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Life Cycle Assessment for Substitutive Building Materials Using the Example of the Vietnamese Road Sector

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Abstract: Road construction usually relies on the utilization of natural aggregates as building materials. However, increasing pressure for sustainable roads highlights the importance of replacing natural materials with industrial byproducts. The scope of the present study was to identify feasible secondary raw materials for road subbase construction, and to investigate their environmental footprint in the context of Vietnam. This work examines road subbase alternatives such as manufactured sand (m-sand), granulated blast furnace slag (GBF), electric arc furnace slag (EAF), construction and demolition waste (CDW), and fly ash (FA). Based on the life-cycle assessment (LCA) approach, the environmental footprints of the alternative waste-based layers were compared with one another and with the corresponding conventional layers. The study comprises following working steps: (i) a comprehensive literature review of the respective materials, (ii) general chemical and soil mechanical analysis of road subbase substitutes, and (iii) LCA of the material alternatives in the context of the Vietnamese road construction sector. The results for the road subbase layer indicated that CDW and FA had lower impacts—particularly in the impact categories global warming potential and mineral resource scarcity. The overall LCA analysis for the road subbase layer highlighted that the greatest footprint contribution was involved in the construction material transportation processes. Thus, sourcing of materials closer to the site or the use of low-emission transport alternatives is needed.

Keywords: life-cycle assessment; substitutive building materials; secondary building materials; road subbase material

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1. Introduction

Road construction is a key infrastructure development for the emerging economies of South-East Asia, and road transport plays an important role in Vietnam due to its high mobility, distribution, and door-to-door features. Road construction relies on the utilization of natural aggregates as building materials. However, growing pressures for sustainable roads highlight the importance of replacing primary materials with industrial byproducts, also known as substitutive building materials (SBMs). Aggregates with good geotechnical characteristics are becoming increasingly scarce. Road pavements comprise multiple layers of different thicknesses, generally including both unbound and bound materials. The essential components of the road structures are embankments, subgrade, subbase, base coarse, and surface coarse [1]. The subbase layer consists of well-graded granular or cement-bound material. However, the performance requirements are lower than those of the road base aggregate. This layer also provides drainage and frost protection. The usual subbase layer applications are composed of aggregates such as gravel, sand, and quarry stones, which are usually virgin minerals that provide the required strength and durability [2]. Sand and gravel are crucial materials used in construction industries, including civil infrastructure projects such as subbase utilization in road construction. However, the increasing sand demands for construction industries lead to the overexploitation of river or delta ecosystems around the globe. The Mekong Delta is particularly vulnerable to sand mining practices, in addition to other threats such as climate change or chemical pollution [3]. The real magnitude of sand mining impacts requires further investigations in countries such as Vietnam [4]. Unregulated sand mining operations pose serious risks to river ecosystems and nearby human settlements. Marine sand extraction is also an unsustainable option to be considered as an alternative to river sand mining [5]. Therefore, alternatives to river sand must be put in place to feed future road construction projects at the national and regional levels. One solution is to manufacture the sand (m-sand) instead of extracting it from rivers and deltas, avoiding damage to complex ecosystems [6]. Manufactured aggregate industries (m-sand, crushed stone) have emerged in China in the last decade due to the natural supply shortages reaching 78% of the total primary supply in 2018 [7]. In Asia, m-sand is already used as an SBM for roads [8]; however, this puts even more pressure on primary resources.

Many types of secondary raw materials have been used as SBMs for road subbase applications in recent decades, replacing natural aggregates. Several types of research [9–12] have indicated the successful feasibility of construction and demolition waste (CDW) as unbound granular materials in subbase applications. CDW has been commonly used in several countries in road subbase applications, after a recycling process involving the removal of other wastes such as wood, paper, steel, iron, etc., followed by sorting, crushing, and grading. Similar to construction waste, the other prominent waste products are slags, such as granulated blast furnace slag, electric arc furnace slag, steel slags, etc. [13–16]. Previous studies show different mixtures of byproducts and waste streams to be used in road construction [17]. Fly ash produced from thermal energy plants running on coal combustion ends up in industrial or municipal landfills. The mixture of fly ash with other materials or waste streams could be used in road construction. For example, glass waste and fly ash were incorporated in cold mixed asphalt used for road pavement construction [18]. The use of stabilized fly ash and sisal fiber in producing bituminous pavements showed positive benefits in terms of GHG emissions [19]. In China, concrete pavements with fibers made from fly ash seemed to be more resistant to water and other stress factors (e.g., heat, frost), with material and energy savings compared to conventional production [20]. The use of fly ash mixed with other industrial byproducts in different proportions—such as 80% fly ash + 20% granulated blast furnace slag, or 70% copper slag + 30% fly ash—shows good results in laboratory tests combined with samples from road pavement [21].

A mixture of fly ash, an alkaline activator, and crushed aggregates was successfully tested in the laboratory for road base material purposes in Malaysia [22]. A mixture with 33% fly ash could prolong the use of the subbase material, with cost savings of around 23% compared to conventional materials [23]. Laboratory tests confirmed that fly ash could be used as a subbase material for road construction, replacing natural aggregates such as river sand [24]. Other research has focused on byproducts of the steel- and iron-making industries—such as electric arc furnace slag and blast furnace slag—as substitutive materials for sand in road construction [25]. Six foamed bitumen mixtures were proposed and tested in a laboratory study using industrial byproducts (i.e., electric arc furnace slag, fly ash), bottom ash from municipal waste incineration plants, glass waste, or CDW materials such as reclaimed asphalt pavement, in a range of 10–20%, for potential use as road subbase layers, without toxicological problems [26]. Another approach is to use blast furnace slag activated with quicklime to bind dredge sediment for sublayer road applications [27]. Therefore, the literature review shows that different mixtures of industrial byproducts have been tested to check the strength and durability characteristics of road subbase layers [28], with benefits in the extension of lifetime, cost savings, lower surface roughness, and reducing GHG emissions [29]. Research regarding the mixture of industrial byproducts with cement and water has produced cement-stabilized pavement applications that fulfill the technical requirements for highways in China, in addition to reducing GHG emissions [30]. However, further research aims to increase industrial byproduct recycling performances and to reduce practical usage barriers for road subbases in highways with significant traffic loads [31].

In Vietnam, road transport accounts for more than 77.4% of the volume of transported goods and 94% of passengers [32,33]. Decision No. 1454/QD-TTg [34], dated 1 September 2021, approves the master plan on road network development for the period 2021–2030, with a vision to 2050 in Vietnam, and sets the target for 2030 to essentially complete the inter-regional highways, connecting international gateway seaports, international airports, major international border gates with large import and export demand, and high-class cities, and in this framework to strive to build and complete about 5000 km of expressways. The contained vision to 2050 is to complete the road network throughout the country in a synchronous and modern manner, ensuring reasonable connection and development between modes of transport. Transport quality and services will be improved, ensuring convenience, safety, and reasonable costs. The road network planning comprises the expressway network, which is planned to be 41 routes, with a total length of about 9014 km, as well as the national highway network, which consists of 172 routes, with a total length of about 29,795 km. Moreover, the rural road system shall be completed. JICA and MOT [35] highlighted the need in Vietnam for the expansion of the national road networks by at least 10,000 km by 2030 for the network coverage to be considered to be well developed.

