sustainability

MDPI

Article

Assessment of Carbon Footprint for the Textile Sector in France

Jérôme Payet [1,2]

[1] CYCLECO, 18 Avenue Roger Salengro, 01500 Ambérieu en Bugey, France; jerome.payet@cycleco.eu; Tel.: +33-437-860-712

[2] SIE-ENAC-EPFL, Station 2 CH-1015 Lausanne, Switzerland

Abstract: Global warming represents a major subject on all society levels including governments, economic actors and citizens. The textile industry is often considered a polluting activity. In this project, French textile manufacturers sought to quantify the carbon footprint (CF) of sold clothes and household linen using Life Cycle Assessment in France for the purpose of reducing it to meet the constraints of Paris Agreement by 2050. First, manufacturers calculated the carbon footprint of 17 clothes and household linen products and established alternative scenarios for four production routes. Secondly, they modeled the supply of the upstream sector through different countries. Based on imports of textile products, their calculated CF for one French person reaches 442 kg of CO_2eq/year. Means of action to reduce this carbon footprint by a factor of 6 (74 kg of CO_2eq/person/year for textiles) are calculated and are the following: installing the most energy-intensive production processes in a country with a low carbon electricity mix, avoiding unsold goods, implementing eco-design approaches and enhancing the value of end-of-life products with reuse or recycling. Therefore, CF for textiles per capita is reduced to 43 kg CO_2eq/year which goes beyond the objectives of Paris Agreement and facilitates carbon neutrality in the textile sector. The first priority for reducing the French carbon footprint of clothes and household linen would be to locate textile production in countries with (i) low carbon electricity, (ii) to reduce unsold items, and (iii) to elaborate ecodesign of product including circular economy.

Keywords: textiles; clothes; apparel; household linen; carbon footprint; circular economy; recycling; life cycle assessment; LCA; Product Environmental Footprint; PEF

Citation: Payet, J. Assessment of Carbon Footprint for the Textile Sector in France. *Sustainability* **2021**, *13*, 2422. https://doi.org/10.3390/su13052422

Academic Editor: Silvia Fiore

Received: 13 January 2021
Accepted: 19 February 2021
Published: 24 February 2021

1. Introduction

The awareness of global warming is omnipresent in political strategies and it is increasing more and more in consumer choices. Despite this fact, consumption of mass market products is growing and global Greenhouse Gas (GHG) emissions continue to grow. There is an increase of 1.7% in 2017, 2.1% in 2018, and a little decrease to 0.6% in 2019 [1]. These variations led to annual emissions of more than 53 billion tons of CO_2 equivalent in 2019 [2]. On a worldwide scale, this growth seems to be unappeasable, even if European countries tend towards controlling and reducing carbon emissions. Regarding emissions mitigations, Germany is the leading country reaching 8% in 2019; whereas France has difficulty in following their example (−1% only) [3]. The outcomes are potentially serious, particularly if the predictions believe that the warming level will reach 2 °C in 2050, and exceed 4 °C in 2100. Furthermore, beyond the consideration of the water-level rise that is projected to reach more than 0.7 m [1], the drastic foreseeable consequences are already there, such as increase in climatic hazards, forest fires, etc. [4–6].

With the Paris Agreement in 2015, limiting global warming on the worldwide scale was planned to be maximum 2 °C by 2100 [6]. For this objective to be reached, the GHG emissions must be reduced on average by a factor of 6 for the next 30 years. The first strategy would require targeting the main GHG source sectors and drastically reducing them. Nevertheless, the analysis of emissions indicates that 75% of a citizen's emissions in developed countries are covered by three sectors: mobility, heating and food [7]. In that context, dividing the emissions by 6 seems difficult as a solution since nobody wants to stop these three main causes of emission. In addition, these large emission sectors can be subdivided into small sources of GHG emissions contributing to global warming. This observation leads to the main proposed solution by maintaining the same standard of living while reducing GHG emissions by a factor of 6.

The worldwide textile sector is accused of being "the second most polluting industrial sector after hydrocarbons" according to the French President [8]. However, it is known that one consumer buys on average a few kilograms of textiles each year. This general accusation is raising many questions from the manufacturers of textiles in France, among them, their impact on the environment. To address this issue, they decided to quantify the carbon impacts of the household linen and clothes industry (excluding footwear) using the Life Cycle Assessment method (ISO 14040-44). [9,10] This method, now highly regulated by ADEME (French EPA) and European Union within the framework of the Product Environmental Footprint (PEF), quantifies the environmental impact of products from the extraction of resources till their end-of-life [11,12]. For such a calculation, the challenge is to define the function that must be satisfied, the scope of the study, and the impact categories covered. For that purpose, this work studied the CF (carbon footprint) for one kilogram of the textile purchases (mix of household linen and clothes) during the year 2019 [13].

The textile sector is at the same time a first-rate economic sector, but also an industrial and retail sector with an astonishing complexity. This is due mainly to the globalization of the textile production sector, the successive offshoring of production means, and the consequences coming out of modern fashion temporality [14]. Thus, an important part of the study is describing the calculation methodology of the CF and its implementation in the textile sector in order to identify and quantify improvement solutions. The questions addressed in this study are therefore the following:

- How to account for the French CF and carbon emissions?
- What are the greenhouse gas (GHG) emissions from the production of clothes and household linen in the world and how to assess it?
- What is the environmental footprint of textiles, clothes and household linen in France?
- How much should this impact be reduced to achieve the objectives of the Paris Agreement?
- How should we act at the level of a company, a consumer, and a government to achieve these objectives for the textile sector?

2. Method and Results for the Calculation of the Carbon Footprint (CF) and Emissions for France

2.1. Distinction between Carbon Footprint and Emissions

The CF and emissions are often referred to as the "carbon" footprint and emissions. They are measured at the level of a country or of an individual. A country's CF is directly and strongly linked to purchases and consumer behavior. In each country, every consumed product (e.g., food, clothes) and every service (e.g., mobility) will generate GHG emissions during its life cycle. The sum of these emissions over a year in a specific country is called the country's CF. To calculate the CF of one person, this sum is divided by the number of inhabitants of this country. CF is composed of two components: one is the GHG emissions of a country, commonly called carbon 'emission' and described in the national inventory of carbon emissions; and a second one is related to the emissions of products imported from a country. The sum of the two components, i.e., imported GHG emissions and the emissions from the national inventory form the CF [8,9].

2.2. Carbon Emissions in France

The national inventory of carbon emissions includes direct emissions from households (housing, vehicles) and emissions from domestic production which comprises the emissions linked to exports. These emissions are expressed in quantity of CO_2 equivalent which corresponds to the sum of each GHG contribution to global warming. The French law on energy transition for green growth (LTECV) and Paris Agreement require a commitment from the French government for the reduction of carbon emissions. It aims to decrease the GHG emissions from 1990 (551 million tons of CO_2) by 40% in 2030 and by 75% in 2050, i.e., 137 million tons of CO_2eq. Figure 1 shows the change of the emissions in the industrial sector in France between 1990 and 2015 [15].

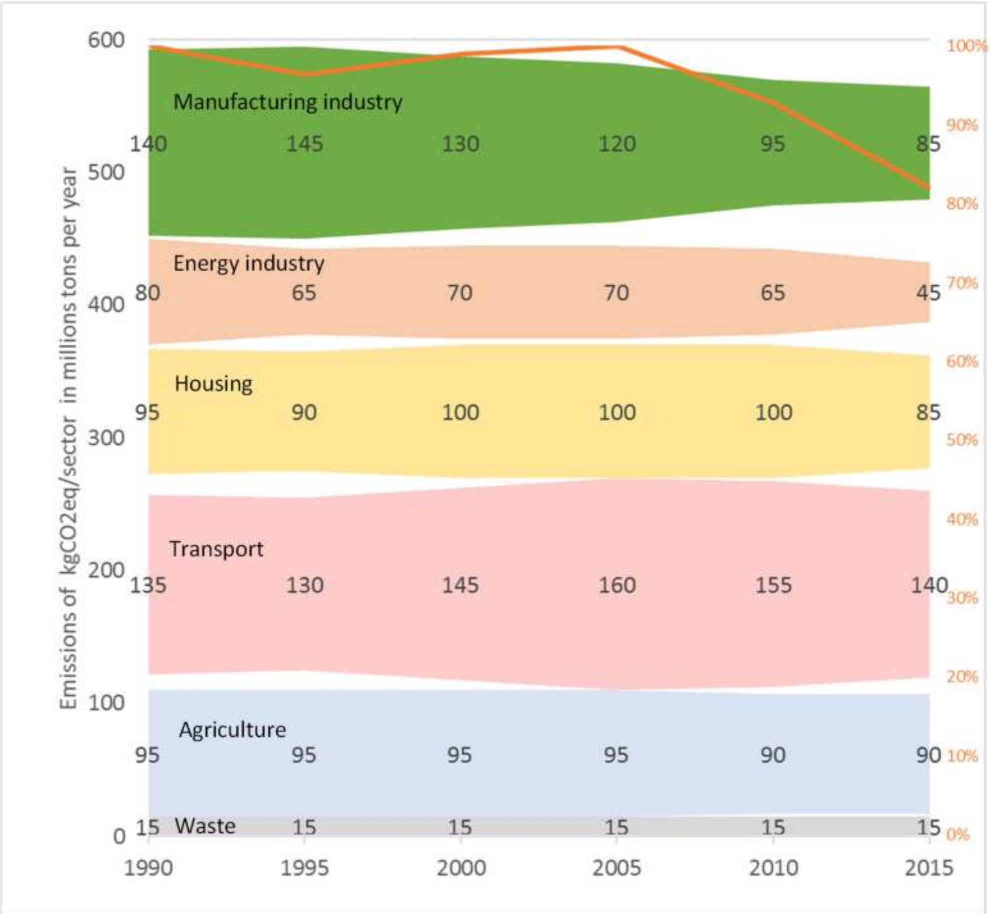

Figure 1. Evolution of the quantity of GHG emissions in France by sector and total percentage between 1990 and 2015. The red curve with Y right axis indicates the percent of decrease of GHG by 42% between 1995 and 2015 while emissions of transport increase by 8% during the same time period.

Figure 1 above shows GHG emissions in France by economic activity sector over a period of 25 years. The curve in red shows the change in the percentage of emissions compared to 1990 emissions. The curve is rather stable for 15 years, then in 2005, it follows a decrease of 19% to reach a total quantity of emissions of 446 million tons of CO_2eq in 2015. The emissions specified by sector indicate how much each sector has contributed the most in this decrease. Carbon emissions from transport increase over the time. Those from waste and agriculture remain stable. However, the emissions from housing (residential and tertiary) sector drop by a value of 10%. This can be explained by the decrease in heating needs due to the rising average temperature in France (from 11.8 °C to 13.4 °C). The industrial energy GHG emissions dropped by more than 40% even though it only represented 15% of the total emissions in 1990. The manufacturing industry represents the quarter of all the GHG emissions until 2005, it displays a noticeable diminution in GHG emissions that reaches more than 40% in 2015.

This sharp reduction should be put into perspective. Indeed, the inventory of national GHG emissions takes into account emissions linked to national production but not to imports; therefore, industrial offshoring led to a drop in national emissions [9,10]. Figure 2 puts into perspective the GHG emissions over 25 years (French Ministry of the Environment) and the evolution of the French trade balance.

