REPORT:
Carbon fibres in post-user waste in Switzerland

By mandate of ASED

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Content

Executive summary:

Carbon fibre reinforced polymers (CFRP) are increasingly used in various applications due to their attractive mechanical properties over density ratio. As a result, it is expected that a significant amount of end-of-life products containing carbon fibre composites will end up in waste collection facilities in the coming years. However, this material causes various problems in waste processing facilities, such as short circuits or machine blockages. It is therefore important to identify the carbon fibre products consumed in Switzerland and estimate their volume in order to assess the potential problems in waste treatment facilities.

The objective of this study is therefore to analyse the main goods consumed in Switzerland, which are entirely or partially made of carbon fibre, in order to estimate the annual waste volume for this material. To do so, the study focuses on five main categories of consumer products: boats, cars, sporting goods (e.g. bicycles, skis, rackets, golf clubs…), construction and medical sectors. For each type of product, three parameters were estimated: the number of products sold annually, the carbon composite content and the lifetime. These three parameters were used to calculate a final metric to compare the products in terms of their potential waste volume.

It was then estimated that 121.8 tonnes of CFRP waste are produced annually in Switzerland, resulting in 69.7 tons of carbon fibre. 80% of this waste falls into six categories: manufacturing waste, bicycles, hockey sticks, skis & snowboards, boats and unihockey sticks. For some products, such as bicycles or cars, collection and recycling options already exist today and they would not cause so many problems in waste disposal centres. However, there are twelve types of products for which there is no collection system in place and then the recycling is not possible so that the easiest solution for consumers is to put them in the bin with municipal waste. These twelve products account for 61 tons of waste per year, or 50.1% of the total.

1. Introduction & Global market:

The industrial use of carbon fibres began in the early 1960s, notably with Rolls Royce, which implemented carbon fibre composites in jet engines. Since then, high performance carbon fibre composites are reaching many more industrial applications due to their interesting specific strength and stiffness. Consequently, the demand for carbon fibres grows every year (except in 2020 due to the Covid-19 situation) and the worldwide demand increased from about 33 kilotons in 2010 to approximately 82.5 ktons in 2019, while the demand in 2020 fell to 71.5 ktons [1]. This volume of carbon fibres is processed into Carbon Composites (CCs), with polymer matrices (Carbon Fibre Reinforced Polymers, CFRPs) representing around 83%, the remaining part being metal or ceramic matrices [1]. Hence the global volume of CFRPs was 138 ktons in 2019 and should be around 119 ktons in 2020 [1]. The distribution of global CFRP demand by application is shown in FIGURE 1 below:

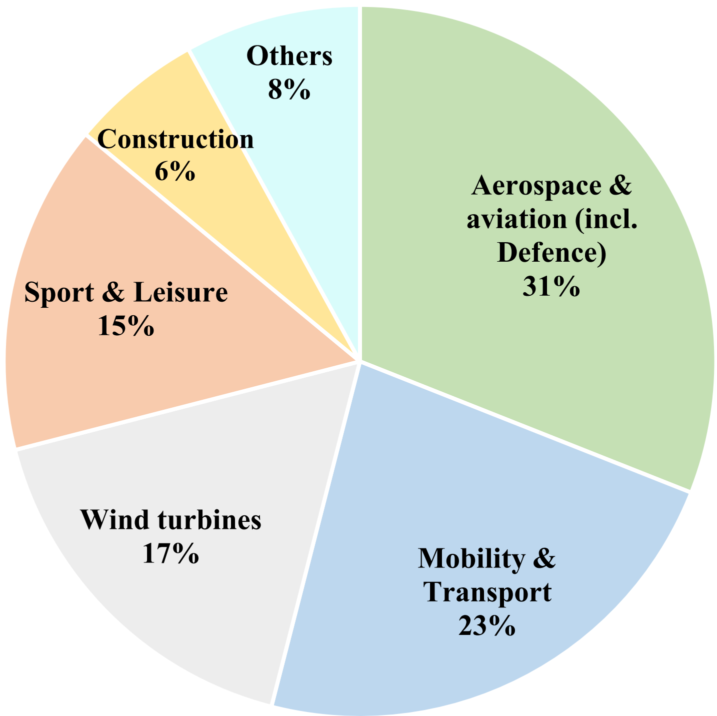

FIGURE 1 - Distribution of the worldwide CFRP consumption by application [wt.%] [1]

More than 90% of the demand can be attributed to five different fields: aerospace, aviation & defence industry (31%), mobility & transport (23%), wind turbines (17%), sport & leisure (15%) and construction (6%) [1]. These sectors are responsible for the very rapid upward carbon composite global consumption. TABLE 1 below shows the composite carbon consumption for these sectors in 2017 [2], 2018 [3] and 2020 [1] (note that the values for 2020 have been strongly affected by the Covid-19 crisis, particularly in the aviation and automotive sectors, thus the trend between 2017 and 2018 is more representative):

TABLE 1 – Carbon composite consumption for different sectors in 2017, 2018 and 2020

Sector	Carbon composite consumption [ktons]		
	2017	**2018**	**2020**
Aerospace, aviation & defence	37.93	55.31	44.1
Automotive	27.88	37.13	33.4
Wind turbines	16.33	20.88	25.2
Sports & leisure	14.97	20.11	21.9
Construction	6.01	7.74	8.6

From this Table, it is clear that the aerospace & aviation industry and the automotive industry lead the global carbon fibre composite consumption trend, with the exception of 2020, with an increase of 17.38 ktons and 9.25 ktons respectively between 2017 and 2018. For example, in the aviation industry, the use of carbon fibre in aircraft fuselages is constantly increasing, e.g. 30% of the Airbus A380 was made of CFRP, while the new Airbus A350 contains over 50% CFRP [4]. Regarding the automotive sector, the strong increase in the use of CFRP is mainly related to the development of new propulsion methods (electric and hydrogen) which require lighter cars to offer a greater range. For the wind turbines sector and the sport industry, the impact of the Covid-19 crisis is less significant and the carbon fibre consumption growth is fast. For the former sector, this can be explained by the need to develop longer blades to improve efficiency and therefore lighter materials than glass fibre composites are required. Finally, the sports and leisure industry has always been an area of experimentation for the maturation of new materials, particularly for CFRPs, which are being used in more and more sports equipment because of the improved performances they allow. To sum up, the implementation of Carbon Fibre Reinforced Polymers in the global industry is growing at approximately 11.45% every year [1] and this is just the beginning. Indeed, the more CFRPs are used, the lower the price of carbon fibre will be, the more applications can be implemented, the greater the demand will be. The price of carbon fibre fell from $30 in 2012 to approximately $10 in 2020 [5] and therefore, it is becoming more and more competitive compared to other structural materials such as metals.

Concerning the trend in Switzerland, the production of Fibre Reinforced Polymers (FRPs) in 2019, in Austria and Switzerland, has been estimated to be 19 ktons. Then considering that carbon fibres are used globally in 1.2% of the composites [6] and also that the production is distributed according to the number of residents, i.e. that the production in Switzerland is approximately the same as in Austria, the annual production of CFRPs in Switzerland is approximately 115 tons.

However, manufactured products made from carbon fibre composites do not have an infinite lifetime and, at the end of their life, they will enter the waste stream. Currently, 98% of the composite waste ends up in waste collection centres [7], [8]. Some are just buried in those areas while others are treated with municipal waste in revalorizing centres but carbon fibres can cause a lot of disruption inside the waste treatment circuits. Indeed due to their high strength, carbon fibres can block shredding machines, they can also create short circuits in electrostatic precipitators because they are electrical conductors and finally they cannot be chemically or thermally degraded easily. According to the strong growth of the CFRPs market, many products containing such materials are expected to be withdrawn from the market in the coming years and this could become a burning issue. For example, the mass of wind turbine composite blade[1] waste is expected to reach 2'020 ktons per year by 2050 [8], [9] and a cumulative mass of blade waste of 43 million tons, among which more than 93% are composite materials [9]. Considering that around 30% of the wind turbine blades are currently manufactured using CFRPs [10], this sector would then create approximately 600 ktons of CFRP waste globally every year. Another important source of CFRP waste are aircrafts, from which about 500 ktons of CFRP waste are expected in 2050 at rate of 30 ktons per year from 2025 [4], [7]. Hence recycling methods become very important in order to manage this future waste flow, all the more so since the global production of virgin carbon fibres can no longer satisfy the demand since 2020 [8] and then recycled fibres could fill the gap. However, CFRPs offer a great freedom in terms of processing and shape so that manufactured products containing carbon fibres can be simple tubes, like for golf club shafts (cf. FIGURE 2), or it can also be very large parts (e.g. BMW *i*3 life module, cf. FIGURE 3) or complex multilayer products (e.g. skis and windsurf boards, cf. FIGURE 4 and FIGURE 5), and in such cases, recycling can be even more complex.

FIGURE 2 - Golf club's graphite shaft [11]

FIGURE 3 - BMW i3 CFRP life module (upper part) [12]

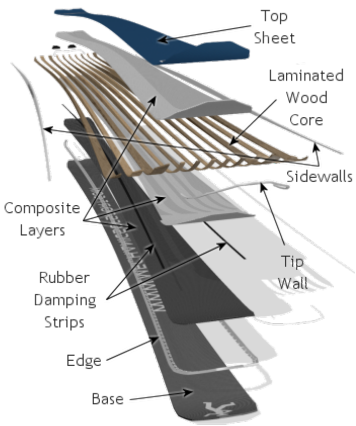

FIGURE 4 - Detailed structure of a ski [13]

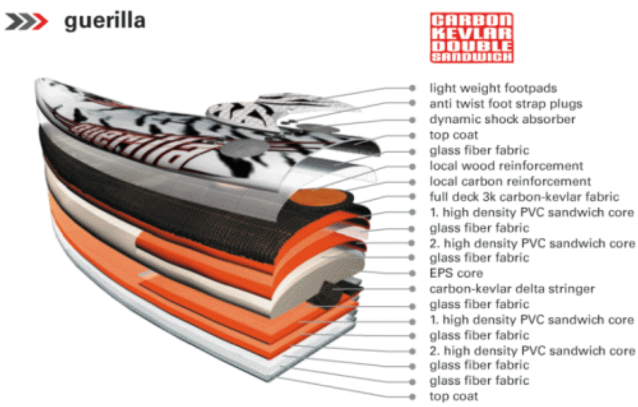

FIGURE 5 - Structure of a windsurf board [14]

[1] Mainly Glass Fibre Reinforced Polymers but the recent large blades are built with CFRP.

This report intends thus to analyse the main consumer products containing carbon fibres in Switzerland which would then cause some issues in waste-treatment facilities. Consumer products are defined as goods bought by consumers for their personal usage, e.g. food, cars or sporting goods.

2. Methodology:

As mentioned in the introduction, this analysis focuses on consumer goods because in other fields such as aerospace, aviation or wind turbines, carbon composite waste is most of the time, if not all the time, not treated with municipal waste but rather in special affiliated treatment facilities [15], [16], the waste stream should therefore be more easily controlled. The range of applications of CFRPs in consumer products is very wide and ANNEX 1 provides a non-exhaustive list of consumer products where carbon fibres can be found.

In order to estimate the volume of carbon fibres contained in consumer products in Switzerland, a detailed study of the Swiss market for those products as well as an analysis of their composition have been done and are presented in the following. This allowed to evaluate the following parameters: first, the number of products sold each year for each candidate, which is referenced as N_y [units], then their carbon fibre content, called C_f [g/unit] and finally the lifetime Y [years] of each product. With all these parameters, a ranking of the most consumed products containing carbon fibre has been built based on the following metric:

$$A = \frac{N_y \times C_f}{Y} \; [{}^{g}/_{year}]$$

Afterwards, the products were also assigned to a colour that indicates the likelihood of finding them in municipal waste treatment facilities depending on the current state of the recycling or collection channels for those products. Finally, some assumptions and trends concerning the future growth of each product have been established. The sectors focused on are those where carbon fibre composites are commonly found, i.e. mainly those in ANNEX 1.

All the assumptions that have been taken in the framework of this study are presented with the corresponding candidate.

3. Consumer products market analysis:

a) Marine industry:

The penetration of composites in boats is one of the highest (~51% [17]) among all the industries that extensively use Fibre Reinforced Polymers. Composites can be found in different parts of a boat: the hull, the deck, the boom, the mast, the sail or in many other smaller parts. They are widespread due to their non-corrosive nature and their low density, which improves the service life and fuel efficiency of boats respectively. Glass fibres are the most common reinforcement type in the marine industry but carbon or Kevlar fibres can also be found, especially in racing sailboats or in luxury yachts. According to Boat Digest statistics [18], 95% of recreational boats have a composite hull nowadays.

The recreational and sporting boat industry is relatively active in Switzerland, with 178 related companies and 97'899 boats registered in 2017 [19]. During 2017, 23 sailboats & yachts have been produced in Switzerland, as well as 37 inboard & sterndrive motorboats for a total of € 6.6 million. Moreover, 503 sailboats & yachts, 603 inboard & sterndrive motorboats, 3'639 other rigid boats and 30'038 inflatable boats have been imported in 2017 [19]. In total, 34'783 new boats were introduced on the Swiss market.

Assumptions:

1. All the imported and produced boats are sold.
2. Carbon fibre composite is not common material for inflatable boats, which are mainly made out of synthetic rubbers or of plastics such as PVC.
3. According to a quite old survey (2004) [20], 15% of boat manufacturers use carbon fibre as reinforcement material for hulls, 11% for decks and 13% for other parts. This could have change a bit since then but according to another source [21], [22], Glass Fibre Reinforced Polymers dominate largely the market of reinforcing materials for recreational boats so that the share of carbon fibre in boat building industry might not be so different. These market shares will be assumed in the following.
4. The average dimensions [23] of a sailboat in the United States are as follows:
   - Length: 30 ft ≅ 9.1 m.
   - Width (beam): 10 ft ≅ 3 m.
   - Length of the mast: 38 ft ≅ 11.6 m [24].

