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Environmental Overcost of Single Family Houses in Insular Context: A Comparative LCA Study of Reunion Island and France

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Received: 30 September 2020; Accepted: 21 October 2020; Published: 27 October 2020

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Abstract: The building and public works sector is, in France as in Europe, a major consumer of raw materials for both the manufacture of products and the construction of buildings and structures. This sector has a direct impact on the natural and built environment. This effect is even more pronounced in the case of isolated territories, such as islands. The latter have their own constraints (geographical location, production of the local grid mix) and particularities: very small territory, massive importation of goods in all fields, such as food, automobile, building, and others). In this study, we focus on the building branch of the construction industry, which covers housing (single-family houses and apartment blocks). The study is based on the analysis of about twenty single-family houses built in metropolitan France and Reunion Island. The construction standards for these two regions comply with European standards (CE) and French regulations. However, in the case of Reunion Island, a tropical island, it applies in particular to the Thermal, Acoustic, and Ventilation Regulations for New Buildings in Overseas Departments and Regions (RTAA DROM). The approach that is used for the environmental assessment of single-family homes is the Life Cycle Assessment (LCA), from cradle to grave. The results initially showed that there is an additional environmental cost in the construction sector between France and Reunion Island. This is initially due to the choice of origin of materials and products, which can greatly contribute to the impacts of construction. Secondly, to the use of the countries' electricity mix, which also contributes, in part, to the impact of the construction of these single-family homes during the assembly and transformation of the products. Finally, this additional cost also differs according to the transport used (sea, air, rail, road). For the Global Warming Potential (GWP) indicator, in our study we note that the additional environmental cost is 37% higher in Reunion Island. This figure explains the additional impact of the 218 kg-CO_{2eq}/m^2 of built-up area built for Reunion Island. This study is one of the first analyses demonstrating the additional environmental cost that exists between mainland France and overseas France. Thus, the results demonstrate the importance of creating a specialized and regionalized database for the case of remote islands. Thus, this database would allow for professionals to have a precise environmental assessment, not on a national but on a regional scale. This document also provides a framework and guideline for policy decision-making in the overseas islands.

Keywords: LCA; single family houses; island; environmental assessment; regional scale

1. Introduction

The building sector is strongly associated with high environmental impact due to heavy energy and natural resource consumption [1]. France has been engaged for several years in the energy transition, in order to reduce energy consumption and the replacement of current energy sources by renewable energies, hence the need to act on the energy system and the building sector. The latter is responsible for 43% of French final energy consumption. The Grenelle has set the target of a 38% reduction in energy consumption by 2020. The French government wishes to bring one million homes to high levels of thermal performance each year, five hundred thousand in new construction and five hundred thousand under renovation. In addition, the Grenelle 2 law stipulates that work to improve energy performance is to be carried out in existing buildings for tertiary use or in which a public service activity is carried out by this year in 2020. Among the key measures, the gradual introduction of a work obligation for all older housing to bring them up to the level of the BBC Renovation label requirements by 2050 [2]. For the evaluation of the impacts of a system, Life Cycle Assessment (LCA) is the most widely used methodology. LCA is a well-developed tool to assess the environmental performance of materials, products, systems or even the whole building by quantifying the consumption of resources and the production of waste from the upstream flow of extraction, manufacturing, transport, construction and use of raw materials, and the downstream flow of deconstruction and end-of-life disposal [3]. LCA is used in several fields, whether for construction [4] or renovation [5], building materials [6], and in production chains [7,8]. The use of LCA for assessing the environmental performance of materials and buildings has increased considerably over the last few decades. In the literature, LCA studies show that buildings have a significant impact on the environment and the construction of buildings consumes about 50% of raw materials, 71% of electricity, 16% of water consumption, and produce 40% of waste going to landfills [9]. However, buildings offer the greatest potential for mitigating environmental impacts. A construction project can have different levels of environmental impacts at different stages of the life cycle of a building [10]. Many stroke studies are now considered in the literature. Some studies have focused on building construction to determine its use for decision-making [11], other studies to determine the impacts by LCA phase and building type [12,13], and other studies have focused on single-family houses to evaluate strategies for simplifying methods [14]. The studies focus mainly on assessing the environmental impacts of buildings [15–17], but very few are compared with each other. The main objective of this document is to assess and then compare the environmental impact of the construction of about twenty individual houses with the same building standards, but not in the same geographical situations: in Metropolitan France (continental environment) and in Overseas France (tropical environment). Although Reunion Island follows the same standards as France (EUROCODES, CE-certified materials), geographical and climatic constraints lead to specific constructive adaptations to achieve thermal comfort conditions. As the sources of supply of products and materials are not the same, it is therefore not possible to carry out an environmental analysis of houses based on international generic data. As pointed out by Michele Morales et al., there is a need to adapt and regionalize data from island territories to improve the accuracy and relevance of LCA study results [18].

The gap that exists for the same typology of houses between mainland France and overseas France underlines in this paper the importance of regionalizing the data specific to island territories. An island territory cannot use the same inventory databases as a continental territory. This work aims at precisely quantifying the environmental overcost in order to adapt future national environmental regulation or policy objectives in a near future. This paper fills the gap of information the overall French territory in terms of comparative study in the building sector. Previous studies in the French context have only been investigated for continental condition not for the overseas. The environmental overcost highlighted in this paper will enable decision-makers, politicians, and building professionals to make decisions on both the environmental and economic aspects. The sections presented in this paper are the introduction, the methodology and data of the LCA, the overall analysis of the results, and the discussion and conclusion for policy implications.

2. Context and Background

2.1. A Brief Overview of Reunion Island

Reunion island is a French overseas territory of 2512 km^2 located in Indian Ocean, between Madagascar and Mauritius, see Figure 1. This small island is subject to a subtropical climate that is organized in two seasons: hot and humid austral summer (October to March) and a cool and dry austral winter (April to September). The island is organized into three main climatic zones. However, the particularly sharp relief of Reunion Island leads to a large number of microclimates. Because of its geographical isolation, the island is highly dependent on imports in all sectors, including energy. The production of electricity is 64% dependent on fossil resources, despite a high potential in renewable energy [19]. The willingness to move towards territorial autonomy is a 20-year-old ambition. The objective of electrical autonomy is on the agenda of Reunion Island for 2030–2032, a period that will correspond to the stabilization of the population of Reunion Island. In spite of a very voluntarist political discourse, the actions and figures to date do not reflect a real energy transition. There are no encouraging signs of any kind of beginning of change in our territory.