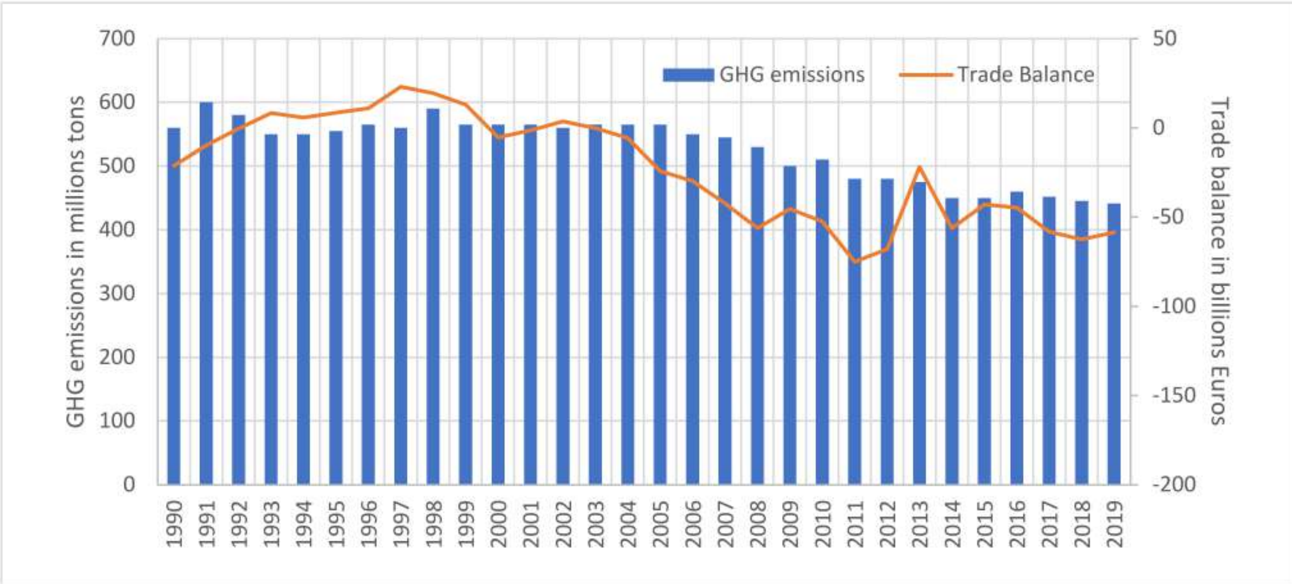

Figure 2. Comparative evolution of GHG emissions in France and the French trade balance over the period 1990–2015.

Figure 2 displays two perspectives: the variation of GHG emissions in France and the variation of French trade balance. From 1990 to 2015, trade balance and GHG emissions were stable. Between 2005 and 2015, the drop in GHG emissions of around 100 million tons of CO_2 equivalent is the result of a progressive deficit in the trade balance which reaches over 50 billion in 2019. While Figure 1 showed a drop in emissions mainly due to the sector's manufacturing industry, Figure 2 shows that this does not come from an improvement in the manufacturing performance but from a gradual deindustrialization of the French economy. This is coherent with the reduction of emissions in the "Energy Industry" sector (due to the decrease of energy consumption of the manufacturing industry) and the increase of emissions of the transportation (partly due to the increase of the road and air freight for importing goods).

Focusing on the diminution of textile manufacturing, we can assume a transfer of production to other countries (importation, subcontracting, or dislocation which may lead to a transfer of carbon emissions).

2.3. Presentation of the French Carbon Footprint (CF)

The CF is scaled to a specific country or its citizens by taking the CF value and dividing it by the population number. In France, the CF is calculated yearly by the Ministry of the Environment. Unlike the national carbon emissions inventory, the country's CF does not count exports but it takes into account the impact associated with imports. According to the data published by the Ministry of the Environment, France's CF for 2018 is 749 million tons of CO_2 and it is split between 57% of emissions linked to imports and 43% of internal emissions (inside the country) [15]. Figure 3 shows the breakdown of the French CF by economic sector.

Figure 3 shows that the French CF (749 million tons of CO_2eq) is higher than carbon emissions (445 million tons of CO_2eq). This difference is attributed to the share of imports which severely affects the CF. Energy is the main contributor to the French footprint and is obviously largely dominated by imports of oil and gas. After that, the industrial production sector is very important and is also largely dominated by imports, which are mainly imports of transformed products manufactured abroad. The only sectors where imports are not dominant are transport and housing; both are strongly influenced by direct household emissions and transportation (goods and persons) occurring in the country.

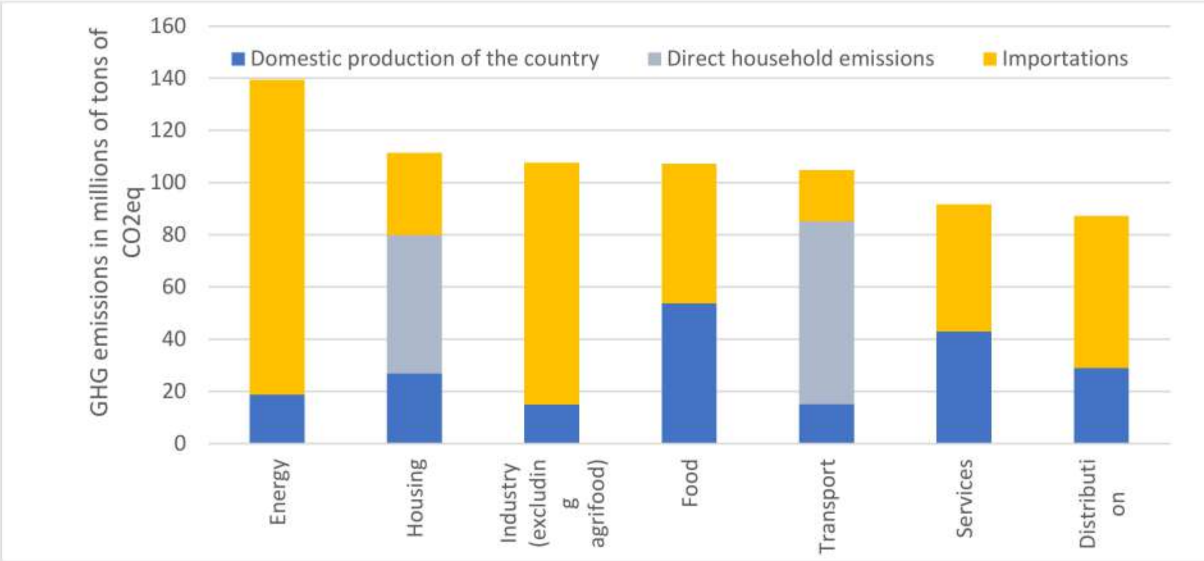

Figure 3. Contribution of the various economic sectors to the French CF (carbon footprint) in 2018.

Figure 4 details the contribution of different industries (excluding the food industry) to the CF.

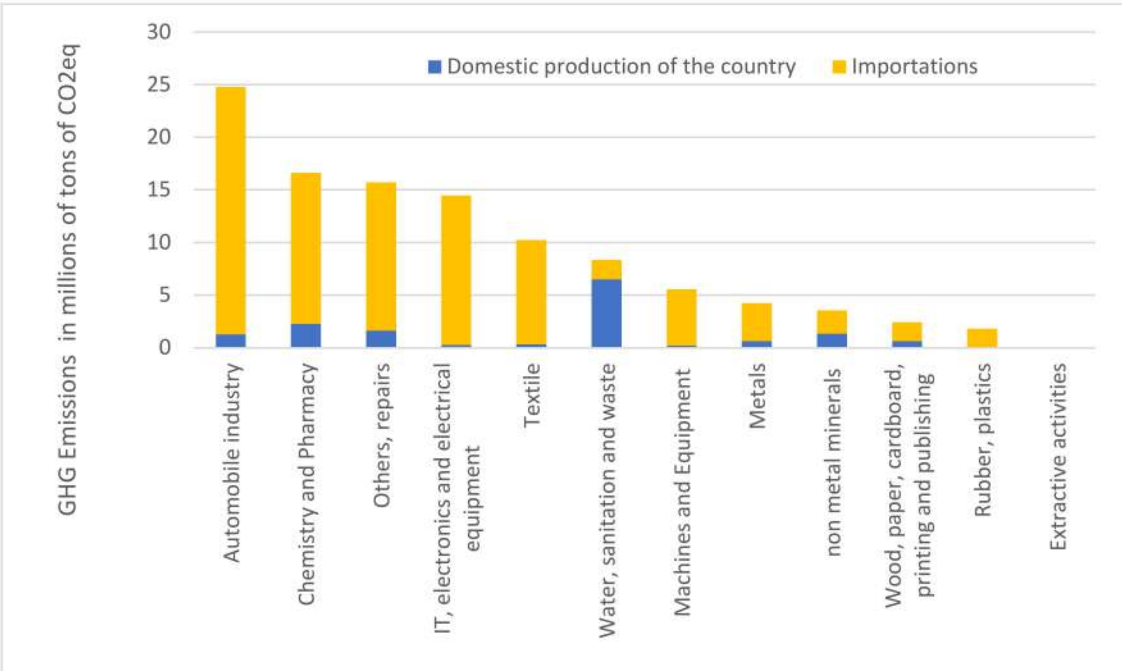

Figure 4. Details on the contribution of the French industry in the national CF.

All industrial sectors in France excluding water and sanitation are largely dominated by imports. The automotive industry sector is the largest contributor with nearly 25 million tons of GHG (from which 95% originate from outside the borders). According to the official data, the textile sector represents 10% of the CF from the French industry with 10.2 million tons of GHG emitted, from which only 3% are linked to the industrial activity in France.

Data from the Ministry of the Environment show that the French environmental footprint is stagnating [16,17]. Their estimations claim that in 1995, it was 10.5 tons of CO_2eq/inhabitant, 11.8 tons of CO_2eq/inhabitant in 2005 and 11 tons of CO_2eq/inhabitant in 2015 [15]. However, the High Council on Climate (HCC report in October 6, 2020) estimated that in the past 25 years, "imported" emissions increased by 78% [18]. The stagnation of the environmental footprint is questionable in view of the strong deindustrialization of the French economy. Due to regulatory constraints, France developed for half a century less impactful technological production. It benefits from one of the least carbon-intensive electricity generation on the planet. Additionally, the national production reduces the impact of transport of merchandise. At the same time, the French economy was growing for a decade, and it is therefore unexpected to keep a constant environmental footprint with a substantial decrease in national production mainly due to the reduction of manufacturing industry [19].

This could be explained by the calculation method (input/output calculation). Environmental data such as carbon emission is well documented in Europe; however, there is small documentation in the rest of the world. The calculations of the CF for widely imported products is very dependent on assumptions and extrapolations which can lead to largely underestimated impacts.

The difficult balance between the support to the French industry, the control of CO_2eq emissions, and the perilous calculations of the imported GHG emissions of the CF are studied in the following section with a focus on the industrial case and the distribution of textile articles in France. This part relies on Life Cycle Assessment method and it is less dependent on statistical data gaps of the input/output approach used by the Ministry of the Environment in order to calculate the CF of imports.

2.4. Calculations of the Environmental Footprint of Mass Market Textile Products in France

The life cycle of a textile product can commonly be distributed over several continents and many countries, and it can involve many complex production processes over which only companies have the control. Alternatively, the textile sector has undergone very strong globalization for almost 40 years and nevertheless represents an important economical market. Thereby, the calculation of CF for textile products is more difficult compared to other daily consumer products (except electronic products which present similar complexity) [20]. Two steps are followed to assess the environmental footprint of consumer textile products in France: First, the calculation of the quantities processed in different countries of the world on the basis of national and international statistical data; second, the calculation of the average footprint of the main processing steps for 1 kg textile product based on the information collected from textile manufacturers.

2.4.1. Evaluation of Quantities Related to Textiles Used for the Consumer Market in France

The consumer textile products studied below are textile clothes and household linen, (focusing primarily on data for 2019). Footwear is excluded from the scope of this study.

Market data are delivered by Refashion (previously ecoTLC), a French eco-organization that produces annual marketing statistics on textiles. In 2019, it recorded 548,430 tons of textile items in the market, including 427,512 tons of clothes and 120,918 tons of household linen sold to individuals in France. Those items sold are counted by value, by piece and by mass. The analysis of the quantities marketed in France and processed worldwide is based on the total mass of items sold.

