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Impact Analysis Using Life Cycle Assessment of Asphalt Production from Primary Data

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Abstract: Road construction and maintenance have a great impact on the environment, owing to the huge volumes of resources involved. Consequently, current production procedures and technologies must be properly investigated, for identifying and quantifying the life cycle environmental impacts produced. In this paper, primary data, i.e., site-specific data directly collected or measured on a reference plant, are analyzed for calculating the impact of the production of a hot mix asphalt. The analysis is performed in a from "cradle to gate" approach to estimate the environmental burdens of the production process in an average plant, representative of the existing technology in Italy and Southern Europe. The research outcomes are useful to increase reliability in quantification of asphalt production impacts and the contribution of each component. The results represent a reference basis for producers, designers, and contractors in the decisional phases, identifying the most critical aspects in the current practice and the possible improvements for reducing impacts of road industries. In this regard, efficient energy technologies for reducing the production temperature (such as warm mix asphalt) and burned fuels are proven to assure relevant improvements in the environmental performance.

Keywords: asphalt production; foreground data; LCA; emissions; energy consumption; environmental impacts

1. Introduction

The infrastructure construction industry, continuously growing in recent years all over the world for both construction and maintenance activities, requires relevant consumption of precious materials, with huge consequences for the natural ecosystem [1]. These environmental problems are also due to the huge volumes involved in pavement constructions and to the required technology for material extraction and production, traditionally characterized by strong impacts [2]. It may be considered that, in the transportation sector, road construction determines a contribution up to 10% of total greenhouse gas (GHG) emissions, representing a useful indicator for sustainability assessment. For example, according to the Federal Highway Administration estimates, pavement construction, maintenance, and rehabilitation in the United States roughly produce 75 million tons CO_{2eq} per year [3]. In the last decades, relevant attention to these issues and environment preservation has remarkably risen. In this regard, numerous researchers have investigated and analyzed the possible sustainability issues caused by traditional approaches and technologies in pavement construction and maintenance phases, and proposed modern and more efficient sustainable solutions that may effectively reduce consumption of energy and resources, as well as the production of waste [4–6].

From this perspective, in order to assure comprehensive and exhaustive analysis of product and technology impacts, life cycle assessment (LCA) represents an appropriate and accurate methodology for any kind of material and process, regarding the whole life cycle of the products. The International

Organization for Standardization (ISO) provided accurate and general instructions and regulations for proper performing of LCA in its 14040 series publications [7,8]. Concerning the pavement industry, LCA can actually be adopted for estimating impacts of different asphalt mixtures and technologies, for both production and construction. The assessment can assure an overview of the entire life cycle of the material by taking into consideration production of raw materials and mixtures, construction, effective exercise and final disposal, listing all the involved resources and evaluating, with relevant accuracy, and the produced impacts on the environment in "cradle to grave" approaches.

With specific regard to existing literature for the road construction sector, many scientific researchers investigated material production and pavement construction, maintenance and rehabilitation processes, and technologies, using LCA to understand the main drawbacks of the current practice and evaluating possible improvements in methodologies and operative solutions [9–18]. These studies provided a helpful and various reference for a practical application of the methodology and, further, they have sometimes evidenced critical aspects and positive strategic solutions for industries, road agencies, and government subjects aiming to improve the entire process. However, in these studies, several research gaps can be identified [19] and two main issues emerged: first, several assessments rely on secondary data for production processes and technologies; secondly, most of the literature focused on specific models and case studies that may be relevant only for the evaluated scenario or the reference country [20]. Indeed, as any data-based analysis, reference information reliability remains remarkable for homogeneous markets/contexts only.

Owing to these complications and in order to directly define and quantify impacts of road pavement construction and maintenance, usually researchers focused mainly on these stages of the product life cycle only, in a from "gate to grave" approach. If production steps are kept in consideration, LCA applications commonly rely on numerical values and quantities extracted from available datasets, with possible inconsistencies due to the origin or the quality of the different data [21]. Indeed, the lack of reliable and solid primary data on road materials and technology components, provided with significant accuracy by manufacturing companies, generally represents a remarkable issue [16,18,22]. Though some attempts were performed in foreign contexts for accurate primary data collection [23–27], in few cases LCAs related to the Italian or Southern European contexts have been based (sometimes partially or with strong hypothesis) on foreground data directly collected on site [15,16,22,28,29]. Consequently, as the definition of the eco-profiles of the considered products and processes generally relies on secondary data derived from different (foreign) contexts, the accuracy and reliability of the derived results should be questioned. Instead, a complete and exhaustive analysis of all the involved inputs and outputs assures good accuracy in the determination of the from "cradle to gate" impact on several environmental indicators. Obviously, as accurate calculations of pavement impacts require the examination of every phase and process, each of them should be properly analyzed, considering the specific process conditions and scenarios, for assuring exhaustive and reliable results.

The production stage of the asphalt mixture naturally determines a relevant contribution to the overall impacts of the product [18,30]. Further, it can strongly influence the quality of the product and determines the consumption of natural resources (both raw components and fuels) during the production cycles. Then, the production phases of the asphalt mixture have to be properly investigated and analyzed for assuring adequate quality and reliability of the whole life cycle impact interpretation and also for identifying strategies aimed at increasing the eco-efficiency of the asphalt mixture production process and the resource productivity [31].

Consequently, the main goal of this research is to carry out a complete environmental LCA of the production of an asphalt mixture in an Italian plant, fully representative of the average technology common in the Italian and Southern European area, following a from "cradle to gate" approach based on foreground data collected in the field, determining a useful benchmark for the Italian context. This goal is of particular interest, considering that over 26 million of tons of asphalt mixtures have been produced only in 2018 in Italy for maintenance and construction needs, with an increase of more than 10% with respect to 2017 [32], while in 2017 over 250 millions of tons were produced in Europe, according to the European Asphalt Pavement Association [33]. Based on a preliminary and accurate phase of primary data collection and on the definition of the eco-profile of the selected product, the LCA analysis is performed to evidence the most impactful elements in the process. All the relevant data related to input/output for the asphalt production were measured and quantified, including raw materials and energy consumption, emissions, and solid wastes. In summary, indeed, the study mainly aims to define a reliable context-related impact analysis of hot mix asphalt (HMA) production phase based on foreground data directly collected on a representative plant for the analyzed geographical area and the related market. More details regarding novelty and motivation of the present research are provided in "Goal and scope definition" section. Moreover, for improving result quality, a preliminary sensitivity analysis was also performed, to better evaluate the effect of the different components and, further, to control the influence of eventual slight inaccuracies in the provided data. Moreover, a comparative analysis evidences possible benefits and improvements assured by different configurations of the plant, especially from an energetic perspective. In detail, different alternative energy sources and technological solutions are compared for estimating impact variations, relying on the primary data acquired at the plant. After a brief discussion on the LCA framework, the following sections present, first, goal and scope definition, and inventory analysis, then, life cycle impact evaluation and result analysis are provided and discussed.

2. Methodological Approach

2.1. Life Cycle Assessment

LCA is a powerful methodological framework to determine in a reliable way impacts on the environment of specific products, processes, and technologies. The general framework for a correct application of the methodology is provided in the ISO 14040 and ISO 14044 standards [7,8].

In general, LCAs are cradle-to-grave analyses of the products or services and include four basic steps:

1. Goal definition and scoping, required for identifying the goal of the study, the system boundaries, the functional or declared unit (FU or DU), the target audience, etc.;
2. Inventory analysis, for the quantification of resource consumption, waste flows, and emissions for the reference unit attributable to the different processes in the life cycle system;
3. Impact assessment, providing useful environmental characterizations, for a better and deeper understanding of the inventory data;
4. Interpretation, stating specific conclusions and strategic recommendations for improving the analysis or evidencing relevant aspects and critical issues for the decision makers.

2.2. Technology Benchmarking

According to the aim of the paper, the first step for performing the LCA of HMA production is the selection of the reference technology and production processes. Therefore, at the beginning of the research activity, a preliminary analysis of the existing technology in Italy and Europe (significantly different from the American context, for which several studies are available) was performed in order to select a representative plant as reference. As known, there are several configurations and technologies for asphalt mixture production, characterized by the mixing process and technology. Generally, the batch-mix plant is the most common solution in Europe [34,35] and, in particular, in Italy [36], especially due to its adaptability with regards to design mix and productivity. Considering the Italian scenario, in 2010, almost 90% of the asphalt plants (606 of 693 active plants) relied on the batch-mix technology [36] and this scenario can be considered constant for the last 10 years. Furthermore, since it is reasonable to think that relevant practical technology will not affect the existing plant configuration in the next decade (especially for traditional HMA production), the technological characteristics as well as the operating conditions of batch-mix plants refer to an existing large-scale technology in Italy, and in Southern Europe too. Further, the strong crisis of the bitumen/asphalt market in the last decade [37] and its recent evolution towards minor maintenance and rehabilitation projects have discouraged possible modifications in the current technology. In terms of adopted heating technologies in the production process, according to U.S. Environmental Protection Agency [38], in batch mix HMA plants, the rotary dryer for heating the aggregates are typically oil- or gas-fired.

