UNIVERSITÀ DEGLI STUDI DI PADOVA

DIPARTIMENTO DI SCIENZE ECONOMICHE ED AZIENDALI “MARCO FANNO”

CORSO DI LAUREA MAGISTRALE IN ENTREPRENEURSHIP AND INNOVATION

TESI DI LAUREA

“Sustainability and digital technologies: a comparative analysis of the environmental impact between the Euro cash payment system and the Bitcoin payment system using an LCA-based approach”

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ANNO ACCADEMICO 2020 – 2021

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Firma dello studente

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INTRODUCTION

"*...we not only want to overcome the consequences of the crisis, but also build a better economy for the future: greener, more digital, more resilient.*" (Ursula von der Leyen, President of the European Commission, 2020)

This is just one of the many similar statements we have been hearing over the past year, just as we often hear about a digital and green transition going hand in hand, the so-called "twin green and digital transition" (von der Leyen, 2020).

Most people react positively when they hear "digital transition" and "green transition" in the same sentence: it's pretty much the same feeling we get when encouraged to "go paperless and save trees!". What no one seems to be asking, however, is whether these changes are at all beneficial. In the same way that using less paper did not automatically lead to more trees around the world, because ultimately using less paper did not mean that wood harvesting would be reduced (this is just a common, simplistic and erroneous view given that the wood market focus shifted to other opportunities besides paper, such as lumber or fuel pellets), we currently do not know fully whether digitalization and green transition can really go well together to achieve the desired results, such as the reduction of our carbon footprint.

This is to say that there are always two sides of the same coin and not always the direction taken to solve a problem gives the desired results, sometimes it does not solve it, sometimes it mitigates it, and sometimes it even creates additional troubles. Hence, some questions we should ask ourselves are: is digitalization green? What is the price to pay for these technological advances? Will there be any side effects?

The aim of this thesis is to gain a deeper understanding of both the positive and negative consequences of digitalization in order to determine whether the introduction of new digital technologies brings benefits from the perspective of a sustainable development that also cares about the environment.

FIRST CHAPTER – WHAT IS SUSTAINABILITY? – The first chapter provides a brief overview on the road taken to get to the definition of the Sustainable Development Goals established on Agenda 2030, from the 1960s to the present day. Moreover, it describes the origins of the sustainability concept, its dimensions, and the relationship among them. At the end a small recap to try to understand what progress has been made to date and how far we are still from the objectives set.

SECOND CHAPTER – THE ENVIRONMENTAL FOOTPRINT OF DIGITAL TECHNOLOGIES – The second chapter explores the concept of sustainability applied to the digital world. In particular, it examines positive and negative effects of the digital transition, trying to understand how ICT can foster the sustainable development but also the side effects resulting from this. In this regard, through a literature review, the chapter investigates about rare metals extraction, e-waste disposal, and especially energy consumption growth linked to digital technologies.

THIRD CHAPTER – COMPARATIVE ANALYSIS OF THE ENVIRONMENTAL IMPACT OF DIFFERENT PAYMENT SYSTEMS: AN LCA-BASED APPROACH – In the third chapter, through the Life-Cycle Assessment method, a comparative analysis of the environmental impact between the Euro cash payment system and the Bitcoin payment system is performed. The aim is to investigate if switching from analog (cash) to digital (cryptocurrency or digital currency) would be recommendable from the point of view of the environmental sustainability and, for this, to quantify the difference in the carbon footprint of the two payment systems. The results emerged from this empirical analysis are also compared with those arisen from previous studies found in the literature.

CHAPTER 1

WHAT IS SUSTAINABILITY?

The issue of sustainability may appear as a recent concern: actually, it is not. Sustainable development has been discussed for many years. There have been many summits, meetings and conferences on this topic (see *Figure 1*).

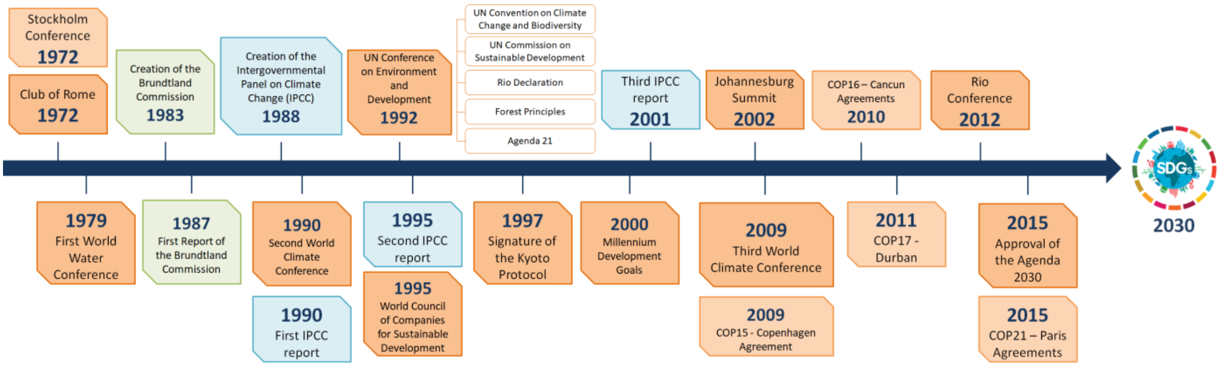

Figure 1 - The stages towards sustainable development
Source: Personal elaboration

1.1 The long journey to SDGs Agenda 2030

In order to find out how the Sustainable Development Goals (SDGs) of Agenda 2030 were drawn up, it is first necessary to take a step back and understand who first brought out the sustainability problems.