One of the difficulties of the study is the estimation of the quantities of textiles transformed in each country from the first stages of textile production until they reach the consumer market in France [21]. In this context, two data sources are necessary beyond the data produced by Refashion. One part of the data concerns the French trades (importation and exportation) of the textile products; those originate from the customs administration. Additionally, another part of the data is those related to French production which is accessible in the European Prodcom database [22]. This information is compiled annually by two French organizations: the IFM (Institut Français de la Mode) and the UIT (Union des Industries Textiles) [21,22]. The data produced by these organizations is commonly presented in value or quantity, and includes all imports and exports supplying (or supplied by) the French market. Figure 5 presents the quantities and aggregates the countries according to the main market shared used by French manufacturers. Thus, beyond the French production, the selected import/export zones include Euromed zone (which includes the European countries plus Tunisia and Morocco), Turkey, Bangladesh, China, and the other countries that are gathered under "RoW" (Rest of the World) category. The data presented below are adapted from the main data sources [22–25].

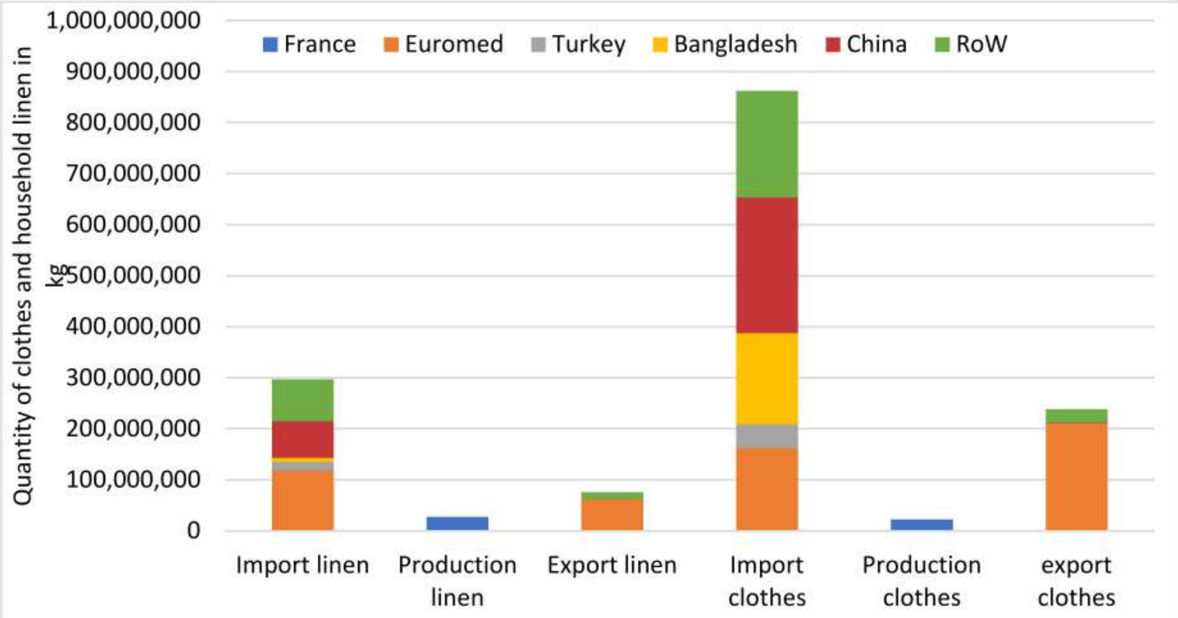

Figure 5. Assessment of French imports, exports and production of household linen and clothes in 2019.

The imports/exports registered by the administration are related to finished products which are distributed in France or exported from France. This represents 863,000 tons of clothes and 297,000 tons of household linen. As for the exports, they represent 238,000 tons of clothes and 75,000 tons of household linen, and they take place largely in the Euromed zone. French production is concerned about products having at least the last processing step (making) taking place in France; it represents 2.5% of clothes textiles and 8.4% of household linen. Import and export data show the importance of intra-community trade which largely dominates the Euromed category. Beyond the imports within a single community, China and Bangladesh together represent 52% of clothing items and 27% of household linen imports.

The evaluation of the produced quantities, importations and exportations estimate the quantity of textile articles associated to the French market. The calculation of importation added to the French production minus exportation indicates the total quantity available for the French market (consumers and businesses). The quantities of clothes and household linen are respectively 646,375 and 249,024 tons in 2019. However, not all these quantities have been purchased by consumers. Table 1 presents the fate data of the various items in percentage by mass for the French market for the year 2019.

Products placed on the market (French importation and production) are recorded after subtracting the number of products out of private sale, the ones intended for the professional market and image items. All remaining items are considered necessary to supply the French consumer market. Some of the items remain not sold, either because they are defective or because no one buys them in the stores [21,23]. Figure 6 presents the fate of textile products meant to be sold in France [Detailed data are available as Supplementary Materials Table S1a–d].

Table 1. Distribution of articles by their intended fate in the French market. The quantities are expressed in tons, the breakdowns in percent (sources of sales data in France: Refashion; import/export, IFM ((Institut Français de la Mode) and UIT (Union des Industries Textiles); breakdown of the fate of articles: IFM and manufacturers) [21,23].

	Clothes	Household Linen
Quantities sold	427,512	120,918
French production	22,237	27,355
Importation	862,636	297,150
Exportation	238,498	75,481
Sale of textiles to individuals in France	66.14%	48.56%
Part of professional products and image (out of private sale)	10.00%	30.00%
Packaging	7.00%	7.00%
Unsold (in the strict meaning)	4.00%	2.00%
Defective recyclable products	0.55%	0.55%
Defective nonrecyclable products	0.25%	0.25%
Unsold goods in the broad sense (EcoTLC not taken into account)	16.06%	13.64%
Total quantity available for the French market	646,375	249,024
Quantity available for sale in France outside companies	581,738	174,317

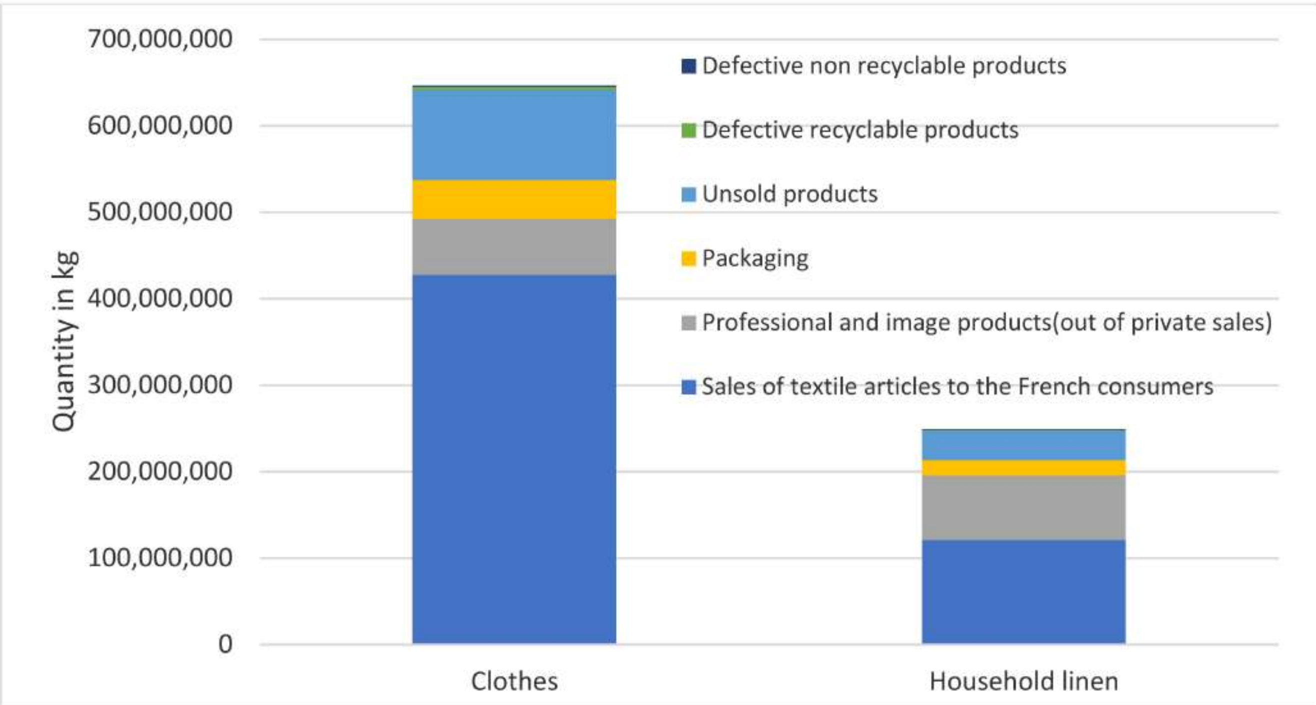

Figure 6. The fate of textile products in the French market for clothes and household linen.

Considering the French population with 66,990 million inhabitants in 2019, it is possible to calculate the mass of textile articles purchased by each consumer which is on average 8.19 kg (6.38 kg of clothes and 1.81 kg of household linen). However, for the consumption of 8.19 kg of textile, 11.29 kg of items (8.68 kg of clothes and 2.60 kg of household linen) is produced.

According to Figure 7, 50% of the clothes are imported from China and Bangladesh (25% for household linen), and 18% from the Euromed zone (36% for household linen). However, the importing country is the last country registered in the production chain.

Assuming that the whole production takes place in the last importing country can lead to a significant bias in the repartition of the activities in the upstream chain. Statistical data are not available for all countries and does not include the same details as the European one. In order to limit this bias, we have estimated the distribution of the upstream production based on the export shares of the 10 main world exporting countries in clothing products and in non-clothing textile articles (assimilated to household textiles). Data are from WTO (World Trade Organization) [26].

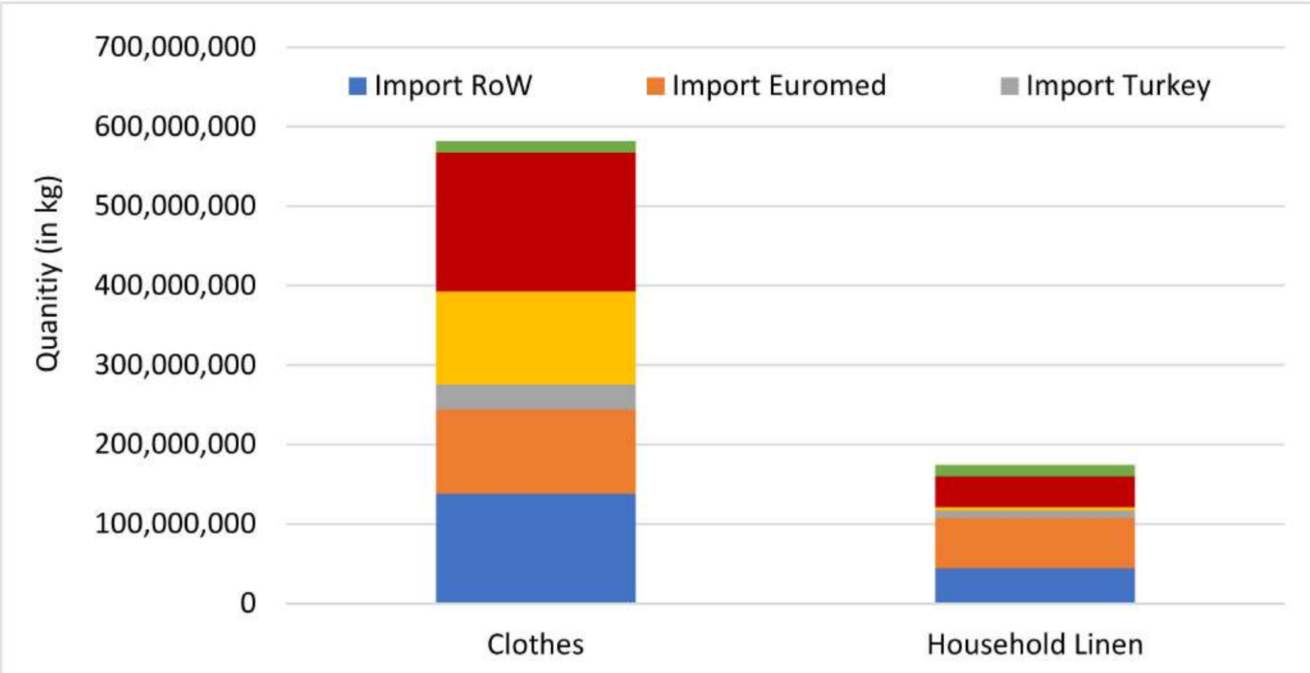

Figure 7. Distribution of textile articles intended for the French market expressed in quantity (kg) according to the different importing countries including French production.