Thus, according to the above-mentioned information, the average technology in Italy and in Southern Europe is represented by a batch-mix asphalt, including oil and gas burners for aggregate and bitumen heating. For the purpose of this study, in order to assure technological representativeness, an Italian batch-mix plant was selected as reference, representing a reliable “average plant”. Further details on the selected plant are provided in Section 3.2.3.

3. Case study: Production of Asphalt Mixture in a Southern Italy Batch-Mix Plant

3.1. Goal and Scope Definition

3.1.1. Goal of the Study

The main goal of this study is to assess the environmental impacts of the production of a hot mix asphalt (HMA) mixture in an Italian plant, useful as a benchmark for the Italian, mainly, and Southern European context and for providing accurate results to be included in from “cradle to grave” LCAs of asphalt pavements. For performing this task, an accurate preliminary data collection campaign was performed in the considered plant. Further objectives of the investigation were: (1) to assess possible variations in the final outcomes due to eventual small inaccuracies of the provided data; (2) to quantify the environmental advantages of operating the plant through electricity produced by renewable sources, instead of electricity produced by private generating-set or obtained from the grid; and (3) to estimate possible benefits of more sustainable technologies, such as warm mix asphalt (WMA).

The results of this research may provide a reference basis for improving LCA analysis of asphalt pavements, considering with more accuracy and reliability actual plant information. Further, as the considered plant represents the most common technology in the reference context, the results of the study may also constitute a benchmark for other plants, providing useful data on their sustainability to their owner, for possible technological modifications and improvements.

The study is performed in compliance with the LCA regulations provided by the international standards of series ISO 14040 [7,8] and by the Environmental Product Declaration (EPD) product category rules [39]. According to the reference methodology framework, input and output flows of each productive step are considered for the different processes in which they occur, considering an attributional approach [40].

3.1.2. Declared Unit and System Boundaries

The investigated product is an asphalt mixture for road pavement industry. The reference unit adopted in this study, according to the standards, is represented by the declared unit (DU), consisting of 1 metric ton of HMA mixture, suitable for binder courses in compliance with Italian regulations. The included raw materials are limestone aggregates and bitumen.

For the definition of the system boundaries, first it is fundamental to consider the entire life cycle of asphalt pavements, from production to disposal. In general, it is possible to identify five different stages in the pavement life cycle, as shown in Figure 1.

In this research, the analysis focuses on the production stage and, thus, it is stopped at the exit factory gate (from “cradle to gate”). Therefore, the considered processes are: bitumen supply (including oil extraction and its transformation); aggregate supply (including extraction and transformation); aggregate and bitumen transportation to the production plant; and plant production processes.

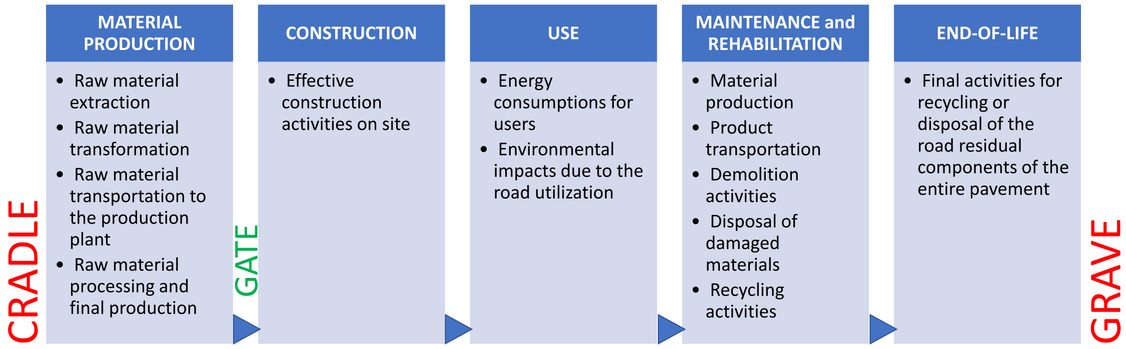


Figure 1. Stages of road pavement life cycle.

3.1.3. Impact Assessment Methodology and Impact Categories

Impact calculations were based on impact categories and characterization factors of the EPD 2018 method [41]. The following seven impact categories were calculated according to the above method in order to describe performance and effects of the considered product system:

- AC: Acidification (fate not incl.) (kg SO_{2eq});
- EU: Eutrophication (kg ${PO_4}^{3-}{}_{eq}$);
- GW: Global warming (100 year) (kg CO_{2eq});
- PO: Photochemical oxidation (kg NMVOC);
- OD: Ozone layer depletion (kg CFC_{11eq});
- AD and AD*: Abiotic depletion (total (kg SB_{eq}) and fossil fuels only (MJ), respectively).

3.2. Life Cycle Inventory Analysis

3.2.1. Data Collection and Quality

A crucial aspect of LCA is the nature of the considered data, that greatly affects the reliability and accuracy of the results. LCA applications should always define source and collection approaches for each type of data involved in the analysis. In the following, specific information regarding product and production plant, primary data collection, and eventual assumptions for the various stages are provided. Secondary data concerning raw material extraction and transformation (background processes) were directly derived from the Ecoinvent database [42]. Secondary data have been used for modeling energy generation from low Sulphur fuel (LSF), liquid petroleum gas (LPG), and diesel included the gas pollutants emitted during the fuel combustion [42]. The eco-profile of limestone was used for modeling crushed stones, sand, and filler, since they have the same geological nature that is the parameter that, above all, affects the energy for quarrying and mining operations, while the energy differences for further crushing and sieving between fractions may be neglected. Furthermore, the different aggregate fractions are always provided by the same quarry, thus it was reasonable to apply the "average" eco-profile for the same mineral deposit. For more clarity, the following list reports reference to the issues considered for the unitary impact data extraction from the Ecoinvent database: bitumen, at refinery; limestone, crushed, washed, production; heat, central or small-scale, other than natural gas, heat production, light fuel oil, at boiler 100 kW, non-modulating; heat, central or small-scale, natural gas, propane extraction, from liquefied petroleum gas; diesel, burned in diesel-electric generating set, market for; transport, freight, lorry 16–32 metric ton, EURO4.

Transportation effects have been properly computed, based on actual supplier locations and effective travelled distances (see Section 3.2.4). Other quantities and flows (regarding material components, fuels, etc.) consist of primary data, directly collected in the selected production plant.

3.2.2. The Examined Product

As anticipated, the DU of the study consisted of 1 ton of HMA, composed of different gradations of limestone aggregates and bitumen (50/70 pen grade), suitable for construction and maintenance activities of binder courses. The mix-design of the mixture (i.e., the actual recipe of the product), which fulfills typical technical specifications for road flexible pavements, requires three different classes of crushed stone (considering min ÷ max diameter of aggregates: 30% in class 15 ÷ 20 mm, 12% in 10 ÷ 15 mm, 10% in 5 ÷ 10 mm), sand (0 ÷ 6 mm—45%), filler (3%), and bitumen (5.5% on aggregate mass).

3.2.3. The Production Plant

Based on the context/market analysis in Italy and Southern Europe, a reference plant (located close to the city of Palermo, in Italy) was selected. The asphalt plant has an average hourly production of 65 ÷ 75 tons. A single production cycle is about 60 s long, while the relative mixture production is about 1400 kg, with a production temperature of 165 °C, on average.

According to the study aim, all the different production processes performed in the plant (material movements and proportioning, drying and heating, mixing, etc.) were specifically analyzed and included in the assessment by acquiring data and all the available information for deriving inputs and outputs of each step and of the entire production process.

Concerning energy needs for production, different fuels and energy sources were considered for the plant equipment and parts. Indeed, the largest energy contribution is assured by power energy, used for general plant operation and for internal material movements (conveyor belts, bucket elevators, etc.). Since there is no direct connection to the grid, a diesel engine produces the required energy in the analyzed plant. For aggregate drying and heating, a powerful LSF oil burner is adopted, while the bitumen is heated by means of an LPG burner. Finally, a wheel loader allows operators to load the various aggregate components in the cold feeder and, thus, this requires other diesel consumption. A representative scheme of the processes and elements involved in the production activity is shown in Figure 2: in detail, the main plant elements are depicted in blue, while transport processes are in gray; activities for production of components and fuels are in green (related information was extracted from secondary data).

The first element to be considered is the need for virgin raw materials required for production of the DU. According to the mix-design presented in Section 3.2.2, in Table 1 the related mass of the various components for 1 ton of asphalt mixture is provided. Practically, there is no significant raw material scrap, since in the continuous process all the aggregates effectively mixed in a single batch enter in the final product.

Table 1. Mass of the various components of the selected mixture for the DU.