In particular, it is necessary to go back to the 1960s, when after two centuries of industrialization and urbanization the undesired effects of this development were beginning to be seen: it is precisely in this context that the first environmentalist movements were born (Elliott, 2009).

As a result of this growing interest, in the early 1970s some studies about the "global future" were published. The best known of these is The Limits of Growth (also known as the Club of Rome Report) commissioned at MIT by the Club of Rome[1] and published in 1972 by Donella H. Meadows, Dennis L. Meadows, Jørgen Randers and William W. Behrens III. The objective of this study was to simulate the consequences of a continuous and exponential growth on a planet that is characterized by limited resources, analyzing the interactions among 5 different

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[1] Founded in 1968 at Accademia dei Lincei in Rome, Italy, the Club of Rome consists of current and former heads of state, UN administrators, high-level politicians and government officials, diplomats, scientists, economists, and business leaders from around the globe. [https://en.wikipedia.org/wiki/Club_of_Rome]

dimensions (world population growth, industrialization, pollution generation, food production, and nonrenewable resource depletion)[2].

The worrying result of this study fueled the awareness that actions were needed to prevent that the tragic scenario produced by the simulation became reality, so that in the same year the first UN Conference on the Human Environment was held in Sweden. One hundred and twelve nations participated in Stockholm to debate the human impact on the environment and the way it had been associated with economic development, with the aim of providing guidelines for action by national governments and international organizations for facing environmental issues.

These developments led in 1983 to the creation of the Brundtland Commission (formerly known as the World Commission on Environment and Development - WCED), which in 1987 released the Brundtland Report (entitled Our Common Future). The focus of this report was that "equity, growth, and environmental maintenance are simultaneously possible and that each country is capable of achieving its full economic potential while at the same time enhancing its resource base" (Shah, 2008).

In the following years many other conventions and agreements for the protection and conservation of the environment were adopted, but most of these were negotiated individually and, above all, were not integrated with the social and economic spheres (*ibidem*).

This was until 1992, when the UN Conference on Environment and Development, the Earth Summit, took place in Rio, which brought international governments to deliberate and negotiate a common line of actions to follow for the sustainable development in the 21st century, the so-called Agenda 21, and subsequently integrated with the Kyoto Protocol in 1997.

The lack of progress in turning Agenda 21 into actions led to the 2002 Johannesburg World Summit (Rio+10) on sustainable development and, prior to this, to the setting of concrete targets with the Millennium Development Goals (MDGs) in 2000 (Shah, 2008).

In 2012, 20 years after the first Rio Earth Summit, the UN Conference on Sustainable Development (Rio+20) was held and a new declaration (The Future We Want) was released. The Declaration includes broad sustainability objectives within themes of poverty eradication, food security and sustainable agriculture, energy, sustainable transport, sustainable cities,

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[2] https://clubofrome.org/publication/the-limits-to-growth/

health and population and promoting full and productive employment.[3] Moreover, the negotiation and adoption of new internationally agreed Sustainable Development Goals by the end of 2014 was requested.

This is how, in 2015, the UN approved the 2030 Agenda (see *Figure 2*), which is a non-legally binding call to action to guard the Earth planet, end poverty and guarantee the well-being of individuals (Taylor, 2016).

Figure 2 - Sustainable Development Goals (SDGs)
Source: https://sdgs.un.org/goals

Agenda 2030 has five overarching themes which span across the 17 SDGs[4] and 169 targets:

- *People*: to end poverty and hunger and to ensure that each one citizenry can fulfil their potential in dignity and equality and in a healthy environment;
- *Planet*: to protect the planet from degradation, including through sustainable consumption and production, in order that it can support the needs of the present and future generations;
- *Prosperity*: to make sure that all human beings can enjoy prosperous and fulfilling lives and that economic, social and technological progress occurs in harmony with nature;
- *Peace*: to foster peaceful, just and inclusive societies which are free from fear and violence;
- *Partnership*: to mobilize the means required to implement this goals through a revitalized global partnership, based on a spirit of strengthened global solidarity.

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[3] https://www.eea.europa.eu/policy-documents/the-future-we-want-2013declaration

[4] https://sdgs.un.org/2030agenda

But 2015 was a landmark year also for the adoption of another major agreement, the Paris Agreement on Climate Change. After several negotiations (Copenhagen 2009, Cancun 2010, Durban 2011) and years of efforts by the international community to bring about a universal multilateral agreement on climate change, finally the participating countries agreed to scale back emissions and to do their best to keep global warming to well below 2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C, recognizing that this would substantially reduce the risks and impacts of climate change.[5]

It is clear how the road to reach these agreements has been long and how challenging and demanding is the path we have to take in order to comply with them.

1.2 Defining sustainability

In the previous paragraph the term "sustainable development" has often emerged. What is sustainable development, then?

According to Elliott (2009), “the concept of sustainable development has gained some degree of notoriety for its ‘slippery nature’ (the multiple definitions that it has), its ambiguities (the various interpretations that flow from those definitions), and its fundamentally oxymoronic character (the suggested opposition between the two encapsulated terms)”.

The first definition of the term *sustainable development*, which later became also the most recognized and widely accepted, is contained in the Brundtland Report. Following this report, it is “the human ability to ensure that the current development meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987).