   Since there is no ocean in Switzerland, the average sailboat size should probably be lower and is estimated to be 7 m in length [25]. Translating this difference for the beam and mast results in average width of 2.3 m and average mast length of 8.9 m.
5. The distribution between yachts and sailboats is 50:50, i.e. there are 252 sailboats and 251 yachts sold yearly in Switzerland.

Following the previous assumptions, the TABLE 2 below summarizes the estimated number of carbon fibre hulls, decks and other parts in Swiss boats:

TABLE 2 - Total number of CFRP boat parts sold yearly in Switzerland

Category	Part	Amount
Sailboats & Yachts (considering a 50:50 distribution)	Hull	75
	Deck	55
	Sail	33
	Mast	33
	Boom	33
Inboard & Sterndrive motorboats	Hull	90
	Deck	66
Other rigid boats	Hull	546
	Deck	400

Concerning the weight, a standard carbon fibre boom weighs around 20 kg [26] while an average mast weighs approximately 50.9 kg [27]. For the sail, as carbon sails are in general for small racing boats, the total weight of a set of carbon sails is estimated to be around 50 kg [28]. Finally, for the hulls and decks, an estimation based on a real boat model has been done in order to approximate their CFRP content. The whole boat's dry weight is 1'380 kg [29] including the engine that weighs about 126 kg [30]. Hence it has been estimated that the weight of the structure, i.e. the hull, the deck and the keel is close to 1 ton (others parts such as seats or driving controls bring a certain mass in the structure). However, since keel is generally made out of lead or steel, it is estimated to represent about 40% of the total boat mass [31]. Therefore, the deck and the hull weigh around 600 kg in total. Considering a common sandwich panel structure [32] with a 15 mm foam core, of density 100 kg/m^3, and two CFRP skins for a total thickness of 1.3 mm and a density of 1'600 kg/m^3. With this configuration, CFRP represents 58% of the total sandwich's weight. Finally, assuming that the hull is two third of the remaining weight and the deck one third, this ends up in 282 kg CFRP in hull and 116 kg CFRP in deck.

Final metric value: summing up all the elements in TABLE 2 with their estimated average mass given just above, the total weight of CFRP in new sold boat parts reaches 264'928 kg CFRP. The lifetime of a boat can vary a lot depending on how the owner takes care of it but in general, a boat can last between 10 and 20 years [33], so that considering a maximum lifetime of 20 years, the final metric *A* is equal to at least 13'264 kg CFRP/year.

End-of-life: there is no recycling facility for end-of-life boats in Switzerland due to the low volume of withdrawn boats. Indeed, boats last a very long time, especially if they are well maintained. Consequently, the few recycling channel attempts have failed due to a lack of both profitability and volume. Therefore, withdrawn boats in Switzerland are generally exported in other countries, especially in Eastern Europe, or treated with municipal waste after some decommissioning operations from shipyards or just stored by the customers for many years [34].

Discussion: the volume of CFRP in personal recreational boats in Switzerland was expected to be important since such products are big and the Swiss boat fleet is in constant growth [35]. However, some assumptions, although necessary, introduced significant uncertainties on the final metric. Indeed, the hull and the deck's weight depends a lot on the boat type and its length thus the CFRP content in hull and deck is therefore approximate and should be refined. But in general, the mean length of Swiss boats is around 6 to 8 m [35] so that taking an average length of 7 m allows to give a first order of magnitude. Finally, it is quite complex to estimate the share of CFRP in boatbuilding materials but several sources indicate that glass fibres accounts for more than 80% in recreational boats, meaning that CFRP could not be more than 20%.

Future growth: the penetration rate of composites on the recreational boat industry is already high at over 52% by volume in 2020 [17] and is not expected to increase as it is already almost at its peak. Indeed, the remaining part of boats could not necessarily be made out of composites then they cannot penetrate further the market. This was for example the industry with the lowest growth in value according to the JEC Group, with 3% between 2016 and 2021 [17]. However, the penetration of carbon fibres in the marine composites market is likely to increase in the coming years, for example with the development of electrically powered boats which would compete with petrol powered boats only if they have sufficient autonomy and then the low density of CFRP could be an advantage. According to [36], the carbon fibre demand for marine industry increases by 8 to 9% annually.

b) Automotive industry:

The automotive industry constitutes the second largest demand of carbon composites in terms of weight, with a global demand around 33.4 ktons in 2020 [1]. The penetration of carbon fibre composites in the automotive industry is currently concentrated in sport and luxury cars, generally manufactured in a very low volume and at a very high cost. In 2013, CFRPs accounted for more or less 0.05% of the global material requirements for the automotive sector [37]. But the trend evolves quickly because of the need to reduce vehicle fuel consumption and greenhouse gas emissions, which pushes the manufacturers to make their products as light as possible. For this reason, CFRPs can play an important role in the automotive field in the coming years, especially in the alternatively powered vehicles where competitive autonomy requires lightweight structures. However, the obstacles of production time and cost of CFRPs have to be overcome in order to spread in this field. In this regard, many manufacturers, such as Nissan [38], have conducted or are still conducting projects to develop new processes for CFRPs allowing high rates and then suited for mass-production. The very first manufacturer to launch a car with significant use of CFRP parts in high volume is BMW, with its *i*3 model launched in 2013. One year later, the cars manufacturer also released its *i*8 model, a plug-in hybrid sport car with a CFRP life module and in 2016, they inserted carbon fibre parts in the body-in-white of the 7 Series [39]. Those developments have shown that CFRPs are not necessarily incompatible with mass-production, although manufacturing time and cost are currently an obstacle to an extensive use in automotive industry.

Based on new car sales in Switzerland in 2019 [40] (considering that the statistics on year 2020 have been affected by Covid-19 situation then they are not the most representative), the TABLE 3 below gathers the results for the consumption of CFRPs in Switzerland for the automotive sector.

Assumptions: only the models where it is clearly mentioned in the sources that they contain CFRP parts have been taken into account and the cars with less than 5 units sold per year have been neglected.

TABLE 3 - Car sales in Switzerland, in 2019 and their corresponding carbon content

Brand	**Model**	**Sales 2019 [unit]** [40]	**Estimated CFRP content [kg]**	**Total CFRP content [kg]**	**Sources**
BMW	*i*3	1082	68.5	74’117	[39]
BMW	7 Series	371	9.7	3’595	[39]
Lamborghini	Huràcan	65	31.2	2’028	[41], [42], [43]
Audi	A8	50	2.6	130	[44]
BMW	*i*8	46	~70	3’220	
Alfa Romeo	4C	39	65	2’535	[45]
Lamborghini	Aventador	35	147.5	5’163	[46]
McLaren	720S	33	75	2’475	[47]
Audi	R8	26	31.2	811	[41], [42], [43]
Hyundai	Nexo	16	46.4	742	[48], [49]
Maserati	Granturismo	15	100	1’500	[50]
Bugatti	Chiron	12	110	1’320	[51]
McLaren	Senna	12	75	900	[47]
Toyota	Mirai	9	46.4	418	[48], [49]
			TOTAL	98’954	

Final metric value: considering an average lifespan of passenger cars close to 12 years [52], <u>this gives a metric *A* equal to 8’246 kg CFRP/year</u>.

End-of-life: according to the Federal Office for the Environment [53], approximately two thirds of Swiss vehicles that have been withdrawn from the circulation are exported abroad to be reused by other people in different countries. The remaining third cannot be exported and are generally treated in affiliated waste disposal companies. The functional parts that can be reused are removed and become spare parts. The rest is treated: the skeletons are shredded in order to separate and recover metals. Then, it remains a shredder residue (ASR) containing plastics, rubbers, glass and other metals, as well as composites when used. Therefore, it is possible to find CFRP parts in waste collection centre as fraction of Automotive Shredder Residue.

Discussion: the list of cars in TABLE 3 is not exhaustive and there are probably other parts that are made out of carbon fibres in other cars. Moreover, some spare or customised parts can also be found in the market but they are not original parts and the volume could probably be neglected. Furthermore, since the BMW *i*3 represents more than three quarters of the total CFRP weight in the list and that this is the only high-volume manufactured car in the list, the result seems to be consistent.

Future growth: according to forecast, composites are likely to increase their penetration rate in the transportation field due to the need of decreasing the vehicles' mass in order to improve their fuel/energy efficiency. In addition, the market for carbon fibre composites in the automotive industry is expected to grow significantly with the development of hydrogen cars. Indeed, fuel cell stacks and hydrogen tanks take advantage of CFRP properties (the next generation of hydrogen tanks will be made almost entirely of CFRP [8]). The market for carbon fibre composites is therefore expected to grow with the development of hydrogen powered vehicles. The market size of composites in the hydrogen transportation field is expected to grow from 10 M$ in 2020 to 110 M$ in 2030 [8] and this will probably be reflected on the carbon fibre composite market. According to [36], the growth rate of the carbon fibre demand for the automotive industry is estimated around 50%.

c) Sports and leisure:

i. Bikes:

Carbon Fibre Reinforced Polymers have well penetrated the bike market, especially in sport bikes such as racing, mountain, gravel or triathlon bikes. CFRPs have more recently been introduced in electrical bikes, for which the lightweight is important for the battery energy consumption. Nowadays, few parts of a bike can be built with CFRP: the frame, the fork, the handlebar, the rims, the seat post or even the saddle. This material competes mainly with steel, aluminium or titanium, that are heavier but much more cost-effective.

Cycling is one of the Swiss' favourite sports, with 42% of the population citing cycling as a sport they practice and 7.9% citing mountain biking MTB, according to a national study [54]. Moreover, 501'829 bikes have been sold in 2020 in Switzerland including: 233'074 sport bikes, 97'622 city bikes and 171'133 electric bikes [55]. The TABLE 4 below details the different bike sales in Switzerland:

TABLE 4 - Details on the sales of bikes in Switzerland, in 2020

Category	Type	2020 sales
Sport	Mountain bikes	129’374
	Cross bikes	14’004
	Racing bikes	24’424
	Triathlon & Time trial bikes	364
	Gravel	8’686
	Junior freestyle	56’222
	TOTAL	**233’074**
City	City bikes	81’384
	Junior bikes	14’054
	Special bikes (tandems…)	2’184
	TOTAL	**97’622**
E-bikes	Mountain e-bikes	68’234
	Road e-bikes	675
	Gravel e-bikes	184
	City e-bikes	100’101
	Cargo e-bikes	1’939
	TOTAL	**171’133**

Interview: the Sustainability Manager of Scott Sports Mr. Andrew Goodman (discussion on 29.07.2021) provided some orders of magnitude concerning the number of carbon fibre frame bikes sold every year in Switzerland by the company. These values allowed to give a certain credit to the final metric based on the market share of Scott Sports. He also added that Scott Sports does not produce e-bikes containing carbon fibre composites. Finally, they are currently participating in different projects in order to improve the end-of-life management and the recycling of CFRP bikes but they also take the advantage that a bike is an assembly of hundreds of mechanical parts hence it is a reparable product that can have an very long lifetime.

Furthermore, according to Velosuisse, the Swiss association of bicycle suppliers, the market share of carbon fibre composites in bicycles is estimated to be around 20 to 25%, representing about 60’000 to 75’000 bikes per year in Switzerland. They have estimated also that their share in the e-bike market is less than 10%, representing approximately 15’000 bikes.

Assumptions:

1. Due to the lack of data concerning the share of carbon frames in bicycle fleet, this study considers 90’000 carbon bikes sold each year in Switzerland, based on the estimation of Velosuisse.
2. The carbon content of a bike differs according to the type of bike. Indeed, a time trial bike is built with as many carbon parts as possible (frame, fork, handlebar, rim, seatpost…) while other types can only have a carbon fork or a carbon frame. A carbon frame weighs in general between 700 and 1100 g [56] and adding the fork and the seatpost, which is the most common

configuration for carbon bikes, the mass of CFRP reaches 1.5-1.6 kg, which is consistent with the weight indication given by the Manager of Scott Sports during the interview.

Final metric value: multiplying the number of carbon frame bikes sold per year in Switzerland (~90'000 units) by an average weight of 1.5 kg results in 135'000 kg CFRP. The lifetime of a bike can vary a lot depending on the maintenance but manufacturers recommend to change the carbon frame after 6 or 7 years [57]. Taking into account this lifetime, <u>the final metric *A* is worth at least 19'286 kg CFRP/year.</u>

End-of-life: the bicycle industry is active concerning the end-of-life bikes question and especially the recycling of them. Indeed, according to Mr. Goodman, they are currently working on different projects regarding carbon fibre composites waste management. Moreover, there is for example, Velo Plus, a Swiss bike retailer which collects carbon bike frames to send them to recycling in Germany, at CarbonNxt. Finally, there are also different associations that collect end-of-life bikes in Switzerland in order to fix them and then to rent them to other customers [58] or to export them in other countries [59]. However, in general, end-of-life or old bikes just stay a long time stored at customers' houses and end up being thrown away at disposal waste centres one day.

Discussion: the main source of uncertainty is the number of carbon bike frames sold every year in Switzerland or in other words, the market share of carbon frames. However, 90'000 should be not so far from the reality. Indeed, as mentioned before, the sales of Scott Sports in the Swiss market have been taken as a basis and thanks to an estimation of the market share of this brand (according to a survey done in Germany, Austria and Switzerland [60], 3.3% of the respondents ride a Scott mountain bike), a certain consistency of the final result is ensured.