Component	Mass (kg)
Crushed stone 1.5 (fraction 15–20 mm)	284.4
Crushed stone 1.0 (fraction 10–15 mm)	113.7
Crushed stone 0.5 (fraction 5–10 mm)	94.8
Sand (fraction 0–6 mm)	426.5
Filler (recovered)	28.4
Bitumen	52.1

In terms of the energy consumption for production of the DU, the electric power globally required by the plant is about 100 kW. In order to assure such a value, the generating set burns on average 260 kg/day or 0.6 ton/cycle of diesel. It should be considered that the generating set has a low efficiency (around 30–35%), as is common for similar equipment, determining high quantities of fuel burned for assuring low effective energy to plant equipment working. According to the effective production rates of the plant in a single hour, the various consumption values have been related to a single cycle and, thus, to the DU. In particular, for the generating set, the diesel consumption is equal to 0.44 kg/DU. Aggregate movement and loading in the hoppers is performed by means of a diesel wheel loader, operating for all the four aggregate classes. The loader diesel consumption is around 0.19 kg/DU. The consumption of LSF oil for aggregate heating is around 5 ton/day, thus 8.42 kg/DU. Regarding LPG for bitumen heating, available measurements prove a consumption of around 375 kg/day, thus 0.63 kg/DU. Taking into consideration the calorific value of each fuel (average values here assumed are in line with the typical calorific values for selected petroleum products [43,44]), the energy values in MJ have been calculated for each of them: diesel for electric generator set 18.8 MJ, diesel for loader 8.0 MJ, LPG 25.9 MJ, LSF oil 387.9 MJ.

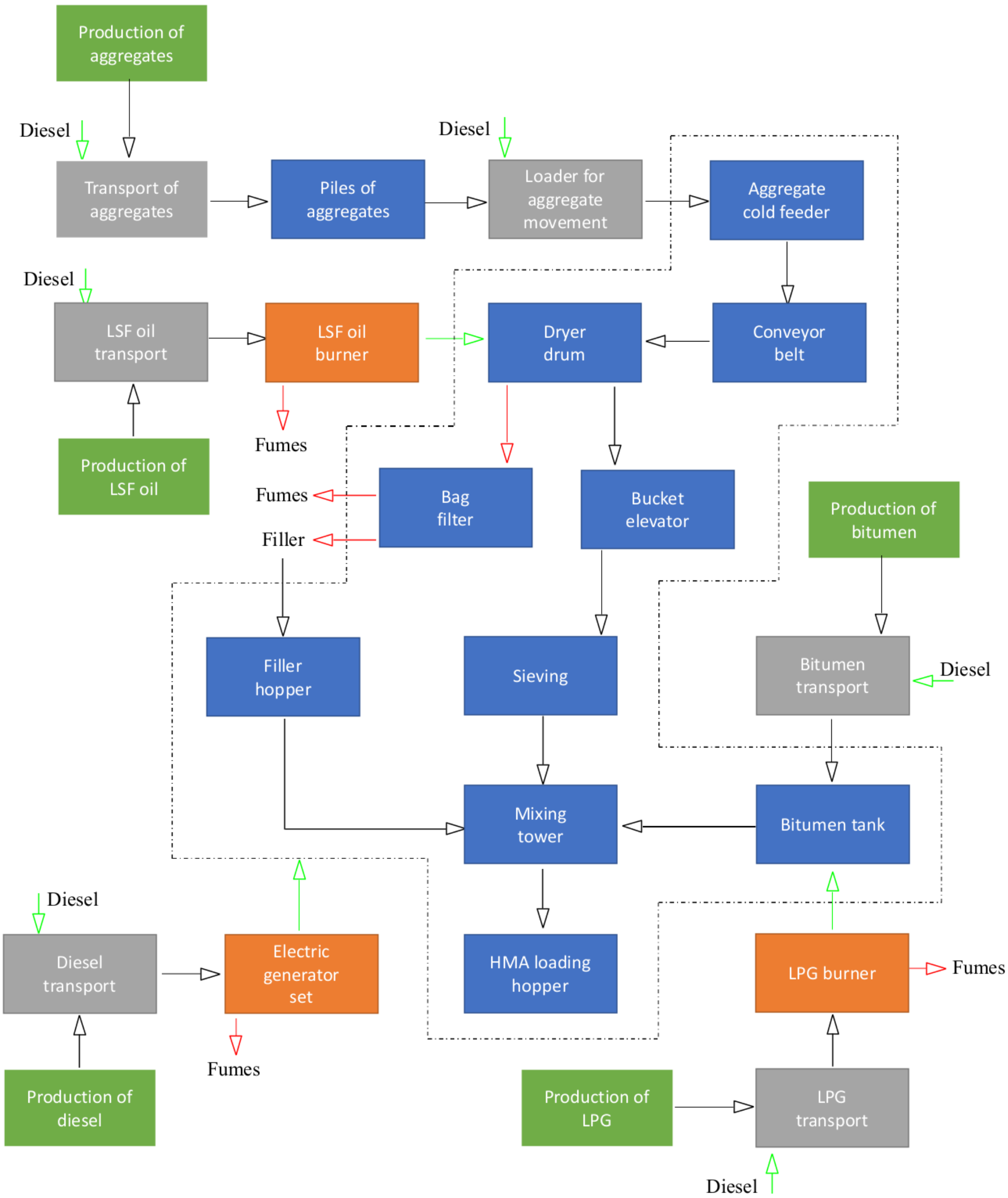


Figure 2. Production processes of a batch-mix asphalt production plant.

Furthermore, for a more accurate electrical analysis of the plant, the main elements were equipped with ammeters for continuous electricity measurements, during the production phases. The acquired measurements were used to calculate the required electricity for the DU, as shown in Figure 3. As mentioned, the overall plant involves a total electric power (including also secondary equipment and devices) of around 100 kW in normal operations, as evaluated by the plant direction. Consequently, the total required power energy for the DU is equal to 1.35 kWh, corresponding to 4.86 MJ/DU.

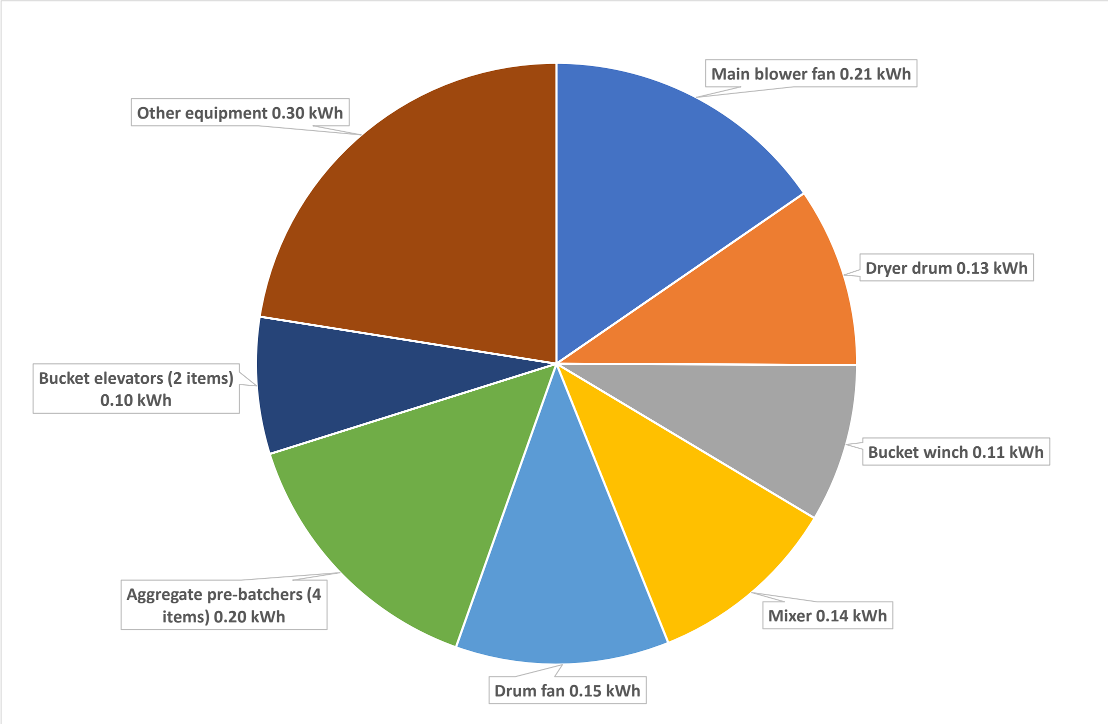


Figure 3. Electricity demand of the main plant components per declared unit (DU).