At this point, some might wonder if there are differences between sustainable development and sustainability or if they are synonyms. The answer is that the two terms are closely related, but are not the same. According to UNESCO, sustainable development refers to the set of actions and processes implemented to achieve the *sustainability*, that is therefore a long-term goal[6].

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[5] https://ec.europa.eu/clima/policies/international/negotiations/paris_en

[6] https://en.unesco.org/themes/education-sustainable-development/what-is-esd/sd

This long-term goal of sustainability encompasses three main aspects (Becker, 2012):

- *continuance* related to the ability to keep going, to the continued existence of something in a certain state over time, whether it is a system, an entity or a process; in this perspective, it can be interpreted as the capacity of a certain system, entity or process to preserve itself, or the intelligence of humans in recognizing factors that have to continue to exist and to be stable despite the context is dynamic and ever-changing;
- *orientation* referred to the fact that sustainability is something good we should seek and strive to, and that should become a priority and a guiding principle;
- *relationships* with regard to the relation between individuals and group within the present generation, to the relation between present and future generations, and to the connection between humans and nature.

In other words, "sustainability is the ability to establish continuance as a means for orienting human actions and life toward the threefold relatedness of human existence to contemporaries, future generations, and nature" (Becker, 2012).

Typically, sustainability is represented by three pillars or dimensions that describe the relationship among environment, economy and society (Basiago, 1999; Giddings et al., 2002, Jeronen, 2013; Mensah, 2019; Purvis et al., 2019).

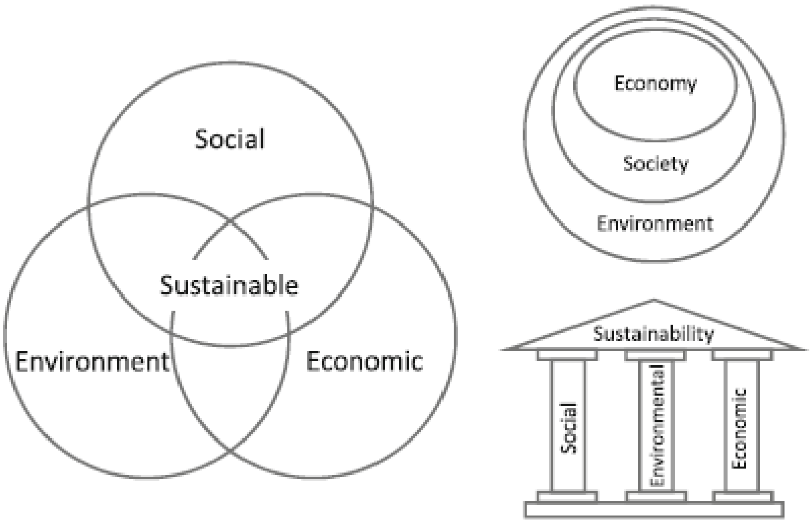

Figure 3 - Left, typical representation of sustainability as three intersecting circles. Right, alternative depictions: literal 'pillars' and a concentric circles approach (Three-Nested-Dependencies Model)
Source: Purvis et al., 2019

Although the Three-Overlapping Circles Model (see *Figure 3 left* and *Figure 4* below) is the most popular, the more accurate depiction is given by the Three-Nested-Dependencies Model (see *Figure 3 upper right*).

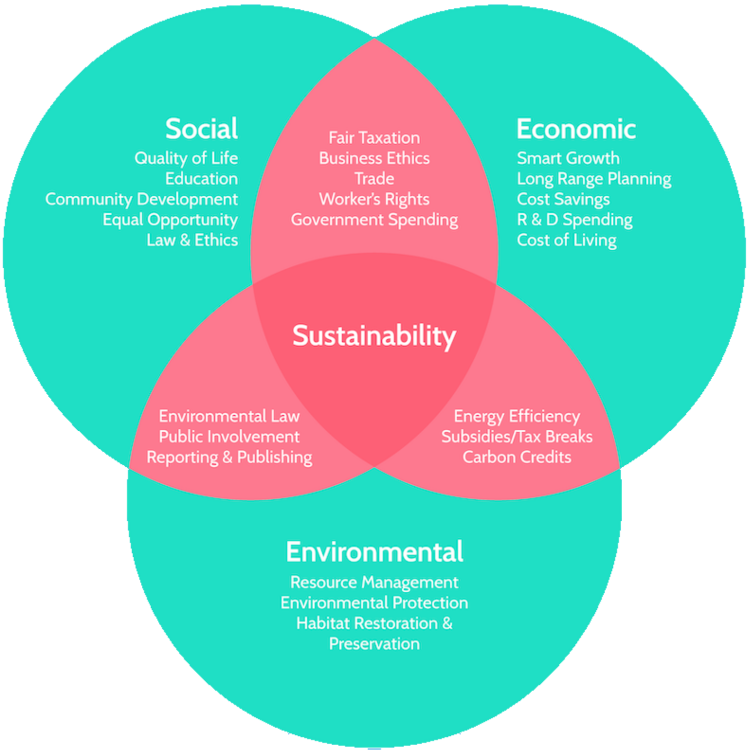

Figure 4 - The Three Spheres of Sustainability
Source: Courtnell, 2019

In the Three-Nested-Dependencies Model economy, society and environment are co-dependent (Kochi Carballo, 2020). While the Three-Overlapping Circles Model entails that the economy can exist without the environment, the Three-Nested-Dependencies Model acknowledge that the economy is fully subordinate to society, which in turn is totally reliant to the environment. This means that without the environment, society and economy cannot exist, and so the Three-Nested-Dependencies Model points out that there is no another planet and that without food, clean water, fresh air, fertile soil, and healthy ecosystems the society and the economy no longer operate.

