconstruction of the houses may be less impactful in 2040 than today due to decarbonization. However, since most goods and items are buried or shipped to other countries at the end of their lives, the effects of a reduction in the energy mix would be minimal in this final process. The export of materials and products underlines the island's inability to treat its houses' waste at the end of their life due to the lack of infrastructure and the mistrust of artisans to use recycled materials, despite an initial cost divided by two in most cases. Finally, there is no doubt about decarbonization's effect on the construction sector. However, this decarbonization must be viewed in terms of vulnerability, with biomass resources being relocated to replace coal. To this end, a study is currently underway to create a forest dedicated to electricity generation.

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Abbreviations

The following abbreviations are used in this manuscript:

ABWA	American bloc wall
ADP-E	Abiotic Depletion Potential-elements
ADP-F	Abiotic Depletion Potential-Fuels
ALBL	Aluminium blinds
AP	Acidification Potential
BAU	Business-As-Usual
CINB	Cinder block
COMS	Concrete mortar screed
CONP	Concrete paving
EFCP	External facade coating type paint
EJMR	Exterior joinery type motorized roller shutter
En	End-of-life
EP	Eutrophication Potential
EXTC	External coating
FCPL	False ceiling in plasterboard
Fu	Functional
GWP	Global Warming Potential
IFCP	Interior facade coating type paint
INTP	Interior plastering
ODP	Ozone Depletion Potential
PORT	Porcelain tile
PURL	Purlins
SAED	Solid aluminium entrance door
SFH	Single Family House
SRM	Secondary Raw Materials
STER	Steel roofing
WTE	Waste treatment energy

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