Future growth: in general, the penetration rate of composites in sporting goods is not increasing very fast and the demand for carbon fibres is estimated to grow at a rate of 15% approximately [36]. In Switzerland, the popularity of cycling is in constant growth: in 2008, 35% of the population rode a bicycle (including MTB) [61], in 2014, 38.3% of the population cited cycling as their sport and 6.3% MTB [62] and in 2020, 42% of the population cited cycling and 7.9% MTB [54]. Therefore, the bicycles sales should follow the same trend and as a consequence, those of carbon fibre bikes too. Moreover, the market of e-bikes is growing very quickly in Switzerland, especially mountain e-bikes [63] and as mentioned, the market share of carbon frame in e-bikes is less than 10%. A significant growth of penetration rate could then be expected in the bicycle market in the coming years.

ii. Skis and snowboards:

Skis and snowboards are quite complex products requiring different materials arranged in layers in order to fulfil the requirements. Indeed, they are highly subjected to bending, torsion or different impacts while at the same time, they must offer comfort and good handling to customers, all of this keeping the mass as low as possible. Both skis and snowboards are generally composed of a hardwood core surrounded by composite sheets. The most common reinforcement material for those composite layers is glass but carbon and Kevlar are also common. The structure is shown in FIGURE 4 in introduction.

Skiing is the fourth most practiced sport in Switzerland, with more than 35% of Swiss practicing it and 5% go ski touring [54]. The Swiss' ski federation counts 95'000 members, including 290 professional athletes [64]. In 2015, the Federal Customs Administration announced that 320'262 pairs of skis have been imported, including downhill and Nordic skis (and probably touring skis) [65]. Regarding snowboards, there is no direct data on the sales but assuming that 2.520 millions of Swiss ski while 367'000 use a snowboard [66], it can be considered that the ratio of snowboards sold to ski sold is equivalent to the ratio snowboarder/skier and this gives nearly 46'641 snowboards purchased in Switzerland every year.

Assumptions:

1. All imported pairs are sold.
2. The most common density for CFRP is 1'550 kg/m^3 [67].
3. Due to a lack of data about the part of skis and snowboards that are made out of carbon fibre composites, a market share of 20% is assumed, based on the market share of carbon bikes. Indeed, skis and snowboards using carbon fibre layers are mainly for high-end and high-performance products so that it does not represent the majority of skis.

As mentioned before, composites are used in skis and snowboards as reinforcing layers surrounding the wood core. It has been estimated that in snowboards, the composite skins have a volume of 0.5 dm^3 and about 0.8 dm^3 in a pair of skis [68]. Considering a common CFRP density of 1'550 kg/m^3, this gives 775 g and 1'240 g of CFRP in a snowboard and in a pair of skis respectively.

Final metric value: assuming CFRP is present in 20% of skis and snowboards, the total amount of carbon fibre products is consequently 64'052 pairs of skis and 9'328 snowboards containing carbon fibres sold every year in Switzerland. Then, by taking into account that roughly 775 g of CFRP are contained in a snowboard and 1'240 g in a pair of skis, this results in a total of 86'654 kg CFRP. Finally, ski manufacturers recommend to change skis every four to five years for intermediate use (between 80 and 100 days of use) [69] hence the metric *A* is equal to at least 17'331 kg CFRP/year.

End-of-life: there are different possibilities for end-of-life skis and snowboards: first, they can be sold to another user if they have been well maintained, or if not, users can dispose them in waste collection centres with municipal waste or they can put them to recycling in "bulky items" [70].

Discussion: the number of pairs of ski sold every year in Switzerland seems to be consistent with the data found for border countries such as Germany and France, in proportion to the number of local skiers. However, there are two main sources of uncertainties: the share of CFRP on the ski market and the lifetime of skis, since most of the time, when a skier changes its skis, he/she sells the old ones to another person so that the lifetime can be longer than 4 or 5 years. Concerning the share of CFRP, the part of this material in skis should not be more than 20% because they are a lot of people that practice skis as recreational sports and do not need very high-performance skis. According to the report of the Federal Office of Sport OFSPO [54], only 1.7% of Swiss practice ski as their main sport.

Future growth: skiing has been among the most popular sports in Switzerland for several years and the number of Swiss that ski stayed approximately constant since 2014 (35.4% of the population in 2014 [62], 34.9% in 2020 [54]). As a result, ski sales are not expected to increase significantly over the next few years and thus the demand for carbon fibre composites into these products is not expected to increase as much.

iii. Tennis rackets:

In the racket manufacturing field, the term "graphite" is employed instead of Carbon Fibre Reinforced Polymers. However, there is no major difference between graphite fibres and carbon fibres, the main difference is located in the composition: carbon fibres contain less than 10% of nitrogen, around 1% of oxygen and less than 1% of hydrogen whereas graphite fibres are almost pure carbon (around 99%) [71]. By extension, the term CFRP will also be used for graphite fibre composites. In tennis rackets, graphite is widely used for the frames and competes against metals, mainly aluminium. But currently, CFRP is the most used materials for confirmed and intensive players but frames generally contain additional components such as Kevlar fibres, boron fibres or more recently titanium fibres [72].

The Swiss Tennis federation has 161'271 active members (111'793 adults (69%) and 49'478 juniors (31%)) [73] and between 500'000 and 600'000 Swiss play tennis as a leisure, according to the director of the Swiss Tennis Popular Sport department. Furthermore, according to the Federal Customs Administration [74], 66'845 tennis rackets were imported in 2011 in Switzerland so this data will be taken as reference in what follows.

Assumptions:

1. All the imported goods are sold.
2. CFRP is the main material for racket frame, the weight of the possible other constituents are neglected.
3. The percentage of racket models made of graphite available on the website of the main brands represents the market share of graphite in the market of tennis rackets.
4. The share of rackets that are adult models is the same that the share of tennis players that are adults.

The TABLE 5 below regroups the number of models proposed by the 5 mains tennis racket manufacturers (Wilson [75], Babolat [76], Head [77], Prince [78] & Tecnifibre [79]) and the percentage of these models made out of graphite:

TABLE 5 - Analysis of the penetration rate of graphite in tennis rackets

Category	Number of models	Percentage made of graphite
Adults	213	89%
Juniors	145	17%

Final metric value: based on the assumptions given above, 20'660 tennis rackets imported yearly are junior models and the remaining 45'985 are adult models. Then, according to the penetration rate given in TABLE 5, this ends up in 3'512 graphite junior tennis rackets and 40'927 graphite adult tennis rackets. Furthermore, a tennis racket weighs in average 300 g [80] and there are some small parts in a tennis racket, such as stringing, grip, heel or grommets so that approximately 10 wt.% of the racket is not the frame. As a consequence, a total weight of 11'999 kg of CFRP frames are sold every year in Switzerland. Finally, in general, tennis rackets last between 2 and 6 years [81] thus taking 4 years as an average lifetime, the final metric *A* is equal to 3'000 kg CFRP/year.

End-of-life: no special regulation or collecting channels concerning end-of-life rackets. According to the director of the Popular Sport department, their members just either give/sell their old rackets or they dispose them in waste collection centres.

Discussion: the first assumption that all the tennis rackets imported are sold is potentially an overestimation of the Swiss sales. However, as mentioned, the number of members is close to 160'000 and there are between 500'000 and 600'000 leisure players in Switzerland, then the imports correspond to around one new tennis racket per eight players which seems rational.

Future growth: graphite, i.e. carbon fibre composites, is already the main player in the tennis rackets market and a very large part of the rackets are nowadays made out of graphite so that this market is not likely to increase significantly. Moreover, the number of tennis players in Switzerland stays relatively constant over the years (5.2% of the population played tennis in 2014 [62] and 5.4% in 2020 [54]) hence the sales of tennis rackets might follow this trend.

iv. Golf clubs:

As for tennis rackets, CFRP is called "graphite" in the golf dictionary and it strongly penetrated the market during last decades. Indeed, this material has an increasing popularity in golf equipment because golf clubs with CFRPs parts are lighter, enabling a higher club velocity hence longer shots. Carbon fibres can be used in different parts of a club: the shaft, the sole or the back while the other parts require properties only achievable with metals. In volume, graphite composites can potentially cover between 75 and 80% of a club [17].

There are different club types according to the desired shot length and CFRP is more or less use regarding the type:

- For drivers and woods, almost all shafts are made of graphite [82]. There are also some manufacturers that use CFRPs in club's heads.
- For irons and wedges, CFRPs can compose the shaft, the back and/or the sole. But metals, especially steel, are also widespread for irons.
- For the putter, CFRPs is almost not used because of the requirements of this type of club.

In Switzerland, there are 89'236 golfers registered with 60% of males, 34% of females and 6% of juniors [83]. According to the Federal Customs Administration, over the past five years, 87'791 kg of golf clubs have been imported every year in average [84].

Assumptions:

1. All the imported goods are sold.
2. Based on the golf clubs contained a professional player's bag (14 clubs) [85], a beginner's one (10-11 clubs) and a junior's one (7 clubs) [86], an "average" set of clubs has been determined in order to estimate the sales for each type of club. The TABLE 6 below summarises the clubs inside such a set with their weight:

TABLE 6 - Estimated average golf bag with the weight of each club

Type	Golf club	Average weight [g] [87]
Woods	Driver	336
	3-wood	395
	5-hybrid	431
Irons	5-iron	435
	6-iron	440
	7-iron	444
	8-iron	449
	9-iron	458
	Pitching Wedge	463
	Sand Wedge	1'133
Putter	Putter	531
	TOTAL	5'515

Given these assumptions, this ends up in approximately 15'920 "average" golf sets sold yearly and consequently, the TABLE 7 indicates the sales for each type of clubs:

TABLE 7 - Annual sales of each type of golf club

Type of club	Annual sales
Woods	47'760
Irons	111'440
Putter	15'920

According to the literature [82], in 2011, almost all wood shafts were made of graphite and then considering that graphite popularity has increased, the assumption that every wood shaft are built with graphite. For the irons, the assumption that half of the shafts are graphite and the second half are steel based on reference [88]. Finally, the penetration rate of graphite in putters is close to zero.

Final metric value: this results in approximately 103'840 graphite shafts sold every year in Switzerland. Moreover, a graphite shaft generally weighs between 50 g and 85 g [89] so that between 5'192 and 8'826 kg CFRP are sold every year in Switzerland in golf club shafts. Finally, according a survey [90], around 57% of golfers change their club before or every 4 years and 43% keep them for more than 4 years. Hence, given an average lifetime of 4 years for a golf club, the final metric A ranges between 1’298 and 2’207 kg CFRP/year.

End-of-life: there is no special regulation or collecting channels at the moment concerning golf clubs that are no longer usable, but things are evolving. For example, Swiss Golf federation is partnering with Swiss-Recycling in order to develop sustainability in Swiss golfs [91], consequently, some recycling possibilities can be expected during coming years. However, most of the times, when golfers have clubs that they no longer want, either they dispose them in waste collection centres or they sell/give them to another golfer.

Discussion: as before for tennis rackets, the number of golf clubs is probably a bit overestimated since not all the golf clubs that are imported are necessarily sold, some will never be retailed. However, in Switzerland, there is no regulation concerning unsold goods [92] so that those products are generally either sold at very low prices in outlets or just disposed in waste collection centres and then they can potentially enter in the waste stream. There are also club types that are more sold than others thus the “average” club set has probably introduced some deviations. However, this analysis considered only the shaft while there can have some other parts of a golf club that can contain graphite but they have been neglected due to lack of data and this can compensate a bit the potential overestimation on annual club sales. In summary, the obtained metric gives a good order of magnitude of the weight of CFRPs contained in golf clubs in Switzerland.

Future growth: graphite is already a key player on golf clubs market and its penetration rate in clubs is already at its maximum because the remaining parts cannot be made out of composites because they require metal-like properties. However, golf increases its popularity in Switzerland, with a share of 1.2% of the population in 2008 [61], 1.8% in 2014 [62] and 2.3% in 2020 [54] then the sales of golf clubs should probably grow up at the same time and then a slight increase in the carbon fibre demand could be expected for this market.

v. Hockey sticks:

Hockey sticks are quite complex parts that must have different properties such as the ability to store and release an important amount of energy or to resist to important bending loads during games. Then, composites have deeply penetrated the market and currently, almost all professional hockey players are equipped with a CFRP stick. However, as mentioned, they are subjected to important loads and some usually break during games. Indeed, professional players usually change their stick more than once per match which ultimately leads to an important amount of waste. In NHL, the national league in USA, it has been reported that around 5’000 sticks are used per team and per season. This represents about 2.5 sticks per player per game [93]. For recreational hockey, it is more around 2 or 3 sticks per year [94].

Hockey is among the most famous sports in Switzerland, in terms of media coverage and TV broadcasting but it is not so much played. Indeed, the national federation counts about 27’000 members and 300 clubs [95] while there are 380’000 gymnasts and 281’521 football players [96].

There are two professional hockey leagues in Switzerland: the National League and the Swiss League. In TABLE 8 below is presented a summary of both leagues, the number of teams and the number of match played by the teams during one season:

TABLE 8 - Summary of the Swiss hockey leagues

League	Number of teams	Number of match played in one season by each team
National League	13	52
Swiss League	11	44

Currently, all the professional players use full CFRP sticks whereas those for amateurs can be made out of wood, aluminium, GFRP or plastics such ABS. Indeed, blades are generally built with GFRP or ABS and shafts are a mix of carbon and glass fibre composites. A stick weighs between 415 and 475 g, so that an average weight of 445 g can be considered.

Assumptions:

1. Professional players consume 2.5 sticks per game like in NHL.
2. The remaining members of the federation use 2 or 3 sticks per year.
3. One season is equivalent to one year.
4. All the professional player's sticks are 100% CFRP while the other can be made with cheaper materials (foam are generally used in the blade but foams have very low density and the pieces are relatively small so that the mass of foam can be neglected).
5. All the 300 federation club's players use CFRP sticks, i.e. about 6000 amateur players use CFRPs sticks.