Vietnam has six classes of roads: national motorways, provincial roads, district roads, rural roads, urban streets, and special roads for government officials. In Vietnam, common pavement types include asphalt concrete, cement concrete, bitumen-treated crushed stones, crushed stones, and soil. In contrast, each type consists of a specific number and a combination of layers [36]. The road embankment, serving as the foundation or subbase, usually consists of soil mobilized from cutting slopes/sections along the road, or natural sand. Future network development will need vast quantities of aggregates, which might put pressure on the existing resource budget. Therefore, it would be a strategic and sustainable advantage to adopt secondary raw materials as a resource in future development projects. Among the alternatives, it would be essential to identify sustainable materials with low global warming potential and a low environmental footprint, considering the climate change situation. Previous material property investigations in Vietnam have indicated that feasible materials to replace sand in the road construction sector, other than m-sand, include slags [37], ashes [38], and CDW [39,40]. The present study focuses on the environmental footprint and sheds light on the environmental impact of the extraction of primary raw materials in comparison to secondary raw materials as SBMs for the road subbase. The scope of the present study was to identify feasible SBMs, and to investigate their environmental footprint using the example of the road sector in Vietnam.

2. Materials and Methods

2.1. Regulatory Framework and Local Setting

The decree 09/2021/ND-CP [41] specifies the management of the development and production of building materials, along with their use in construction work, to ensure safety, efficiency, sustainable development, environmental protection, and resource conservation. The strategy for the development of building materials in Vietnam for the period 2021–2030, with a vision until 2050 [42], underlines the need for an efficient and sustainable building materials industry, which essentially meets domestic demand, gradually increases exports, contributes to socioeconomic growth and development, and fosters the minimization of the environmental impact of the extraction and processing of minerals for building materials and their manufacture. Moreover, further requirements are defined in the strategy for building materials in Vietnam:

- Period 2021–2030: Focus on strengthening the development of artificial sand products to meet the demand; strive to achieve the target of using crushed sand and recycled sand from industrial and construction wastes to replace at least 40% of the use of natural sand in construction.
- By 2025: Use at least 20% (by 2030: at least 30%) fly ash (FA) or other industrial wastes as SBMs in clinker and as additives in cement production.
- Period 2031–2050: Achieve at least 40% admixtures of FA for cement use.
- Period of 2031–2050: Minimize the use of natural sand in construction; increase the share of m-sand, recycled sand from industrial and construction waste, and brackish water sand to at least to 60% of the total construction amount.

The different classes of roads in Vietnam are documented in the work of Schiller et al. 2020 [36], as well as in TCVN 5729: 2012 [43] and TCVN 4054: 2005 [44]. The design standards for streets, roads, squares, and urban areas in Vietnam are laid down in the regulation TCXD 104-1983 [45], supported by the specifications for construction and acceptance for graded aggregate bases and pavement subbases in TCVN 8859: 2011 [46], which requires a soaked California bearing ratio (CBR) at K98 of >100% for the subbase material's installation. For the LCA study's purposes, we considered the class III type of national road, with a pavement width of 6 m and roadbed width of 9 m, and with a subbase layer thickness of 0.3 m.

2.2. Overview of the Investigation Approach

In the present LCA study, different road subbase alternatives with relevance to availability in Vietnam were considered—namely, manufactured sand (m-sand), two types of steel slag (granulated blast furnace slag (GBF) and electric arc furnace slag (EAF)), construction and demolition waste (CDW), and fly ash (FA). Using LCA, the environmental footprints of the substitutive building materials were compared with one another and with the corresponding conventional layers made from primary materials (m-sand). The study comprised the following working steps:

i. A comprehensive review of the respective materials (as documented in the introduction/literature review).
ii. Chemical and soil mechanical analysis of secondary road subbase alternatives.
iii. LCA of the material alternatives in the context of the Vietnamese road construction sector.

The material alternatives can be characterized as follows (illustration in Figure 1):

Figure 1. Impression of the considered SBMs (from left): GBF, EAF, CDW, and FA (Figure source: Petra Schneider and Thomas Lange).

Manufactured sand (m-sand): Crushed primary rock material containing processed aggregates smaller than river sand's grain size using confined process machines

Granulated blast furnace slag (GBF): Blast furnace slag is a non-metallic byproduct formed in molten conditions along with molten iron during the processing of iron ore, along with coke and limestone. Blast furnace slag consists of silica, alumina, and lime, combined with magnesia, sulfur, and oxides such as iron oxide and manganese oxide [47,48]. Based on molten slag cooling, there are three types of blast furnace slag: granulated, air-cooled, and expanded/pelletized [49]. GBF is formed by the rapid cooling of slag by water jets and ground to produce sand-like granules, widely used in cement production.

Electric arc furnace slag (EAF): Obtained in steel production when steel scrap is remelted. After defined cooling, metallurgical tool slag is similar to natural volcanic lava.

Construction and demolition waste (CDW): Mineral waste such as walls, roof tiles, tiles, rubble, or sand that accumulates during construction measures such as the renovation, gutting, or demolition of buildings.

Fly ash (FA): Fine, powdery material composed mostly of silica made from the burning of finely ground coal in a boiler.

2.3. General Chemical and Soil Mechanical SBM Overview Analysis

The abovementioned secondary materials were characterized through a general chemical and soil mechanical overview analysis. The soil mechanical investigation program is shown in Table 1. The purpose of the analysis was a general material characterization.

Table 1. Soil mechanical investigation program (x indicates the performed analytics per material type). Explanation of abbreviations: w_n: natural water content acc. to DIN EN ISO 17892-1 [50]; CSS: combined sieve and sludge analysis acc. to DIN 18123 [51]; WS: wet sieving acc. to DIN 18123 [51]; ST: shear test acc. to DIN 18137 (3 partial tests: 50 kN/m^2, 100 kN/m^2, and 200 kN/m^2) [52]; OeD: one-dimensional compression test acc. to DIN 18135 (oedometer test) [53].