3.2.4. Raw material and Fuel Transportation

Regarding material and fuels transportation, all the components are provided to the plant by means of both Euro 4 and Euro 5 diesel trucks. Although all the material providers are located in Sicily, the different components are generally transported from different production sites (Figure 4), along paths of different lengths. Moreover, two different providers are involved both for bitumen and diesel, so calculations for both scenarios are presented. The reference unit for transportation calculations is represented by "ton-kilometer" (t·km), i.e., the mass of involved components transported for the relative distance for each DU. Data regarding transportations, acquired by the plant and analyzed in this study, are provided in Table 2.

It is straightforward to notice that transportation distance plays a fundamental role in this context: the exploitation of locally available materials may significantly reduce the truck travelled distances, producing relevant environmental advantages. According to this, both road engineers and industry managers should move towards more sustainable solutions, overpassing only direct economic considerations: raw materials and fuels supply from distant sources or plants should be avoided, their direct costs, in fact, do not take into account environmental drawbacks that, indeed, require significant attention and consideration. Therefore, pavement design and related technical specifications (including materials acceptance criteria) should also be carefully adapted to the local conditions and materials.

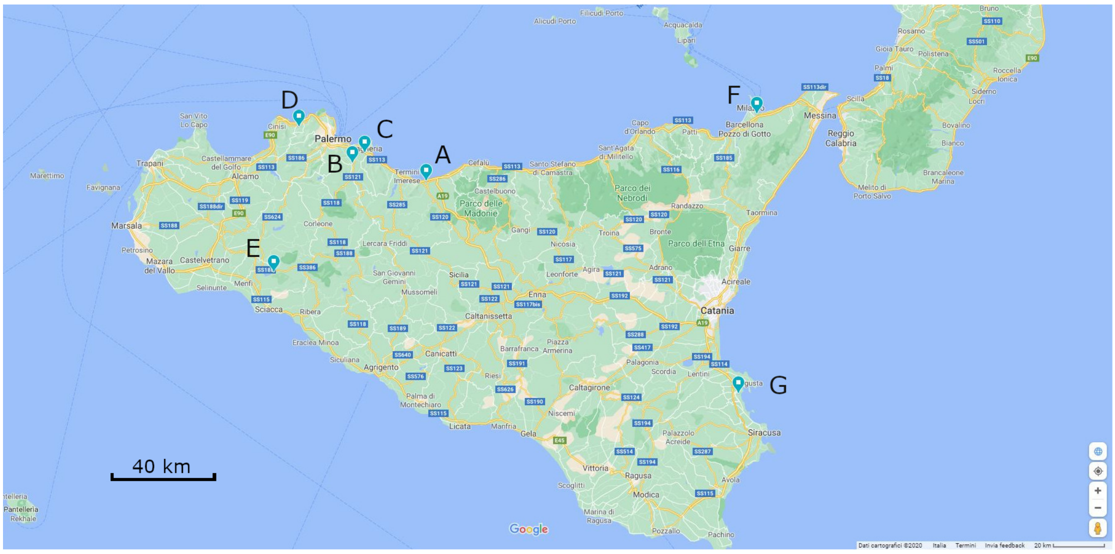


Figure 4. Location of the selected plant (A) and the various raw material providers: (B) diesel, (C) aggregates, (D) LPG, (E) diesel, (F) bitumen, LSF oil, (G) bitumen. Elaboration of map on [45].

Table 2. Transport information for each component and fuel involved in the production process (the letter in the distance column refers to plant location in Figure 4).

Component/Fuel	Distance from Asphalt Plant (km)	Mass for the DU (kg)	Ton-Kilometers for the DU (t·km)
Crushed stone 1.5	35.0 (C)	284.4	9.95
Crushed stone 1.0	35.0 (C)	113.7	3.98
Crushed stone 0.5	35.0 (C)	94.8	3.32
Sand	35.0 (C)	426.5	14.93
Filler (recovered)	35.0 (C)	28.4	0.99
Bitumen	152.0 (F)	52.1	7.92
	193.0 (G)	52.1	10.06
Diesel	123.0 (E)	0.6	0.08
	47.8 (B)	0.6	0.03
Low Sulphur fuel (LSF) oil	152.0 (F)	8.4	1.28
Liquid petroleum gas (LPG)	76.6 (D)	0.6	0.05

4. Life Cycle Impact Assessment and Discussion

4.1. Environmental Impacts

Results regarding impacts calculations are provided in the following figures and tables. In detail, first, the total values of the impact categories related to raw materials production and fuels production and use are listed in Table 3. Results related to transportation impacts are reported in Table 4, while Table 5 provides total impact values for each component (including raw materials production, fuels production and use, and transport). The obtained life cycle impact assessment results for AC and GW are of the same order of magnitude of those obtained by Mukherjee [24] for different asphalt mixtures (in [24] AC resulted equal to 2.95×10^{-1} $kgSO_{2eq}$ and GW to 6.46×10^{1} kg CO_{2eq}), but higher for OD (in [24] OD was 5.8×10^{-9} kg CFC_{11eq}). However, it is important to outline that, as stated in the "Introduction" section, Mukherjee examined asphalt mixtures produced in a different geographic context and characterized by different recipes than the DU of the present study and applied a different impact assessment method (TRACI 2.1).

Table 3. Impacts for raw materials and fuels for the DU.

Impact Category	Limestone Aggregates	Bitumen	Diesel	LSF oil	LPG	Total
AC (kg SO_{2eq})	4.47×10^{-2}	2.57×10^{-1}	3.08×10^{-2}	8.07×10^{-2}	5.37×10^{-3}	4.19×10^{-1}
EU (kg $PO_4{}^{3-}{}_{eq}$)	8.80×10^{-3}	4.19×10^{-2}	5.33×10^{-3}	1.06×10^{-2}	7.43×10^{-4}	6.74×10^{-2}
GW (kg CO_{2eq})	2.30×10^{0}	2.28×10^{1}	2.34×10^{0}	3.61×10^{1}	7.52×10^{-1}	6.43×10^{1}
PO (kg NMVOC)	5.30×10^{-2}	1.67×10^{-1}	4.25×10^{-2}	4.56×10^{-2}	3.28×10^{-3}	3.11×10^{-1}
OD (kg CFC_{11eq})	3.34×10^{-7}	2.30×10^{-5}	4.31×10^{-7}	6.65×10^{-6}	5.82×10^{-7}	3.10×10^{-5}
AD (kg SB_{eq})	4.29×10^{-6}	4.63×10^{-6}	4.05×10^{-7}	9.09×10^{-6}	3.43×10^{-7}	1.88×10^{-5}
AD* (MJ)	2.93×10^{1}	2.52×10^{3}	3.36×10^{1}	5.18×10^{2}	4.63×10^{1}	3.14×10^{3}

Table 4. Transport impacts for the DU.

Impact Category	Limestone Aggregates	Bitumen	Diesel	LSF oil	LPG	Total
AC (kg SO_{2eq})	2.46×10^{-2}	6.67×10^{-3}	3.98×10^{-5}	9.49×10^{-4}	3.59×10^{-5}	3.23×10^{-2}
EU (kg $PO_4{}^{3-}{}_{eq}$)	4.99×10^{-3}	1.35×10^{-3}	8.07×10^{-6}	1.93×10^{-4}	7.28×10^{-6}	6.56×10^{-3}
GW (kg CO_{2eq})	5.42×10^{0}	1.47×10^{0}	8.76×10^{-3}	2.09×10^{-1}	7.90×10^{-3}	7.11×10^{0}
PO (kg NMVOC)	2.93×10^{-2}	7.93×10^{-3}	4.73×10^{-5}	1.13×10^{-3}	4.27×10^{-5}	3.84×10^{-2}
OD (kg CFC_{11eq})	1.01×10^{-6}	2.73×10^{-7}	1.63×10^{-9}	3.89×10^{-8}	1.47×10^{-9}	1.32×10^{-6}
AD (kg SB_{eq})	1.64×10^{-5}	4.44×10^{-6}	2.65×10^{-8}	6.32×10^{-7}	2.39×10^{-8}	2.15×10^{-5}
AD* (MJ)	8.26×10^{1}	2.24×10^{1}	1.34×10^{-1}	3.19×10^{0}	1.21×10^{-1}	1.08×10^{2}

Table 5. Total impacts for the DU.

Impact Category	Limestone Aggregates	Bitumen	Diesel	LSF oil	LPG	Total
AC (kg SO_{2eq})	6.93×10^{-2}	2.64×10^{-1}	3.09×10^{-2}	8.16×10^{-2}	5.40×10^{-3}	4.51×10^{-1}
EU (kg $PO_4{}^{3-}{}_{eq}$)	1.38×10^{-2}	4.32×10^{-2}	5.34×10^{-3}	1.08×10^{-2}	7.50×10^{-4}	7.39×10^{-2}
GW (kg CO_{2eq})	7.72×10^{0}	2.43×10^{1}	2.35×10^{0}	3.63×10^{1}	7.59×10^{-1}	7.15×10^{1}
PO (kg NMVOC)	8.23×10^{-2}	1.75×10^{-1}	4.26×10^{-2}	4.67×10^{-2}	3.32×10^{-3}	3.50×10^{-1}
OD (kg CFC_{11eq})	1.34×10^{-6}	2.33×10^{-5}	4.33×10^{-7}	6.69×10^{-6}	5.83×10^{-7}	3.23×10^{-5}
AD (kg SB_{eq})	2.07×10^{-5}	9.07×10^{-6}	4.32×10^{-7}	9.72×10^{-6}	3.66×10^{-7}	4.02×10^{-5}
AD* (MJ)	1.12×10^{2}	2.54×10^{3}	3.38×10^{1}	5.21×10^{2}	4.64×10^{1}	3.25×10^{3}

For simplifying the impact analysis, Figures 5 and 6 show the contributions of the various elements to the impact categories, respectively for the raw materials and fuels only and for their transportation.