In any case, whatever way they are represented, given that these three dimensions are highly interconnected and given that the actions in one area can affect the goals of another, only through a virtuous balancing of the economic, social and environmental factors it is possible to achieve the true sustainability. This implies that the sustainable development pathway carried out to reach the sustainability has to be "environmentally and economically viable, economically and socially equitable as well as socially and environmentally bearable" (Mensah, 2019).

1.2.1 Environmental sustainability

Since its very beginning, the Earth system has been a resilient system with an environment that has remained stable until about 10,000 years ago (Abe, 2020). This is the proof that it is able to maintain its integrity or return to a state of equilibrium after a mild disorder.

However, unexpected and heavy shocks to the Earth system can cause it to lose its resilience. This is exactly what happened at the beginning of Anthropocene, with the First Industrial Revolution in 1760, which probably has been the starting point of the significant human impact on Earth's geology and ecosystems.

In this era the aggregate effects of the increased human activities and the nonstop acquisition of natural resources from the planet to sustain our contemporary lifestyle are altering various aspects of the Earth system and are degrading the global environment (Abe, 2020; Akinsemolu, 2020), causing irreversible and catastrophic changes, beyond the safe limits of resiliency (Rockström et al., 2009; Steffen et al., 2015).

In fact, it is possible to identify nine “planetary boundaries” describing the level of biosphere integrity, climate change, land-system change, freshwater use, biochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion and novel entities (such as new substances and modified life forms that have the potential for unwanted geophysical and/or biological effects), within which humanity can operate safely (*ibidem*) (see *Figure 5*).

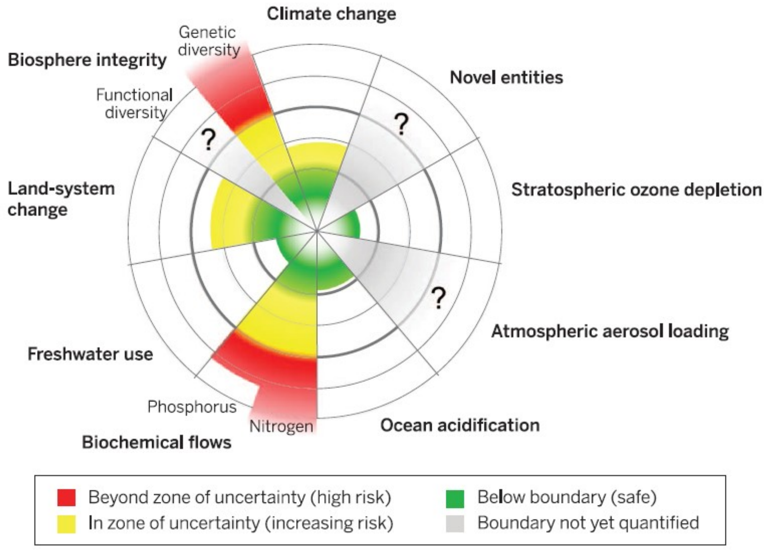

Figure 5 - Current status of the control variables for seven of the nine planetary boundaries
Source: Steffen et al., 2015

The transgression of only one boundary doesn't lead instantly to an irreversible change to the global environment, but the longer a boundary is trespassed, the higher is the risk of unsustainability of human activities and, of consequence, the fewer is the capability of the Earth system to be resilient.

According to Rockström et al. (2009) and Steffen et al. (2015), humankind has already exceeded three of the nine planetary boundaries - climate change (measured by the CO_2 concentration in the atmosphere), rate of biodiversity loss (measured by the rate of extinctions per million species) and level of biochemical flows - as a result of the uncontrolled and exponential growth.

In practice, every year, due to our consumerist and largely city-based existence, many more natural resources are consumed than the planet is able to renew and planetary boundaries are overtaken. This fact is also highlighted by the Global Footprint Network, an international research organization that annually calculates the Earth Overshoot Day, an indicator of the date in which "humanity's demand for ecological resources in a given year exceeds what Earth can regenerate in that year"[7]. Earth Overshoot Day is estimated by dividing the planet's biocapacity (the amount of ecological resources Earth is able to generate that year), by humanity's ecological footprint (population's demand for plant-based food and fiber products, cattle and fish products, timber and other forest products, space for urban infrastructure, and forest to soak up carbon dioxide emissions from fossil fuels for that year), and multiplying by 365, the number of days in a year.

From *Figure 6*, it is possible to note that, except for a few rare cases, from 1970 onwards the fateful date has gradually moved away from the end of the year, i.e. December 31st. Currently, humanity uses the resources of 1.6 planets and, proceeding at this rate, around 2050 mankind will consume twice as much as the Earth produces.[8]

Based on these evidences, it is possible to state that *environmental sustainability* is the responsible interaction with the environment in order to discourage the degradation or depletion of natural resources (Akinsemolu, 2020) and it is therefore related to the production of goods and services without compromising the carrying capacity of the Earth system.