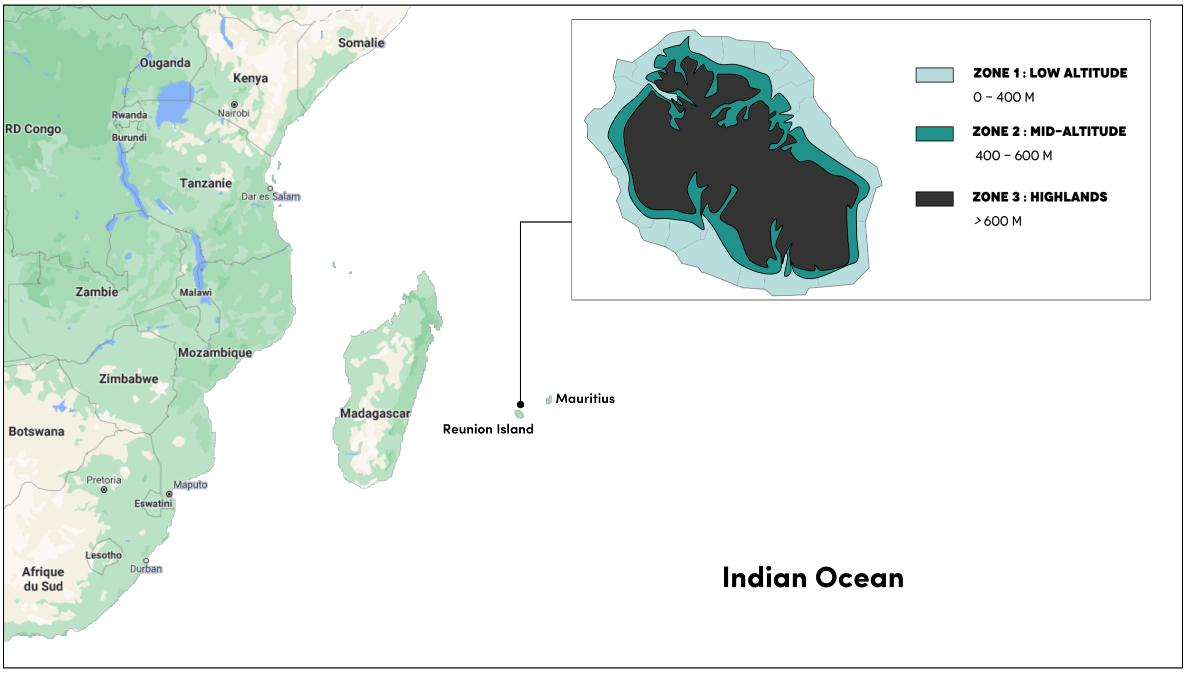

Figure 1. Reunion island location and climate zoning. Source: Author'sillustration, data from Google Maps.

2.2. Reunion Construction Sector Situation

Following its departmentalization in 1946, Réunion underwent a rapid demographic transition in less than fifteen years, as compared with more than fifty years for France. Despite a slowdown of population growth in the 1990s, the evolution of construction between 1999 and 2013 does not follow the same trend. For example, there is an increase of 43%, which would correspond to the annual construction of nearly 8500 housing units over the next four years. In 2017, the construction of housing units in La Réunion reached more than 5% when compared to 2016 (with more than 7000 housing units allowed) [20]. The individual housing sector is the main contributor to overall development and it is the majority in the local market. Reunion remains the French region after Corsica where new construction is the most dynamic. As part of the French overseas departments, Reunion Island has a climate and lifestyle that makes metropolitan regulations inappropriate in terms of thermal, acoustic, and ventilation characteristics of new residential construction. Over the period 2013–2035, 168,900 housing units are expected to be built in Reunion. More than 60 per cent of this demand is related to the expected increase in the number of households [21]. In addition, this demand is expected to be even greater because of the need to rehabilitate ageing local housing. The main differences between France and Reunion Island are at the level of the finishing materials (construction phase) and the house's operating phase. Concrete remains the main common element in construction whatever the territory. The climatic context greatly influences the choice of finishing products or materials according to the requirements: thermal insulation, solar protection, natural ventilation...). Indeed, in tropical environments, the objective is to build passive houses limiting heat gain. In the case of France, the objective is often twofold: to limit heat gain during the summer and heat loss during the winter. This induces different modes of operation of the houses, for example, a significant impact of heating.

The insular specificity of Reunion Island imposes on the actors of the construction sector and political decision-makers to implement a better environmental quality of the constructions, by favouring a voluntarist development of an industry of recycling of construction materials. Thus, LCA is a tool for assessing the various impacts of construction.

2.3. A Brief Litterature Review

The first studies on environmental impacts date back to the 1960s and 1970s. Private companies carried out the first LCA studies. The objective of these studies was to quantify the consumption of raw materials and energy in order to make the public domain transparent [22] and also to optimize industrial processes. LCA received more attention in the early 1990s due to the accelerated deterioration of the environment [23]. LCA is a holistic approach to the environmental interactions of construction buildings throughout their life cycle, while taking upstream impacts into account [24]. LCA is defined as a quantitative method that is used to assess the environmental burden of a product, process or system throughout its life cycle [11,25,26]. From a broader perspective, it helps to understand the trade-off between different impacts, such as the potential for acidification, the potential for depletion of non-renewable resources, and the depletion of the ozone layer. In the construction sector, the research theme of LCA the analysis and discussion of reducing environmental impacts is becoming an increasingly important field of research. In recent years, the number of publications has increased steadily and significantly. In total, more than 250 construction LCA documents were referenced in 2015 [4]. Several review articles have been published in the field of LCA in buildings between 2009 and 2014, and at least 10 review articles in 2015–2016 [6,11,14,27–32]. From top to bottom, there have been additional critical reviews articles on the construction of LCA [4,33,34]. These recent reviews have taken several aspects of the buildings into account, such as embodied energy, residential buildings, and materials with the highest impact. In the literature, LCA studies have focused on risk assessment that is based on the energy life cycle energy-saving systems in buildings, embodied energy efficiency, use of building materials to minimize environmental impact, and emissions associated with the operational phase [4,5,28,34]. Existing cases The studies compare concrete and wooden houses, as well as the pre-use phases of a standard house. Buildings, building materials, and systems are also evaluated [35–38]. Other more recent studies have focused on building renovation [39–41], prefabricated buildings [42,43], construction [42,44,45], hybrid building footprint [46], public buildings [47], operational carbon (heating), cooling, hot water, and embedded carbon (material supply, production, transport) [48,49]. The built environment is recognized as a major factor in resource use and environmental impacts. Studies on LCA in buildings are mainly carried out in developed countries, where databases exist and are applicable to their territories. On the other hand, case studies on building LCA in emerging countries or developing countries are infrequent, due to a non-specific (or not directly applicable) database. Because of their specificity, the data for these territories must be regionalised and consistent, while taking into account their geographical location, own resources, and imported products. In this document, we underline the effect of insularity, the additional environmental cost that can exist between two territories respecting the same construction standards, but not having the same geographical constraints. In the literature for the case of territories with specificities, the case of Brazil [18] shows the importance of integrating regional specificities, since the environmental impacts vary considerably when compared to regionalized data. The results clearly show that the impacts of buildings depend on their geographical location. This could be explained in two ways: the first is the origin of the materials and processes used for construction. The second is the accuracy of the database adapted to the geographical location. The database and case study that are presented in this work are defined for developed countries in Europe, China, and North America [44]. In this paper, we will then discuss environmental quality in the light of a comparative study between France (continental environment) and Reunion Island (tropical environment). The results provide the first elements to define new guidelines for decision-makers, architects, and other professionals wishing to draw up a roadmap for low-carbon urban development. Our work fills this gap by proposing a comparative study between two distinct environments.