WTO export data are expressed in dollars. French import and export data are expressed in mass for calculating the CF. Conversion from values to quantities is achieved assuming a certain quantity transformed per dollar of exportation. This conversion factor depends on the textile productivity cost in the country concerned. Relative productivity values (i.e., the amount of textile transformed per dollar spent) are calculated for the major textile exporting countries in the world.

Productivity data presented in Figure 8 are extrapolated from two studies of the textile sector. In this case, one part is related to a comparative study of production costs for the textile sector produced by the UIT [23] and the other part is based on labor costs by country [27,28]. Productivity values allow the conversions of the exported value of textile, clothes and household linen (Figure 9, left part) to exported quantities (Figure 9, right part).

When production takes place in low-cost countries, the gap between value and quantity becomes very important. As an example, a comparison of exports in dollar between China and Europe shows similar values for both clothes and household linen but this difference is greater than a factor of 3 for the quantities exported between Europe and China. Similarly, the relative importance of Bangladesh's production is growing by 40% when quantities are considered instead of values. This point is of particular importance in our study since the carbon emissions depends on quantity manufactured and not on the value.

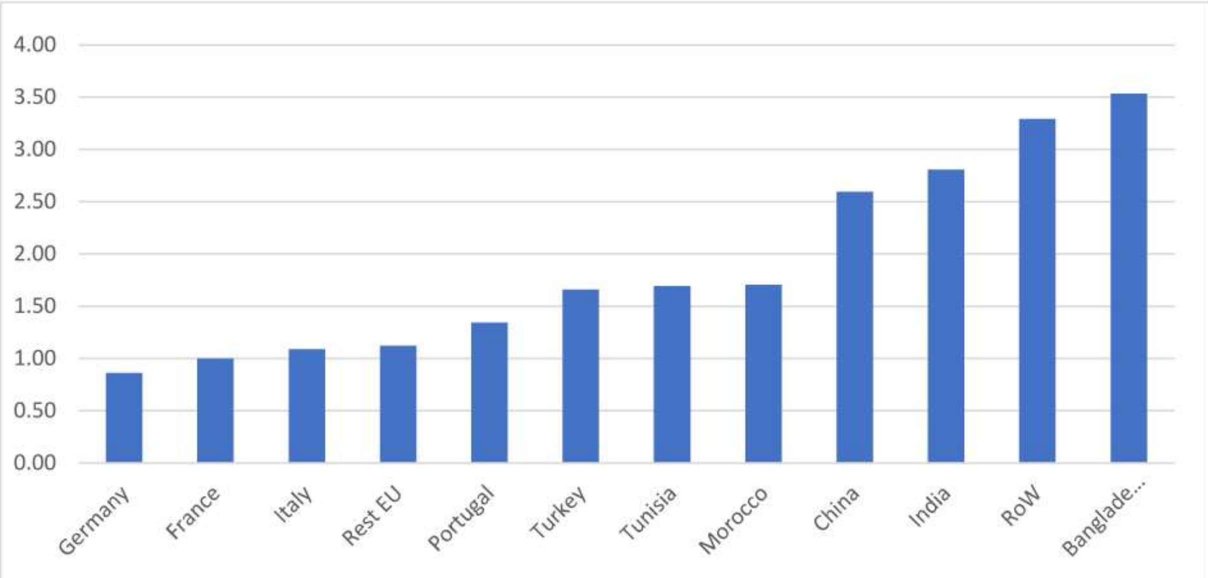

Figure 8. Comparison of productivity values for 12 countries. The benchmark of 1 is given for productivity in France. The higher the productivity value, the greater the amount of textile produced per dollar.

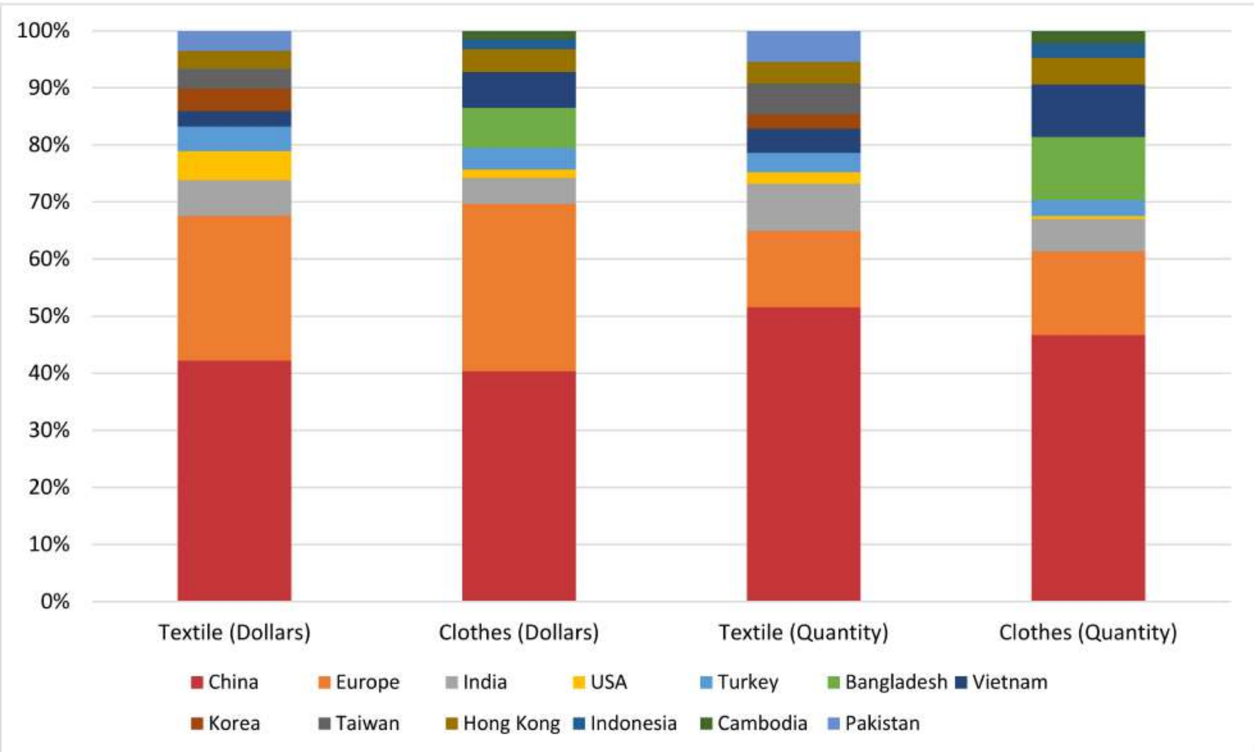

Figure 9. Relative shares of world textile exports of the 10 main exporting countries in value and in mass.

In order to be able to establish a link between the industrial production system and the international and national statistical data on exports/imports, it is necessary to describe the upstream shares of the production between countries. For this purpose, the three main stages of textile transformation commonly used in the national statistics are considered: transformation of fibers and yarns, transformation of woven and knitted fabrics, and the stage of preparation and distribution. The last stage is reported in French import statistics. The distribution key for the main exporting countries presented (Figure 9) is used to establish the relative part of different countries in the two successive upstream stages. This distribution key is used in two successive calculation matrices to estimate the quantities processed in the main production areas of the study during the two upstream stages. The first calculation matrix estimates the quantity of fabrics and tissues processed in different countries through the imported quantities of clothes in France. The second matrix estimates the quantities of fiber and yarns transformed in different countries by considering the results of transformation of woven and knitted fabrics. This assessment corresponds to the best proxy of the actual textile exchanges between countries based on available data. Those two matrices are applied separately for clothes and for household linen [Detailed data are available as Supplementary Materials Table S2]. The flows indicating the exports to different countries and the distribution of final imports of textile products in France are presented in Figures 10 and 11 for clothes and household linen [29].

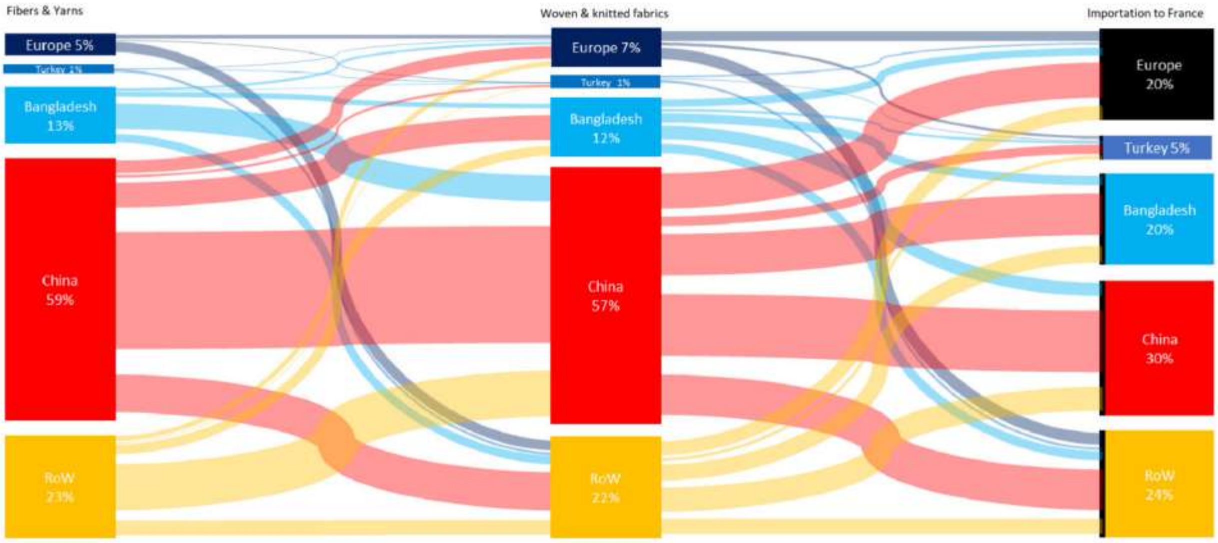

Figure 10. Modeling of the world clothes market from the textile export rates of 10 main world exporting countries and Asian export modeling of the stages from Fibers & Yarns to Fabrics & Knits. The zones and countries represented are Europe, Turkey, Bangladesh, China, and rest of the world countries (RoW). The model is simplified in order to visualize the three main textile stages: Fibers & Yarns, followed by Fabrics & Knits then Distribution in France. The values presented correspond to the estimated distribution of production for each stage of processing and distribution of clothes [29].

Figure 12 expresses the results in quantity of clothes and household linen processed in the concerned countries.

The application of the two successive matrices shows that the relative weight of the Euromed zone is becoming smaller and smaller when modeling the upstream value chain. At the same time, the share of the Asian zone becomes more important. The same calculation is made to estimate the relative importance of the countries in the upstream household linen production chain.

Figure 13 presents the results expressed in main production countries and the quantity of clothes and household linen processed to feed the French market.

The relative weight of the Euromed part is decreasing, the Asian part is growing, and rest of the world countries' weight remains stable. The assumptions made for modeling the upstream distribution allow a realistic approximation of the impacts in line with the export markets observed in Asia and in the world. As soon as processed quantities can be estimated, it becomes possible to calculate the environmental impact of the entire textile industry required to supply the French market sales to consumers.