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[7] https://www.overshootday.org/about-earth-overshoot-day/

[8] https://www.overshootday.org/newsroom/press-release-august-2020-english/

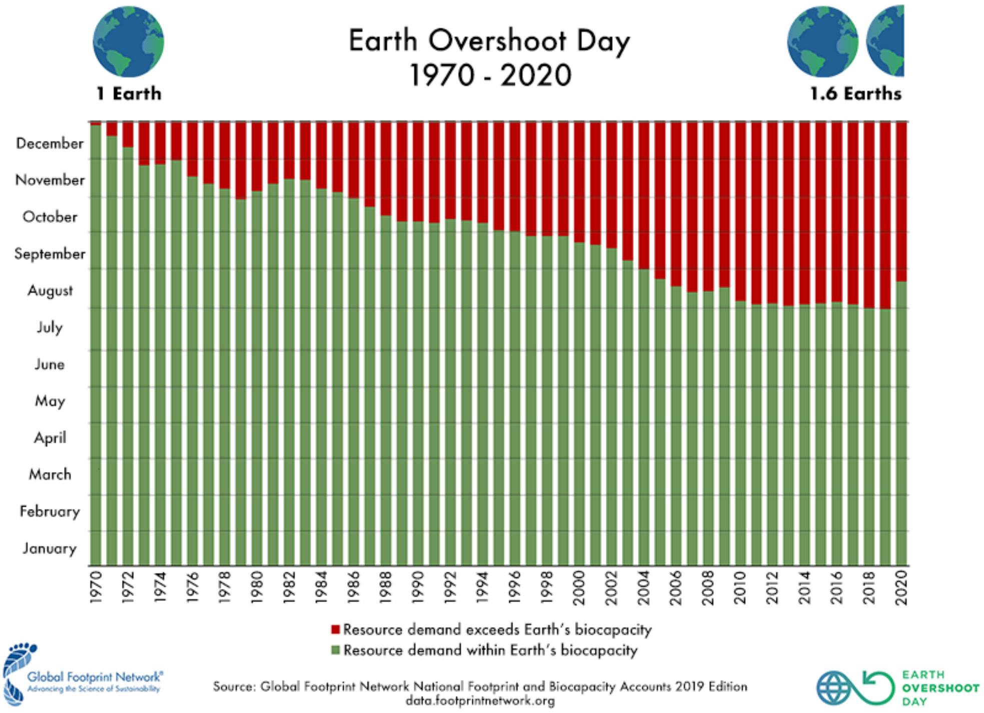

Figure 6 - Earth Overshoot Day 1970 - 2020
Source: https://www.overshootday.org/newsroom/past-earth-overshoot-days/

For this reason, environmental sustainability is not a theme in itself but is linked to various human behavior and to the correspondent problems that must be deal with simultaneously (Akinsemolu, 2020):

- *constructions and human settlements*: the rapid urbanization results in a pressure increase on the environment due to the expanded Earth's land area covered by cities (Moldan et al., 2012); it is also necessary to address the issue of energy efficiency within infrastructures given that over 40% of carbon emissions come from cooling, heating and powering buildings (Akinsemolu, 2020);
- *emissions and wastes*: since 1990, global carbon dioxide (CO_2) emissions from fossil fuels (such as coal, petroleum and natural gas) and industry have continued to steadily and rapidly grow, and in 2018 reached a record of 36.6 billion tons (Gilfillan et al., 2019), notwithstanding the implementation of new protocols and legislations to cut and bring them under control; additionally, also wastes are a constant concern in relation to the soil, water and air pollution;
- *agriculture*: farming is responsible for 7.1 gigatonnes of greenhouse gases per year, representing around 14.5 percent of all anthropogenic GHG emissions (Gerber et al, 2013), and making the agricultural industry one of the largest emitters; it is not just farming agriculture that needs to be taken into account, but also other forms of food production and harvesting, such as fishing and its overexploitation;

- *water*: due to its essentiality for all life forms, water demand grows day after day but the ongoing population growth and economic and technological expansion has caused a significant downturn in groundwater levels, the loss of a large part of planet's wetlands and also the worsening of the quality of the water with the consequent need for expensive treatments (Akinsemolu, 2020);
- *energy*: the utilization of fossil fuels as an energy source is one of the major contributing factors to global warming; in fact, it is estimated that when carbon dioxide (CO_2) is released from the burning of fossil fuels, only half is absorbed by the so-called "carbon sinks" (soil, plants, trees and oceans), while the remaining 50% stays in the atmosphere (Watson and Shutler, 2020);
- *manufacturing*: in the 18th century the first generations of factories utilized wind mills, water mills, and wood that produced only a small amount of energy, but the following development of fossil fuel technology enabled manufacturers to develop larger, more efficient factories; as output increased, so did the environmental damages caused by manufacturing, and the rate at which the consumption and the demand of goods increased have led to the development of a fossil fuel-dependent economy (Greenberg, 2020);
- *transportation*: transport contributes for around one-fifth of global carbon dioxide (CO_2) emissions; road travel accounts for 75% (passenger vehicles and trucks carrying freight) of total transport emissions, while aviation, shipping, rail travel and other transport (movement of materials such as water, oil and gas) are responsible for 11.6%, 10.6%, 1% and 2.2% of total transport emissions respectively (Ritchie, 2020).

So, in order to tackle on this unsustainable situation, to give some examples, it is important to improve public transport and increase pedestrianization to minimize traffic on city roads and so to abate car pollution; to better design city buildings in order to make them more efficient and lower energy demand; to increase green open spaces and water features with the aim to reduce the "heat island effect" which results from the abundance of asphalt that make urban areas significantly warmer than rural areas; to diversify energy sources including renewable and clean ones by installing solar panels or wind turbines; to manage crops to reduce water loss and to incentivize farmers to stop using slash and burn techniques to clear their land; to safeguard quality of water against contaminants; to improve factories operations efficiency and to develop better transportation methods.