Material	w_n	CSS	WS	ST	OeD
Mixed CDW	x	x		x	x
FA	x	x		x	x
GBF	x		x	x	x
EAF	x		x	x	x

In Vietnam, there are no regulatory requirements for chemical properties for road subbase materials. In order to provide an overview of the chemical properties of the secondary building materials, a chemical overview analysis was performed according to the German recommendation “Requirements for the recycling of minerals. Residues/Waste-Technical Rules” LAGA M20, [54]. These rules are not mandatory for the application in practice; however, they are foreseen to provide guidance and overview on potential environmental burdens that might be associated with the former use of secondary materials or their processing history. The chemical investigation program is shown in Table 2. All samples were taken as solid materials in plastic containers according to DIN ISO 18400-102:2020-11 [55]. Since CDW usually has a heterogeneous composition depending on the original building substrate, different CDW samples were analyzed—namely, mixed CDW (CDW mix), crushed concrete (CDW CC), and crushed bricks (CDW CB). The installation class IC 2—which stands for “Restricted installation with defined technical safety measures (impervious or only slightly water-permeable construction)”, which applies to road construction—was considered as a benchmark. The installation classes take into account the origin and nature of the secondary materials, as well as the installation methodology and the site conditions at the installation site. According to LAGA M20 [54], for the use of secondary building materials, particular requirements regarding the prevention of precipitation input are recommended to be respected. The large-scale distribution of pollutants should be prevented by restricting the installation options and organizational security measures.

Table 2. Chemical investigation program and analysis methods.

Parameter	Method	Unit	Benchmark IC 2
Polycyclic aromatic hydrocarbons (PAHs)	DIN ISO 18287: 2006 [56]	mg/kg	30
Hydrocarbons (C10-C40)	DIN ISO 16703: 2005 [57]	mg/kg	1000
Extractable organically bound halogens (EOX)	DIN 38414-S 17: 2014 [58]	mg/kg	10
Zinc	DIN EN ISO 11885 (E22): 2009 [59]	mg/kg DM	1500
Mercury	DIN EN 1483 (E 12): 2007 [60]	mg/kg DM	5
Nickel	DIN EN ISO 11885 (E22): 2009	mg/kg DM	500
Copper	DIN EN ISO 11885 (E22): 2009	mg/kg DM	400
Chromium	DIN EN ISO 11885 (E22): 2009	mg/kg DM	600
Cadmium	DIN EN ISO 11885 (E22): 2009	mg/kg DM	10
Lead	DIN EN ISO 11885 (E22): 2009	mg/kg DM	700
Arsenic	DIN EN ISO 11885 (E22): 2009	mg/kg DM	150
pH value	DIN 38404-5: 2009 [61]		5.5–12
Electric conductivity	DIN EN 27,888 (C 8): 1993 [62]	µS/cm	2000
Chloride	DIN EN ISO 10304-1 (D 20): 2009 [63]	mg/L	100
Sulfate	DIN EN ISO 10304-1 (D 20): 2009	mg/L	200
Arsenic	DIN EN ISO 11885: 2009	µg/L	60
Lead	DIN EN ISO 11885: 2009	µg/L	200
Cadmium	DIN EN ISO 11885: 2009	µg/L	6
Chromium	DIN EN ISO 11885: 2009	µg/L	60
Copper	DIN EN ISO 11885: 2009	µg/L	100
Nickel	DIN EN ISO 11885: 2009	µg/L	70
Mercury	DIN EN ISO 12,846 (E 12): 2012 [64]	µg/L	2
Zinc	DIN EN ISO 11885: 2009	µg/L	600
Phenol index	DIN EN ISO 14402: 1999-12 [65]	mg/L	100

The installation classes are limited by allocation values in the eluate (eluate concentrations in µg/L or mg/L depending on the dimensions and the extracted leachate from the respective solid material) and in the solid material itself (solids content in mg/kg dry mass DM). The eluate concentrations and solids contents for installation class 2 apply to the respective secondary building materials and their requirements for the site conditions at the installation site, with technical security measures. The eluate was obtained from a sample share of 1:10 eluate (1 part solid; 10 parts eluent), which was shaken end-to-end for 24 h.

2.4. Life-Cycle Assessment of the Material Alternatives

2.4.1. Life-Cycle Assessment Approach

Life-cycle assessment (LCA) is the most widely used holistic methodology—a multi-stage process whose detailed definition is given in the international standards of the series ISO 14040 [66] and ISO 14044 [67]. According to [66], LCA is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". LCA serves the purpose of expressing the potential environmental impacts and damages associated with a product or service system along the whole life cycle, in a way that supports comparisons between alternatives, both at the level of the individual substance emission and at the level of the entire studied system [68] The LCA methodology comprises two steps: life-cycle inventory analysis, and life-cycle impact assessment. LCA is especially effective in comparisons of products, e.g., building materials that differ in their raw material composition but have the same functionality [69]. In such cases, LCA can serve as a basis for decision-making to improve sustainability in the construction industry [70]. The LCA methodology is also normed in Vietnam through TVCN ISO 14040: 2009 [71], TVCN ISO 14041: 2011 [72], TVCN ISO/TR 14047: 2018 [73], and TVCN ISO/TR 14048: 2012 [74].

2.4.2. Functional Unit and Methodology

The functional unit for this study was the road subbase layer of the class III type national road, where the materials are mainly produced outside of the construction area. The production of the materials comes within the product system. The functional unit for the study was a 1 km long national road of class III with a pavement width of 6 m and roadbed width of 9 m, has and with a subbase layer of 0.3 m thickness, using conventional and alternative materials. The substitution was assumed to be 100% of the subbase material layer through (a) m-sand, (b) CDW, (c) GBF slag, (d) EAF slag, and (e) fly ash. The primary goal of this study was to evaluate the potential environmental benefits of using recycled materials and determine which of the alternative mixes were relatively more or less sustainable. The normal scenario involves comparing conventional river-sand-based subbase layers and alternative-material-based subbase, without considering the avoidance of using alternative materials. The avoidance scenario involves comparing the conventional subbase layer and alternative material subbase layers with the avoidance process to technosphere factors. A cradle-to-gate approach was considered. In terms of the system boundaries, the onsite installation process, other layers, and service life in conventional or alternative subbase layers were assumed to be similar, so they were not considered in the analysis.

The LCA was carried out using the Ecoinvent 3.6 database (www.ecoinvent.org, accessed 1 January 2022) and the software SimaPro 9.2 (https://simapro.com/, accessed 1 January 2022) [75]. The study adopted the ReCiPe 2016 Midpoint (H) V1.04/World method to assess the impacts. This method was introduced in 2008 [76] and combines the strengths of other methods such as CML and Eco-Indicator 99 [77]. The primary objective of the ReCiPe method is to transform the long list of life-cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category. This method was chosen because of its advantages, with a broad set of midpoint categories, and utilizing an impact mechanism with global scope [78]. The following impact categories expressed through the respective indicators were considered:

- Global warming potential (infrared radiative forcing increase), in kg CO_2eq;
- Mineral resource scarcity (ore grade decrease), in kg Cu eq;
- Fossil resource scarcity (upper heating value), in Kg oil eq;
- Terrestrial acidification (proton increase in natural soils), in kg SO_2eq;
- Freshwater eutrophication (phosphorus increase in freshwater), in kg Peq;
- Fine particulate matter formation (PM2.5 population intake increase), in kg$PM_{2.5}$ eq;
- Stratospheric ozone depletion (stratospheric ozone decrease), in kg CFC_{11}eq;
- Ozone formation (terrestrial ecosystem tropospheric ozone increase), in kg NO_xeq;
- Cumulative energy consumption (Total of used primary energy), in KJ.