The analysis of the numerical outcomes evidences the most relevant components in the production of the DU of HMA mixture in a batch-mix plant. First, it appears that bitumen is the most relevant contributor to total impacts, almost for all categories, except for GW (Figure 6). Its incidence varies from 23% (AD) to 78% (AD*). LSF oil causes the main impact (51%) on GW while virgin aggregate consumption has the higher influence (51%) on AD. A negligible contribution (lower than 2%) comes from LPG for all the examined impact categories and from diesel for the impacts on global warming, ozone depletion, and abiotic depletion.

The above results strongly depend on the considered production technology, representing, as already underlined, the most common and adopted solution. In detail, the required quantities of bitumen in the mixture and of LSF oil for proper drying and heating of aggregates determine significant impacts. According to their nature, consumption of even small masses may cause huge consequences on environment. Obviously, based on current technologies, bitumen and LSF oil quantities used in the production cycle derive from specific mix-design and system efficiency evaluations. These quantities aim to assure proper mixing and workability to the mixture and, mostly, adequate mechanical performance to the final product. Then, in order to reduce relative and absolute impacts of asphalt mixture production in a similar plant, it is reasonable to boost innovative technological and technical solutions, requiring less volumes of raw materials (both bitumen and aggregates) and of fuels, with equivalent or comparable performance on field. Furthermore, replacing virgin aggregates with non-conventional aggregates (e.g., recycled aggregates) or using supplementary materials to reduce the binder content (obviously taking into account the specific recipe of the mixture) can represent other helpful strategies to promote sustainability [46]. In this regard, recent studies have proposed innovative non-petroleum-based binders for bitumen substitution for significantly improving sustainability of the product.

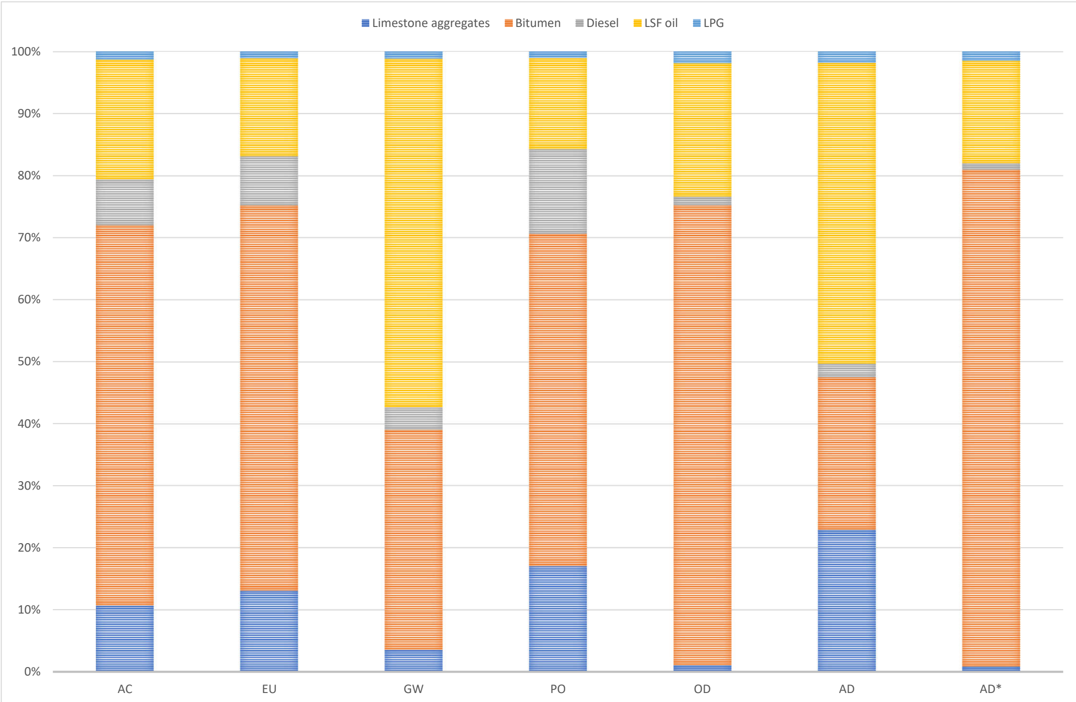


Figure 5. Raw materials and fuels impact for the DU.

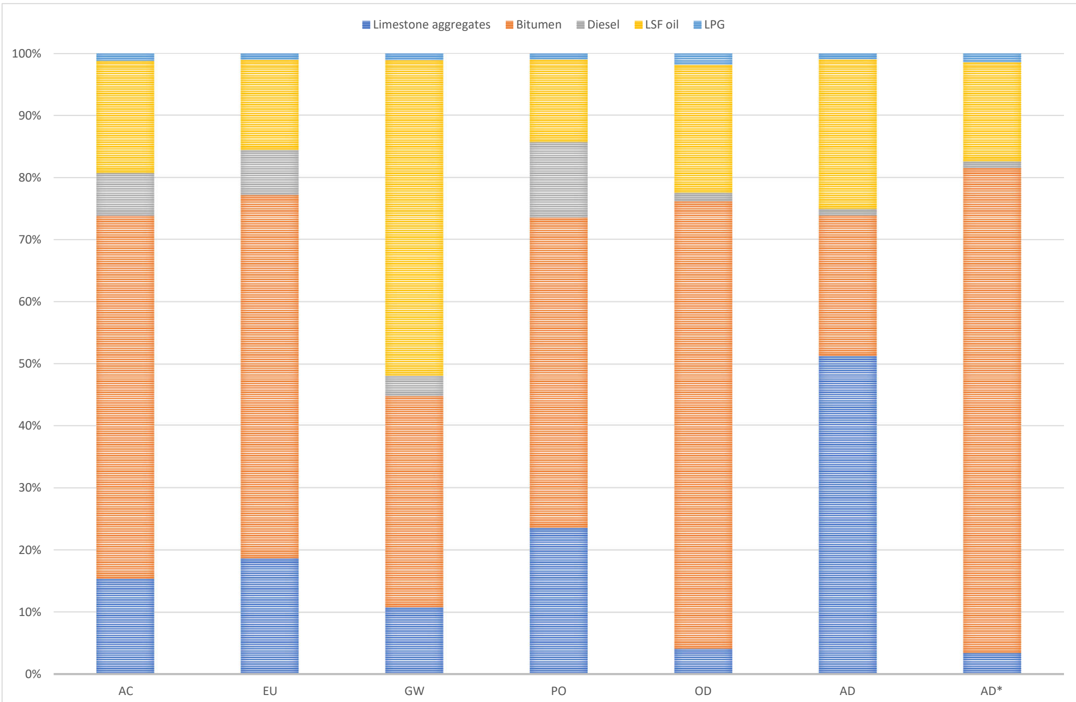


Figure 6. Total impacts of the components (including transport) for the DU.

Further, moving towards lower mixing temperatures—considering WMA production—will remarkably reduce the burned fuels for drying and heating aggregates, determining several benefits in terms of sustainability of the road industry sector [35,47–49], even though the effective consequences of additive adoption have to be properly taken into account [15,28]. Asphalt mixture with high percentages of reclaimed asphalt pavements (RAP) represents another possible positive sustainable solution, saving lot of natural virgin resources [6], even though Italian rates of RAP utilization are less than 25%, remarkably less than other countries [50].