Final metric value: according to the data on TABLE 8, 23'200 sticks are consumed by professional hockey players each year in Switzerland, which represents approximately 10'324 kg of CFRP per year. In addition, about 81'000 sticks are used each year by recreational or amateur hockey players but as mentioned before, not all the sticks are CFRP. Considering the assumption n°5, about 18'000 additional CFRP sticks are bought every year. Therefore, 41'200 CFRP sticks represent an annual amount of carbon fibre composite of around 18'334 kg. The final metric *A* is consequently equal to 18'334 kg CFRP/year.

End-of-life: there is no special regulation or collecting channels concerning end-of-life sticks, but a lot of the sticks are probably withdrawn because they have been broken during a game thus one can expect to find a relative high part of those sticks in waste collection centres.

Discussion: the lack of information on the popularity of CFRP sticks in amateur ice hockey introduces non negligeable uncertainties into the results, but as the number of sticks used by professional players is based on the data obtained in US professional league, it gives a good idea of the order of magnitude in a first approximation. The final metric shows that the waste stream coming from hockey could be very large, especially if the unihockey sticks market (see below) is added. This is mainly due to the very short lifetime of a hockey sticks compared to other sporting goods such as tennis rackets or golf clubs.

Future growth: no special growth could be expected for hockey sticks carbon fibre demand since CFRP is currently one of the most used materials for these products. Furthermore, the number of Swiss that practice ice hockey is not increasing either (1.2% in 2014 [62], 1.1% in 2020 [54]). Finally, main consumers of hockey sticks are professional leagues and this would not change in the future so that the metric should not change significantly.

vi. Unihockey sticks:

Unihockey sticks are similar to ice hockey ones except their blade. Indeed, they are composed by a shaft, mainly made of composites nowadays while the blade is built with polymers such PE or PP. Furthermore, the weight of the stick is crucial in unihockey as the whole stick must weigh a maximum of 380 g [97]. Consequently, carbon-based sticks are preferred in most of the cases, except for beginners and for school purposes [98].

In Switzerland, unihockey is more practiced than ice hockey, with a share of 1.7% of the population [54] (1.1% for ice hockey) and 0.6% playing unihockey as their main sport (0.3% for ice hockey). According to the Swiss federation, more than 500'000 people play unihockey "regularly" in Switzerland and the federation counts 33'976 license holders in season 2019/20 [99].

Assumptions:

1. Due to lack of data, it will be assumed that all the license holders have a CFRP stick since they have a high-end use for it.
2. Unihockey stick's blade can be exchanged when broken so that the lifetime of a stick is not short as ice hockey stick. Then, according to the Sport Director of Swiss Unihockey, the sticks have an average lifetime of one year and the players use two sticks per year.

Final metric value: following assumptions 1 and 2, 67'952 CFRP unihockey sticks are bought every year. The stick's weight ranges between 170 and 250 g with the blade weighing 70-80 g [100]. Therefore, considering that the remaining weight is only due to the shaft and that the average weights of a whole stick and of a blade are 210 g and 75 g respectively, an average shaft has a mass equal to 135 g. Hence the final metric *A* for unihockey sticks is estimated around 9'174 kg CFRP/year.

End-of-life: there is no special regulation concerning end-of-life unihockey sticks but, as for ice hockey, a relative high part of withdrawn sticks can be found in waste collection centres since when they are changed, it probably means that they have been broken.

Discussion: carbon fibre composites are very common for unihockey sticks, even for children but they are expensive. However, since unihockey is popular in Switzerland, probably more players possess a carbon fibre sticks and that the number of CFRP sticks is probably underestimated in this case. When comparing it to ice hockey, unihockey is more popular and then the difference in the number of CFRP sticks seems to be a bit too high even if there are probably less impacts and violence during unihockey games than during ice hockey ones.

Future growth: like ice hockey sticks, CRFP has already well penetrated the unihockey sticks market and this would not change in the future. Moreover, the number of people that practice this sport does not change over the years according to the federal reports (1.7% of the population in 2008 [61], in 2014 [62] and 2020 [54]) and then no significant growth is expected.

vii. Ski poles:

Like for many other sporting goods, CFRP competes mainly with aluminium on the ski poles market. Carbon fibre composites are mainly used for the pole's shaft and for high-performance usage, sometimes mixed with glass fibres. There are several advantages and drawbacks for both materials: obviously, carbon fibre poles are lighter than aluminium ones but are generally less tough, i.e. if they are loaded too much, carbon fibre poles will break while aluminium ones will generally bend irreversibly.

As mentioned earlier, skiing is the one of the most popular sports in Switzerland (35% of Swiss practice it, 5% go ski touring [54]). There is no direct data concerning the amount of pairs of ski poles sold every year in Switzerland but an estimation can be made based on the 320'262 pairs of skis imported [65] yearly. Indeed, for example, in the USA, 677'836 pairs of Alpine skis have been sold in 2015/16 [101] while an average of 528'614 pairs of poles are there sold each year [102], which corresponds approximately to 0.78 poles pair per skis pair. By applying the same trend on the Swiss market, this results in almost 249'804 pairs of ski poles sold every year in Switzerland.

Assumptions:

1. The percentage of pole models made out with CFRP available on the retailer websites [103] [104] represents the market share of carbon fibre in the market of ski poles: over almost 500 articles, 76 poles are composed of carbon fibre, i.e. a market share of 15.3%.
2. An average pole's weight of 200 g is assumed [105] and as a pole has other parts such as the grip and the washer (18 g, for example [106]), it is estimated that the shaft accounts for 80% of the weight. Consequently, an average carbon pole contains 160 g of CFRP.

Final metric value: with assumption 1, 37'471 carbon fibre ski pole pairs are retailed each year and with assumption 2, this gives about 11'990 kg CFRP. Finally, it is assumed that ski poles are changed as often as skis and then they last four or five years. <u>Hence the final metric *A* is probably greater than 2'398 kg CFRP/year.</u>

End-of-life: as end-of-life poles are generally broken, the vast majority might end up in waste collection centres with municipal waste but they can also be collected with skis in recycling points as "bulky items" [70].

Discussion: as written before, there is no direct data about the imports and the sales of ski poles in Switzerland then it is quite difficult to comment the degree of accuracy of the final metric but other assumptions are based on real data so that they are more consistent. Overall, the metric looks quite rational compared to other products like golf clubs but it needs to be refined in order to refine the analysis.

Future growth: because the market for ski poles is linked to that of skis, there are no special indicators that predict a significant growth of carbon fibre ski poles, all the more so as carbon fibre poles are already well established on the market.

viii. Country walk poles:

Exactly like for ski poles, walking poles are mainly made out of aluminium or carbon fibre composites for the same reasons. Carbon fibre poles can be preferred for trail and for Nordic walking while aluminium is generally used for hikes [107].

Hiking and mountain walking are by far the most popular sport in Switzerland, with more than 56% of the population doing it, of which 10.8% as main sport [54]. This is consequently more than 4’500’000 people that hike at least once per year. However, they do not all use walking poles and mainly confirmed and regular hikers have their poles. The TABLE 9 below details the frequency and duration of hikes done by Swiss people [108]:

TABLE 9 - Frequency and duration of hiking in Switzerland [in % of the population]

	1-5 days	6-10 days	11-20 days	21-50 days	51-100 days	101-200 days	> 200 days	Total
Up to 30min	-	-		1	-	-	1	2
31min-1h	-	1	1	2	2	2	4	12
1 to 2h	2	3	3	6	3	2	2	21
2 to 3h	3	5	6	5	2	1	1	23
3 to 5h	6	9	8	6	2	-	1	32
> 5h	2	3	3	2	-	-	-	10
Total	13	21	21	22	9	5	9	100

Assumptions:

1. All the hikers that walk at least 2 hours more than 6 days per year possess trekking poles, i.e. 54% of the hiker population.
2. The same assumptions than those used for ski poles will be taken into account: carbon fibre poles shares about 15.3% of the market, the lifetime is approximately 5 years and 20% of the weight is not due to the shaft.
3. The average weight is around 425 g per pair of poles [109]. Then, about 340 g of CFRP are used per pair.

Final metric value: applying the first assumption on the total number of hikers gives about 2'430'000 pairs of trekking poles in total in Switzerland. Then, considering that they are changed every five years, this means that about 486'000 pairs of trekking poles are sold every year in Switzerland (compared to ski poles, it is 1.6 times more while there are 1.54 more hikers than skiers). With assumptions 2 and 3, 25'282 kg CFRP are sold in trekking poles every year in Switzerland and consequently the final metric *A* is equal to 5'056 kg CFRP/year.

End-of-life: due to the similarities between ski and trekking poles, the same possibilities exist for the end-of-life products: they can be put in waste collection centres or in recycling points, where they would be valorised, i.e. probably incinerated.

Discussion: the final metric is very inaccurate due to a lack of hard data. Indeed, the actual percentage of people using trekking poles or the annual sales of poles have not been found. Moreover, the market share of carbon fibre trekking poles is not based on real data and then this introduces uncertainties. Carbon fibre poles seem to be common and then a share of 15.3% looks a bit underestimated. But in overall, hiking is very popular in Switzerland and certainly many poles are sold for this purpose, thus walking poles are likely to represent a non negligeable waste stream. Finally, the average lifetime of these products could be much longer than 5 years because there a not subjected to very high loads, so they can last a very long time.

Future growth: over the years in Switzerland, more and more people go hiking and it is now the most popular sport in Switzerland. Between 2008 and 2020, the number of Swiss people who said they hike increased from 33.7% [61] to 56.9% [54]. Consequently, the sales of hiking equipment, including walking or trekking poles, should have increased significantly since 2008. Considering this and also the fact that carbon fibre poles penetrate more and more the market, an increase of this market could be expected in the next few years.

ix. Windsurfing:

Carbon fibre composites are common materials in windsurfing industry and are used for the mast, the booms or even in the board. Indeed, the board is in general a multilayer products with different layers of foam (polyurethane, PVC and/or polystyrene) surrounded by rigid layers of composites or epoxy/polyester resin, as shown in FIGURE 5 in introduction. Therefore, as usual, carbon fibre composites compete with cheaper materials in the market of windsurfing boards.

For masts and booms, they are mainly made from aluminium or from fibre reinforced epoxy resin, with glass, carbon or a mix of both as reinforcements [110]. Finally, the sails are mainly made out of materials patented by companies named Dacron (polyester), Mylar (coated Dacron) and Monofilm.

Windsurf is among the most favourite water sports in Switzerland with 2.1% of the Swiss population practice windsurf or kitesurf [54], which corresponds to 179'445 people including 28% (~50'245) club members [111]. The number of sales for windsurfing equipment are not available in Switzerland but an extrapolation from the market in France will be done in order to estimate them. In France, in 2012, about 8'000 windsurfing boards, 10'000 masts and 10'000 wishbones/booms [112] have been sold for about 270’000 licence holders [113]. As said before, there are about 50’245 licence holders in Switzerland [54], hence using the same ratio sales over licences holders, it has been estimated that 1’480 boards, 1’852 wishbones and 1’852 masts are sold every year in Switzerland.

Assumptions:

1. Carbon fibre is not common for windsurfing sails as mentioned before so that it has been assumed that there is no carbon sails among the sales.
2. The average carbon content of windsurfing masts represents the market share of carbon fibre and the same share is taken for booms.
3. Carbon fibre layers are usually used as local reinforcements in windsurfing boards all the more so as it is not the most common material for boards, therefore the contribution of boards in carbon fibre consumption has been neglected here.

Carbon fibre composites are really common for masts and boom, probably less for the boards. Conversely, for masts and wishbones/booms, carbon is very common and widespread and they are often mix with glass fibre. The carbon fibre content generally varies between 30 and 100%. Using the assumption 2, the market share of carbon fibre in masts is around 70% [114]. For booms, carbon is also common and the same market share than that of masts is applied due to lack of data. The average weight of a mast is close to 2.1 kg [115] and that of a boom is around 2.5 kg [116].

Final metric value: taking into account all the values mentioned above, a minimum of 5’963 kg of CFRP are sold annually in Switzerland through windsurfing equipment. The lifetime of windsurfs is not necessarily expressed in years but more in number of sessions, but some opinions give a lifetime between 5 to 15 years for the wishbones and 1 to 12 years for the masts [117]. Consequently, the lifetimes considered in this study are 10 and 6 years respectively. Thus the final metric *A* is worth 778 kg CFRP/year.

End-of-life: there are no special facilities for end-of-life windsurfing equipment, users probably store it at home or drop them off at waste collection centres. The likelihood of windsurfing equipment being treated as municipal waste is therefore high.

Discussion: in order to give more accuracy to the final metric of this product, different points must be refined: the exact number of sales per year and the market share of carbon fibre composites in such products. But to conclude on this product, the volume appears quite low so that the result should not be much higher than the value found here and it should not be significant compared to high volume products such as boats, cars or bicycles.

Future growth: during the last few years, windsurfing and kitesurfing have experienced a significant growth in terms of popularity in Switzerland, with only 0.6% of the population in 2014 [62] but 2.1% in 2020 [54]. This should have boosted the sales of equipment and therefore the carbon fibre consumption. This could be explained by the fact that the Federal Council authorized the kitesurfing in Swiss water bodies which was not the case before and also the fact the windsurfing and kitesurfing equipment are more easily transported than other sailing sports equipment [111]. Therefore, the trend will probably continue and sales will follow.

x. Kitesurf:

Composites are widespread for kitesurfing boards due to their corrosion resistance and their specific strength. The wing or the kite is mainly made out of nylon or polyester. Moreover, the construction of a board is similar to that of windsurf boards with a foam (or wood) core surrounded by rigid layers but here mainly built with glass fibre or carbon fibre composites (glass fibre is the main player on the market currently) [118]. There is also the control bar that allows to steer the wing and which is usually made of aluminium, stainless steel or composites.