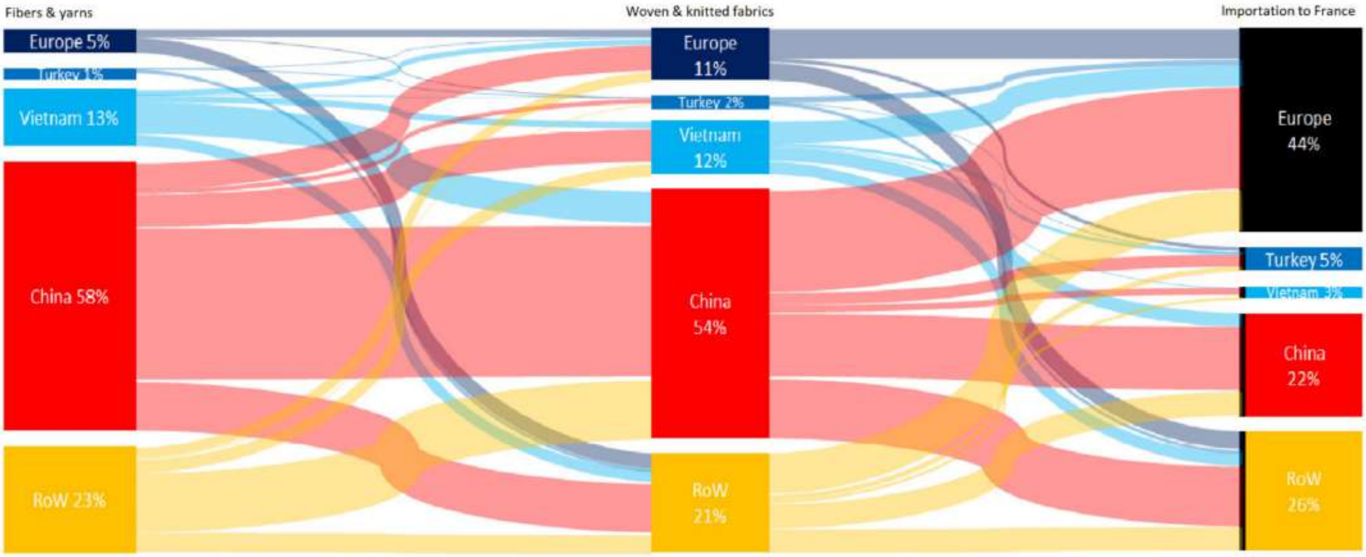

Figure 11. Modeling of the world household linen market from the textile export rates of 10 main world exporting countries and Asian export modeling of the stages from Fibers & Yarns to Fabrics & Knits. The zones and countries represented are Europe, Turkey, Vietnam, China, and rest of the world countries (RoW). The model is simplified in order to visualize the three main textile stages: Fibers & Yarns, followed by Fabrics & Knits then Distribution in France. The values presented correspond to the estimated distribution of production for each stage of processing and distribution of household linen [29].

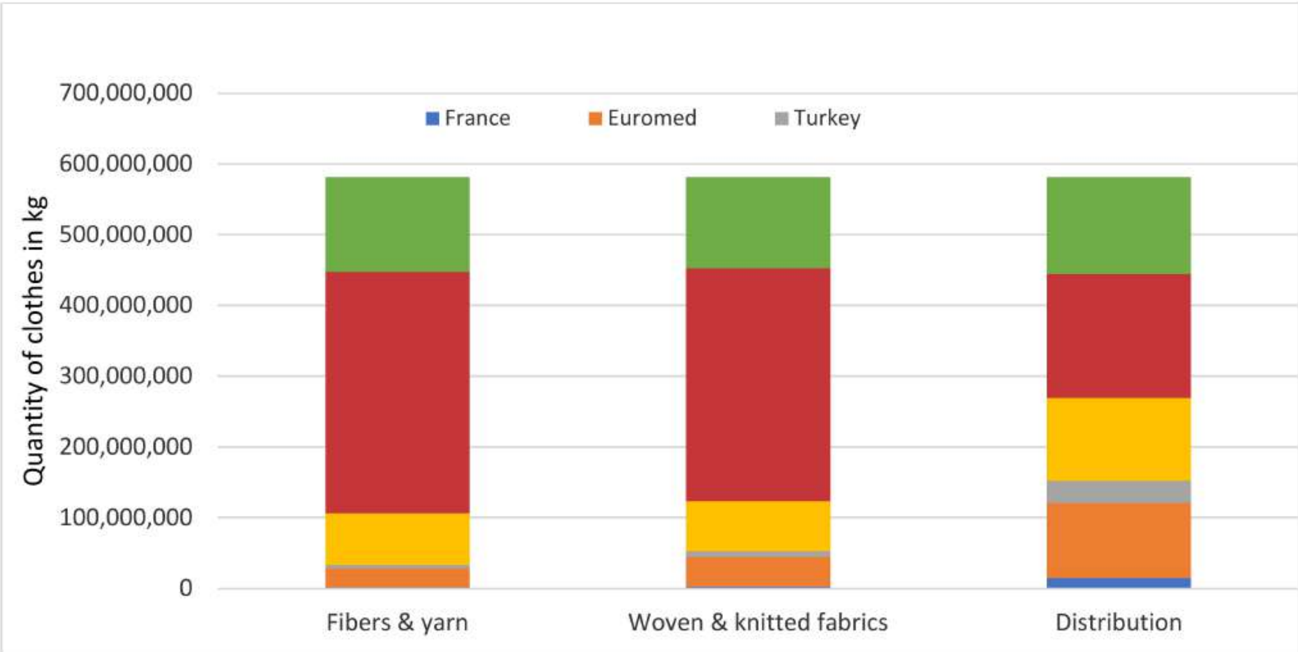

Figure 12. Relative shares of the various producing countries in the main stages of transformation of clothes sold in France in quantity. (Note: The quantities considered in each of the stages are the final quantities of clothes produced. The losses during the transformation steps are taken into account directly in the processes and do not interfere in the statistical calculation).

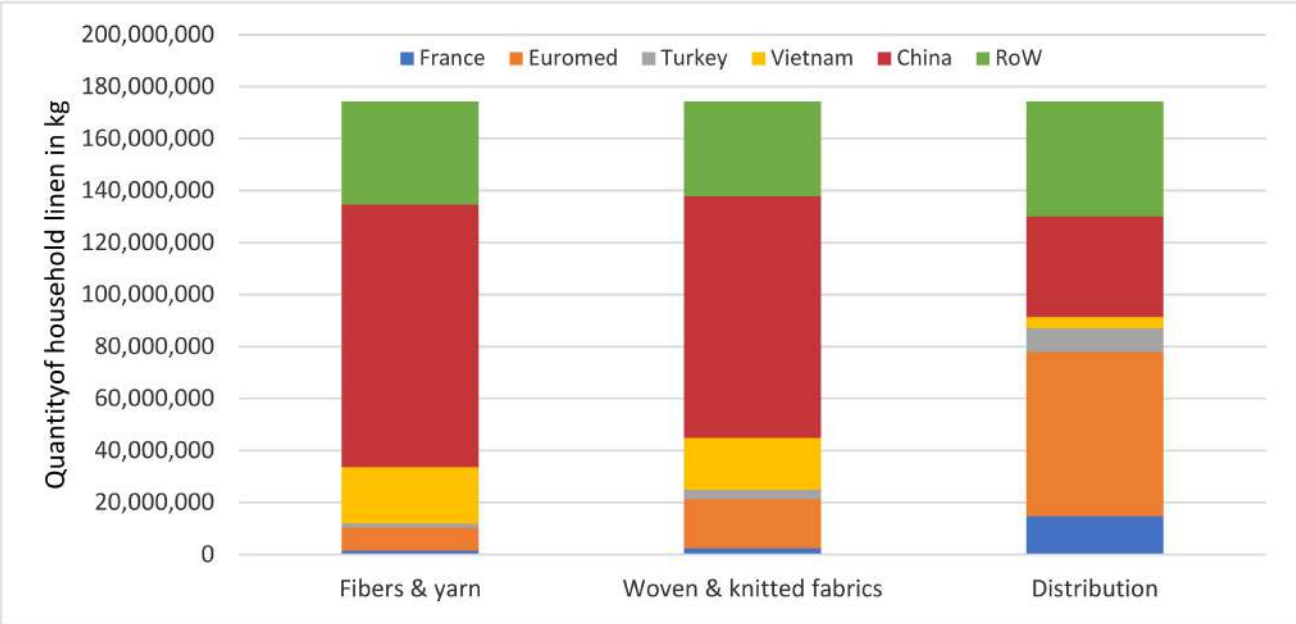

Figure 13. Relative share of various producing countries at the main stages of transformation of household linen sold in France in quantity. (Note: The quantities considered in each of the stages are the final quantities of clothes produced. The losses during the transformation steps are taken into account directly in the processes and do not interfere in the statistical calculation).

2.4.2. Calculation of Carbon Footprint of Textiles for the Consumer Market in France

One of the challenges of this calculation is the reduction of any possible bias in the quantification of the CF in the textile industry. Experience shows that the studies of textile transformation processes typically underestimate the number of processes required for textile transformation. To avoid this pitfall, an in-depth work is carried out with 20 French companies in order to model 17 textile products with a detailed description of production, use and end-of-life stage [Detailed data are available as Supplementary Materials Table S3a,b]. All the information on the stages of spinning, weaving/knitting, finishing, transport and use of those textile products were taken from manufacturers who described them in detail. Those products reflect the diversity of the market, and are divided between clothes: pants, shirt, T-shirt, swimsuit, blouse, skirt, shorts, jacket, and coat; and household linen: tablecloths and curtains. For each of the items, four production routes are modeled: France, Euromed, Turkey and China.

The 68 models (17 products and 4 production routes) were carried out using Life Cycle Assessment method (LCA). Product modeling has been done for each textile transformation process. After modeling, the processes are grouped so as to correspond to fibers, transformation and preparation and distribution. For each of these major stages, an average carbon impact per kg of processed textile is calculated and covers the 17 studied products. Table 2 presents the results for the different production routes [30].

The impacts mainly take place during the processing stage of knits and fabrics. The use phase is taken into account on the basis of the assumptions proposed by ADEME for environmental footprint, and they are located in France similarly to the end-of-life stage.

Table 2 values are reported in Figure 14 and used for the calculation of CF of textile products.

Table 2. Comparison of CF for the main stages of transformation of textile articles (clothes and household linen). Values refer to $kgCO_2eq/kg$ of textile articles.