3. Methodology

3.1. Goal and Scope Definition

Because Reunion is a French territory, the building sector has the same regulations constraints and same building standards. The selected houses were built in the period from 2009 to 2019 according RTAADOM (Réglementation Thermique, Acoustique et Aération des Départements d'Outre-Mer) [50]. We initially investigate a sample thirty houses, and then reduce to twenty as a clustering analysis show us the consitency of the sample with the twenty most representative houses in the case of Reunion island. The studied houses area range from 80 to 180 m^2 and contain from four to nine rooms. They are located for the majority on the coast of the island, i.e., between 0 and 400 m above sea level. The type of houses was chosen according to what was considered to be representative at the national level (classic single family concrete house with aluminium joinery). The areas of the units being compared are similar in size, and the construction methods and materials used are also similar. Since 2009, the RTAADOM has been applied in Reunion Island as in all the overseas regions of France for more than 10 years. This has resulted in the harmonization of bioclimatic building standards in tropical environments. Thus, although the island is organized into three climatic zones, limiting heat gain is the main issue of thermal comfort in our latitudes. The LCA was conducted while using regionalized and non-regionalized inventory data that were based on ISO 14040/44 [51,52] and EN 15804 [53] standards. In this comparative study, the stages of production (supply of raw materials, transport, manufacturing) and construction (transport, construction, installation process) were taken into account when applying the LCA methodology. The transport of materials is taken into account at the production stage and at the construction process stage. The materials and products used in construction on Reunion Island are mainly imported from Europe, China, Asia, and Singapore. Table A1 in Appendix A summarizes the different origin countries and most common routes used for sea freight to Reunion. The case of maritime freight transport for France is provided by Table A2 in Appendix A.

3.2. Functional Unit

According to the ISO 14040 standard [51], the functional unit (f.u) is defined as the unit reference through which a system performance is quantified in an LCA study. The chosen functional unit is 1 m^2 of constructed area floor with an assumed lifespan of 30 years for the house. The assessment is carried out in the following three steps:

- The definition of gross emission factors (FE) for Reunion and France.
- The quantification of these emission factors to obtain total emissions by impact category.
- Finally, the ratios per m^2 of area floor were calculated.

House caracteristics, such as indoor climate quality, soundproofing characteristics, and cost, are not considered in the functional unit for this study.

3.3. System Boundaries

This study presents an LCA from the cradle to the construction site. The structural aspect was only considered. Firstly, due to the fact that the same type of house is built in two totally different locations (temperate and tropical climate), and secondly, due to the totally different functioning of the uses in the two locations (heating or air conditioning consumption), it seemed to be appropriate to us to only use the scale of the construction in the first instance, in order to demonstrate that environmental impacts are not to be considered only at the functional scale, but also at the structural scale.

3.4. Life Cycle Inventory

In this study, the process-based LCA method was used in order to calculate the environmental impacts. For this purpose, the GEMIS (Global Emissions Model for Integrated Systems) impact estimator [54] was used to define the emission factors for France and Reunion Island. One of the advantages of GEMIS is that it integrates energy and material flows, transport, and a consequent database for the definition of product emission factors. It was developed in 1989 by Öko-Institut, and distributed on the IINAS International Institute for Sustainability Analysis and Strategy [55] platform. This assessment tool is free of charge. It integrates more than 10,000 processes and products. The processes that are included in the software refer to different countries of the world, but the particularity of this estimator also lies in the so-called "generic" processes that can be used as basic processes, not assigned to a particular country, and that can be adapted to a territory according to the specificities of the region studied. For our study, we used the official French INIES (INIES is a national reference database on environmental and sanitary characteristics for the building industry) database, which defines the emission factors for each material and product used in building construction. These emission factors are in accordance with ISO 14040/14044 for base materials, construction products and components, fuel use, and transportation. In this study, the calculated quantities were extracted from GEMIS and the final calculations were performed in MATLAB. The methodologies used to calculate life cycle phases, such as production and construction of houses while taking into account regional specifications, are provided below: site construction: this phase includes the acquisition of raw materials, transportation of materials or components to the construction site. Transport distances are based on French and Reunionese regional surveys. In addition, calculations are carried out from a platform suitable for maritime transport. The materials transport is considered for the product stage and the construction process stage for Reunion Island case Table 1.

Table 1. Considered transportation distance (in kilometer) per building material and modal distribution for the product stage and construction process stage. Source: Author's calculation from GEMIS.

Building Material	Distance of Transportation (km)	Modal Distribution	Distance of Transportation from the Industry to the Construction Site (km)	Modal Distribution
Cement	0	Maritim freight	51	Freight lorry
Aluminium	14,139	Maritim freight	66	Freight lorry
Ceramic tile	9148	Maritim freight	66	Freight lorry
Galvanized steel	13,386	Maritim freight	56	Freight lorry
Glass	9395	Maritim freight	56	Freight lorry
Gravel	0	Maritim freight	51	Freight lorry
Gypsum board	12,400	Maritim freight	78	Freight lorry
Paint	6389	Maritim freight	56	Freight lorry
Reinforcing steel	9395	Maritim freight	14	Freight lorry
Wood	14,940	Maritim freight	14	Freight lorry
Sand	0	Maritim freight	51	Freight lorry

Concerning regional specifications, in this study, for the case of France, the French electricity mix, using more than 70% nuclear, which implies a very low Global Warming Potential (GWP) value of about 0.083 kg CO_2eq/kWh, as well as the modes of transport used, such as road, air, or rail, and the manufacturing of products are used to calculate the environmental impacts of the materials and products. In the case of Reunion Island, we also considered its own electricity mix, which is more than 38% fossil fuel-based, and obtained a GWP value of 0.662 kg CO_2eq/kWh see Figure 2.

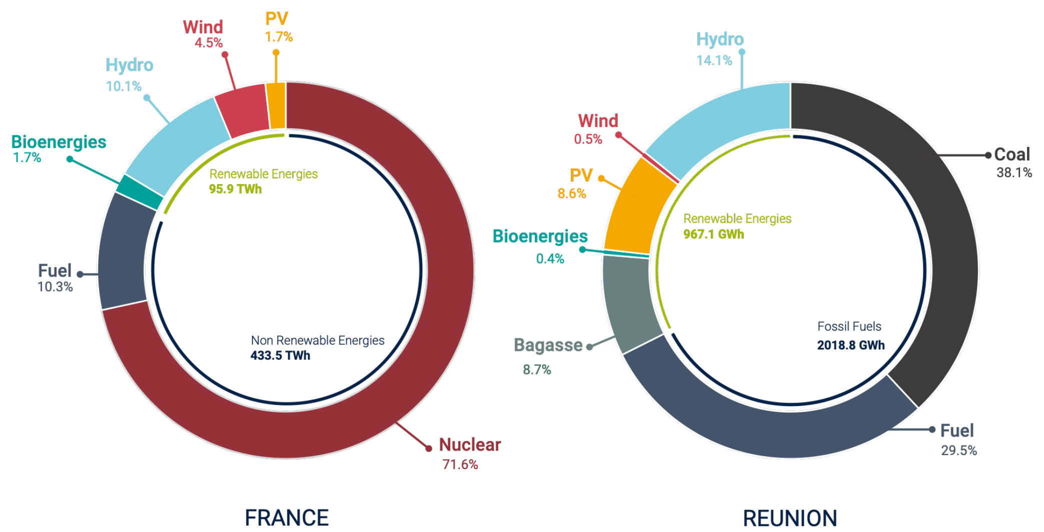

Figure 2. Electricity mix shares of France and Reunion island in 2018 Source: Author's illustration based on data from [56].

Its various modes of transport used for the import of goods by sea or air, including local road transport, and the manufacture of products were also used to calculate the impacts of the materials and products used for local construction. Therefore, in this study, emission factors for each material and product were calculated from cradle to grave, as in Figure 3. In particular, several indicators, such as the greenhouse effect (Global Warming Potential), resource depletion (Abiotic Resource Depletion Potential-elements), and air emissions (Acidification Potential, Ground-level Ozone Pollution, and Non-Methane Volatile Organic Compounds Project), are evaluated.