The popularity of kitesurfing has grown very rapidly in recent years and it is gradually taking over windsurf. As written above, 2.1% of the Swiss population practice windsurf or kitesurf [54], i.e. 179’445 people and it is estimated that there are 5’000 practitioners in Switzerland [119].

Exactly like windsurfs, an extrapolation from the French market has been performed in order to evaluate the number of kitesurf sold every year in Switzerland: in France, there are 8’000 kitesurf boards sold every year and 15’000 wings [112] for about 40’000 practitioners [120]. Consequently, considering 5’000 practitioners in Switzerland [119], the extrapolation gives about 1’000 boards and 1’875 wings.

Assumptions:

1. Carbon fibre composites are not necessarily the most used materials for both boards and control bars so that the market share should not be more than 50%. Consequently, a market share between 25 and 50% is assumed for both in order to evaluate the final metric.
2. A carbon kitesurfing board weighs between 2 and 3 kg [121] in general but a lot of different structures exist with more or less carbon layers, thus a carbon content between 500 g and 1 kg per board is assumed (for example, five layers of 300 g/m^2 carbon tape in a 137x42cm [122]) board weighs approximately 863 g).

As indicated before, the board is built with a foam core that represents the main volume and the composites skins are just thin layers around this core, but foams have generally a much more lower density compared to composites. A carbon kitesurfing board weighs between 2 and 3 kg [121] in general and a carbon control bar is around 115 g according to this example [123].

Final metric value: putting all the assumptions and estimated values together gives between 179 and 608 kg of CFRP sold in kitesurfing equipment per year. Boards have a lifetime of at least 10 years and control bars between 4 and 5 years [124], <u>consequently the final metric *A* is equal to at least 24.5 and 74 kg CFRP/year.</u>

End-of-life: exactly like windsurfing equipment, no special facility for treating kitesurfing equipment so that when users wants to replace their equipment, they sell or give them to another person or they put them at waste collection centres.

Discussion: the resulting measure is highly estimated as no concrete data was available for the kitesurfing equipment market. Information on the market share of carbon fibre composites as well as the actual number of sales per year would be needed to better assess the final measure for this category. However, at first glance, it appears to be totally negligible compared to the products evaluated in the first place.

Future growth: the same trend than for windsurfing can be expected for kitesurfing, maybe even a bit stronger than since the latter is more and more preferred to the detriment of windsurfing.

xi. Fishing rods:

Composites are currently the most common choice for the blanks of fishing rods in order to fulfil their high strength requirement while at the same time keeping the mass as low as possible to ensure a good customer's comfort. Both glass fibre and carbon/graphite fibre composite are used depending on the application and the price. Indeed, carbon fibres offer more power which can be useful for fishing big fishes. Therefore, glass fibre fishing rods are better suited for amateurs while carbon fibre rods are more adapted for confirmed fishermen.

Fishing is particularly popular in Switzerland due to the numerous lakes and rivers all over the country. According to the federal statistics on fishing, about 100'000 members take a fishing permit in Switzerland every year to fish at least one day [125]. The data from Federal Customs Administration indicates that an average of 26'747 kg (based on the previous five years) of fishing rods are imported every year in Switzerland [84].

Assumptions:

1. All the imports are sold.
2. Considering that carbon fibre/graphite is the most used materials, as found in some sources [126] [127], its market share is assumed to be between 50% and 75%.
3. In average, a reel weighs about 227 g and the whole rod's weight depends on the length: the length can vary between 2.1 m and 4 m so that a medium rod of 3 m weighs in average 650 g [128]. Therefore, the blank represents nearly 65% of the overall rod's weight, neglecting the other small parts in the rod, such as the handle.

Final metric value: with all the assumptions given previously, the weight of carbon fibre composites in fishing rods in Switzerland is estimated to range between 8'693 and 13'039 kg CFRP. However, since they are strong, they can last a very long time, i.e. specialists estimate that they can last about 40 years [129]. Consequently, the final metric *A* is estimated to stand between 217 and 326 kg CFRP/year.

End-of-life: no special regulation or collecting channels about end-of-life rods, they have to be disposed in waste collection centres where they would be treated as they should.

Discussion: carbon fibre or graphite composites are the most common material used in modern fishing rods so that the market share should not be so far from the assumption. But as before, the assumption stating that all the rods imported are sold may probably overestimate the number of fishing rods sold every year in Switzerland. However, in summary, due to its very long lifetime, the carbon fibre flux originating from fishing rods should be quite low during the coming years.

Future growth: since 2008, the number of fishing licences increases constantly [130] thus it should probably be reflected on the sales of fishing equipment, especially fishing rods. Because graphite is common for modern fishing rods, a slight growth of the carbon fibre consumption can be expected in this sector.

xii. Badminton rackets:

Exactly like for tennis, the market for badminton rackets is mainly dominated by two materials: aluminium and graphite (i.e. CFRP). Aluminium (and in some cases steel) composes low-end, beginners cheap rackets while graphite ones are more expensive and all experienced players have one in their hands. Therefore, as with tennis rackets, the most used material for badminton rackets is CFRP, called "graphite" in the field.

Badminton is more popular than volleyball, golf or table tennis among Swiss citizens with a share of 3.5% (~300'000 players) of the population but only 0.5% (43'000 active members) practice it as their main sport. According to Federal Customs Administration data, an average of 83'339 kg of badminton and squash rackets has been imported every year in Switzerland [84] during the past five years. However, it seems to be huge compared to imports of tennis rackets and then an extrapolation from the tennis rackets market will be done. Indeed, if one considers that 66'845 tennis rackets are imported for about 550'000 players and a mean lifetime of 4 years, hence for 300'000 badminton players and an average lifespan of 3 years [131], approximately 48'615 rackets are necessary.

Assumptions:

1. All the imported goods are sold.
2. For badminton, the percentage of racket models made out of graphite available on the website of the main brands represents the market share of graphite in the market: over 130 models, only 22 were not made out of graphite [132] [133] [134] [135], i.e. only 17% (including models adapted for juniors).
3. The average weight of a badminton racket is 85 g [136] without strings and grip. But this includes the handle of the racket as well as some other small parts. Then, as for tennis rackets, about 10 wt.% is not the frame and the average frame's weight is about 76.5 g.

Final metric value: with the assumptions that graphite rackets represent 83% of all rackets and that a graphite frame weighs in average 76.5 g, nearly 3'087 kg CFRP are incorporated in badminton rackets. <u>Finally, the metric *A* is equal to 1'029 kg CFRP/year with a lifetime of 3 years.</u>

End-of-life: there is no regulation, information or collecting channels for end-of-life badminton rackets but as with tennis rackets, if the racket is not broken, it can simply be sold/given but if it is broken, it is likely to end up in waste collection centres.

Discussion: the main source of uncertainty for this product is the total number of rackets sold per year in Switzerland. Indeed, the share of materials for racket frames as well as the lifetime might not be so different that the values assumed in this study. The total weight of badminton and squash rackets imported in Switzerland is very large compared to tennis rackets and following a quick calculation, it corresponds to more than 700’000 rackets, which seems highly overestimated. Then, more details about this customs data would be required to properly determine the number of rackets imported yearly. This is why the extrapolation from tennis market has been done. Therefore, in order to have a more accurate study, more precise information on the sales of badminton rackets should be found.

Future growth: exactly like tennis, graphite is currently the most used materials in the badminton racket market and this would probably not changed in coming years. Furthermore, the number of players in Switzerland has slightly decreased since 2014, from 3.2 to 3.1% of the population. Consequently, nothing predicts an increase of the carbon fibre consumption in the badminton sector.

xiii. Squash rackets:

As previously, squash rackets are mainly made from two materials: aluminium, for low-end cheaper rackets and graphite, for regular and competition players. CFRP is currently the most common material for squash racket available on website of retailers.

Squash is cited by 1.6% of the population [54] in Switzerland, i.e. 137’000 people and 0.2% (~17’0000) are regular, active players. As in the previous section, data from Federal Customs Administration data (average of 83’339 kg of badminton and squash rackets imported yearly [84]) looks to introduce important overestimation compared to data for tennis rackets. Therefore, the same extrapolation than for badminton rackets will be done. For squash, with almost 137’000 players and also a lifetime of 3 years [131], 22’200 rackets would be needed every year.

Assumptions:

1. All the imported goods are sold.
2. According to the source [137], carbon fibre represents more than 70% of the materials used for squash rackets, thus a estimated share of 75% is taken into account.
3. The average weight of a squash racket is 140 g [138] (excluding strings and additional protecting features). Removing 10 wt.% for other parts, the average frame’s weight is about 126 g.

Final metric value: with the assumptions above, 2’098 kg CFRP are used in squash rackets each year in Switzerland and <u>the final metric *A* is worth 699 kg CFRP/year (lifetime of 3 years).</u>

End-of-life: same than for badminton rackets.

Discussion: the main source of uncertainty is again the number of rackets sold per year as no value was found and the Federal Customs data does not seem to be relevant. Therefore, as before, in order to get a more accurate study of this market, it is necessary to determine the annual sales

Future growth: again, graphite is the most used materials for squash rackets but conversely to badminton, the number of players grew up since 2008 from 1.2% [61] to 1.6% [54] of the population thus an increase of the squash racket sales can be expected and as a consequence, an increase of the CFRP or graphite consumption.

d) Construction industry:

Today, concrete is mainly composed of cement, water, aggregates and various additives, but recently new types of concrete have been developed to tackle the very high CO_2 emissions associated with the construction sector. Indeed, the global CO_2 emissions produced by the cement plants constitute 8% of the whole global emissions [139] and the construction sector is responsible for 39% of the global CO_2 emissions [140]. Consequently, a lot of research has been conducted on concrete formulation, cement production as well as the addition of CFRPs in the concrete as reinforcing bars. This later method allows to produce lighter concrete, which is useful for the transport as well as for using less sand and water while obtaining better mechanical properties. CFRPs are also commonly used as reinforcing materials during maintenance and reparation operations of existing concrete structures. Therefore, the adoption of carbon fibre composites in the construction industry is constantly increasing for the past few years, representing now a global Carbon Composites consumption around 8.6 ktons per year [1].

In Switzerland, the consumption of building materials is one of the highest in the world. For example, the annual Swiss consumption of cement is the fifth highest in the world at 584 kg every year per capita, behind Saudi Arabia, China, South Korea and Turkey [141]. Regarding CFRPs, some Swiss companies produce and sell reinforcing bars for construction, like Sika [142], and some projects already implemented concrete prestressed by a CFRPs network, like a small bridge for cyclists in Winterthur [143].

Assumptions:

1. The ratio of CC used in the construction sector over the total consumption of building materials is the same in the world and in Switzerland.
2. The average densities of the main building materials are as follows: 2'500 kg/m^3 for concrete, 7'850 kg/m^3 for steel, 1'700 kg/m^3 for bricks, 1'440 kg/m^3 for cement and 500 kg/m^3 for wood [144].

The annual consumption of building materials worldwide was estimated at 28.7 billion tons in 2020 [145] and as mentioned in introduction, the world consumption of Carbon Composites in construction was approximately 8.6 ktons in 2020 [1], i.e. approximately 3.10^{-5} % of the overall building materials consumption. In Switzerland, more than 19 million cubic meters of building materials are consumed each year, with the following repartition: 16 million m^3 of concrete, 1.6 million m^3 of cement, 1 million m^3 of wood, 0.6 million m^3 of bricks and 0.14 million m^3 of steel [146]. This results in approximately 44.9 million tons of building materials using the corresponding densities mentioned above. Using the ratio derived just before, the annual Carbon Composites consumption for the building sector in Switzerland is about 13’476 kg.

Final metric value: the average life span of buildings in Switzerland is estimated between 70 and 100 years according to real estate experts [147], the final metric *A* is therefore at least 134.7 kg CFRP/year for the construction sector, considering the maximum lifespan of buildings.

End-of-life: the problem of end-of-life building materials constitutes nowadays a burning point in Switzerland, because the annual amount of destruction waste is tremendous. Therefore, the recycling channels of this type of materials are well established in Switzerland and today, between 80 and 90% of the waste are recycled in the country [148]. In addition, various recycling associations exist to further develop the circular economy in the construction industry. However, there is no special regulation or research regarding the recycling of CFRP-reinforced concrete and this would probably be a problem when these structures will reach the end of their life, as the benefits of CFRP reinforcements may be lost during recycling.

Discussion: the uncertainty is concentrated on the share of CFRPs in the total building materials in Switzerland. Indeed, this CFRP-reinforced concrete technology is already implemented in Switzerland (like in the bridge for cyclists in Winterthur) and it is also known that various structures across the country use Ultra High-Performance Fibre Reinforced Concrete (UHPFRC) [149] but the fibres are usually steel or polymer. The total amount of CFRPs in the construction sector is probably overestimate.

Future growth: implementation of CFRPs in the construction field has an important potential because it will allow to reduce the use of concrete up to 50% and the associated CO_2 emissions by 70% [150]. Consequently, the consumption of Carbon Composites in the building sector is expected to increase rapidly in the coming years, at an estimated annual long-term rate of 9% [151]. However, this growth is also strongly linked with the evolution of the price of carbon fibre, since steel reinforced concrete is quite inexpensive.

e) Medical sector:

Several applications in the medical sector take advantage of the properties of Carbon Fibre Reinforced Polymers, such as prostheses, orthoses, medical instruments or assistive devices for the disabled persons. Indeed, CFRPs are transparent to X-rays, stiff, strong and light which is very useful for the applications mentioned before. For prostheses, CFRPs are mainly used for high-end products, such as in prostheses for disabled sportsmen or sportswomen.