3. Results and Discussion

3.1. Results of the General Soil Mechanical Characterization

The soil mechanical results are presented in Table 3. Materials used for road construction must demonstrate a high bearing capacity, so that no settlements or accidents are caused when vehicles come off the paved part of the road [79]. Stability and high bearing capacity are usually mainly achieved through the gravel fraction of the building material. Practically, this requirement also applies to secondary building materials, which usually also contain a semi-natural sand fraction in the case of CDW, while slags are broken down to a grain size similar to that of sand and gravel. Typically, even having a similar grain size distribution after processing, the material properties of crushed slags are different to those of natural building materials. Shear strength is the property or ability to withstand shear stresses with limited deformation. The shear strength of a soil depends on the type and composition of the soil particles, the structure of the soil, the water content of the soil, and its previous loading (this applies only to cohesive soils). Friction is the resistance in the contact area of two material bodies that are pushed against one another. When it comes to cohesion, a distinction is made between real and apparent cohesion. Real cohesion is independent of normal stress and only occurs in cohesive soils. Apparent cohesion, or capillary cohesion, also occurs in non-cohesive soils. The values for the cohesion ranged from 0.86 to 11.09 KN/m^2. The angle of friction covered a range from 25 to 56°. The stiffness moduli of the investigated secondary building materials covered a range from 81.72 to 187.81 MN/m^2.

Table 3. Results of the soil mechanical investigation program.

Material	Water Content (%)	Angle of Friction φ (°)	Cohesion c (kN/m^2)	Stiffness Modulus $E_{s,max}$ (MN/m^2)
Mixed CDW	0.39	25.45	11.09	97.52
FA	0.69	27.81	4.02	81.72
GBF	0.19	56.50	1.34	187.81
EAF	0.16	55.57	0.86	94.48

In the present case, FA had characteristics similar to those of natural cohesive soils, while the material properties of GBF and EAF were comparable to those of very coarse non-cohesive soils. Behiry, in 2013 [80], reported that the mechanical characteristics and the resistance factors were improved by adding steel slag to the crushed limestone in road pavement layers. The use of steel slag, especially at an optimal ratio, improved the subbase layer's density, strength, and failure resistance—especially at a horizontal distance of 60 cm from the load center. Moreover, in crushed CDW, there can be a high proportion of fine material. While the angle of friction of mixed CDW and FA was within the range of natural cohesive soil, the values for the slags were above typical values from natural sand and gravel, and within the range of values reported for slags in the literature [81]. The results of the angle of friction indicate that the slags form a particularly stable layer, from a soil mechanical point of view. Following the results of the oedometric compression test, the stiffness modulus $E_{s,max}$ was determined on the second loading cycle (reloading modulus); the investigated secondary building materials fulfilled the requirements for substructure materials after qualified soil improvement according to ZTV E-StB 09 [82] for road classes with $E_{v2} \geq 70$ MN/m^2 (after usual compaction). The in situ plate load test for the determination of E_{v2} after compaction follows the same principle, with a cycle of loading–unloading–reloading. Using the E-CBR relation of Fillibeck and Schwabbaur [83], the CBR value was estimated, showing that GBF fully corresponds with the Vietnamese requirements for road subbase, while mixed CDW and EAF are slightly below the required CBR value and might require material modifications/adaptations, as was also indicated in [40]. The values for the measured stiffness modulus are comparable to the results for broken aggregates and recycled aggregates reported in [81]. The material properties of secondary building materials for road construction can be adapted to the necessary requirements through respective material processing (for instance, the grain size distribution). In the event that a higher bearing capacity is required—for instance, for expressway construction—the fine grain content should be further reduced. Moreover, it must be considered that feasibility assessments for SBM use must be proven individually for each material and set of site specifications.

3.2. Chemical Analysis Results

Table 4 shows the results of the chemical analysis for the substitutive building materials. Generally, the values complied with the guidelines; however, individual exceedances were determined. This applies for the chromium content in solid EAF material, which exceeded the recommended benchmark value by nearly 5-fold, and for sulfate in crushed brick, which exceeded the recommended benchmark value by 1.65-fold. The increased sulfate content also leads to an increased electric conductivity, as it determines the mineralization of the eluate. The sulfate concentrations depend on the natural sulfate content in the clay used for brick production. It should be mentioned that the increased chromium content in the solid EAF material is not environmentally dangerous, as it is not leached from the solid material, as proven through the lack of increase in the eluate values.

Table 4. Results of the chemical investigation program.

Parameter	Unit	Benchmark IC 2	CDW Mix	CDW CC	CDW CB	GBF	EAF	FA
Polycyclic aromatic hydrocarbons (PAHs)	mg/kg	30	<0.01	0.96	5.22	<0.01	<0.01	<0.01
Hydrocarbons (C10-C40)	mg/kg	1000	22	140	79	<10	32	<10
Extractable organically bound halogens (EOX)	mg/kg	10	<1	<1	<1	<1	<1	<1
Zinc	mg/kg DM	1500	189	81	156	6.1	253	40
Mercury	mg/kg DM	5	<0.1	0.18	<0.1	<0.1	<0.1	<0.1
Nickel	mg/kg DM	500	22	15	11	2.8	40	11
Copper	mg/kg DM	400	100	28	26	6.7	224	19
Chromium	mg/kg DM	600	24	30	19	21	2900	24
Cadmium	mg/kg DM	10	0.75	0.67	0.26	<0.1	2.8	0.26
Lead	mg/kg DM	700	33	42	37	<5	<5	7.6
Arsenic	mg/kg DM	150	12	5.4	5.9	5.5	7.4	19
pH value		5.5–12	8.4	10.9	11	9.2	10.4	10.7
Electric conductivity	µS/cm	2000	117	501	1.040	486	239	427
Chloride	mg/L	100	2.3	3.3	14	1.6	2.2	2.0
Sulfate	mg/L	200	8.3	85	330	230	5.0	77
Arsenic	µg/L	60	7.2	<5	<5	<5	<5	72
Lead	µg/L	200	14	23	17	7.6	22	4.7
Cadmium	µg/L	6	0.11	<0.1	1.3	<0.1	<0.1	<0.1
Chromium	µg/L	60	5.2	11	16	6.1	9.7	148
Copper	µg/L	100	8.4	9.0	13	9.1	12	14
Nickel	µg/L	70	3.8	<0.5	3.5	4.6	5.0	48
Mercury	µg/L	2	<0.2	0.22	<0.2	<0.2	<0.2	<0.2
Zinc	µg/L	600	39	2.8	5.6	20	30	21
Phenol index	mg/L	100	0.008	<0.005	<0.005	0.02	0.007	0.02

All samples complied with the recommended benchmarks for the organic compounds—namely, PAHs, hydrocarbons, and EOX in the solid fraction, and phenol index in the eluate. This is an interesting result, particularly for FA, as PAHs are mainly a pollutant resulting from incineration processes. Moreover, hydrocarbons might result from the use of material processing machines being used, for instance, for building demolition. This might lead to the slightly higher hydrocarbon contents in CDW compared to other secondary building materials.