To sum up, it is imperative to regulate the maximum level of harmful emissions, to subsidize and encourage more sustainable environmental practices and to raise consciousness about environmental issues.

1.2.2 Social sustainability

Basically, *social sustainability* refers to the ability of a society to persistently achieve a good social well-being and to ensure that it can be maintained in the long term (Jones, 2014). In particular, “social sustainability is not about ensuring that everyone’s needs are met. Rather, its aims at providing enabling conditions for everyone to have the capacity to realize their needs, if they so desire” (Mensah, 2019).

This not only concern the current generation, but also the future ones: future generations should have the same or greater quality of life and at least the same possibilities as the current generation.

In Wanamaker’s (2018) and Mensah’s (2019) opinion social sustainability encloses many current issues such as human rights, gender equity and equality, healthcare, social capital (which includes social networks, social cohesion, the level of trust and the norms and values in a society), education, employment, wealth and justice. More specifically, according to Nobel Laureate Amartya Sen, social sustainability has 6 dimensions (Harris et al., 2001):

- *equity* in the terms of ensuring equitable opportunities for all the members of the community, in particular the poorest and most vulnerable;
- *diversity* concerning the promotion and encouragement of diversity;
- *social cohesion* with regard to the promotion of solidarity and sense of belonging among the community;
- *quality of life* in terms of ensuring that basic needs are met and fostering a good quality of life for all members at the individual, group and community level (e.g. health, housing, education, employment, safety);
- *maturity* regarding the cooperation of each member of the community;
- *democracy*.

All this themes, if taken up with commitment, can contribute to achieve a meaningful and sustainable life across the globe, now and in the future.

The situation in relation to the above points can currently be considered rather unsatisfactory. In 2016, in fact, the Happy Planet Index (HPI) report by the New Economics Foundation revealed that we are still living on unhappy planet, where "unhappy" means "unsustainable". This index measures the level of sustainable wellbeing for all and tells us how well nations are doing at achieving long, happy, sustainable lives. It combines four elements (wellbeing, life expectancy, inequalities and ecological footprint) to show where in the world wellbeing is being achieved sustainably. Wealthy, western nations tend to score highly on life expectancy and wellbeing, but do not score highly on the HPI overall, because of the environmental costs of how their economy is run (see *Figure 7*).

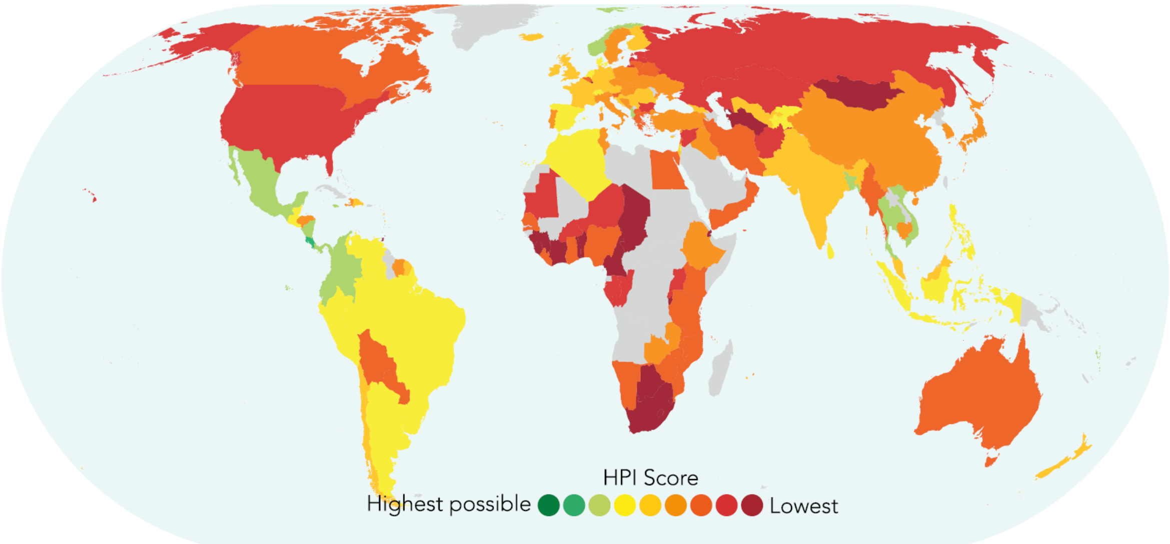

Figure 7 - Happy Planet Index 2016
Source: NEF, 2016

It is therefore necessary to protect and improve human well-being and quality of life as well as protect and maintain basic natural resources for current and future generations, enhancing the education about sustainability and promoting the development of communities in a sustainable perspective.

1.2.3 Economic sustainability

Economic sustainability is inevitably linked to both environmental and social sustainability.

The concept of economic sustainability arises from the idea that a productive system has to satisfy present consumption needs without prejudicing future ones (Khan, 1995; Basiago, 1999), and originates from the notion of "income" by Hicks (1946), which defines it as "the amount one can consume during a period and still be as well off at the end of the period".

Although some economists initially believed that natural resources were unlimited, and that economic growth thanks to an efficient allocation and with the help of technology could replace the resources destroyed during the production process (Khan, 1995; Basiago, 1999), it has been realized that “natural resources are not infinite and not all of them can be replenished or are renewable” (Meadows et al., 1972).

This new awareness combined with an increasingly growing and constantly developing economic system has led many to reassess and question the feasibility and sustainability of uncontrolled growth and consumption (Khan, 1995; Basiago, 1999).