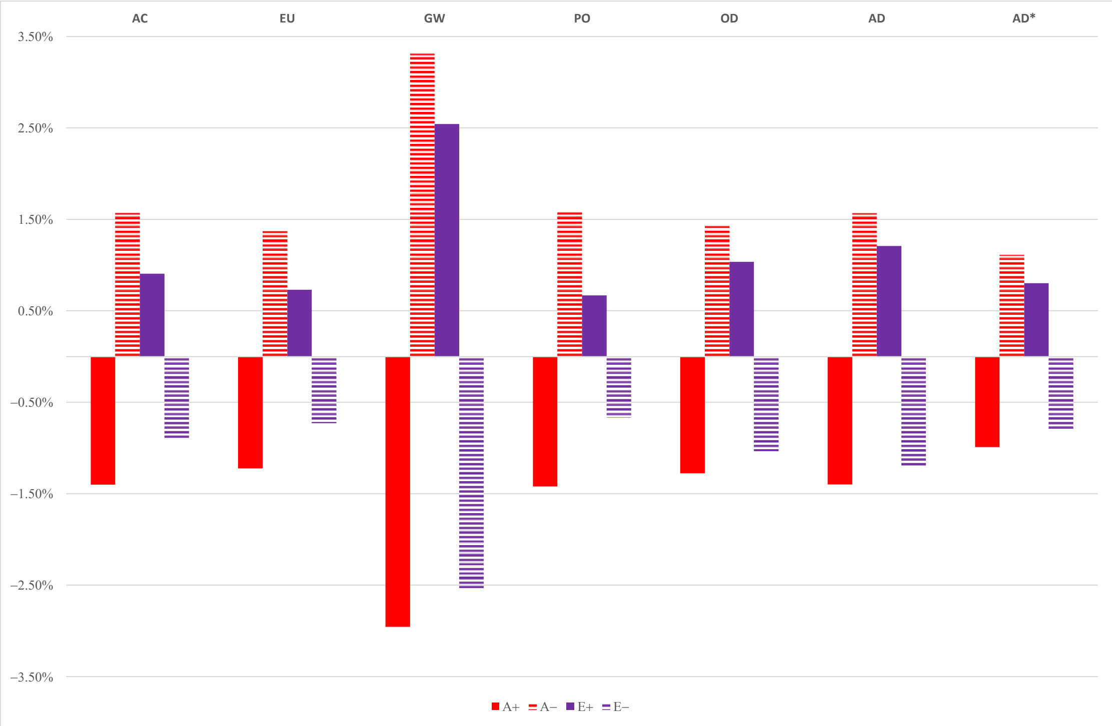
Moreover, data also evidence how much transportation contributes to global impact values, generally less than 10%. Considering AD, the rate of incidence for transportation reaches 53% of the total impact. Although not only distance plays a role in transportation issues, efforts in reduction of transportation distances may increase product sustainability. This consciousness may effectively boost practical use and exploitation of locally available resources, even if slightly less performing than others, as long as they are proven to be adequate for the intended use. Sustainability evaluations, thus, should be effectively taken into consideration in mix-design procedures, in a continuous balance with mechanical performance. For instance, improved mixtures (including, for instance, specific additives) based on local products may assure equivalent service-life of traditional high-level solutions [51] but can increase the environmental efficiency of the asphalt mixture. Finally, recycling asphalt mixture from pavement dismission (both in plant and in place) may also appear as a strategic choice, as it may determine reduction of consumption of aggregate and binder and related transportation impacts in addition to the previously described benefits [29].

4.2. Sensitivity Analysis: Primary Data Variations

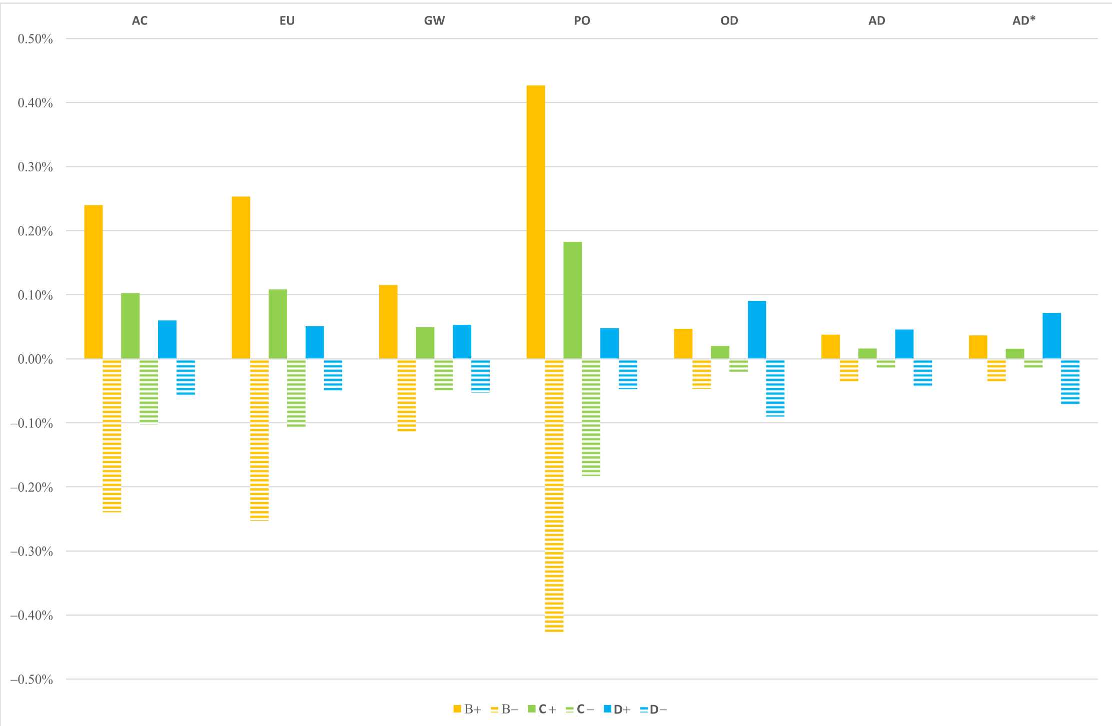
The numerical elaboration presented in this paper was mostly based on the analysis of primary data directly collected in the selected plant. However, due to the nature of the survey, provided and acquired data may be affected by some kinds of inaccuracies and errors [21,52]. In order to increase robustness of the numerical evidence provided in the previous paragraphs and, mostly, for assuring a clear overview on the considered scenario, the effects of eventual inaccuracies in the available primary input data were investigated. In particular, the influence on the impact values of five different variables has been investigated: (1) production rate per hour (t/h); (2) generating-set diesel consumption (kg); (3) loader diesel consumption (kg); (4) LPG consumption (kg); and (5) LSF oil consumption (kg). In detail, a 5% variation was applied to each of these variables, alternatively increasing and decreasing, as shown in Table 6, determining 10 different cases, called from A to E. Positive variations are indicated with symbol "+", while negative with "−": thus, "A+" and "A−" represent scenarios with production rate per hour respectively increased and decreased by 5%. Then, the values of the seven impact categories were recalculated for each case and compared to the reference ones (Tables 3–5), as shown in Figure 7.

Table 6. Reference and modified values for the five parameters. FU, functional unit.

Case	Parameter	Reference Value	+5%	−5%
A	Production rate per hour (t/h)	75.00	78.75	71.25
B	Generating-set diesel consumption (kg/FU)	0.44	0.46	0.42
C	Loader diesel consumption (kg/FU)	0.19	0.20	0.18
D	LPG consumption (kg/FU)	0.63	0.66	0.60
E	LSF oil consumption (kg/FU)	8.42	8.84	8.00



(**a**)

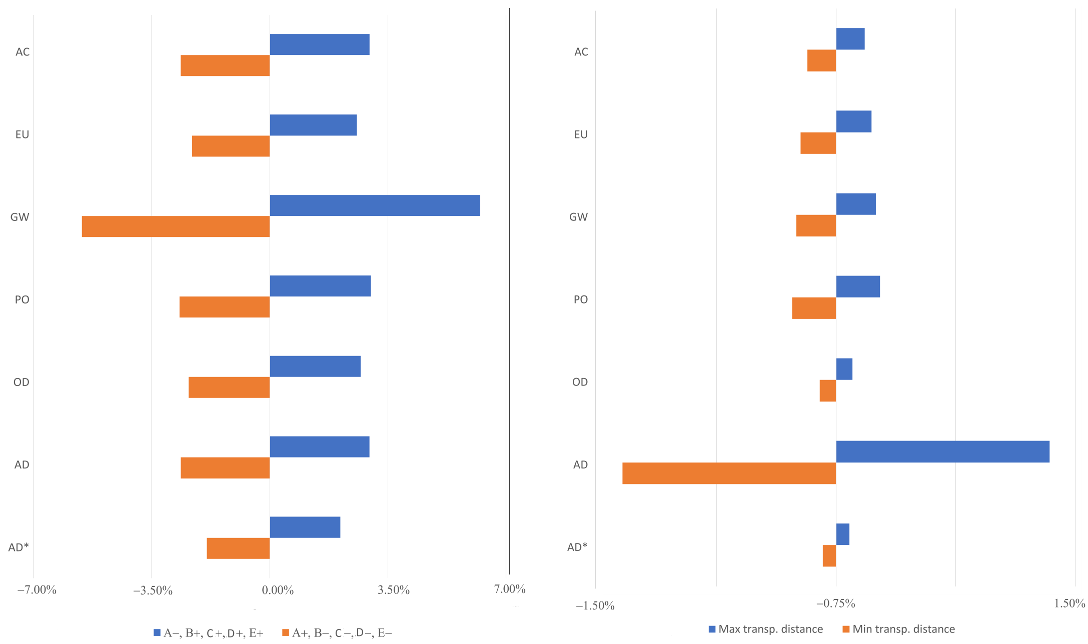


(**b**)

Figure 7. Impact variation for the examined scenarios: (**a**) scenarios A+, A−, E+, E−; (**b**) scenarios B+, B−, C+, C−, D+, D−.