All secondary materials showed an increased pH value in the eluate—a phenomenon that has already been reported in the literature [84]. However, the measured values do not restrict their use as secondary building materials. Generally, all investigated materials contained certain contents of metals, which can be explained through the history of the materials. Particularly for FA, the metal content depends on the original metal content in the lignite that was used for fossil energy material combustion. This situation needs to be kept in mind when FA is used for construction purposes, as it requires individual material testing before use. Not all of the investigated metals are toxic—this applies particularly to zinc, copper, and nickel. Thus, a focus must be put on mercury, cadmium, and lead, which are toxic; however, their concentrations were low in the solid matrix and in the eluate.

3.3. Life-Cycle Assessment Results

Figures 2–9 illustrate the results of the life-cycle impact assessment (LCIA). The normal scenario involves comparing conventional river-sand-based subbase layers and alternative-material-based subbase layers, without considering the avoidance of using alternative materials. In this comparison, EAF slag had a higher global warming potential (GWP) impact than the other materials. All other alternative materials, in general, had a lower GWP contribution than the river sand layer. Overall, GBF slag had approximately seven times higher impact than all other materials. Therefore, the comparison of GBF slag and conventional river sand was kept separate so as to better understand the other alternatives. The GWP contribution analysis of the different material-based layers in a normal scenario indicated that more than 52% of the CO_2 footprint was associated with the transportation process rather than the material processing stage for all materials except GBF slag, the footprint of which was about 91.5% from material processing. The entire GWP impact for fly ash arises from the transportation process, as the material production carries a zero allocation. The contribution of GWP from transportation remains very low when compared to material processing in the use of GBF slag. Compared with EAF slag, the CDW layer and fly ash layers had 61% and 70.7% lower GWP impact contributions, respectively, among the alternative materials. In the mineral scarcity impact category, the CDW and fly ash layers exhibited 71% lower impact than EAF slag and 19% lower impact than river sand. In general, among the alternatives, except for GBF slag and m-sand, the other alternative materials possessed very low levels of land use and water consumption impacts. The impacts generated from the GBF slag were seen as higher than those of all other materials (Figure 2).

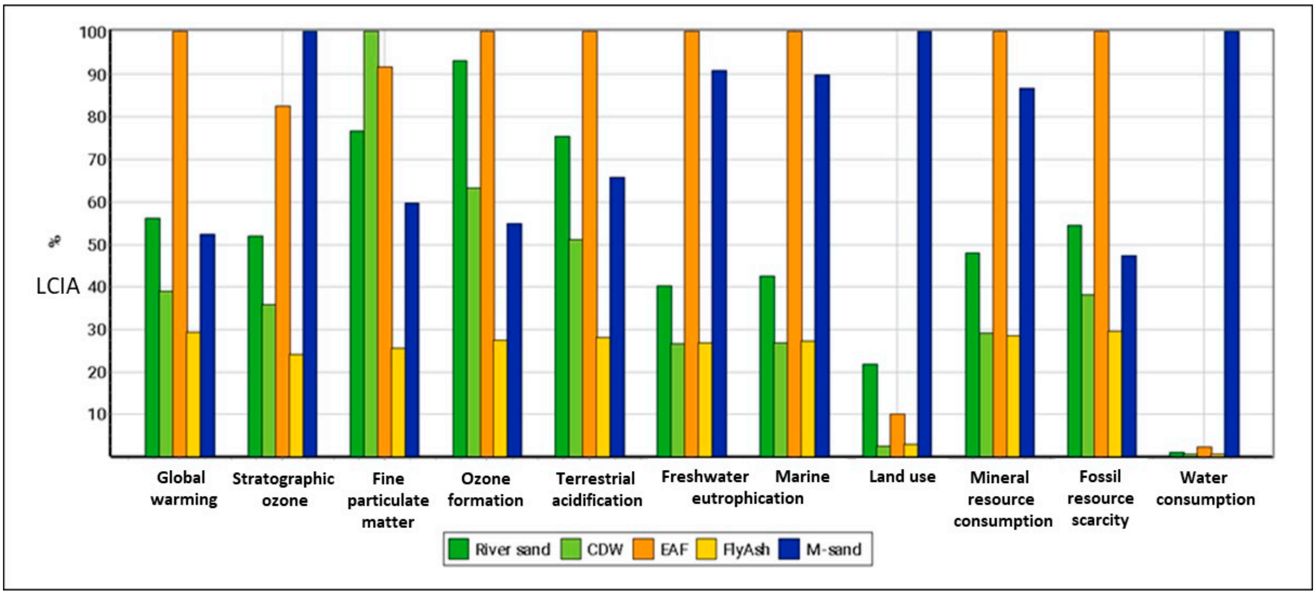

Figure 2. Life-cycle impact analysis for subbase layers made from river sand, CDW, EAF, FA, or m-sand (normal scenario).

The higher ratio of GBF would be because steel processing is a very energy-intensive process using abiotic materials, and blast furnace slag is a residue of those processes. Large energy consumption has impacts on GHG generation and ozone formation, and it might also produce fine particulate matter. In parallel, steel manufacturing uses abiotic materials that lead to resource scarcity and higher water consumption, land consumption, and eutrophication. Therefore, the comparison of GBF slag and conventional river sand was kept separate to allow for a better understanding of the other alternatives (Figure 3).

In a normal scenario without GBF slag, the EAF slag subbase layer had the highest energy demand across most categories (Figure 4). All other layer alternatives possessed lesser energy demand in the fossil-based category than the conventional river sand layer. Overall, across all energy source categories, the energy demand remained low for the fly ash mix layer. The water-based renewable energy share was highest for the m-sand layer. Figure 5 shows that the GBF slag has a high energy demand—about nine times higher than that of the conventional sand layer. This indicates that steel processing is an energy-intensive process.