In Switzerland, it exists a registry of prostheses but only for knee or hip prostheses, therefore it is quite hard to find reliable data and then estimate the market volume .

Interview: according to the General Manager of the medical sector of Composites Busch SA, Dr. Nicolas Bernet (discussion of 03.11.2021), the market for medical carbon fibre products is small in Europe and may very likely be negligible compared to the other products detailed above. Indeed, carbon fibre prostheses are by far more commonly used in the USA, while in Europe, alternative materials are preferred. Consequently, no further analysis of this sector has been done.

End-of-life: however, according to Dr. Nicolas Bernet, there is currently no recycling channel for medical or orthopaedic carbon fibre devices in Switzerland, thus most products are incinerated. Moreover, these products cannot be reused after contact with a patient for contamination reasons, consequently the life span of prostheses or orthopaedic assistive devices goes from a few weeks to a few months, but not more.

Future growth: CFRPs can be used in many applications in the medical sector because of their attractive properties, but the cost of carbon fibre parts is a barrier to a more important market penetration. However, as mentioned before, the cost is constantly decreasing with the increasing consumption of these fibre and then, in the coming years, the volume of carbon fibre composites used in the medical sector will increase.

4. Conclusions: general ranking, interpretation & ways of improvement:

First of all, another source of carbon fibre waste, which is not a consumer product but is non negligible, must be added and can be a reference to compare the obtained results: the manufacturing waste, i.e. cut-offs of carbon prepregs, outdated tapes, etc. According to the Managing Director of Composite United Switzerland Mr. Stève Mérillat (discussion on 21.07.2021), it is estimated to represent about 20 tons every year in Switzerland. This is consequently the biggest stream of carbon fibre waste compared to the obtained final metrics and it can be expected to increase significantly in the future, following the increasing demand of carbon fibre composites. Most of this waste ends up in waste collection centres nowadays, but a recycling system is being set up to collect and send them to recycling facilities.

The FIGURE 6 below summarizes all the metrics:

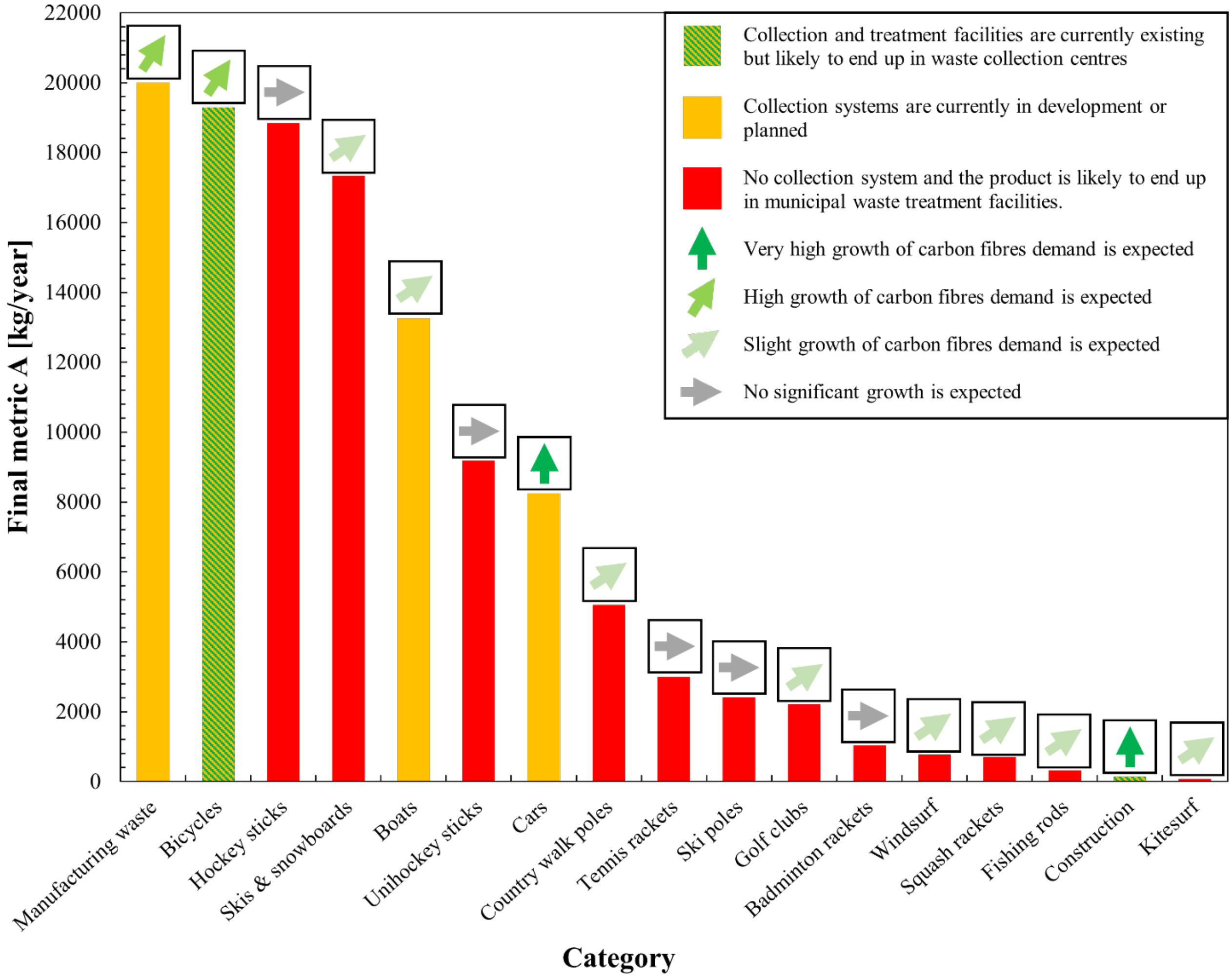

FIGURE 6 - General ranking of all evaluated goods according to their final metric A

The sum of all the metrics is then equal to 121.8 tons of CFRP/year and the first six categories, i.e. manufacturing waste, bicycles, hockey sticks, skis & snowboards, boats and unihockey sticks account nearly for 80%. It was rather predictable that boats, bicycles, skis & snowboards and cars have an important contribution in the carbon fibre demand but the high values for both ice hockey and unihockey sticks appear more surprising since these sports are not among the most practiced in Switzerland. But their metrics are so high because of the very short lifetime, hence a lot of waste are produced. Moreover, for twelve categories representing approximately 61 tons of waste per year, i.e. 50.1% of the total, no collection system is currently in place and, as a result, these products cannot be transported to recycling facilities and are therefore most likely to be found at waste disposal sites.

Depending on the application and the desired properties, the fibre content in a composite varies, in general between 40 and 60 wt.%. According to the values given in introduction, the total demand for Carbon Composites reached 144.2 ktons in 2019, of which 138 ktons contain polymer matrices (~95.7%) while the demand for carbon fibre was about 82.5 ktons [1]. Considering that 95.7% of the fibre are used in CFRPs, the average carbon fibre content in CFRP is estimated around 57.2 wt.%. Consequently, the estimated carbon fibre weight that can end up in waste treatment facilities every year in Switzerland is around 69.7 tons.

It should be noted that there are also other goods where carbon fibre composites are usually used that have not been studied in this analysis, like for examples athletic goods, camera mono-, bi- or tripods, bows and arrows. But when analysing the FIGURE 6, the fact that the first six products represent more than 80% of the total gives a certain relevance to the study. Indeed, for these products, the result is based on quite reliable data that has been found in internet or from people involved in the sector, and then a certain accuracy is ensured.

However, a lot of parameters and values have been estimated and numerous assumptions have been taken, as detailed in every section. Therefore, they are several ways to refine this study by finding more precise data on market shares, on annual sales. For this, it seems to be appropriate to contact companies and actors from each sector in order to obtain information or advices.

Furthermore, another source of carbon fibre waste has not been studied but can represent an important amount in total. Indeed, generally when companies use carbon fibre composites, they have to made moulds for the processing and to avoid thermal expansion issues, they are generally made of CFRP and they can even be heavier that the final part. Overall, the fact that the metrics of the most consumed products and the annual production waste are of the same order of magnitude gives relevance to the results.

Finally, we have seen in a first hand that there are not a lot of recycling facilities for carbon fibre products inside the country and consequently, the major part of the consumer products are likely to end up in waste collection centres with municipal waste. However, there are nowadays three main well established recycling technologies for carbon fibre composites [152] [153]:

- **Mechanical recycling:** composites are ground, shredded, crushed then sorted and sieved in order to obtain a powder recyclate that can be used as a substitute for either the matric or the fibres, or as a filler in new composite materials or in concrete, asphalt… The advantage of this method is that it allows to treat easily a high volume of waste but the in the recyclate, fibres became short and then the advantage of long fibre have been lost.
- **Thermal recycling:** the matrix is degraded either by pyrolysis or by thermo-oxidation using a fluidised bed in order to recover the fibres. By pyrolysis, the matrix is degraded at controlled temperature and pressure and it results in a mixture of oils, gases and other

components that can be further valorised as substituents of fossil fuels. However, it is generally not suited for end-of-life products that can contain other components but rather for manufacturing pure composite waste. With fluidised bed technique, the fibres are recovered by degrading the matrix using a flow of hot air and silica sand but in general, their tensile strength and their length decrease. But thermal recycling allows to recover long fibres that can be further processed into new long fibre composites.

- **Chemical recycling:** with this technique, the matrix is degraded by solvolysis or by steam thermolysis in order to recover long fibres like the thermal recycling. Solvolysis is still at lab scale level but steam thermolysis starts to be implemented at industrial scale. It has also several drawbacks: loss of fibre-resin adhesion, depends on matrix composition, sensitive to mixed composite waste.

To conclude, different recycling technologies exist today for carbon fibres composites and some of them are suitable on an industrial scale, mainly pyrolysis and mechanical processing, but they also have drawbacks. However, recycling will be necessary in the coming years in order to compensate for the shortage of resources compared to demand and especially to better valorise the expected increasing volume of carbon fibre composite waste.

5. References:

[1] M. Sauer, "Composites Market Report 2020 - The global CF Market 2020 - Market Development, Trends, Outlook and Challenges," 2020.

[2] M. S. &. M. K. (. Dr. Elmar Witten (AVK), "Composites Market Report 2017 - Market developments, trends, outlook and challenges," 2017.

[3] M. S. &. M. K. (. Dr. Elmar Witten & Volker Mathes (AVK), "Composites Market Report 2018 - Market developments, trends, outlooks and challenges," 2018.

[4] S. G. L. J. B. P. G. S. Anaële Lefeuvre, "Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050," *Resources, Conservation and Recycling,* vol. 125, pp. 264-272, 2017.

[5] S. T. G. A. R. K. P. &. R. K. G. Shama Rao N., "Carbon composites are becoming competitive and cost effective," 2018.

[6] A. Bledzki, H. Seidlitz, K. Goracy, M. Urbaniak and J. Rösch, "Recycling of Carbon Fiber Reinforced Composite Polymers—Review—Part 1: Volume of Production, Recycling Technologies, Legislative Aspect.," *Polymers,* vol. 13, no. 2, p. 300, 19 January 2021.

[7] V. S. C. H. W. C.-H. W. Jin Zhang, "Current status of carbon fibre and carbon fibre composites recycling," *Composites Part B: Engineering,* vol. 193, 2020.

[8] J. Group, JEC Observer - Current trends in the global composites industry 2020-2025, 2021.

[9] C. Y. B. Pu Liu, "Wind Turbine Blade Waste in 2050," 17 Charles Babbage Road, Cambridge, United Kingdom CB3 0FS.

[10] L. Rousselle, "Et si on arrêtait d'enfouir les pales d'éoliennes?," *L'Usine Nouvelle,* 20 February 2019.

[11] Golfers Authority, "TPT Red Range Golf Shaft Review," [Online]. Available: https://golfersauthority.com/tpt-red-range-golf-shaft-review/. [Accessed 28 October 2021].

[12] "Essai BMW i3 : L'électrique électrisante?," 12 Janvier 2014. [Online]. Available: http://www.automotive-marketing.fr/8550/essai-bmw-i3-lelectrique-electrisante. [Accessed 12 August 2021].

[13] "Ski Construction," [Online]. Available: https://www.mechanicsofsport.com/skiing/equipment/skis/ski_construction.html. [Accessed 11 August 2021].

[14] "LES PROCÉDÉS DE FABRICATION DES PLANCHES DE WINDSURF," 19 June 2019. [Online]. Available: https://www.f2windsurfing.fr/les-procedes-de-fabrication-des-planches-de-windsurf/. [Accessed 11 August 2021].

[15] I. A. T. A. IATA, "Best Industry Practices for Aircraft - Decommisioning Mannual," 2018.

[16] "Démantèlement et recyclage des éoliennes," 30 September 2020. [Online]. [Accessed 22 July 2021].

[17] J. Group, Overview of the global composites market - At the crossroads, F. Reux, Ed., Paris, 2017.

[18] "EXPLORING THE HULL MATERIAL USED IN MODERN BOAT DESIGN," 30 April 2018. [Online]. Available: https://www.shmgroup.com/blog/exploring-hull-material-used-modern-ship-design/. [Accessed 4 August 2021].

[19] Internal Council of Marine Industry Associations ICOMIA , "Recreational Boating Industry Statistics 2017," Egham, Surrey, TW20 8BF, United Kingdom, 2017.

[20] S. GÖLPINAR, "COMPARATIVE ANALYSIS OF MATERIALS IN RECREATIONAL BOAT DESIGN: FIBER REINFORCED PLASTIC BOAT IN SERIAL PRODUCTION," Izmir, 2005.