The numerical results of Figure 7 show different influences of the various parameters. For more clarity, the results of the various scenarios are grouped according to the entity of variations: then, Figure 7a shows results related to scenarios A and E, while those of scenarios B, C, and D are shown in Figure 7b. Generally, if inaccuracies underestimate burned fuels (A−, B+, C+, D+, E+), the impact values increase, and vice versa. In detail, as expected, the most sensitive scenarios are A+, A−, E+, E−, i.e., those characterized by variations in plant productivity and in LSF oil consumption. For the former, larger (or smaller, in the opposite case) production rates are related to faster (or slower) production cycles, with consequent smaller (or higher) quantities of all the involved burned fuels. For scenarios E, as impacts related to LSF oil appeared as the most relevant among fuels, its variations have more effects on the results. GW is the most affected impact category, with a 3.31% increase in A− and 2.96% decrease in A+, thus for 5% variation in production rate. On average, 5% variations in production rate determine 1.70% variations in all impact categories. In cases E+ and E−, GW evidences 2.54% increase and decrease respectively, with an average 1.13% variation in all impact categories.

Considering the combined effects of all these possible variations (Figure 8a), results go towards two extreme scenarios: better (A+, B−, C−, D−, E−) or worse (A−, B+, C+, D+, E+) in terms of sustainability. For 5% change in production rate of the plant and of fuel consumptions, the impact categories show an average 2.8% decrease or 3.2% increase compared to the reference values, respectively in the better or worse scenario. GW undergoes the most relevant variations: it may reach up to 6.2% increase if all parameter values are actually more critical than measured, while it may be characterized by 5.5% decrease in the opposite scenario. These numerical outcomes are useful to prove that, despite the possible uncertainty due to the primary data collection in plant, the evidence provided in Section 4.1 still remains sound and reliable. Indeed, even taking into consideration significant variations in the original data, the derived impact values do not show particular alterations.



(**a**) (**b**)

Figure 8. Impact variations: (**a**) combined effect of all parameter variations; (**b**) impact variations considering a single provider only for bitumen and diesel, respectively the closer and the farther.

Further, transportation distance was also numerically tested. In particular, for components with alternative providers, the effect of transportation distance maximization (and minimization) has been studied. As underlined in Section 3, bitumen and diesel are generally alternatively provided by two different production plants located in two different areas of Sicily (Figure 4, Table 2). In previous calculation, thus, the average distance was taken into consideration. In order to quantify possible effects of distance variations (even for these two components only), Figure 8b provides the variations for the various impact categories when both components are bought from the farther or the closer plant. AD results as the most influenced impact, with a positive or negative 1.35% change in the two cases. Although it seems that, compared to reference impacts of Figure 6, these variations are not relevant, it should be considered that passing from the farthest to the closest providers determines about 3% reduction in AD, confirming the advantages for limiting transportation distances.

4.3. Scenario Analysis: Effects of Changes in the Energy Production

In the evaluation of LCA of HMA mixture production in a plant, another crucial aspect is represented by the source of energy used for plant general operation. The considered plant is electrically powered using a diesel-based generating set. This choice derives from the specific configuration of the plant and some difficulties occurred in the grid connection to the factory. Considering the aim of the paper, in order to quantify possible improvements in impacts due to asphalt mixture production, the environmental impacts of the same plant powered by two different solutions were estimated: the electricity grid and a dedicated set of photovoltaic panels. Data for unit impact assessment were derived from the Ecoinvent database, as for other secondary data previously. For quantifying the required energy (in MJ), a 30% efficiency rate for the electric generator was considered. Consequently, based on data provided in Section 3.2.3, the effective required energy for plant operation is considered, prudently, equal to 5.63 MJ. Figure 9 shows impact variations for the two alternative options compared to the actual energy supply (raw materials and fuels only), while Figure 10 reports total impact variations, including transportation.

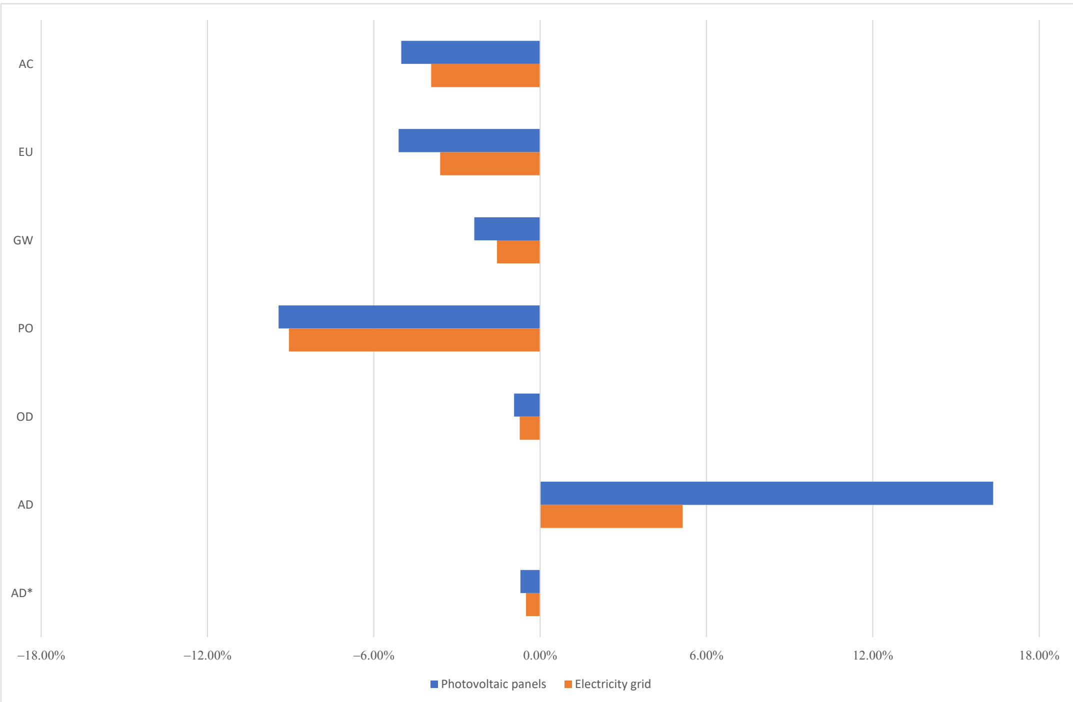


Figure 9. Variations of impact of raw materials and fuels for different energy supply technologies.

The provided results generally confirm a noticeable improvement in the sustainable performance of the selected production plant. From a global perspective, despite a not negligible increase of AD—especially for the photovoltaic panels—the two alternative ways of feeding energy assure important reductions for all the selected impact categories. PO is the most reduced category, with a peak around 8% for both solutions, followed by AC and EU (around 5% reduction for photovoltaic panels and 3% for the grid). However, in both cases, AD shows a remarkable increase, but this is substantially due to the specific reference technology. In particular, for the photovoltaic panels, AD is mainly related to the rare and precious minerals quantities required for panel production [53]. In summary, despite this aspect, the choice of a different source for electricity supply appears convenient from an environmental perspective, assuring improvements for the considered impact categories. Also taking into account the avoided impacts due to the diesel transportation (Figure 10), an increase in AD is observed as well as a higher decrease of the other impact categories. This result further confirms the improvement achievable by substituting electricity from the diesel-based generating set with electricity from the grid or from photovoltaic.