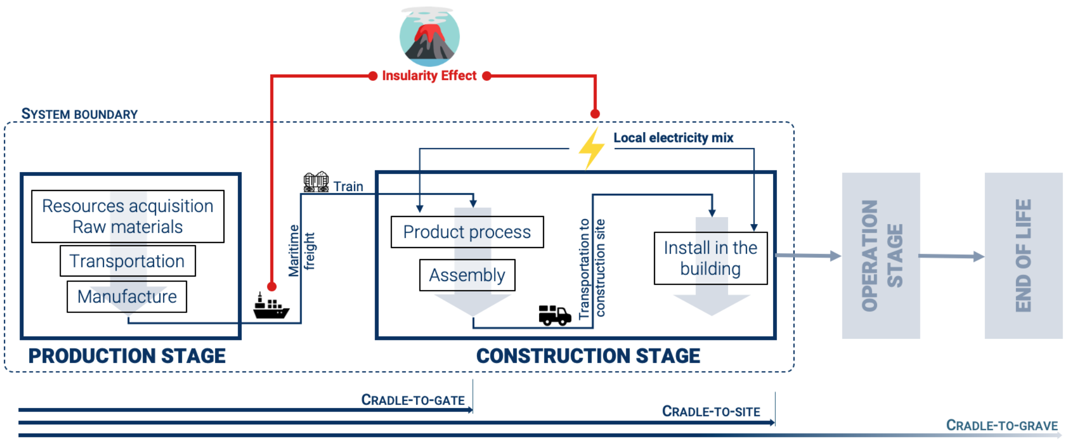

Figure 3. System boundary used in this work to assess the effect of insularity. Source: Author's illustration.

3.5. LCA Impact Categories

Based on the literature review, the impact categories evaluated in this study are the most commonly used, as also suggested by EN 15978:2011 [57] and EN 15804:2013 [58]. Indicators's sustainability considered to be relevant by the scientific literature are also taken into account. Below, the impact categories and indicators used in this comparative study :

- Global Warming Potential (GWP) kg CO_2eq [59].

- Abiotic Resource Depletion Potential for Non fossil ressources (ADP-E) kg Sbeq [60].
- Acidification Potential kg SO_2eq [60].
- Tropospheric Ozone Pollution Project (kg).
- Non Methanic Volatiles Organic Compounds (kg).

3.6. Measuring Insularity Effect

Referring to insularity means emphasizing isolation and specificity, sometimes even singularity. An island territory has an original spatial organization, with its geophysical boundaries. Insularity refers to the finiteness of an island, a limited stock of resources, and the fragility of endemic species under very localized anthropogenic pressure [61]. The construction sector in Reunion Island, such single-family homes, collective housing buildings, offices) often face constraints due to the unavailability of immediate natural resources for construction products. Therefore, the island is confronted with a massive import of building materials and products. The choice of the origin of the construction products or materials used for the construction of these single-family houses in Metropolitan France and France Overseas made it possible to explain initially that, depending on the location of the house, the type and distance of transport, are "specific" according to the geographical location of the house. Other constraints are mainly related to the construction of buildings: the use of the local, highly carbonized electricity mix. Thus, the choice to import raw or semi-finished products also has an impact on the environmental impact assessment of each product. Finally, a third constraint was considered in this comparative study for the case of Reunion Island: the environmental impact of maritime transport. The impact of maritime transport is more pronounced for Reunion Island, as it presents geographical constraint and unavailability of raw material resources. A large part of the materials and products are imported from China, Italy, Europe, Indonesia, and South Africa, with different routes (Suez Canal, Cape of Good Hope, Strait of Magellan, Panama Canal, Cape Horn), see Table A1 in Appendix A. For the case of France, the freight distance are compilated in Table A2. Thus, to analyze this effect of insularity, each emission factor is decomposed according to the schematic that is proposed in Figure 3. This study aimed to address the environmental over cost due to insularity. This effect is assessed through the impact of freight transport and electricity mix on the LCA results.

3.7. LCA Data Statistics

This study presents the LCA results for Reunion and the national database (France). Equation (1) defines the variability of the impact values of a building. The relative standard deviation (RSD) is expressed in percentage:

$$\mathrm{RSD}_{l,f_i} = \frac{\sigma_{l,f_i}}{\mu_{l,f_i}} \times 100 \tag{1}$$

where
l is the location and
f_i is the impact of factor i.

The average percentage relative deviation (PRD), as defined in Equation (2), represents the difference in impact values between the two locations. The national database is considered to be the reference for comparison

$$\overline{PRD}^j = \left(1 - \bar{r}^j\right) \times 100 \tag{2}$$

with,

$$\bar{r}^j = \frac{1}{n} \sum_{i=1}^{n} \frac{f^j_{i,national}}{f^j_{i,regional}} \tag{3}$$

where:
$f_{i,regional}$ and $f_{i,national}$ are the impacts of factor i, respectively, for Reunion island and France;

subindex *i* refers to each studied house;
and subindex *j* denotes each of the five impact factors.
Thus, the relative deviation is calculated for each of the twenty houses. In this study, we also discuss the deviation at the material level. We have selected the five most impactful products or materials, as the database contains more than 100 items.

4. Results

4.1. Environmental Impact at the House Level

As discussed in the previous section, the LCI has been collected by calculating some specific regionalized impact factors. The study investigates 20 typical residential houses, for a life span of 30 years.

Using regionalized and national LCI database, Table 2 presents the statistic of the overall environmental impacts. The relative standard deviation (RSD) is systematically greater for Reunion than France, except for the case of the NMVOC, as can be shown in Table 2. The percentage of relative deviation is high for all factors (>26%) and even reaches 88% in the case of ADP, see Figure 4. This higher value for Reunion is explained, partly, by an electricity mix that is highly dependent on coal imports. This brings an additional impact on the minerals in the local manufacture of products. The particular case of the higher value of NMVOC's RSD in France is explained by the wide variety of European supply points for raw materials or products.

Table 2. Descriptive statistics at the database level.

	NMVOC		GWP		TOPP		AP		ADP Element	
	Reunion	**France**	**Reunion**	**France**	**Reunion**	**France**	**Reunion**	**France**	**Reunion**	**France**
μ	0.100	0.074	814.507	595.689	2.943	1.916	2.043	1.317	0.016	0.002
σ	0.035	0.028	188.571	123.786	0.701	0.419	0.500	0.284	0.005	0.003
RSD	35.24	38.53	23.15	20.78	23.82	21.87	24.49	21.56	33.47	148.84
$\overline{PRD}$	26.72		26.34		34.29		34.66		88.16	