So, economic sustainability has to focus on economic growth and investments that generate wealth for all, without harming the environment.

More accurately, we can then understood *economic sustainability* as a set of “practices that support long-term economic growth without negatively impacting social, environmental, and cultural aspects of the community” (UWM, 2017). This implies that it is crucial to encourage a “smart growth” for example through subsidies or tax benefits for green development, financial support for universities and research and development, fair taxation, cost savings etc.

1.3 Progress to date

The road to reach sustainability and comply with SDGs has been, and still is, challenging. Which are the progress to date? Where are we and what can we expect?

Since the Sustainable Development Goals (SDGs) adoption, there have been many positive initiatives. Countries have begun to include the goals into national plans and strategies, and many have established coordinating structures for consistent implementation (United Nations, 2019). There have also been nature-directed initiatives, particularly with respect to climate change, land use, or the oceans. In addition, also the private sector started to move faraway from business-as-usual models, for instance by adopting and reporting on sustainability standards (*ibidem*). At the same time, the efforts of civil society and non-governmental organizations in favor of sustainable development is increasing.

Despite this, initial efforts have not yet reversed several negative trends blocking progress toward sustainable development, and there is still limited success in implementing the 2030 Agenda (*ibidem*). In the Global Sustainable Development Report 2019 by United Nations (2019), the rates at which, globally, progress is being made towards the targets associated with SDGs have been estimated, in order to determine whether a target will be met and, if not, how close it will be by 2030 (see *Figure 8*).

GOAL	WITHIN 5%	5–10%	>10%	NEGATIVE LONG-TERM TREND
Goal 1		1.1. Eradicating extreme poverty	1.3. Social protection for all	
Goal 2		2.1. Ending hunger (undernourishment)	2.2. Ending malnutrition (stunting) 2.5. Maintaining genetic diversity 2.a. Investment in agriculture*	2.2. Ending malnutrition (overweight)
Goal 3	3.2. Under-5 mortality 3.2. Neonatal mortality		3.1. Maternal mortality 3.4. Premature deaths from non-communicable diseases	
Goal 4	4.1 Enrolment in primary education	4.6 Literacy among youth and adults	4.2. Early childhood development 4.1 Enrolment in secondary education 4.3 Enrolment in tertiary education	
Goal 5			5.5. Women political participation	
Goal 6		6.2. Access to safe sanitation	6.1. Access to safely managed drinking water 6.2. Access to safely managed sanitation services	
Goal 7		7.1. Access to electricity	7.2. Share of renewable energy* 7.3. Energy intensity	
Goal 8			8.7. Use of child labour	
Goal 9		9.5. Enhancing scientific research (R&D expenditure)	9.5. Enhancing scientific research (number of researchers)	
Goal 10			10.c. Remittance costs	Inequality in income*
Goal 11			11.1. Urban population living in slums*	
Goal 12				12.2. Absolute material footprint, and DMC*
Goal 13				Global GHG emissions relative to Paris targets*
Goal 14				14.1. Continued deterioration of coastal waters* 14.4. Overfishing*
Goal 15				15.5. Biodiversity loss* 15.7. Wildlife poaching and trafficking*
Goal 16			16.9 Universal birth registration **	

Note: Selected indicators only. SDG 17 is not included as it consists of a wide range of indicators that cannot easily be captured using the methodology for assessing distance from reaching targets. Estimates of the distance from the target by 2030 are based on forecasted value of the corresponding indicator in 2030, relative to target. Forecasts based on best-fit trends of individual indicators, given the available data range.

* Quantitative target for 2030 is not specified in the SDG indicator framework; targets are estimated.

** Assessment is based on indicators outside the SDG indicator framework; inequality in income is based on data from household surveys.

Figure 8 - Projected distance from reaching selected targets by 2030 (at current trends)
Source: United Nations, 2019

A simple reading suggests that, at current rates of progress, a number of the Agenda 2030 targets should be achieved by 2030 (those depicted in *Figure 8* as within 5% of the target, e.g. reduction of child mortality and full elementary school enrollment), while others should be, but additional effort is required (those depicted in *Figure 8* as within 5-10% of the target, e.g. elimination of extreme poverty, ending hunger, universal access to electricity, literacy among youth and adults).

However, that straightforward projection ignores possible complexities. As targets approach, rates of progress may begin to slow[9], therefore projections based on previous rates will be overly optimistic.

Then we have targets whose trends are in the desired direction (those depicted in *Figure 8* as >10% of the target), but progress is just too slow to realize them, such as maternal mortality, child malnutrition, access to clean water, share of renewable energy sources within the energy mix etc., while at the bottom of the list we find targets for which recent trends are not even in the right direction (those depicted in *Figure 8* as negative long-term trend).

For the latter, which are also the most concerning, it is probably that the implementation of the goals has not yet been able to reverse pre-existing deterioration, such as in the case of obesity, inequalities, greenhouse gas emissions etc. Four negative trends, in particular, not only are difficult to change, but also make it harder to reach other goals and targets (United Nations, 2019): rising inequalities, climate change, biodiversity loss, and the increasing amount of waste from human activities.

- ➢ In Chapter 2 we will go beyond the purely environmental, economy and society dimensions that characterized the birth of the sustainability concept to discuss about sustainability in a digital world.