[21] B. Ertuğ, "Advanced Fiber-reinforced Composite Materials for Marine Applications," *Advanced Materials Research,* vol. 772, pp. 173-177, 04 September 2013.

[22] "Marine Application of Fiber Reinforced Composites: A review," *Journal of Marine Science and Engineering,* vol. 8, no. 1, 6 January 2020.

[23] D. Wade, "Average Sailboat Size," 8 July 2021. [Online]. Available: https://www.lifeofsailing.com/post/average-sailboat-size. [Accessed 4 August 2021].

[24] D. Wade, "Average Sailboat Mast Height," 21 July 2021. [Online]. Available: https://www.lifeofsailing.com/post/average-sailboat-mast-height. [Accessed 5 August 2021].

[25] M. Hoffstetter, "Faute de tropiques, les Suisses investissent dans les bateaux," *Bilan,* 28 March 2021.

[26] Seldén, "Bômes carbone Seldén".

[27] Seldén, "MÂTS EN CARBONE".

[28] P. Desmedt, "Les secrets des voiles en composite qui vont gagner le Vendée Globe," *L'Usine Nouvelle,* 3 November 2016.

[29] Say Carbon Yachts, "Say 29 - Specifications," [Online]. Available: https://saycarbon.com/en/pdf/SAY_Carbon_Yachts_SAY_29_Booklet_2020.pdf. [Accessed 9 August 2021].

[30] Volvo Penta, "VOLVO PENTA INBOARD DIESEL," [Online]. Available: https://www.volvopenta.com/marine/products/inboard-shaft/inboard-shaft-engine-range/#/all. [Accessed 9 August 2021].

[31] S. Buckles, "Average Weight of Sailboat Keels (5 Most Common Types)," [Online]. Available: https://improvesailing.com/sailboat/keel/weight. [Accessed 8 November 2021].

[32] P.-M. Bourguinat, "Le sandwich : à boire et à manger," *Voiles et voiliers,* 09 28 2010.

[33] M. Storgaard, "How Long Do Boats Last? 17 Helpful Facts (Complete Guide)," 4 July 2019. [Online]. Available: https://www.godownsize.com/boat-durability/. [Accessed 5 August 2021].

[34] V. Gillioz, "Déconstruction : les bateaux se cachent pour mourir," 3 June 2020. [Online]. Available: https://skippers.ch/swiss-sailing/actu-swiss-sailing/deconstruction-les-bateaux-se-cachent-pour-mourir/. [Accessed 9 August 2021].

[35] M. Hoffstetter, "Faute de tropiques, les Suisses investissent dans les bateaux," *24 heures,* 13 April 2021.

[36] M. Kechidi, "Le Marché des matériaux composites," *Nacelles [En ligne],* 22 May 2020.

[37] C. Red, “Automotive CFRP: The shape of things to come,” 30 November 2013. [Online]. Available: https://www.compositesworld.com/articles/automotive-cfrp-the-shape-of-things-to-come. [Accessed 27 July 2021].

[38] S. Nair, “Nissan Has Revolutionised Carbon Fibre Part Production,” 14 September 2020. [Online]. Available: https://www.dsf.my/2020/09/nissan-new-cfrp-process/. [Accessed 27 July 2021].

[39] “Recent trends in CFRP development: Increased usage in European vehicles,” 08 July 2015. [Online]. Available: https://www.marklines.com/en/report_all/rep1419_201506. [Accessed 27 July 2021].

[40] “Immatriculations des voitures par marque - Archives 2019,” 2019. [Online]. Available: https://www.auto.swiss/fr/#statistics. [Accessed 23 July 2021].

[41] “2015 Lamborghini Huracán: A Legitimate Meteorological Event,” 08 April 2014. [Online]. Available: https://www.caranddriver.com/features/a15110667/2015-lamborghini-huracan-feature/. [Accessed 26 July 2021].

[42] T. Etienne, “Lamborghini Huracan, un taureau dompté,” 01 May 2014. [Online]. Available: https://www.lefigaro.fr/automobile/2014/05/01/30002-20140501ARTFIG00144-lamborghini-huracan-un-taureau-dompte.php. [Accessed 27 July 2021].

[43] “Audi R8 Spyder V10 – Audi Space Frame,” [Online]. Available: https://www.audi-technology-portal.de/en/body/aluminium-bodies/audi-r8-spyder-v10-audi-space-frame. [Accessed 27 July 2021].

[44] D. F. M. (. A. &. D. L. H. (. C. G. &. C. K. David Roquette, *High Volume Manufacturing of Carbon Fiber Reinforced Plastics for Body in White,* 2017.

[45] J. Maxime, “LA FIBRE DE CARBONE ET L'AUTOMOBILE,” 12 April 2015. [Online]. Available: https://www.automobile-sportive.com/technique/monocoque-carbone.php. [Accessed 26 July 2021].

[46] M. Gauthier, “Lamborghini LP700-4 Aventador all-carbon fiber monocoque revealed,” 11 February 2011. [Online]. Available: https://www.motor1.com/news/25843/lamborghini-lp700-4-aventador-all-carbon-fiber-monocoque-revealed/. [Accessed 27 July 2021].

[47] G. Christian, “Englische Sportwagen im exklusiven Vergleich,” 17 June 2016. [Online]. Available: https://www.auto-motor-und-sport.de/test/mclaren-675lt-und-570s-vergleichstest/. [Accessed 27 July 2021].

[48] *Fiche Technique Toyota Mirai FCHV.*

[49] R. A. J.-K. P. M. K. S. L. K. M. K. L. J. S. Thanh Hua, “Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications,” Argonne, Illinois, 2010.

[50] “MC20 - The first of its kind,” [Online]. Available: https://www.maserati.com/ch/fr/modeles/mc20. [Accessed 27 July 2021].

[51] “Bugatti Veyron Structural Design,” 2 February 2006. [Online]. Available: https://www.motor1.com/news/7786/bugatti-veyron-structural-design/. [Accessed 27 July 2021].

[52] K. Budd, “How Today's Cars Are Built to Last,” 1 November 2018. [Online]. Available: https://www.aarp.org/auto/trends-lifestyle/info-2018/how-long-do-cars-last.html. [Accessed 27 July 2021].

[53] “End-of-life vehicles,” [Online]. Available: https://www.bafu.admin.ch/bafu/en/home/topics/waste/guide-to-waste-a-z/end-of-life-vehicles.html. [Accessed 15 July 2021].

[54] R. B. H. S. Markus Lamprecht, “Sport Suisse 2020. Activité et consommation sportives de la population suisse,” 2020.

[55] VéloSuisse, “Actualités / Statistiques,” [Online]. Available: https://www.velosuisse.ch/fr/news-statistik/. [Accessed 14 July 2021].

[56] “44 Facts of Carbon fiber Bike: The Beginners’ Complete Checklist (2019),” 6 May 2019. [Online]. Available: https://rinascltabike.com/carbon-fiber-bike-checklist/. [Accessed 3 August 2021].

[57] “How long do Carbon Bike Frames last?,” [Online]. Available: https://hobbybiker.com/how-long-do-carbon-bike-frames-last/. [Accessed 3 August 2021].

[58] “Recyclo bike,” [Online]. Available: http://www.recyclo.bike/. [Accessed 3 August 2021].

[59] “Matériaux collectés,” [Online]. Available: https://recycling-map.ch/fr/materiaux-collectes/material.php?detail=velos-42. [Accessed 10 August 2021].

[60] R. Wormer, “Here’s what 28,500 ENDURO readers said – the most exciting insights of our 2020 ENDURO reader survey,” 29 March 2021. [Online]. Available: https://enduro-mtb.com/en/enduro-reader-survey-insights-2020/. [Accessed 2 August 2021].

[61] A. F. H. S. Markus Lamprecht, “Sport Suisse 2008: comportement sportif de la population suisse,” 2008.

[62] A. F. H. S. Markus Lamprecht, “Sport Suisse 2014 : Activité et consommation sportives de la population suisse,” 2014.

[63] “Mobilité: les ventes de e-bikes ont dépassé celles des vélos sans moteur en 2018,” *Le Nouvelliste [online],* 14 May 2019.

[64] “Faits et chiffres,” Swiss Ski, [Online]. Available: https://www.swiss-ski.ch/fr/a-propos/federation/organisation/faits-et-chiffres/. [Accessed 3 August 2021].

[65] “Chiffre du mois 2017,” 2017. [Online]. Available: https://www.ezv.admin.ch/ezv/fr/home/themes/statistique-du-commerce-exterieur-suisse/publications/chiffre-du-mois/zahl-des-monats-2017.html. [Accessed 5 August 2021].

[66] O. B. Giannina Bianchi, “Accidentalité lors de la pratique du ski et du snowboard en Suisse,” Berne, 2015.

[67] P + H Plüss AG, “P + H Plüss AG - CFRP Products,” [Online]. Available: https://www.pluessag.ch/en/cfrp-products/cfrp-technical-information.html. [Accessed 10 August 2021].

[68] Altern Consult, “Facteurs d'émissions d'équipements de sport”.

[69] “«Nous voulons être la meilleure marque de skis du monde»,” AXA, 04 June 2020. [Online]. Available: https://www.axa.ch/fr/unternehmenskunden/blog/nos-pme/pme-entretien-stoeckli-swiss-sports-ski-ceo-marc-glaeser.html. [Accessed 3 August 2021].

[70] “Recycling-Map.ch,” [Online]. Available: https://recycling-map.ch/fr/carte/?pos/46.53855000002303/6.580880000000011/20/626516. [Accessed 4 August 2021].

[71] C. L. B. R. V. M. G. F. R. S. Pettit Mousally, “Les fibres de carbone et de graphite. Éléments pour une évaluation du risque,” *Documents pour le médecin du travail,* Janvier 2002.

[72] P. C. D. &. E. Swinbank, "Making a racket: the science of tennis," 11 October 2010. [Online]. Available: https://plus.maths.org/content/science-tennis. [Accessed 29 July 2021].

[73] Swiss Tennis, "Rapport de l'exercice 2019," Bienne, 2020.

[74] Confédération suisse, "Chiffre du mois 2012," 2012. [Online]. Available: https://www.ezv.admin.ch/ezv/fr/home/themes/statistique-du-commerce-exterieur-suisse/publications/chiffre-du-mois/chiffre-du-mois-2012.html. [Accessed 9 August 2021].

[75] "Raquettes de tennis," Wilson, [Online]. Available: https://www.wilson.com/fr-fr/tennis/tennis-rackets?player_type=7093. [Accessed 22 July 2021].

[76] "Raquettes de tennis," Babolat, [Online]. Available: https://www.babolat.com/fr/tennis/raquettes.html. [Accessed 22 July 2021].

[77] "Raquettes," [Online]. Available: https://www.head.com/fr_CH/tennis/racquets.html. [Accessed 22 July 2021].

[78] "Prince," [Online]. Available: http://www.princetennis.com/racquets-1. [Accessed 22 July 2021].

[79] "Tennis," Tecnifibre, [Online]. Available: https://eshop.tecnifibre.fr/tennis.html. [Accessed 22 July 2021].

[80] "Tennis Racquet Specifications," [Online]. Available: https://www.merchantoftennis.com/blogs/racquets/tennis-racquet-specifications. [Accessed 9 August 2021].

[81] "MA RAQUETTE EST-ELLE ENCORE VALABLE ? DOIS-JE LA CHANGER ?," [Online]. Available: https://www.topcordage.be/News/3_Ma-raquette-est-elle-encore-valable---Dois-je.html. [Accessed 29 July 2021].

[82] Aldila, "Aldila, Inc. Annual Disclosures," 2011.

[83] European Golfer Association, "European Golf Participation Report," 2019.

[84] Federal Customs Administration, "Swiss-Impex," [Online]. Available: https://www.gate.ezv.admin.ch/swissimpex/public/bereiche/waren/query.xhtml.

[85] D. Clements, "What Does a Tour Pro Keep in Their Golf Bag?," Golfshake.com, 31 May 2019. [Online]. Available: https://www.golfshake.com/news/view/13824/What_Does_a_Tour_Pro_Keep_in_Their_Golf_Bag.html. [Accessed 29 July 2021].

[86] R. McGarr, "Best Golf Clubs for Beginners," Today's Golfer, 2 March 2021. [Online]. Available: https://www.todaysgolfer.co.uk/equipment/best/golf-clubs-for-beginners/. [Accessed 29 July 2021].

[87] "HOW MUCH GOLF CLUBS WEIGH (WITH CLUB SET EXAMPLES)," Golf Cart Report, [Online]. Available: https://www.golfcartreport.com/how-much-golf-clubs-weigh/. [Accessed 28 July 2021].

[88] J. S. Berg, "COMPOSITE MATERIAL ADVANCES IN THE GOLF INDUSTRY".

[89] "Golf Shafts Buying Guide," [Online]. Available: https://www.golfalot.com/buyingguides/shafts.aspx. [Accessed 29 July 2021].

[90] "How Long Do Golf Clubs Last?," [Online]. Available: https://golfsupport.com/blog/how-long-do-golf-clubs-last/. [Accessed 28 July 2021].

[91] "PARTENARIATS," [Online]. Available: https://swissgolf.ch/fr/durabilite/partenariats/. [Accessed 10 August 2021].

[92] M. Giovanola, "Que fait la Suisse en matière de gaspillage non-alimentaire?," 25 August 2021. [Online]. Available: https://www.rts.ch/info/suisse/12427804-que-fait-la-suisse-en-matiere-de-gaspillage-nonalimentaire.html. [Accessed 13 September 2021].

[93] "Burning Through sticks? That's The Breaks In The NHL," [Online]. Available: https://www.prostockhockey.com/sticks/how-many-hockey-sticks-do-nhl-players-go-through. [Accessed 30 July 2021].