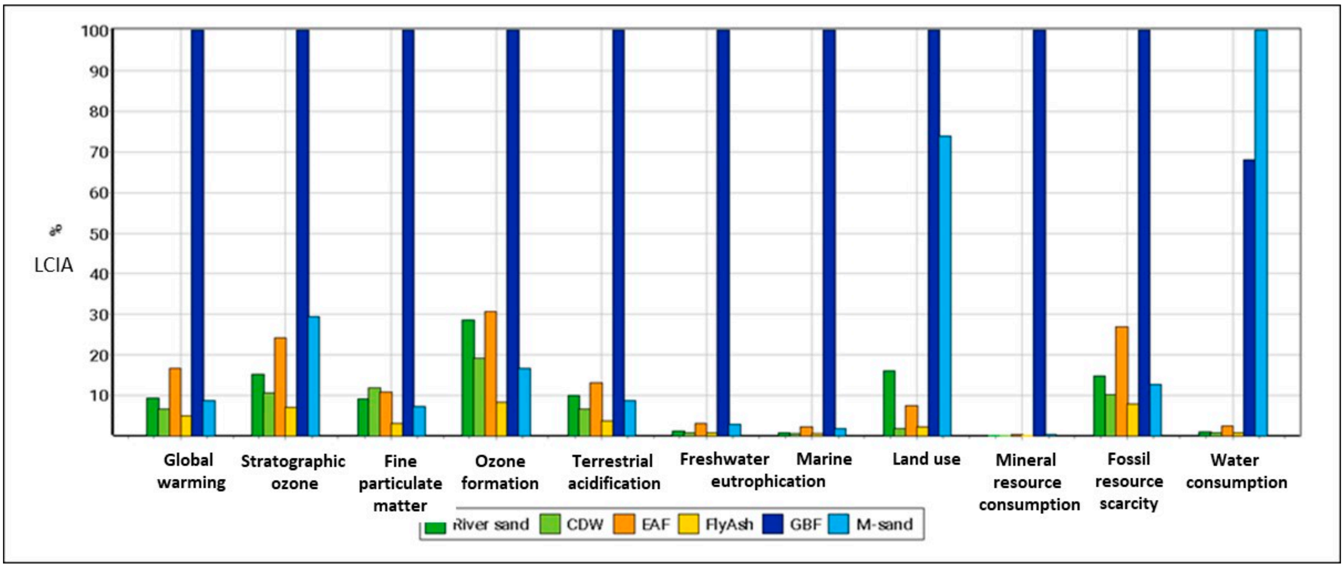

Figure 3. Life-cycle impact analysis for subbase layers made from river sand, CDW, GBF, FA, or m-sand (normal scenario).

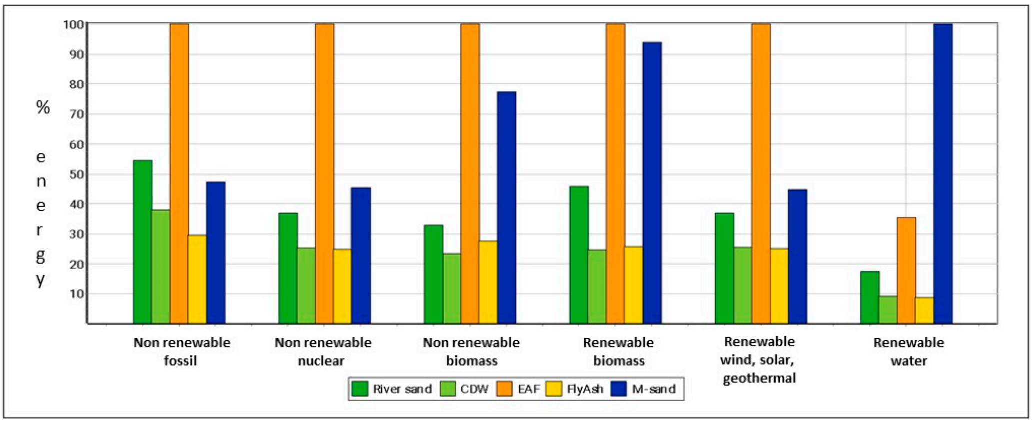

Figure 4. Energy demand analysis for subbase layers made from river sand, CDW, EAF, FA, or m-sand (normal scenario).

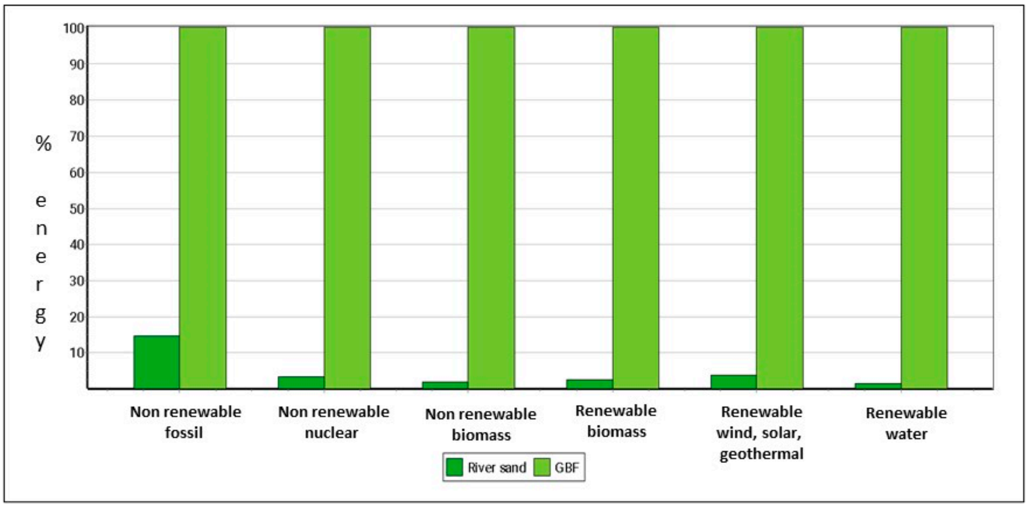

Figure 5. Energy demand analysis for subbase layers made from river sand or GBF (normal scenario).

The avoidance scenario involves comparing the conventional subbase layer and alternative material subbase layers with the avoidance process to technosphere factors. In this comparison (Figure 6), the conventional river sand layer had a higher GWP impact than the other materials. All other alternative materials, in general, had a lower GWP contribution than the river sand layer. Like the normal scenario, overall, GBF slag had approx. 7–8 times higher impact than all other materials. The comparison of GBF slag and conventional river sand, therefore, was kept separate to allow for a better understanding of the other alternatives. Among the alternative materials, CDW had the least impact.