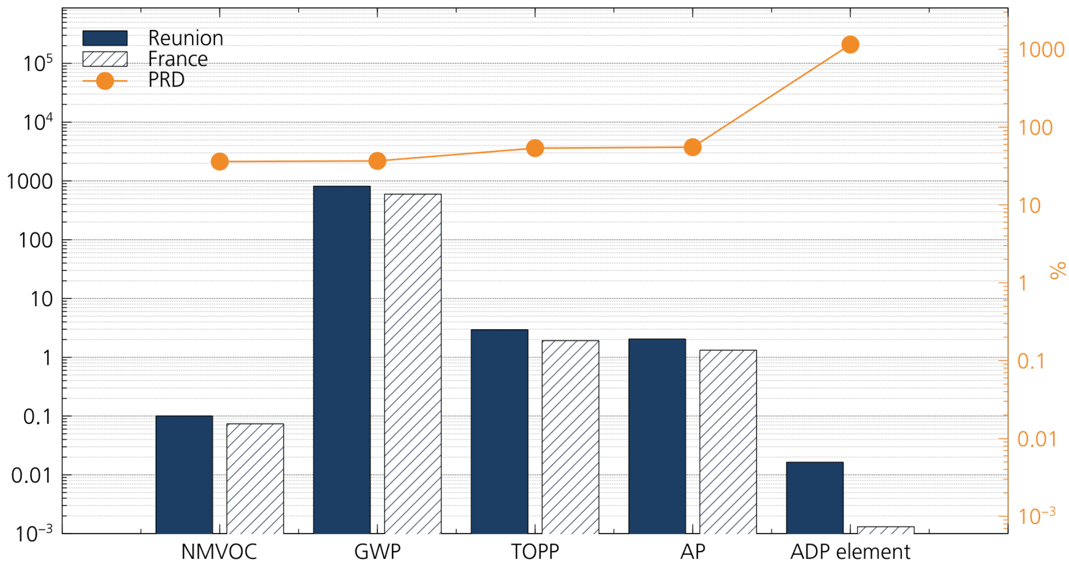

Figure 4. PRD factor and average values of impact factors. Source: Author'sillustration.

Indeed, Zhang et [62] evaluated the emission factors of different modes of transport. Thus road transport has an emission factor of 0.1408 g/ton km, i.e., almost 12 times more than deep-sea transport. The average GWP impact of single-family houses is about 814 kg CO_2eq for Reunion Island and about

595 kg CO_2eq/m^2 for mainland France, which corresponds to a deviation of around 200 kg eq between the two locations. All of the environmental impact factors have a higher value in Reunion. These results emphasize the significant difference in impacts between France and Reunion Island. If we compare our results with other case studies, as shown in Table 3, we can consider that the values of our ratios are in line with those that were obtained in the literature. It can be noticed that the average ratio for Reunion Island is consistent with the high values obtained in the case of construction in tropical conditions.

Table 3. Comparison of the Global Warming Potential (GWP) values obtained in our study and the results from the literature.

Authors	Type of Building	GWP (kg CO_2eq/m^2)
Ya Hong Dong et al. [16]	Residential building	669
Endrit Hoxha et al. [63]	Single Family Houses	415–615–1085
	Residential buildings	575–1035–910
Mohammad Kamali et al. [64]	Single family buildings	979–860–978
Michele Morales et al. [18]	Public housing	750–1000
Ahmad Faiz Rashid et al. [65]	Residential building	828
Our case study-France	Single Family Houses	575
Our case study-Reunion	Single Family Houses	814

Thus, this reinforces the idea of regionalization of emission factor databases to enable more accurate LCA. Using the national inventory data as a reference, it would have led to an underestimation of 36.7% of the GWP ratio. There are two main reasons for this difference. The first, mentioned by Briguglio et [66], is the high exposure to imports of small islands. However, because of their size, small islands, such as the Reunion, are considered price-takers and are exposed to the prevailing pattern's currency, [67]. The second reason is linked to the geographical situation of the island. Furthermore, it is, therefore, intrinsically related to the insular character of the territory. This particular aspect will be discussed in Section 5.1. In summary, the results show that, even if the house is based on the same construction regulation, building in a remote territory leads to additionnal overcost. Therefore, the next section moves on to discuss this overcost at the works and materials scale.

4.2. Breakdown per Construction Process

The first results for the impact category of GHG emissions emphasize that the main structural works (MSW) sector has a greater environmental impact than the finishing works (FW) sector on all 20 houses studied, as shown in Figure 5. Concerning the other indicators, ground-level ozone pollution and acidification are the indicators with the greatest impact on the structural sector (due to manufacture during the construction phase). In contrast, in the FW sector, abiotic depletion and acidification have the greatest impact (due to the assembly part). The structural sector includes all of the building elements in superstructure, roof framework. The ability to reduce environmental impacts is less evident on the FW than on the MSW. To replace some products, such as ceramic tiles by solid wood flooring, would be a solution. On a structural scale, wood has a lower impact than ceramic tiles (if we take the case of the island's solid tamarind wood, which would require no imports, just local processing. Despite the importation of (exotic) wood, its emission factor is still less impactful than that of ceramic tiles, due to its great capacity to store CO_2 emissions throughout its life. We can notably propose replacing aluminium joinery with half-wood/half-aluminium frames and joinery in order to reduce the environmental impact for the finishing sector, among other things. In the case of Reunion Island, the ADP-elements indicator has the greatest impact in the finishing work.

The abiotic resources that are considered in this study are natural resources (including energy resources) such as iron ore, crude oil, which are considered non-living. ADP-E encompasses both the use of non-renewable and renewable abiotic resources, but in this study we will limit the definition to non-renewable resource depletion only. As we saw in Section 4.1, the ADP between France and Reunion is very important. This discrepancy can be seen in the finishing sector. This sector consumes a quantity of rare ores for products such as aluminium for joinery, steel. These elements are important, in relation to the choice of materials and products during the extraction stage, but also during transport and assembly. This is due to the impacts that are related to steel production, diesel and combustion. This study is a first study on the Reunionese LCA of buildings using data from regionalized inventories, local construction practices. Initially, this study reinforces and completes the literature on French LCA's in the building sector, but it also provides a response to an LCA of buildings in Reunion Island, while using data from regionalized inventories, local construction practices, and massive imports of local construction materials and products. This paper demonstrates the importance of considering regional data and not generic or universal data, which are not applicable to all countries in France. The results of this paper have highlighted the relevant differences between the construction systems of 20 single-family houses that were evaluated in two different locations.

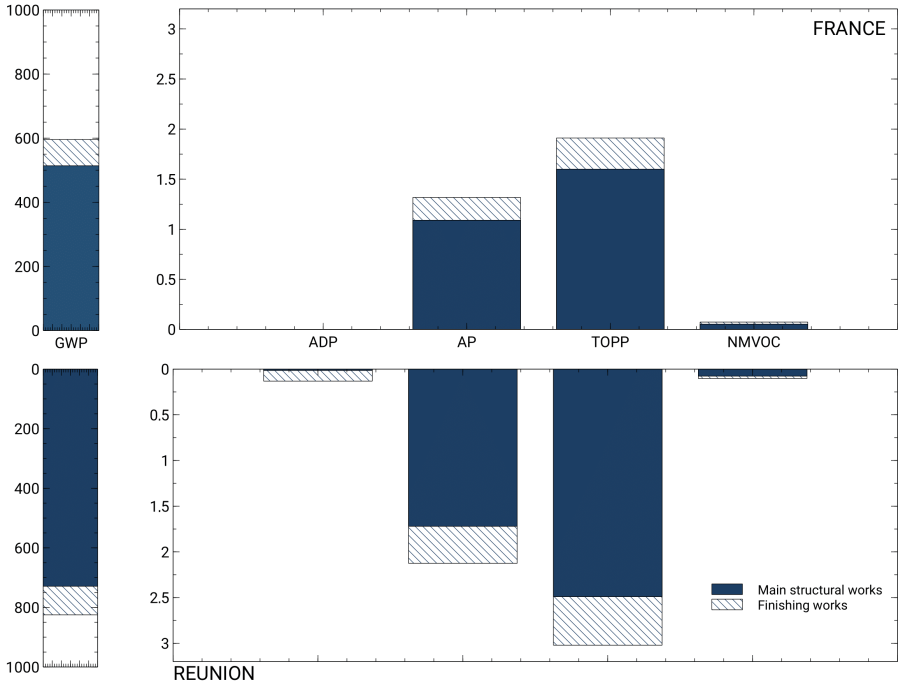

Figure 5. Main structural works and finishing works impacts. Source: Author's illustration.