Country	Impact Fibers	Impact Trans-formation	Impact Preparation & Distribution	Impact Utilization in France	Impact End-of-Life Stage	Total
France	7.10	10.63	0.40	2.44	0.34	20.90
Euromed	7.29	24.96	0.49	2.44	0.23	35.42
Turkey	7.56	25.14	0.82	2.44	0.24	36.21
China	7.64	32.08	1.09	2.44	0.18	43.43
RoW	7.56	25.14	0.82	2.44	0.24	36.21

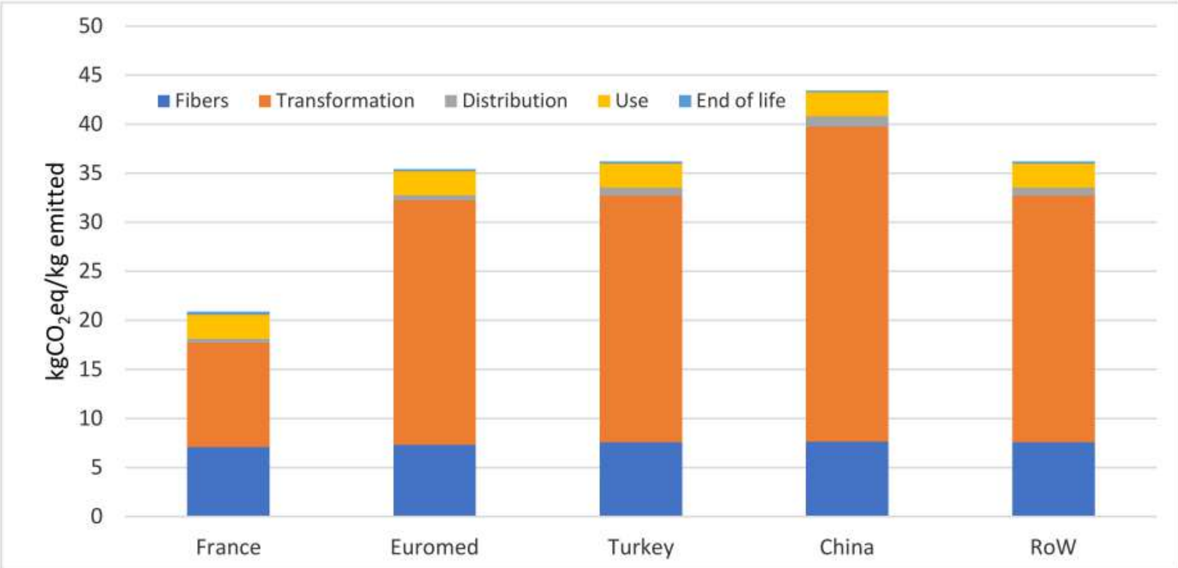

Figure 14. Comparison of GHG emissions per kg of textile and per processing step according to the production routes in $kgCO_2$ for 1 kg of processed textile. For each country, the sum of the processing step represents the CF of 1 kg of textile fully processed in the country and sold in France (Note: The use and the end-of-life takes place in France).

From this data, it is possible to calculate the GHG emissions of the entire textile industry. Figure 14 shows how much textile is processed, taking into account the country and the processing stages of clothes and household linen. The end-of-life of the product has little influence on the results.

Multiplying the quantities of textiles with the corresponding carbon emissions gives CF for the entire production of clothes and household linen that had to be produced to supply the French distribution sector. Figure 15 displays the results.

All textiles produced for the French market and GHG emissions are respectively 22.87 million tons of CO_2eq for clothes and 6.75 million tons of CO_2eq for household linen. From the total of these emissions (29,621,308 tons), the textile production in France emits 83,663 tons of CO_2eq while emissions during use phase and end-of-life (1,415,130 tons) also takes place in France and are included in the carbon footprint.

Considering the French population in 2019 which is 66.990 million inhabitants, it is possible to quantify the average textile CF of a French citizen.

Figure 16 presents the current state of the textile industry at the center of each series for clothes and household linen, and for total textile items. Table 3 presents the detailed results.

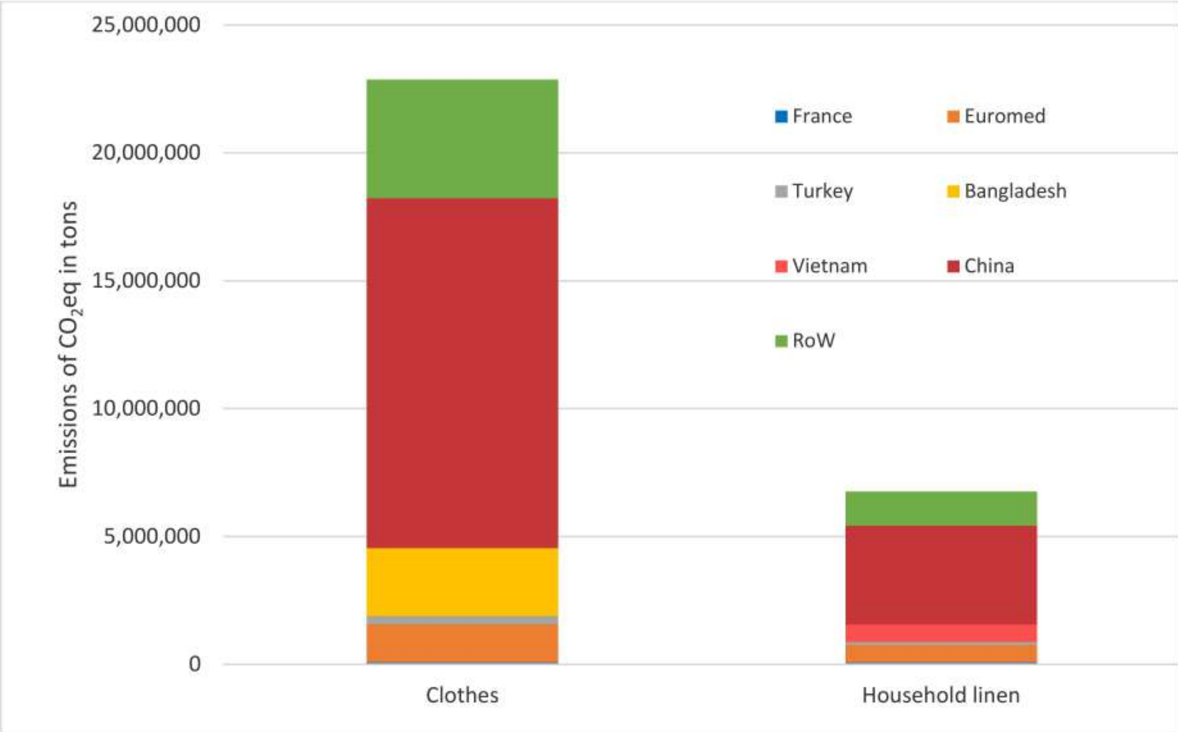

Figure 15. Carbon footprint of the textile (clothes and household linen) sold to consumers in France in 2019.

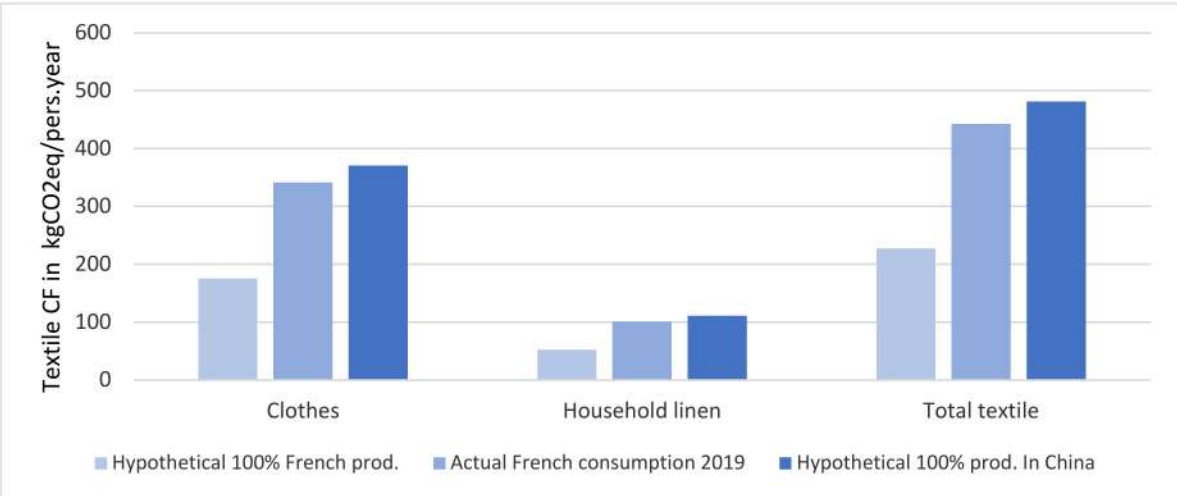

Figure 16. Comparison of the annual CFs for French mass market textiles (clothes and household linen) between 100% production in France, actual 2019 production, and 100% production in China.

Table 3. Presentation of the environmental footprint values calculated for a French consumer.

	Hypothetical Production 100% French	French Textile Market in 2019	Hypothetical Production 100% Chinese
Clothes	175	341	370
Household linen	52	101	111
All articles	227	442	481

The CF originating from the textile product purchased by a French citizen in 2019 is 442 kg of CO_2eq. According to the Ministry of the Environment, a citizen's CF is 11,205 kg per year (in 2018). Thus, it is possible to estimate that the share of textile purchases in the CF is 3.9%. Full production of the sector to a country with a low carbon electricity mix such as France would reduce this footprint by half.

3. Discussion

3.1. Potential and Methods of Reducing the Carbon Footprint on an Individual and Industrial Scale

The Paris Agreement predicts a limitation for global warming to a maximum of 2 °C maximum by 2050. This amount is obtained by dividing by 6 the CF [6]. To reach this objective, all industrial sectors must commit to this goal. To begin with, the offshoring of textile production to the countries with a low carbon electricity mix would allow CO_2eq emissions to be divided by 2. The second point of improvement could be the increase of textile products' lifespan. Extending their lifespan by a factor of 2 can reduce sales (and therefore production) by the same factor. The third area for reducing the textile environmental footprint consists of closing the material loop, by promoting reuse and closed-loop recycling. The LCA of the 17 products has shown that recycled fibers reduce carbon emissions [30].

Furthermore, the evolution of purchasing behavior depends on consumers; the circulation of materials in the economy depends on the structure and organization of the textile sector; the evolution of the electricity mix depends mainly on governmental choices. Thus, a question arises: What could be the possible actions for a company to reduce CF?

The key element is that each company is free to choose its own electricity supplier. Choosing very low carbon electricity strongly reduces the CF. A typical French weaving company produces around 10 tons of fabric per employee for one year with a corresponding electricity consumption of 38,000 kWh. Comparing a production with an electricity mix emitting 110 g of CO_2eq/kWh and the same production with an electricity mix of 750 g of CO_2eq/kWh (average global value) shows differences in GHG emissions of more than 24 tons on average per weaving job.

In general, the detailed LCA study of the 17 products indicated that the optimization of the electricity mix would reduce by about 10% the CF of fibers but it can reach a decrease by a factor of 3 for textile transformations (since it has a significant share of electricity). If the company chooses to supply itself with renewable electricity, the environmental footprint can be further reduced [30].

3.2. Circular Economy and the Influence of the End-of-Life of Textile Products

The challenge of a circular economy is to form a closed loop of used materials in order to reduce the influence of utilized resources and to limit the impacts on the environment. Due to the quantities involved and the potential of revalorization of used products, the textile sector is an emblematic sector of the circular economy. Significant efforts have been made over the past 10 years to stimulate reuse and recycling loops of textile products through actions taken by the eco-organization Refashion (formerly EcoTLC). These efforts led to a considerable reduction in carbon emissions in this sector and showed how the upgrading of textile products at the end of their life could benefit the environment [21].

The results of this study allow comparing different aspects of textile waste treatment routes and processes at the end-life of textile products in France in 2018 (38% treated in the revalorization process, 28% in incineration with recovered energy and 34% in landfills) [11]. The recovery sector is dominated by reuse (58.6%), then recycling (32.4%) but also includes a part of incineration (8.4%) and landfill (0.6%). The calculation of the carbon emissions of this sector per one kg of treated fibers indicates a low environmental impact of textile end-of-life (0.2% of the total impact of one kg of textile) and allows to distinguish the impact of the end-of-life of natural fibers (49 g of CO_2eq/kg of end-of-life fibers) from artificial fibers (249 g of CO_2/kg of end-of-life fibers) [11,21].

Figure 17 compares different environmental impacts of the end-life handling for natural and synthetic textile fibers. Eight treatment routes are compared based on their environmental performance. In every case, impacts cover the collection transport, the treatment (except reuse cases) and the material benefit based on an economic allocation (except for landfill case which do not present benefit). Landfill shows significant impacts depending on whether natural fibers (1.38 kg CO_2eq/kg of fiber) or artificial fibers (0.12 kg CO_2eq/kg of fibers) are being used. In order to avoid any biased data with the incorporation of material recovery benefits, the calculation is made with an economic allocation of the environmental benefits of energy recovery. The impact of artificial fibers' treatment reaches almost 2 kg of CO_2eq emission per one kg of treated fiber. On the other hand, the incineration of natural fibers shows a slight benefit in carbon emissions.