[94] C. Corley, "Do NHL Players Pay for Sticks?," [Online]. Available: https://startinghockey.com/do-nhl-players-pay-for-sticks/. [Accessed 2 August 2021].

[95] Swiss Ice Hockey Federation, "About us," [Online]. Available: https://www.sihf.ch/fr/organization/about-us/. [Accessed 2 August 2021].

[96] L. Favre, "Le hockey en Suisse, une religion sans beaucoup de pratiquants," *Le Temps [online],* 13 December 2019.

[97] M. Lindström, "Improved material performance in floorball sticks - Implementation of the Finite Element Method for helically fiber-oriented laminae in cylindrical hollow composites," Gothenburg, 2015.

[98] "The Floorball Book - Equipment and maintenance".

[99] Swiss Unihockey, "Rapport annuel 2018/19 2019/20," 2020.

[100] A.-J. Hempenius, "How to Choose A Floorball Stick in 2020 (Beginner Guide)," Floorball Today, 17 December 2019. [Online]. Available: https://floorballtoday.com/how-to-choose-a-floorball-stick/. [Accessed 6 August 2021].

[101] "Alpine skis unit sales in the United States from the 2011/12 to 2015/16 (in 1,000s)," [Online]. Available: https://www.statista.com/statistics/257772/units-of-alpine-skis-sold-in-the-us-by-month/. [Accessed 9 August 2021].

[102] "Alpine poles unit sales in the United States from 2011/12 to 2015/16 (in 1,000s)," [Online]. Available: https://www.statista.com/statistics/257789/unit-sales-of-alpine-poles-in-the-united-states/. [Accessed 9 August 2021].

[103] "Bâtons de ski," [Online]. Available: https://www.snowleader.ch/fr/snow/ski/batons.html?fh_location=%2Fis_in_stock%3D%7B1%7D%2F&fh_view_size=20&product_per_line=4. [Accessed 9 August 2021].

[104] "Bâtons de ski," [Online]. Available: https://www.glisshop.com/ski/baton/composite/. [Accessed 9 August 2021].

[105] S. Naylor, "How Much Do Skis Weigh? Average Equipment Weight," New to ski, 27 April 2020. [Online]. Available: https://newtoski.com/ski-equipment-weight/. [Accessed 9 August 2021].

[106] "Large size washers BLACK DIAMOND Powder," [Online]. Available: https://www.alpinstore.com/en/198283-powder-black-diamond-no-color.html. [Accessed 9 August 2021].

[107] "Bâtons en alu ou en carbone?," [Online]. Available: https://www.cimalp.fr/bien-utiliser-batons-randonnee/comment-choisir-ses-batons-de-randonnee-de-marche-et-de-trail/batons-en-alu-ou-en-carbone/. [Accessed 9 August 2021].

[108] M. L. H. Adrian Fischer, “Randonnée en Suisse 2014,” Berne, 2015.

[109] M. G. W. Erin Halpin, “How to Choose and Use Trekking Poles and Hiking Staffs,” [Online]. Available: https://www.rei.com/learn/expert-advice/trekking-poles-hiking-staffs.html. [Accessed 11 August 2021].

[110] J. Eggenkamp, “Windsurf Masts,” 14 December 2020. [Online]. Available: https://www.unifiber.net/en/windsurf-masts. [Accessed 11 August 2021].

[111] Q. MAYERAT, “Démocratisation de la voile : Et s’il y avait une ombre au tableau…,” 21 July 2021. [Online]. Available: https://skippers.ch/actualites/democratisation-de-la-voile-et-sil-y-avait-une-ombre-au-tableau/. [Accessed 11 August 2021].

[112] “Évolution des ventes de planches de 1999 à 2012,” 11 June 2013. [Online]. Available: http://www.wsurfing.com/evolution-des-ventes-de-planches-de-1999-a-2012-224/. [Accessed 12 August 2021].

[113] D. RAVON, “FFVoile. Nicolas Hénard : « Nous visons 500 000 licences fin 2024 ! »,” *Voiles et voiliers - Ouest France,* 18 April 2020.

[114] Arne, “Windsurf Mast Buying Guide,” [Online]. Available: https://howtowindsurf101.com/windsurf-mast-buying-guide/. [Accessed 12 August 2021].

[115] F. Roguet, “[Mâts de windsurf] RDM ou SDM, 40 ou 100% carbone quel mât choisir?,” Windmag, 20 March 2020. [Online]. Available: https://www.windmag.com/conseil-matos-mats-windsurf-rdm-sdm-choisir. [Accessed 12 August 2021].

[116] “WISHBONES WINDSURF,” [Online]. Available: http://www.surfshop.fr/windsurf-134/wishbones-153. [Accessed 12 August 2021].

[117] “Duree vie materiel et securite,” 9 April 2015. [Online]. Available: https://www.windsurfing33.com/forum/viewtopic.php?f=5&t=91615. [Accessed 12 August 2021].

[118] P. Lang, “BELOW THE SURFACE: THE MATERIALS THAT MAKE KITEBOARDING POSSIBLE,” 10 November 2009. [Online]. Available: https://www.thekiteboarder.com/2009/11/below-the-surface-the-materials-that-make-kiteboarding-possible/. [Accessed 12 August 2021].

[119] “Série d'été: c'est bon le kitesurf sur le lac de Neuchâtel,” *Canal Alpha,* 17 July 2020.

[120] Nautisme.com, “Tendance kitesurf !,” *Figaro nautisme,* 4 September 2016.

[121] “Kite - Boards,” [Online]. Available: https://fr.f-one.world/kite/boards/. [Accessed 12 August 2021].

[122] “TRAX HRD Carbon Series,” [Online]. Available: https://fr.f-one.world/produit/trax-hrd-carbon-series-2/. [Accessed 12 August 2021].

[123] “PKS FULL CARBON KISS HYDROFOIL BAR - BAR ONLY,” [Online]. Available: https://kiteboarding.com/proddetail.asp?prod=pks2020_kiss_bar_only. [Accessed 12 August 2021].

[124] “Common Questions about Kiteboarding,” [Online]. Available: https://prokitesouthpadre.com/?page_id=393. [Accessed 12 August 2021].

[125] Office fédéral de l'environnement - Division Eaux - Section Revitalisation et Pêche, “Statistiques de la pêche,” [Online]. Available: https://www.fischereistatistik.ch/fr/statistics?tt=0&dt=0&at=0&st=0&dp=0&ar=CH&wt=0&th=10

&un=0&in=0&yr%5Bfrom%5D=2000&yr%5Bto%5D=2019&sp=100102. [Accessed 4 August 2021].

[126] "Tout savoir sur la canne à pêche pour faire le bon choix !," 2013. [Online]. Available: https://www.peche-partage.fr/tout-savoir-sur-la-canne-a-peche/. [Accessed 5 August 2021].

[127] J. Barlow, "2018: The Golden Anniversary of the Carbon Fibre Fishing Rod," June 2018. [Online]. Available: https://www.anglingheritage.org/p-26863-2018-the-golden-anniversary-of-the-carbon-fibre-fishing-rod.aspx. [Accessed 5 August 2021].

[128] D. C, "How much does a fishing rod weigh? (In Ounces, W/Examples)," [Online]. Available: https://www.reelfm.com/blogs/fishing-blog/how-much-does-a-fishing-rod-weigh-in-ounces-oz-w-examples. [Accessed 5 August 2021].

[129] "How Long Do Fiberglass & Graphite Fishing Rods Last?," [Online]. Available: https://outdooralive.com/how-strong-are-fishing-rods/. [Accessed 5 August 2021].

[130] "Statistique de pêche," 4 February 2021. [Online]. Available: https://www.fr.ch/energie-agriculture-et-environnement/faune-et-biodiversite/statistique-de-peche. [Accessed 12 August 2021].

[131] "HOW LONG CAN A RACKET LAST?," 6 December 2020. [Online]. Available: https://www.racketstringers.com/material/how-long-can-a-racket-last/#:~:text=How%20long%20can%20a%20racket%20really%20last%3F,at%20least%20once%20a%20month.. [Accessed 10 August 2021].

[132] "RAQUETTES DE BADMINTON," [Online]. Available: https://www.babolat.com/fr/badminton/raquettes.html. [Accessed 10 August 2021].

[133] "Raquettes de Badminton," [Online]. Available: https://www.wilson.com/fr-fr/badminton/racquets. [Accessed 10 August 2021].

[134] "Badminton," Yonex, [Online]. Available: https://www.yonex.ch/fr/badminton/produits/raquettes/. [Accessed 10 August 2021].

[135] "Badminton," Talbot Torro, [Online]. Available: https://www.talbottorro.de/en/badminton/isoforce-rackets/isoforce-11/single/article/isoforce-10118.html. [Accessed 10 August 2021].

[136] "LOOKING TO BUY A NEW BADMINTON RACKET?," Spyn, [Online]. Available: https://spyn.co/blog/badminton-racket-specifications/. [Accessed 10 August 2021].

[137] "Squash Rackets Market Size, Share & Trends Analysis Report By Distribution Channel (Brick & Mortar, Online), By Raw Material (Carbon Fiber, Aluminum), By Region (North America, APAC, Europe), And Segment Forecasts, 2019 - 2025," August 2019. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/squash-rackets-market. [Accessed 10 August 2021].

[138] "Les 7 meilleures raquettes de squash 2021," 14 July 2021. [Online]. Available: https://www.bfmtv.com/comparateur/meilleures-raquettes-de-squash-test-comparatif/. [Accessed 10 August 2021].

[139] L. Rodgers, "Climate change: The massive CO2 emitter you may not know about," *BBC,* 17 December 2018.

[140] IEA , "2019 Global Status Report for Buildings and Construction," 2019.

[141] L. Jorio, "Comment le ciment prépare sa révolution écologique," *Swissinfo.ch,* 10 March 2021.

[142] Sika Schweiz AG, “Sika® CarboDur® S - Bandes en fibres de carbone pour les renforcements statiques,” [Online]. Available: https://che.sika.com/fr/construction/refection-protection-ouvrages/renforcements-destructures/sika-carbodur-s.html. [Accessed 21 October 2021].

[143] “Le carbone pourra remplacer l'acier dans le béton armé,” *RTS Info,* 2017.

[144] “Density of Different Construction Materials,” [Online]. Available: https://theconstructor.org/building/density-construction-materials/13531/. [Accessed 21 October 2021].

[145] J. H. (. P. C. v. D. (. E. Marc de Wit (Circle Economy), “The circularity gap report,” 2020.

[146] “Étude sur les matériaux de construction utilisés en Suisse,” Zurich, 2021.

[147] SwissLife, “Combien de temps peut vivre un bâtiment?,” *SwissLife,* 8 May 2017.

[148] ASGB, “Béton - Recyclage et déconstruction,” [Online]. Available: https://www.fskb.ch/beton/recyclage-et-deconstruction-2/?lang=fr. [Accessed 28 October 2021].

[149] Espazium, “Béton fibré ultra performant pour la maintenance, un nouvel élan - Description de deux applications récentes en Suisse romande,” 4 January 2012. [Online]. Available: https://www.espazium.ch/fr/actualites/beton-fibre-ultra-performant-pour-la-maintenance-un-nouvel-elan. [Accessed 28 October 2021].

[150] G. Gardiner, “Carbon fiber-reinforced concrete accelerates in Germany,” *Composites World,* 6 December 2020.

[151] M. K. Thomas Kraus, “Global carbon fibre market remains on upward trend,” *Reinforced Plastics,* November/December 2014.

[152] S. K. R. V. X. W. Esfandiar Pakdel, “Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes,” *Resources, Conservation and Recycling,* vol. 166, March 2021.

[153] L. Meslin, “Où en sommes-nous des technologies permettant de recycler les matériaux en fibre de carbone ?,” 13 May 2019. [Online]. Available: https://www.recycling-carbon.org/2019/05/13/ou-en-sommes-nous-des-technologies-permettant-de-recycler-les-materiaux-en-fibre-de-carbone/. [Accessed 12 August 2021].

[154] “MSI Technology,” [Online]. Available: https://proschoicegolfshafts.com/tech-msi-technology/. [Accessed 12 August 2021].

6. Annexes:

ANNEX 1 – List of consumer products containing Carbon Fibre Reinforced Polymer parts

Sector	Application	Example of parts containing CFRP
Automotive	Cars (mainly in high cost/low volume cars), trucks, motorsports	– Whole bodies or body parts – Wheels and rims – Interior and decorative parts – Body equipment (spoiler, aerodynamic components) – Battery housings – Hydrogen tanks – Seat frames – Technical clothing
Marine	Boats	– Hulls – Sails – Masts – Booms – Foils – Decorative parts
Sport and leisure	Ski (downhill, cross-country, ski touring), snowboards	– Ski or snowboards layers – Poles – Boots – Helmets
	Cycling	– Frames – Forks – Wheels – Handlebars – Boots/Shoes
	Water sports	– Canoes and kayaks – Paddles – Windsurf boards – Kitesurf boards and handlebars – Water skis and wakeboards – Surfboards
	Tennis, badminton, paddle, squash	– Racquets

	Golf	– Clubs shaft, back and sole – Trolleys
	Hockey, UniHockey	– Sticks – Helmets – Skates
	Athletics	– Poles vault – Disks – Running shoes – Javelins – Prosthesis
	Fishing	– Rods
	Archery	– Bows and arrows
	Football	– Shin guards
	Baseball	– Bats
Construction		– Fibre Reinforced Concrete – Reinforcements for old structures
Others		– Pocket knifes – Drones – Suitcases, wallets… – Phone cases – Laptop cases – Rings – Camera monopods, bipods or tripods – Violin bows – Telescope tubes – Medical prostheses