4.3. Impact of Construction Materials

Ahmad Faiz Abd Rachid et al. [13] have identified through their work that the most impacting products in their study of residential buildings are mainly concrete, clay bricks, clay tiles, ceramic tiles and cement screeds. They conducted a contribution analysis process to identify the materials or processes that produce the greatest impact. In their pre-use phase, the sub-structure was identified as having the greatest impact on acidification, eutrophication and GWP. In each impact category, concrete was found to be dominant over steel reinforcement and hard core. The concrete also has a higher impact in each impact category. In the heavy construction sector, it is mainly concrete that has a considerable (between 35 and 50% of global impact of single family-house) impact both in metropolitan France and at the Reunion. More than half of the impact of concrete is linked to the use and integration of cement among its components. In the case of Reunion Island, a part of the concrete components are imported, and concrete is manufactured locally. In particular, we evaluated the product most impactful in the finishing sector. Aluminium has an important emission factor, but its total emission remains low impact, on the one hand because of its small quantity (in m^2 of aluminium installed), on the other hand because of its random contribution for each house (a house of 100 m^2 can have five openings or 12 openings). Aluminium joinery having a greater impact in the case of Reunion is explained in particular by the production of electricity used for manufacturing and assembly, but also by the release of phosphate and NOx into the atmosphere during the transport of materials and products to Reunion (located in the Indian Ocean). We conclude this first analysis by emphasizing out that aluminium has a higher emission factor than concrete, but, when we multiply these impact factors by their quantities, we see that it is concrete that has a greater impact than aluminium.

5. Discussion

5.1. Effect of Insularity

To refer to insularity is to emphasize isolation and specificity and sometimes even singularity of remote. An island territory presents an original spatial organization; having its geophysical limits, insularity refers to the finitude of an island, to a limited stock of resources, and the fragility of endemic species being subjected to very localized anthropic pressure [61]. Since the 1950s, Reunion has embarked on a process of economic catch up with France. At the same time, it has not yet completed its demographic transition, which has created a need on the island for housing and buildings [68]. The construction sector on the island often encounter constraints that are related to the unavailability of immediate resources; in other words, it is a strong dependence on maritime imports One of the significant constraints of insularity is the import of raw materials or products. As the large majority of construction materials are imported (380 millions tonnes in Reunion Island in 2014), transport represents a significant part of their environmental and economic costs. As evaluated in the study of Zhang, [62], the deep-sea transport has an emission factor of 15.98 g/ton.km of CO_2 when compared to road freight, which can reach 168 g/ton.km of CO_2. However, long import distances for maritime transport (Europe, Asia) leads to an increase in total impacts. Figure 6 shows the results of GWP ratio distribution. Overall, it is apparent that there is an environmental overcost in the construction sector in Reunion. The second aspect is that construction practices in Reunion are more varied. This results in a wider dispersion of the distribution than in France. The assembling or local manufacturing of products also leads to an environmental extra cost. Indeed, fossil fuels still heavily dominate the electricity mix.

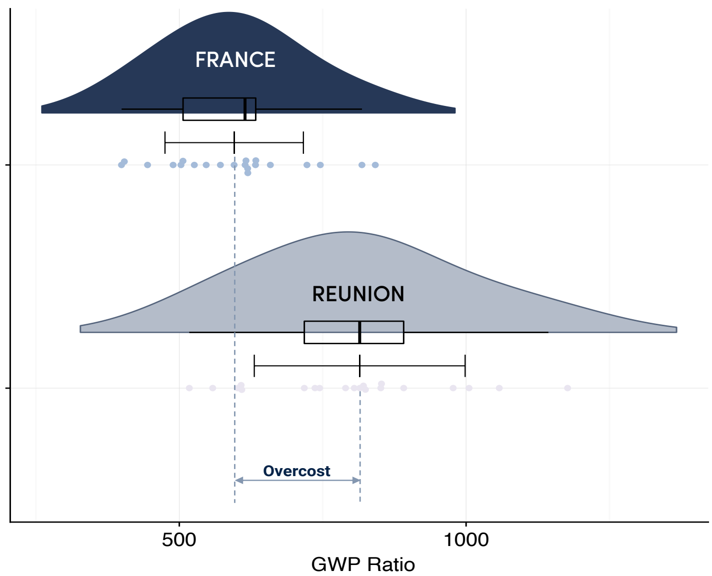

Figure 6. The GWP distribution at the house level for Reunion and France. Source: Author's illustration.

For more than ten years, the share of renewable energy in Reunion has barely exceeded 35%. This highly carbon-based mix has an impact on all stages of house production (product manufacturing, construction). Figure 7 shows the representative part of the effect of insularity when the environmental impact of a residential house was assessed. The effect of insularity is visible in the share of the electricity mix and share of maritime transport. As expected, it seems obvious that remoteness worsens the impact of these exogenous inflows of building materials or products. Thus, due to the isolation in order to dispose of the materials in sufficient quantity, it is necessary to resort to storage, which can induce an environmental extra cost.

The choice of the origin of products or building materials that were used to build these single family houses in France and on Reunion allowed for an initial explanation that, depending on the location of houses, the type and the transport distance is "specific", depending on the layout of the house. In the continental context, the choice of products, construction materials, and import choices are not the same as those of the tropical environment, which automatically includes maritime transport as one of the main means of freight. The transportation of materials to the construction site has inherent environmental impacts to the energy consumption and GHG emissions that are associated with the mode of transport, such as trucks, ships, or aircraft. As discussed by Ramzy Kahhat et al. [69], in the case of their study in the USA, road transport was considered because of the high distance in the country.

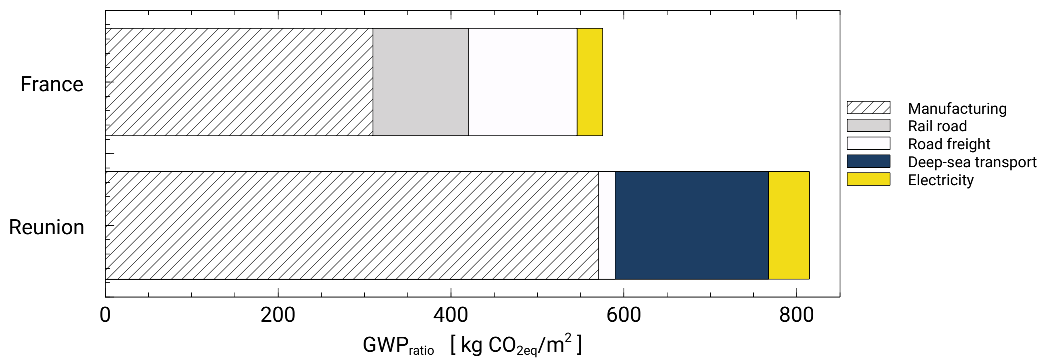

Figure 7. Share of the local electricity mix and transport to the GWP ratio. Source: Author'sillustration.