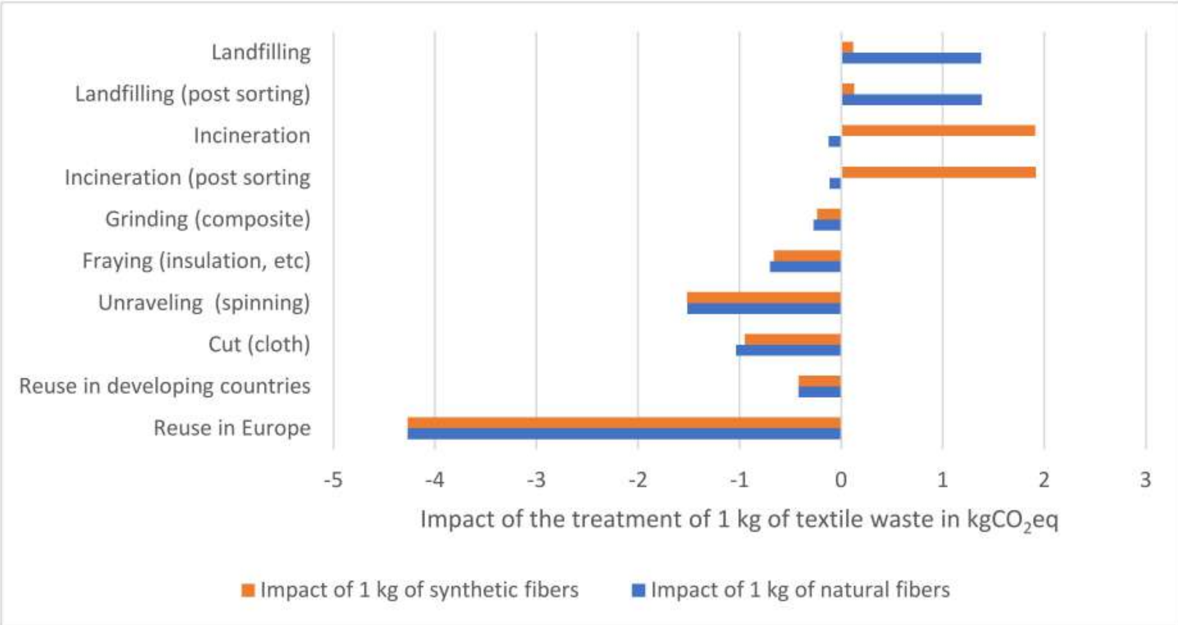

Figure 17. Carbon impact of the various textile fiber waste treatment channels. The calculation is based on an economic allocation of the environmental benefits of the revaluation (the detailed modeling table is presented in the Supplementary Materials). The results underline the difference between the reuse in Europe and the reuse in developing countries. The results are expressed in positive emissions (CO_2eq emissions in the environment) or in negative emissions (impacts avoided due to the recycling of the material).

The results also compare six revaluation methods. Regardless of the chain supply, the environmental benefits are allocated on an economic basis (average textile item price is 7.5 Euros/kg) and due to energy recovery, it is calculated on the basis of the price of energy compared to average price of textile article. This method of calculation in accordance with ISO 14040-44 standard avoids methodological biases. The recycling ways can be quantified with the same assumptions. Thus, two types of reuse take place: Europe or developing countries. The performance between those two types of reuse strictly differ by the sale prices of second-hand clothes. The average price is estimated to be 7.5 Euros/kg of textile for Europe and 0.75 Euros/kg for developing countries. The reuse of the fabric gives less value to the material itself (unlike the reuse that gives value to clothes). The environmental benefit depends on the fabric selling price which is 2 Euros/kg. Fraying, unraveling and grinding lead to fiber recovery in two ways: either in a closed-loop recycling process with the integration of fibers into a yarn, or open-loop recycling with the production of insulation or composite. Due to the rise in electricity consumption in those situations mentioned, the impact of the process increases a little, however, the performance is very largely determined by the price of the secondary material. This price is 3 Euros for producing recycled wires, 1.5 Euros for making insulation materials, and 0.75 Euros for making composites [30].

This economic allocation avoids a biased assessment of the revalorization performance. Nevertheless, the environmental performances are strongly dependent on the prices of secondary materials and then to the downstream demand of recycled material. This parameter plays in the relative importance of the different revalorization routes. In this case, when the demand for reuse and recycling is greater, the smaller becomes the proportion of textiles incinerated and landfilled. Thus, the prices of secondary materials will be higher, leading to a greater environmental benefit. Thereby, a simulation with estimated parameters for 2050 shows the potential gain that can be expected from the optimization of textiles at their end-of-life. The assumptions used are the end of the landfill and the reduction by 2 for the incineration, whereas, in return, there is an increase by a factor of 2 in the reuse in Europe and 1.5 in developing countries (with the price of resold items increasing by a factor of 3); the increase in the use of tissues is estimated to a factor of 2.5, and the increase in defibration for the spinning of recycled fibers is estimated to a factor of 300 (from 0.06% in 2020 to 18.5% in 2050). Additionally, those two chain supplies increase in secondary material prices by a factor of 3. Grinding is considered constant in mass and value. With these assumptions, the end-of-life of textiles would correspond to 4.32 kg of CO_2eq avoided per kg of treated textile article (for a positive impact of 0.2 kg CO_2eq/kg textile treated) [Detailed data are available as Supplementary Materials Table S4].Thus, even if the reorganization of the textile supply chains around recycling is difficult, the stimulation of downstream demands leads to a double effect: a reduction in landfills and incineration, and an increase in the price of the recycled material. This leads to an environmental advantage that grows exponentially.

3.3. Calculation Method of CF

Two approaches are used for the assessment of CF. The method currently used by the French Ministry of the Environment based on I/O matrices (input/output) or the method used in this article based on LCA. I/O matrices allow calculations without any production data details. Economic exchange values between industrial sectors are necessary in this case for the quantification of the purchases of a given sector. This leads to an environmental matrix that quantifies the impacts based on CO_2eq emissions per economic unit for each industrial sector. However, input/output matrices are not declared in all the countries of the world and company emissions are only released by large companies in few countries. Finally, the distribution of industrial sectors often reaches a lot of limitations. Grouping different economic factors induces average quantities of emissions that are extremely different from the real values (for example, the transport sector includes transport by plane and by boat; by using an average of their environmental impacts; ultimately, a bias is going to be introduced to the values). It was purposely chosen in this study, to base the footprint assessment on LCA approach. The LCA approach is closer to the reality of the industry even if aspects such as administrative activities are not considered. However, the data for LCA is more difficult to collect since it is uneasy to ensure the representativity of the products regarding the considered sector [10,25].

In this work, the calculation of the environmental footprint of industrial activities highly depends on imports especially for the textile sector. An industrial sector characterized by very large import shares is very dependent on modeling assumptions. Figure 18 compares the calculated environmental footprint by the Ministry of the Environment (I/O method) and the obtained results (LCA method), it is proven that the outcomes are very different.

The method used by the Ministry of Environment is input/output (I/O) matrix. The main assumptions of I/O in this assessment is the similarity of the structure of trade exchanges in Asia and Europe, and that carbon emissions are adjusted according to emission intensity by Euro of GDP (Gross Domestic Product). In addition, due to missing data characterizing the emissions for France, the assessment relies on European data for CO_2eq emissions per Euro spent which is based on a far higher carbon emission factor per Euro spent.

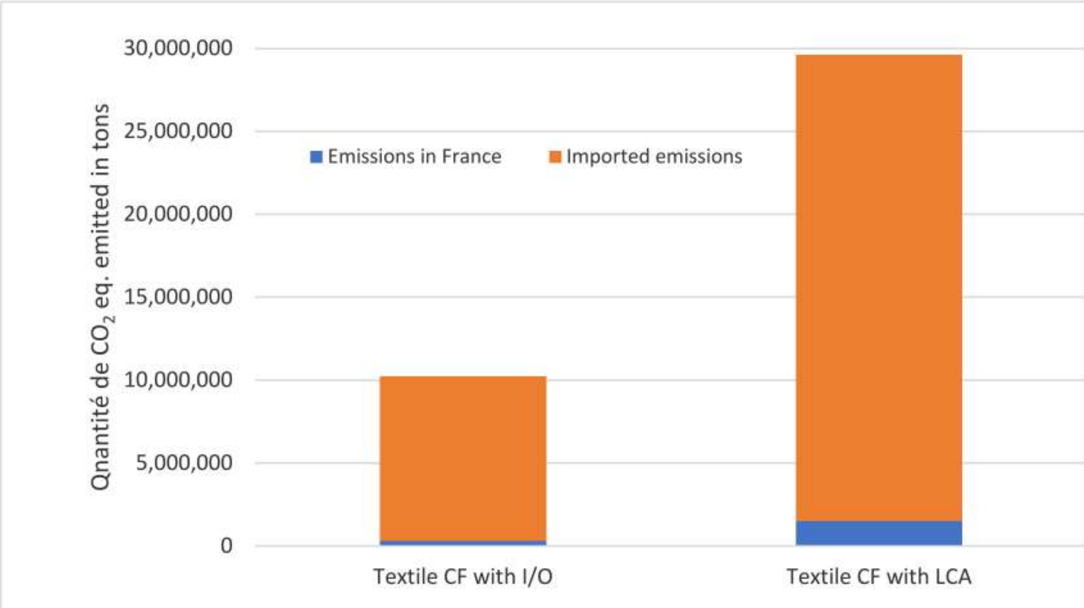

Figure 18. Comparison between the French carbon footprint for textiles calculated with the I/O (input/output) method (Ministry of the Environment in 2018) and the results obtained with Life Cycle Assessment (2019).

The evaluation carried out in this study is based on LCA of representative products, four specific production routes and a modeling of transfers between countries in the upstream textile market. In fact, the modeling of this project considers only clothes and household linen whereas the French Ministry of the Environment modeling includes all the textile sectors (including shoes and technical textiles) but does not include the use phase and the end-of-life. The Ministry of the Environment considers that imports represent 9914 million tons of CO_2 emitted. The assessment carried out in this project is based on Life Cycle Assessment; it does not include shoes nor industrial textiles but considers the use phase and the end-of-life in the CF. The CF for the clothes and linen sold in France are therefore 28,123 million tons. This shows a large difference in the imported textile values where impact of imported textile articles is three times higher in our study compared to the national data. The difference can be explained by calculations for imported emissions. The difference is also caused when assuming that all emissions take place in the last country of importation [16], as well as assuming similar emission factors of CO_2eq/Euros in Europe and France.

It is recommended to improve the precision in the calculations of environmental impact of imported textile products. The textile sector is extremely fragmented and dispersed globally. Therefore, data collection is difficult technically (transformation process implemented) and environmentally (specific emissions from these processes). The statistical data of WTO is very brief and requires significant extrapolations. Conversely, European import and export data is more precise but only represents a minor part of the environmental impacts. In a short-term perspective, we must be able to work in close collaboration with companies in order to reduce bias in carbon emissions assessment and increase the number of textile articles considered for the footprint calculation. For the long term, it is wise to consider a regulatory framework that allows product traceability in order to associate the production steps to the right countries and evaluate them with the relevant electricity mix. Furthermore, a company-wide traceability will surely strengthen its commitment to the environmental process and will rigorously manage emissions data and resource consumption.

4. Conclusions

The impact of this study is calculated using LCA and gives an estimation of 442 kg CO_2eq/person/year. Thereby, as recalled in this study, limiting the global warming impacts to 1.5 °C requires a reduction of GHG emissions by a factor of 6, which means, in other words, reduce the footprint to 74 kg of CO_2eq/person/year.

This work identifies and describes the causes of CF coming from clothes and household linen. It also quantifies the contribution of several life cycle parts in the CF of textile products. Figure 19 presents the main opportunities to reduce the environmental footprint.