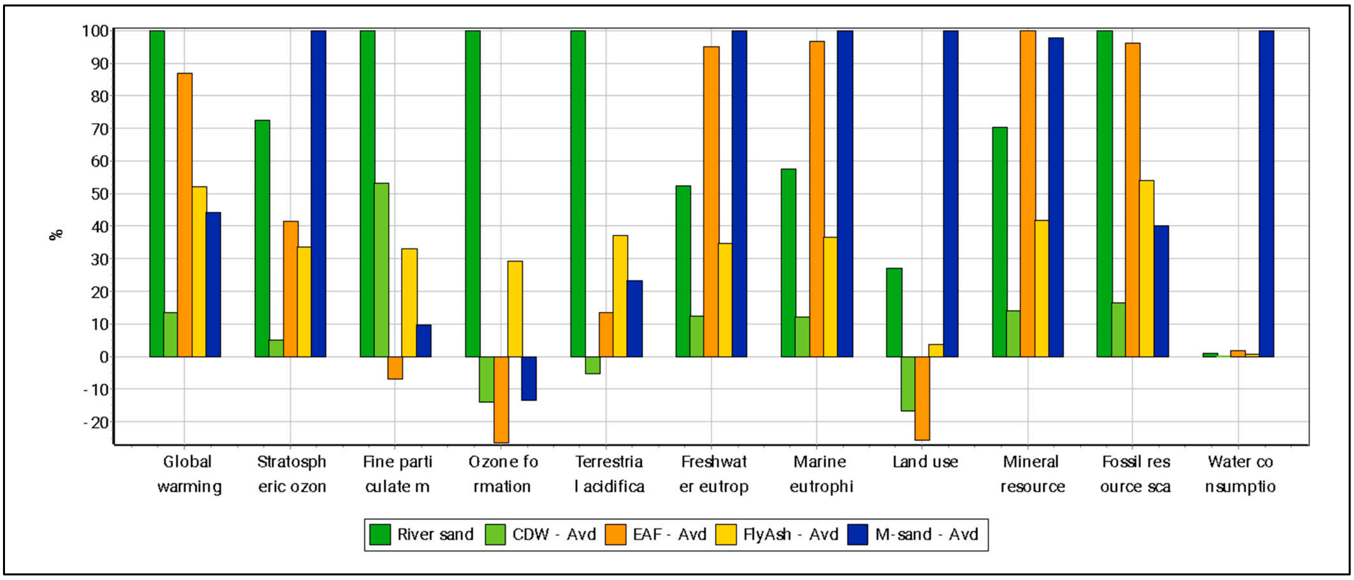

Figure 6. Life-cycle impact analysis for subbase layers made from river sand, CDW, EAF, FA, or m-sand (avoidance scenario).

The contribution analysis in the avoidance scenario showed that among the alternative layers, except for GBF slag, all alternative materials had carbon contribution only from the transportation process. Their carbon contribution from material processing was negative or zero. The construction waste layer had a GWP reduction of about −66%, EAF slag about −37.6%, and m-sand about −16.8% in the material processing area, as compared with the conventional river sand layer. The alternative materials' usage showed a negative GWP impact in the material processing stages. Over the other impact categories, the GBF slag layer had the highest impact across all of the alternative layers (Figure 5). The m-sand layer exhibited a higher water consumption impact than the GBF slag layer—almost 62% higher. In general, CDW, EAF, and FA showed a minimal environmental footprint in the avoidance scenario. In the ozone formation impact category, the CDW layer, EAF layer, and m-sand layer showed some negative reduction. Notably, the CDW and EAF slag layers showed negative reduction benefits in land-use impact categories, which were −16.8% and −25.8%, respectively. The water consumption remained highest for the m-sand layer and least for the CDW layer among the alternatives. Among the alternative layers, CDW, EAF, and FA exhibited lower or negative land-use impacts. The GBF layer showed the highest impacts, similar to the normal scenario, despite the avoidance allocations in this scenario. Thus, the comparison of GBF slag and conventional river sand, again, was illustrated separately from the other alternatives (Figure 7). In comparison with the normal scenario, the GBF slag layer showed about 50% reduction across all impact categories in the avoidance scenario.

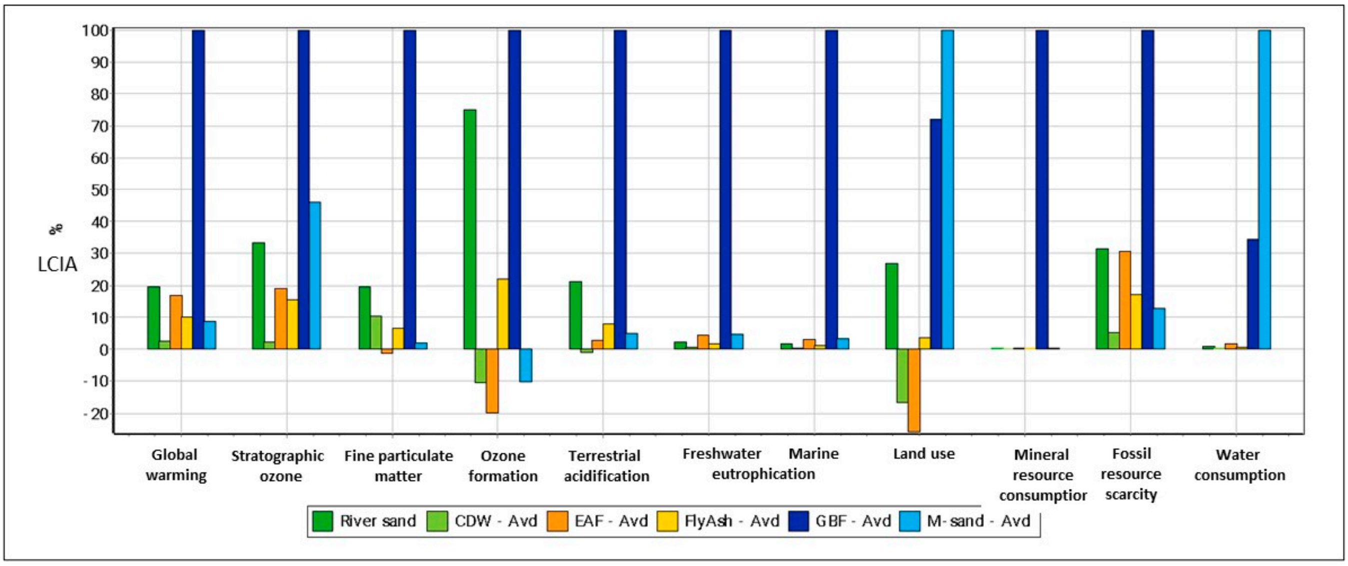

Figure 7. Life-cycle impact analysis for subbase layers made from river sand, CDW, EAF, FA, GBF, or m-sand (avoidance scenario).

In contrast to the normal scenario, the alternative mixes in the avoidance scenario exhibited far better energy demand in non-renewable fossil sources. The conventional sand layer and alternative EAF layer had only a marginal difference in this scenario in the non-renewable fossil category. Overall, across all energy source categories, the energy demand remained high for the conventional mix layer (Figure 8). Among the alternative mixes, the CDW layer utilized less energy, with avoidance benefits. The energy demand reduction was about 80% compared to the conventional layer in the non-renewable fossil category. The m-sand had the highest energy demand in the renewable water category, similar to the normal scenario. Figure 9 shows that the GBF slag layer utilized 50% less energy in the avoidance scenario compared with the normal scenario. At the same time, the energy demand of the GBF slag layer remained higher than that of the conventional layer in this scenario.