However, in our case, due the small size of the island (63 km long and 45 km wide), we have made the assumption that road transport is negligible. The impact of maritime transport is more marked for Reunion, which exhibits a geographical constraint and an unavailability of the majority of raw material resources. A large portion of the construction products and materials is imported from China, Europa, Italy, Indonesia, etc. In addition, the local electricity mix, which has a minimal impact for France, is a major impact on Reunion. The large share of nuclear energy in the French electricity mix and the large share of fossil fuels in the Reunion electricity mix explain these results see Figure 1. Most LCA studies often highlight the effect of shipping on total impact. Our results add a striking nuance. Indeed, the studies of buildings aim at identifying the most impacting steps and propose decision support for strategies to reduce the associated emissions. In addition to transport, our study highlights the significant impact that is induced by the extraction-exogenous manufacturing-local transformation process chain. Thus, it is quite surprising to note that the effect of insularity is measured more by the process chain, which represents, respectively, 70% and 54% of GWP for Reunion and France. In addition, the share of transport does not exceed 22% on Reunion Island. Therefore, it can be clearly stated that the question of insularity or geographical isolation is discussed more through the prism of the Manufacturing parameter. Thus, this brings a new perspective on the reduction of the extra environmental cost first of all by reconsidering the sources of supply of raw materials and products. It is also possible to consider new ways of building construction or processing environmentally less polluting materials.

5.2. Policy Implications

The construction building sector in Reunion Island is a significant issue with a population that grows by 10,000 people every year. The demand for new housing is in the order of 9000/year. Thus, this sector is marked by an important import flow and, consequently, marginal industrialization, [70]. A recent economic study has highlighted an over cost of about 39% of building materials when compared to metropolitan France. In addition to this extra cost, the report showed the incoherence of specific national regulatory standards to the uses and context of the subtropical climate. France is currently evolving its thermal regulation RT2012, towards a new environmental regulation RE2020. This regulation integrates the prefiguring label of energy-efficient buildings E^+ and low carbon C^-. In 2009, a thermal regulation specific to the overseas regions RTAADOM was created in order to take the subtropical climate context into account. The outline of the environmental aspect in the RE2020 is currently still under development. This phase is based on the feedback of experience on 1007 buildings under construction in order to calibrate the desired performance thresholds. Therefore, it is crucial to have environmental regulations adapted to overseas regions. Our study has clearly highlighted an additional cost of 200 kg CO_2eq/m^2 , i.e., approximately 37% more. Thus, the definition of performance thresholds will necessarily have to take into account this initial gap that we have observed in this work. A case study of a low-carbon concrete building in South Korea highlights a GWP of 369.3 kg CO_2eq/m^2 [71]. The authors have investigated a cradle-to-gate analysis results. When compared to the current result for Reunion Island, which is 814, it is clear that a considerable effort will have to be made in order to move towards these levels of environmental performance. In view of the results, the subsequent recommendations will be drawn up: Short term improvments can be made due to the decarbonization of the electricity mix. According to the scenarios developed in Rakotoson's research [72,73], the emission factor of Reunion's electricity mix is expected to decrease to 420 g CO_2eq/kWh. Thus, this decarbonization of the mix only reduces the GWP ratio of the house by 17 kg CO_2eq/m^2. This is a very marginal effect with regard to the GHG emission reduction targets. The second lever, which is related to the shipping industry, is more of a global issue. Thus, at the scale of Reunion, there are no specific policy implications to be defined, because the weight of the territory in the global decision is almost nil. The current thinking points to two types of measures:

- The first aspect is more of a technical nature, which aims to improve the boat's components and also energy optimization in the operational phase [74].
- The second point concerns the integration of renewable energies for electricity generation, but also a transition to zero-carbon fuels.

French and European construction standards require a certain amount of products to be imported from Europe. Reunion Island has already defined an adapted implementation of these buildings to the tropical climate. These efforts must now be supported and extended to the construction methods. Indeed, in the context of an island economy, waste from the building sector is proving to be problematic, leading to additional environmental pressure. Policies need to act urgently by adopting a value chain of recycling of building products in order to encourage the local reuse of materials as much as possible. This ambition leads to the question of the choice of wholly or partially reusable materials.

6. Conclusions

Climate change irrevocably requires urgent public action in all branches of the economy. With 25% of GHG emissions and 31 of energy consumption (excluding the operational phase) and 1.3 million employment [75], the building sector is today at the heart of the challenges of the sustainable transition. The implementation of LCA in tropical island or any remote territory is limited by the lack of accurate inventory data on building materials and products. Our work is the first comparative study featuring the environmental impact of single-family houses in French overseas regions. This comparative study demonstrates the importance of integrating regionalized data since environmental impacts vary considerably according to the object the study. The results highlighted a significant difference of more than 200 kg of CO_2eq/m^2 between Reunion and France. Although transport and the electricity mix weigh heavily in this environmental overcost, it is the part of the extraction-manufacturing process that has the most significant impact. The results reported herein show the importance of building evaluation in the French overseas regions in order to define a knowledge base of building typology. Thus, it will then be necessary to accurately quantify the environmental quality and define performance thresholds. This work has highlighted the need for a regional decline of the future national thermal and environmental regulations due to the important gap existing at this moment between France and the French overseas territories. The results of this study will be used as a guideline for decision-makers and experts to set future thresholds that are adapted to the French tropical regions. It will be important that the case studies be continued as widely as possible in order to characterize each of the overseas regions and, thus, lead to a local translation of national ambitions regarding the ecological transition.

Author Contributions: Conceptualization, L.A.; methodology, L.A.; resources, L.A.; writing—original draft preparation, L.A.; writing—review editing, J.P.P.; supervision, J.P.P.; formal analysis, J.P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This project has received funding from the National Association for Research and Technology and Fibres Industries Bois under grant agreement n° 2017/1242.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AP	Acidification Potential	[kg SO_2eq]
ADP-E	Abiotic resource Depletion Potential elements	[kg Sbeq]
GHG	Greenhouse gases	-
GWP	Global Warming Potential	[kg CO_2eq]
NMVOC	Non Methanic Volatils Organic Compound	[kg]
PRD	Percent Relative Deviation	-
RSD	Relative Standard Deviation	-
TOPP	Tropospheric Ozone Pollution Project	[kgeq]

Appendix A

We have compiled in the table below a summary of the main material supply points for the case of Reunion Island.

Table A1. Maritime freight transport for Reunion island calculated from [76].

ORIGIN	TRANSIT	DISTANCE (km)
SWEDEN	Suez Canal	14,260
	Cape of Good Hope	16,648
	Panama Canal	32,834
	Strait of Magellan	34,219
	Cap Horn	34,338
CAMEROUN	Cape of Good Hope	8391
	Suez Canal	16,899
	Strait of Magellan	29,126
	Cape Horn	29,198
	Panama Canal	33,078
COLOMBIA	Cape of Good Hope	15,282
	Suez Canal	17,940
	Panama Canal	23,696
	Strait of Magellan	30,545
	Cape Horn	30,663