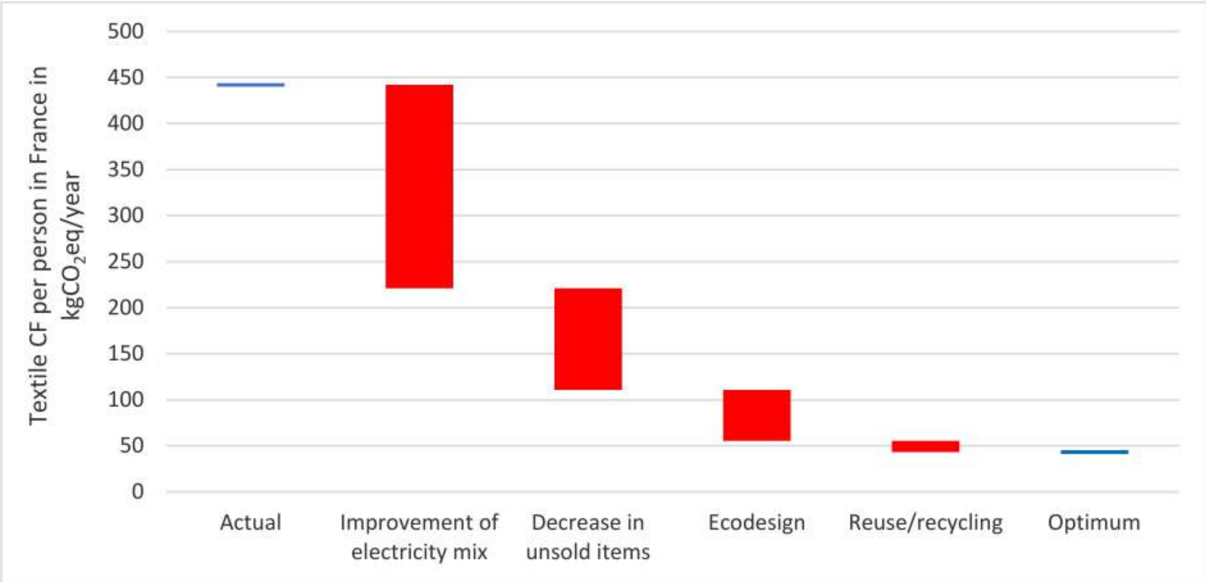

Figure 19. Waterfall presentation of the maximum reduction of CF for the textile industry in France based on current technologies and constant service.

In Figure 19, the waterfall chart shows four main ways of reducing CF and the extent of the corresponding reductions.

The determining action out of all remains the reduction of CF related to the electricity mix. Textile production uses a lot of electricity and the carbon emissions per kWh can be potentially reduced by a factor of 10. Under the assumption that 100% of the textile production is relocated to France (which is completely hypothetical), the environmental footprint would be reduced by 221 kg CO_2eq because of the change in the electricity mix and the diminution of transportation means. Additionally, reducing unsold items would lead to a 111 kg reduction of footprint. Previous work carried out by Cycleco with textile companies showed ecodesign approaches would lead to a potential reduction of 55 kg of CO_2eq on average in carbon emissions. Finally, the emissions linked to the implementation of recycling and reuse process concerning end-of-life products can reach a maximum decrease of 12 kg CO_2eq per kg of textile product. As shown in Figure 19, the implementation of all these means would reduce the annual environmental footprint of textiles to 43 kg CO_2eq/person/year, against 442 kg CO_2eq/person/year at present. This reduction of a factor of 10 greatly exceeds the reduction target (factor of 6) and meets the objectives of the Paris Agreement.

On a company level, the implementation of these objectives requires systematic accounting in CF of items produced or distributed and possibly the display of their environmental performance in order to engage consumers in their efforts. On a sector level, the increase of demands for recycled material and the yearly calculations of the environmental footprint values in the textile sector in France would allow economic stakeholders to be involved with the performance of the entire industry. Finally, on a national level, reducing the environmental footprint of textiles is based on efforts to relocate production means (especially those which consume electricity the most; to know in the decreasing order of importance: weaving, spinning, knitting and some finishing treatments). In addition, monitoring an environmental performance indicator for the sector would be easier using a footprint calculation based on the LCA which directly reflects the impact of imported products and implements a traceability of the imported textiles.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/5/2422/s1, Table S1a–d, Table S2, Table S3a,b, Table S4.

Funding: This research was funded by APV (Association Première Vision).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank the APV association for funding this project, UNITEX for project support and The French Fashion Institute (IFM), Refashion, UIT and La Fédération for their valuable input during the project. In addition, contributions from companies 1083, Balas-Textile, C2S, Chamatex, Denis & Fils, Dutelsa, EMC-Mouzon, Garnier-Thiebaut, Groupe Cheynet, Logoclub, Les, Moulinages Riotord, Les Tissages de Charlieu, Pagastic, Patine, Payen, Porcher Industries, Proverbio, Rocle, Verne & Clet were decisive in carrying out this work. Thanks to Lin Zhao for modeling the LCA of the 17 textile articles. Thanks to Nadine Riachy for reviewing discussing and improving the article.

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

References

1. Commissariat Général au Dévelopement Durable. *Chiffres clés du Clima*; Commissariat Général au Dévelopement Durable: Paris, France, 2020; p. 80. Available online: https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2018-12/datalab-46-chiffres-cles-du-climat-edition-2019-novembre2018_1.pdf (accessed on 18 November 2020).
2. Dugast, C.; Soyeux, A. *Pouvoir Et Responsabilité Des Individus, Des Entreprises Et De L'état Face À L'urgence Climatique*; Carbone4: Paris, France; p. 21.
3. Amt, A. Nette Diminution des Émissions de Gaz à Effet de Serre. 2020. Available online: https://allemagneenfrance.diplo.de/fr-fr/actualites-nouvelles-d-allemagne/05-Developpementdurable/-/2376492 (accessed on 18 November 2020).
4. Friedlingstein, P.; Jones, M.W.; O'Sullivan, M.; Andrew, R.M.; Hauck, J.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; Le Quéré, C.; et al. Global Carbon Budget 2019. *Earth Syst. Sci. Data* **2019**, *11*, 1783–1838. [CrossRef]
5. Peters, G.P.; Andrew, R.M.; Canadell, J.G.; Friedlingstein, P.; Jackson, R.B.; Korsbakken, J.I.; Le Quéré, C.; Peregon, A. Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nat. Clim. Change* **2020**, *10*, 3–6. [CrossRef]
6. Jackson, R.B.; Friedlingstein, P.; Andrew, R.M.; Canadell, J.G.; Le Quéré, C.; Peters, G.P. Persistent fossil fuel growth threatens the Paris Agreement and planetary health. *Environ. Res. Lett.* **2019**, *14*, 121001. [CrossRef]
7. Froemelt, A.; Dürrenmatt, D.J.; Hellweg, S. Using Data Mining To Assess Environmental Impacts of Household Consumption Behaviors. *Environ. Sci. Technol.* **2018**, *52*, 8467–8478. [CrossRef] [PubMed]
8. Les Echos. G7-L'industrie Textile, très Polluante, S'engage Pour L'environnement. *Investir*. Available online: https://investir.lesechos.fr/actions/actualites/g7-l-industrie-textile-tres-polluante-s-engage-pour-l-environnement-1868705.php (accessed on 18 November 2020).
9. ISO 14040. *Environmental Management—Life Cycle Assessment—Principles and Framework*, 2nd ed.; International Standard Organization: Geneva, Switzerland, 2006.
10. ISO 14044. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*, 1st ed.; International Standard Organization: Geneva, Switzerland, 2006.
11. ADEME. Déchets Chiffres clés, l'essentiel année 2019. Available online: https://www.ademe.fr/sites/default/files/assets/documents/dechets_chiffrecles_lessentiel_2019_010695.pdf (accessed on 18 November 2020).
12. European Commission. *PEFCR Guidance Document—Guidance for the 14 Development of Product Environmental Footprint Category Rules (PEFCRs)*, version 6.3; European Commission: Brussels, Belgium, 2017.
13. Muthu, S.S. *Assessing the Environmental Impact of Textiles and the Clothing Supply Chain*, 2nd ed.; Elsevier: Amsterdam, The Netherlands; Available online: https://www.elsevier.com/books/assessing-the-environmental-impact-of-textiles-and-the-clothing-supply-chain/muthu/978-0-12-819783-7 (accessed on 18 November 2020).
14. Ammar, G.; Roux, N. Délocalisation et Nouveau Modèle Économique: Le Cas du Secteur Textile-Habillement—IRES. Available online: http://www.ires.fr/publications-de-l-ires/item/2557-delocalisation-et-nouveau-modele-economique-le-cas-du-secteur-textile-habillement (accessed on 18 November 2020).
15. CITEPA. Evolution de L'empreinte Carbone des Français: Analyse du SdeS. Available online: https://www.citepa.org/fr/2020_01_a09 (accessed on 17 November 2020).
16. Pasquier, J.L. Empreinte Carbone. Méthodologie. 2020. Available online: https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2020-01/empreinte-carbone-methodologie-012020.pdf (accessed on 10 November 2020).

17. Marilena, M.; Diego, G.; Edwin, S.; Monica, C.; Efisio, S.; Jos, O.; Elisabetta, V. Fossil CO2 Emissions of all World Countries—2018 Report. Available online: https://ec.europa.eu/jrc/en/publication/fossil-co2-emissions-all-world-countries-2018-report (accessed on 18 November 2020).
18. Garric, A. Le Haut Conseil pour le climat appelle la France à réduire ses émissions de CO2 liées aux importations, en forte hausse. *Le Monde*, 6 October 2020.
19. Insee Évolution du Produit Intérieur Brut et de ses Composantes | Insee. Available online: https://www.insee.fr/fr/statistiques/2830613 (accessed on 17 November 2020).
20. Jardillier, A. L'économie Circulaire Dans L'industrie Textile. Available online: https://institut-economie-circulaire.fr/wp-content/uploads/2018/10/focus-textile-sept-2018.pdf (accessed on 18 November 2020).
21. Refashion. Rapport D'activité. 2019. Available online: https://refashion.fr/pro/sites/default/files/fichiers/ECO_TLC_FR_BD.pdf (accessed on 10 November 2020).
22. Eurostat. Manufactured Goods (PRODCOM). Available online: https://ec.europa.eu/eurostat/web/prodcom/data/database (accessed on 18 November 2020).
23. Gildas, M. Institut Français de la Mode. Available online: https://www.ifmparis.fr/fr/recherche-academique/desindustrialisation-reindustrialisation-dans-lindustrie-de-la-mode (accessed on 29 July 2020).
24. UIT. Tableaux de Bord de L'industrie Textile. Available online: https://www.textile.fr/files/Uit-comext-Decembre-2020.pdf (accessed on 10 November 2020).
25. Bernard, A.B.; Fort, T.C. Factoryless Goods Producing Firms. *Am. Econ. Rev.* **2015**, *105*, 518–523. [CrossRef]
26. Guinebault, M. Textile/Habillement: Quels Véritables Prix de Revient en Asie et Euromed? Available online: https://fr.fashionnetwork.com/news/Textile-habillement-quels-veritables-prix-de-revient-en-asie-et-euromed-,971860.html (accessed on 12 November 2020).
27. Gaudiaut, T. Infographie: Combien Coûte la Main D'oeuvre de la "Fast Fashion"? Available online: https://fr.statista.com/infographie/18006/salaires-ouvriers-industrie-textile-dans-le-monde (accessed on 6 November 2020).
28. Chaponnière, J.-R. Salaires: L'Asie des petites mains. *Asialyst*. 2015. Available online: https://asialyst.com/fr/2015/12/18/salaires-l-asie-des-petites-mains (accessed on 12 November 2020).
29. ONC. World Manufacturing Production 2019. Available online: https://www.unido.org/sites/default/files/files/2020-09/World_manufacturing_production_2019_q2.pdf (accessed on 18 November 2020).
30. Payet, J.; Zhao, L. *Analyse du Cycle de Vie de 17 Articles Textiles*; CYCLECO: Ambérieu, France, 2020.