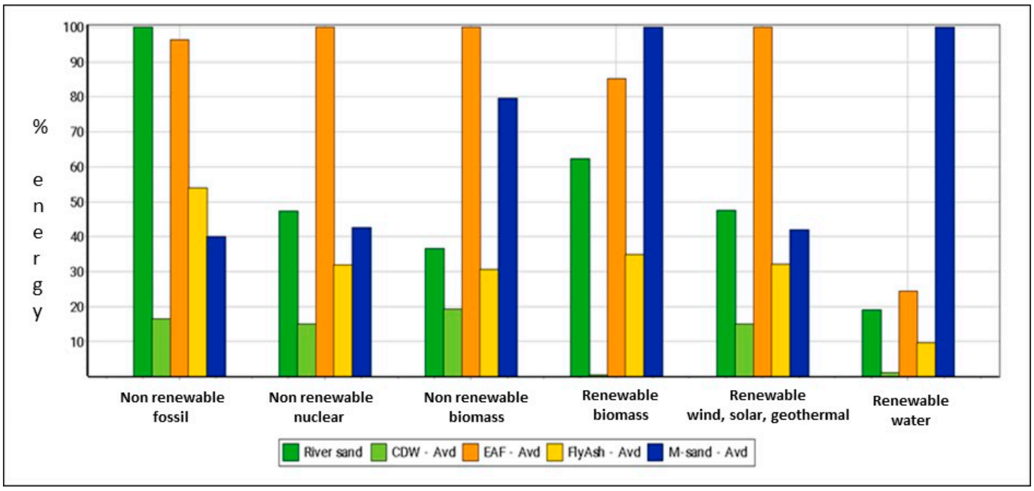

Figure 8. Energy demand analysis for subbase layers made from river sand, CDW, EAF, FA, or m-sand (avoidance scenario).

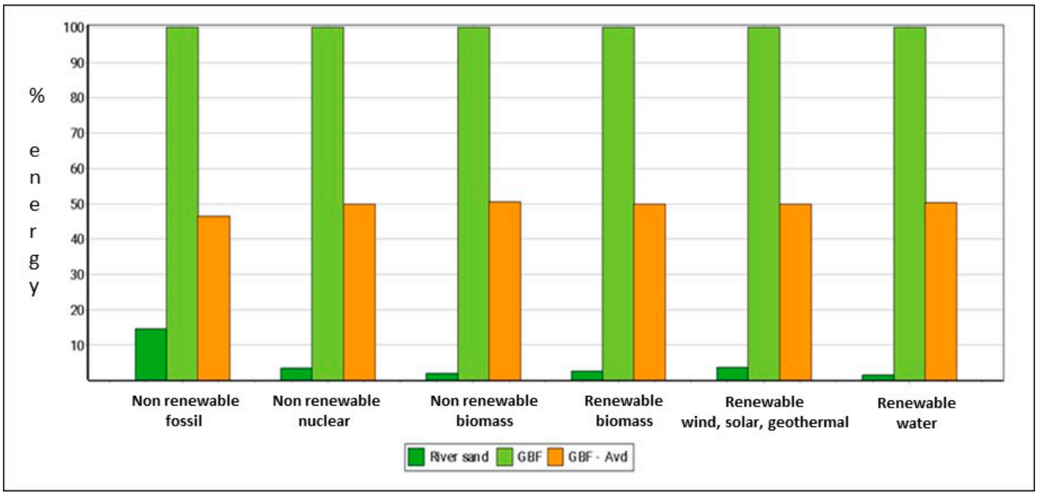

Figure 9. Energy demand analysis for subbase layers made from river sand or GBF (avoidance scenario).

This study's results highlighted the better environmental footprints—especially in the global warming and mineral resource scarcity impact categories—of alternative materials in complete substitution. The LCA analysis results showed differences in the scenario analysis considering a normal scenario and an avoidance scenario.

- The results for the road subbase layer indicated that construction waste and fly ash carried lower GWP, mineral resource scarcity, and other footprints in normal scenarios among the alternatives. Furthermore, on considering avoidance, the footprints of these materials were further reduced. The GWP impact reduced by 86.7% with construction waste, 13.2% with EAF slag, 55.8% with m-sand, and 47.9% with fly ash when considering the avoidance process benefits. With avoidance, except for GBF slag, all of the alternatives had a better impact footprint than the conventional subbase layer.
- The overall LCA analysis for the road subbase layer highlighted that the majority of the footprint contribution was involved in the material transportation processes concerning the construction materials. Thus, sourcing of materials closer to the site or the use of low-emission transport alternatives needs to be considered.
- The cumulative energy demand analysis highlighted the need to shift from fossil-based to renewable energy sources, which could benefit the environment.

Although Vietnam does not yet have a relevant CDW material flow due to the fact that its infrastructure is still being built, the peak for CDW availability is expected by the Asian Development Bank in Vietnam in 2040 [85]. This will result in CDW becoming another key feedstock for road construction as a backfilling or building material, instead of being dumped into landfills or the natural environment [86]. Lockrey et al., in 2016 [87], estimated that the total amount of CDW in Vietnam in 2020 amounted only to 6.3 million tons, and that it would reach 11 million tons in 2025. Moreover, only 1–2% of CDW was estimated to be recycled in Vietnam [40]. However, CDW is a fast-growing waste stream due to the urbanization and expansion of the built environment. A mix of CDW streams (50% demolition mix, 20% ceramic waste, 30% industrial waste) was tested for rural road pavement layers in Italy [88]. Another study revealed that the replacement of natural aggregates with 20% crushed brick and 50% reclaimed asphalt pavement showed the best results in terms of the stiffness and compressibility of the subbase layer, based on the tests performed [89]. Moreover, substitutive building materials can also be used in Vietnam for replacing natural river sand in concrete production [90] and landfill liner installation [91]. Furthermore, the feasibility of mining residues (namely, phosphogypsum) as a subbase material alternative in Vietnam was investigated recently [92]. Further types of mining residues, such as mine tailings [93], might open further options to identify secondary materials for road applications in Vietnam.

4. Conclusions

Industrial activities release huge amounts of byproducts that are disposed of as waste in landfills under the linear economy paradigm. Consumption of landfill capacities, limited land for future sites, and environmental pollution are significant reasons to provide better management operations. However, all secondary materials must be proven in terms of their environmental impacts, especially their chemical composition, in order to prevent the spread of hazardous components into the natural environment, which might result from the industrial history of the materials. The secondary materials examined in this study will be available in Vietnam in the long term. For instance, in terms of steel slags, Vietnam's iron and steel industry has developed rapidly in recent years. Currently, there are 10 blast furnaces operating across the country. According to the World Steel Association (WSA), in 2015, Vietnam's finished steel production output reached about 15 million tons [94]. The finished steel production was about 24.19 million tons in 2018—a 14.9% increase from 2017 [95]. The role of fly ash is emphasized substantially in the current regulatory framework of Vietnam. The prospects for the utilization of such byproducts in the construction sector as replacements for natural resources are gaining attention under the context of sand scarcity, particularly in Asia. Road construction and maintenance of the existing networks are crucial for every country to develop its economy at the national and local levels. Bearing in mind that in Vietnam there is currently a high rate of gasoline-powered motorcycle ownership in cities, and that the country is striving for electric mobility [33], the need for good road infrastructure and the associated building materials is ongoing. These results may also be useful in other countries facing mineral resource scarcity. Future investigation should focus on a deeper understanding of the available secondary material flows and identify applications beyond the road sector—for instance, urban green infrastructure. These results serve as an example for solutions for Vietnam that are transferrable to other countries as well.

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