Table A1. *Cont.*

ORIGIN	TRANSIT	DISTANCE (km)
CONGO	Cape of Good Hope	7343
	Suez Canal	17,353
	Strait of Magellan	28,485
	Panama Canal	33,471
	Suez Canal	14,260
SWEDEN	Cape of Good Hope	10,167
	Suez Canal	18,482
BRAZIL	Strait of Magellan	23,187
	Cape Horn	23,344
	Panama Canal	31,174
CANADA	Suez Canal	14,816
	Cape of Good Hope	15,588
	Panama Canal	27,963
	Strait of Magellan	31,735
	Cape Horn	31,856
FRANCE	Suez Canal	9430
	Cape of Good Hope	14,810
	Strait of Magellan	32,413
	Panama Canal	32,484
	Cape Horn	32,528
GABON	Cape of Good Hope	7565
	Suez Canal	17,071
	Strait of Magellan	28,467
	Cape Horn	28,493
	Panama Canal	33,223
RUSSIA	Suez Canal	16,527
	Cape of Good Hope	18,871
	Panama Canal	34,239
	Strait of Magellan	36,345
	Cape Horn	36,465
BELGIUM	Suez Canal	13,012
	Cape of Good Hope	15,399
	Panama Canal	31,971
	Strait of Magellan	32,971
	Cape Horn	33,089
CHINA	Direct	9395
ESTONIA	Suez Canal	15,003
	Cape of Good Hope	17,390
	Panama Canal	33,576
	Strait of Magellan	34,962
	Cape Horn	3508
FINLAND	Suez Canal	14,940
	Cape of Good Hope	17,327
	Panama Canal	33,513
	Strait of Magellan	34,899
	Cape Horn	35,017
GREECE	Suez Canal	7628
	Cape of Good Hope	16,432
	Strait of Magellan	34,036
	Panama Canal	34,106
	Cape Horn	34,150

Table A1. *Cont.*

ORIGIN	TRANSIT	DISTANCE (km)
GERMANY	Suez Canal	7628
	Cape of Good Hope	16,432
	Strait of Magellan	34,036
	Panama Canal	34,106
	Cape Horn	34,150
INDONESIA	Direct	13,386
INDIA	Direct	8113
ITALY	Suez Canal	9148
	Cape of Good Hope	16,271
	Strait of Magellan	33,874
	Panama Canal	33,945
	Cape Horn	34,360
MADAGASCAR	Direct	1435
MORROCO	Suez Canal	11,293
	Cape of Good Hope	12,667
	Strait of Magellan	30,400
	Cape Horn	30,509
	Panama Canal	30,733
SINGAPORE	Direct	6389
SOUTH AFRICA	Direct	6389
TURKEY	Direct	6389
USA	Direct	19,305

Table A2. Air and road freight for the case of France.

ORIGIN	TRANSIT	DISTANCE (km)
GERMANY	GREAT EAST (Road)	1128
	AIRPORT ERF and MCU (Flight)	823.45
BELGIUM	ILE DE FRANCE (Road)	706.27
	AIRPORT BRU and MCU (Flight)	543.27
SPAIN	SAINT JEAN DE LUZ (Road)	1091.47
	AIRPORT ECV and MCU (Flight)	818.89
Portugal	CASTILLA LEON (Road)	1355.73
	AIRPORT LIS and MCU (Flight)	1252
SWEDEN	HAMBURG (Road)	2480.02
	AIRPORT EVG AND MCU (Flight)	1920.39
ROMANIA	OSTERREICH (Road)	2339.78
	AIRPORT TGM and MCU (Flight)	1687.67
ITALY	PIEMONTE (Road)	1187.65
	AIRPORT PEG and MCU (Flight)	874.23
FINLAND	COPENHAGEN (Road)	3242.70
	AIRPORT OUL and MCU (Flight)	2502.62
UNITED STATES	AIRPORT RSL and MCU (Flight)	7740.48
RUSSIA	KIROV (Road)	7727.82
	AIRPORT UIK and ORY (Flight)	6093.34
AUSTRIA	AIRPORT ASP and MCU (Flight)	15,053

Table A3. Detailed results of the impacts in the cases of France and Reunion Island for the 20 single-family houses.

Single Family Houses	GWP		ADP-E		AP		TOPP		NMVOC	
	Réunion	France	Réunion	France	Réunion	France	Réunion	France	Réunion	France
SFH 1	977.52	658.71	1.76×10^{-2}	1.04×10^{-3}	2.35	1.36	3.35	1.97	8.91×10^{-2}	5.42×10^{-2}
SFH 2	736.64	546.83	2.15×10^{-2}	1.26×10^{-3}	1.4	1.21	2.74	1.74	8.48×10^{-2}	6.36×10^{-2}
SFH 3	1177.05	841.71	2.23×10^{-2}	1.63×10^{-3}	2.96	1.85	4.28	2.73	1.54	1.12
SFH 4	558.41	399.38	1.29×10^{-2}	8.73×10^{-4}	1.5	0.86	1.99	1.17	5.92×10^{-2}	3.70×10^{-2}
SFH 5	744.67	506.52	4.42×10^{-3}	1.02×10^{-3}	1.8	1.06	2.55	1.52	6.68×10^{-2}	4.18×10^{-2}
SFH 6	717.93	489.22	4.82×10^{-3}	1.03×10^{-3}	1.82	1.06	2.47	1.47	6.88×10^{-2}	4.36×10^{-2}
SFH 7	1057.79	745.71	1.66×10^{-2}	1.44×10^{-3}	2.65	1.47	3.67	2.07	1.07	5.95×10^{-2}
SFH 8	517.40	404.23	1.24×10^{-2}	1.56×10^{-3}	2.01	0.84	1.87	1.21	1.60	4.22×10^{-2}
SFH 9	1143.49	818.47	2.16×10^{-2}	1.59×10^{-3}	2.88	1.8	4.17	2.67	1.51	1.10
SFH 10	851.51	619.19	2.03×10^{-2}	1.37×10^{-3}	2.38	1.53	3.37	2.2	1.53	1.15
SFH 11	789.92	633.21	2.14×10^{-2}	1.44×10^{-3}	2.06	1.42	2.93	2.11	8.97×10^{-2}	8.64×10^{-2}
SFH 12	824.70	616.15	2.08×10^{-2}	1.47×10^{-3}	2.16	1.37	3.04	1.97	9.48×10^{-2}	7.35×10^{-2}
SFH 13	1005.00	722.38	1.64×10^{-2}	1.63×10^{-3}	2.63	1.68	3.76	2.45	1.49	1.11
SFH 14	891.15	632.94	1.52×10^{-2}	1.25×10^{-3}	2.2	1.36	3.17	1.99	9.48×10^{-2}	6.85×10^{-2}
SFH 15	804.96	571.72	1.42×10^{-2}	1.13×10^{-3}	1.99	1.22	2.86	1.8	8.56×10^{-2}	6.19×10^{-2}
SFH 16	601.81	526.16	1.29×10^{-2}	1.08×10^{-3}	1.38	1.13	1.99	1.66	5.00×10^{-2}	6.07×10^{-2}
SFH 17	609.09	502.87	1.16×10^{-2}	1.07×10^{-3}	1.39	1.06	2.03	1.51	5.00×10^{-2}	4.43×10^{-2}
SFH 18	852.49	619.35	2.46×10^{-2}	1.42×10^{-2}	2.1	1.59	3.11	2.29	1.54	1.28
SFH 19	821.03	614.58	1.92×10^{-2}	1.90×10^{-3}	2.08	1.33	2.99	1.95	9.22×10^{-2}	7.14×10^{-2}
SFH 20	607.59	444.45	1.66×10^{-2}	1.01×10^{-3}	1.81	1.14	2.54	1.63	1.26	9.12×10^{-2}
Ratio	**814.51**	**595.69**	$\mathbf{1.64 \times 10^{-2}}$	$\mathbf{1.95 \times 10^{-3}}$	**2.08**	**1.32**	**2.94**	**1.91**	**1.04**	$\mathbf{7.37 \times 10^{-2}}$

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