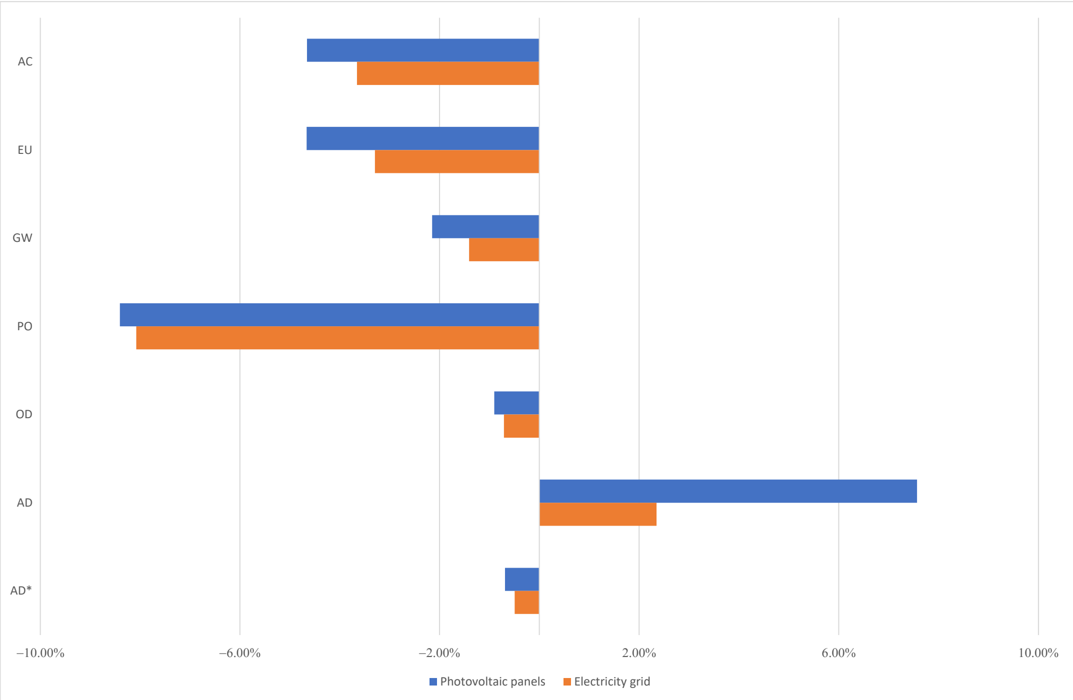


Figure 10. Variations of total impacts for different energy supply technologies.

4.4. Scenario Analysis: Effects of Changes in the Mixing Temperature

As underlined in Section 4.1, fuels have a huge impact on the sustainability of the asphalt mixture. In particular, LSF oil appeared to be the most affecting fuel (Figures 5 and 6). As already discussed, LSF oil is used in the plant for actually preparing aggregates—drying and heating, for allowing correct mixing with bitumen and, according to traditional technology of HMA, the mixture temperature is around 160 ÷ 170 °C. In recent years, alternative technologies have been studied with the aim of assuring equal adequate performance to the final product, without reaching similar temperatures [18,35,49]. Among these, the so-called warm technique (for producing WMA) guarantees mechanical levels in the field comparable with those of HMA, with significantly lower production temperature, around 130 ÷ 140 °C. From a sustainability perspective, such a solution may provide significant benefits, determining potential reduction in terms of impacts and emissions in plant and construction sites [15,28,48], even if the characteristics of the considered additive should be properly evaluated. For a preliminary quantification of the related improvements, according to the general approach of the paper, the impact values for all the considered categories were estimated, considering the production of a WMA, for comparison purposes with those obtained for the HMA. Calculation was based on the available data, considering just hypothetically the possibility of obtaining a DU of asphalt product using WMA technology, without variations in the mix-design. Such a hypothesis allowed useful simplifications in the calculation process and, further, may be accepted since influence of slight variations in the component proportions or the introduction of few quantities of additives do not strongly influence the final results. However, this is no longer valid when the additive percentages are high, and the additive nature and production processes determine such high direct impacts so as to offset the possible advantages assured by the lower production temperature. Regarding the energy consumption when using WMA technology, technical studies always agree on its reduction, although providing slightly different values [49]. Nevertheless, based on this literature, it is reasonable to consider as acceptable a 30% reduction in the energy needs for production of WMA compared to HMA, for a 20 °C reduction in the mixing temperature. This reduction has been applied to the LFS oil and LPG mass quantities provided in Section 3.2.3, passing respectively from 387.9 MJ and 25.9 MJ for HMA to 271.5 MJ and 18.1 MJ for WMA. The variations in the various impact categories due to the WMA technology compared to the original HMA are provided in Figure 11.

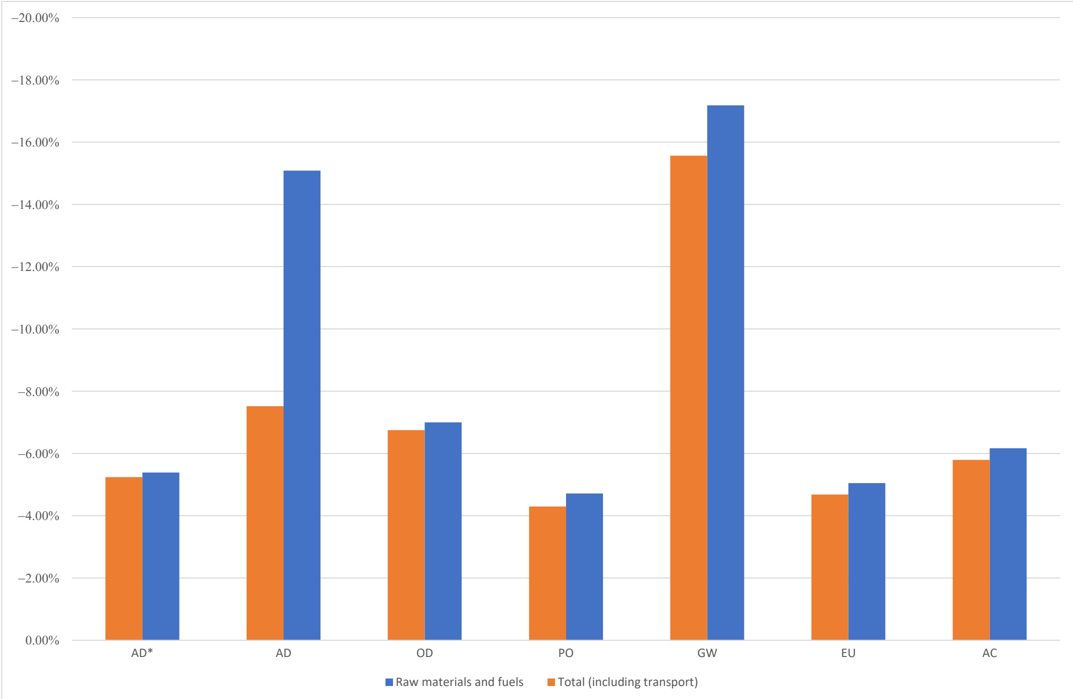


Figure 11. Impact variations (without and with transport) for WMA technology.

As expected, the effects of changes in the mixture temperature are relevant in practice. Relying on the previous hypotheses, considering 20 °C reduction in the mixing temperature, may assure saving 2.5 kg of LFS oil and 0.19 kg of LPG for each DU of asphalt mixture, with remarkable benefits on impact values. Considering the total values (including transport impacts), all the impact categories show more than 5% reduction, with a −15% peak for GW. From the analysis of the figure, it is evident how a similar technology should be boosted, for assuring more sustainable products for the pavement industry. Obviously, as already stated, similar considerations are not relevant if final performance in the field is excluded from the assessment. It would be not acceptable, in practical context, to compare two different solutions characterized by significantly different performance levels in exercise. In this regard, in a more exhaustive LCA of asphalt pavements for a more proper assessment of the numerical differences in impact values among different solutions, specific reference to the actual mix-design and the effective mechanical final responses must be included.

5. Conclusions

In this paper, the LCA of 1 ton of asphalt mixture was investigated, from raw materials extraction to product manufacturing. In particular, based on a detailed phase of primary data collection directly in an Italian production plant, all the inputs and outputs of traditional HMA production for road pavement construction were determined and analyzed. According to the LCA framework, for each productive phase, the data collection was performed within the inventory phase to identify and quantify material and fuel flows, determining their consumption for the DU, together with direct and indirect emissions. Then, all the available data, integrated with secondary reliable data, were used for estimating the environmental impacts of the examined declared unit.

The analysis evidenced the contribution of each component of the product and of fuels on the selected environmental impact categories, for understanding the most crucial phases of the process and the least sustainable materials. Numerical results showed a large influence of bitumen and fuels, in particular LFS oil, on every impact category, evidencing the possible benefits of boosting the development of alternative productive technologies, such as WMA and recycled mixtures. Indeed, similar alternatives require less fuel for drying and heating aggregates and may be equally adequate from a performance perspective in the field, with noticeable reduction of both virgin bitumen and aggregate consumption. In general, the study allowed to collect foreground data for the calculation of a HMA eco-profile and complete the LCA of the product according to the most common production procedure. The collected data and the results of this study may represent a reliable reference and numerical base for following steps of the LCA, considering all the phases of an asphalt pavement service life. LCAs concerning the overall construction process of asphalt pavements can rely on the actual values measured in the plant to provide accurate and reliable outcomes for stakeholders and decision makers in the reference geographical context/market. As preliminarily presented in this paper, the comparison of results of various scenarios may simplify the evaluation of the most convenient and sustainable solutions and approaches (also in terms of technological improvements) for driving improvement and innovation of the entire production industry. In fact, the possible benefits of alternative sources of electricity for the plant working and reduction in the mixture production temperature has been highlighted. In both cases, the considered modifications to the plant or to the product—assuring equal performance levels on field—may generally lower the impacts of the process, with significant environmental benefits, crucial for a novel sustainable approach.

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