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[9] For example, the World Bank's 2020 Poverty and Shared Prosperity Report found that extreme poverty dropped by an average of about 1 percentage point per year over the quarter century from 1990 to 2015, but then the rate of decline slowed from 2013 to 2015 to just 0.6 percentage point per year, and between 2015 and 2017 the rate slowed further to half a percentage point per year. It is clear that, given this decelerating trend, the goal of bringing global extreme poverty to less than 3 percent by 2030 is at risk. [https://www.worldbank.org/en/publication/poverty-and-shared-prosperity]
The reason for this decline lies in the fact that most of the people living in extreme poverty are concentrated in regions that combine also other factors, including conflicts, weak institutions and high population growth rates, and so extraordinary efforts are needed to meet the goals in these types of situations.
Similar patterns can be seen also with regard to other targets achievement.

CHAPTER 2

THE ENVIRONMENTAL FOOTPRINT OF DIGITAL TECHNOLOGIES

2.1 Digital technologies, sustainability and environmental footprint

Nowadays, technology, and in particular digital technology, plays a leading role and profoundly influences many aspects of our life.

The way digital technology impacts business and society can be differentiated based on three distinct levels (Carell et al., 2018):

- *digitization* that is the process of changing from analogue to digital form to have the possibility to process information through computers; the most intuitive and simplest example of digitization can be the conversion of handwritten/typewritten text into digital using dedicated office software;
- *digitalization* is, instead, referred to a deeper use of digital technologies resulting from upgraded hardware and from the adoption of broadband Internet connection; this additional step leads to the improvement of existing products and services and can be exemplified through online shopping or online banking;
- *digital transformation* is the outcome of the massive dissemination of digital technologies (e.g., smartphones, mobile Internet, portable computers, wearable devices) and of a successful progression in digitalization; digital transformation defines the rise of new business models enabled by digital technologies, such as crowdfunding or music and movie streaming platforms.

These processes of ‘going digital’ “have led to an explosion in the production and consumption of information around the world” (World Bank, 2016). The incredible amount of digital data created day-by-day has contributed to a revolution by creating manifold application opportunities, such as the Internet of Things, Big Data and Artificial Intelligence, and also to affect a growing number of industries including retail, banking, transport, energy, and public service delivery (*ibidem*).

Even though the development of this megatrend allows multiple opportunities, it also includes various meaningful challenges. Digital is, in fact, closely related to another hot topic: sustainability.

Digital sustainability is "the sustainability that defines the ways in which digital technology must be developed so that it contributes to the creation of a better world, both with respect to its nature and its instrumental role in the environment, economy and society" (Epifani, 2020).

State the impacts of ICT (Information and Communications Technology), of digitalization and, in an even broader perspective, of digital transformation on sustainability, de facto, means thinking on two dimensions: on the one hand it refers to the fact that digital technologies must be sustainable, e.g. not to produce first damage to the environment, on the other hand it means understanding that technologies can become tools of sustainability able to dynamically redefine scenarios, models and economic, environmental and social contexts (Epifani, 2020).

Digital technologies can, in fact, at a much faster pace than ever before, help (as enablers) to enhance productivity and efficiency across many sectors, and promote circular and shared economies, increasing dematerialization, resource and energy efficiency and savings, etc. (TWI2050, 2019). Also, as reported by the Earth Institute of Columbia University and Ericsson (2016), ICT-based solutions can be the key catalyst for achieving the SDGs.

Despite this tendency to see ICT, digitalization and digital transformation as enormous opportunities, we really do not know how much a more digital world is also a more sustainable world and, in particular, how much ICT affects our environmental footprint.

The concept of *environmental footprint* was firstly introduced by Rees in 1992 (Čuček et al., 2015) to indicate the "effect that a person, company, activity etc., has on the environment"[10].

Under the concept of environmental footprint it is possible to distinguish several types of footprints (see *Table 1*) forming the "Footprint Family", a set of indicators capable to record human pressure on the surrounding environment (Galli et al., 2012), where the pressure is represented by the major environmental impacts, such as global warming, ozone layer depletion, acidification of soil and water, depletion of abiotic resources (energy and non-energy resources), human toxicity, aquatic and terrestrial ecotoxicity, water and air pollution (Hillege, 2019).

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[10] Definition of environmental footprint from the *Cambridge Business English Dictionary* [https://dictionary.cambridge.org/dictionary/english/environmental-footprint]

Footprint	Definition
Carbon footprint (CF)	CF stands for the amount of CO_2 and other GHGs emitted over the full life cycle of a process or product.
Water footprint (WF)	Indicator of direct and indirect water use by a consumer or a producer.
Ecological footprint (EF)	Resource accounting indicator that measures how many bio productive land and water areas are available on Earth, and how much of this area is appropriated for human use.
Energy footprint (ENF)	ENF stands for the specific energy usage per functional unit when considering fossil-based and renewable-based energy.
Nitrogen footprint (NF)	NF is the total amount of reactive nitrogen released into the environment as a result of an entity's resource consumption, and represents the disruption of the regional to global nitrogen cycle and its consequences due to human activities.
Phosphorus footprint (PF)	PF represent the disruption of phosphorus cycle.
Biodiversity footprint (BF)	BF is defined as the summation of all the pressures that have potential consequences for biodiversity.
Land footprint (LF)	LF is related to land requirement and is defined as the summation of all the areas directly and indirectly required to satisfy the consumption.

Table 1 - Key Environmental Footprints
Source: Adapted from Čuček et al., 2015

The most popular environmental protection meter, but also the largest in term of impact, is certainly the carbon one that accounts for 54% of the overall environmental footprint[11].

Following the definition proposed by Wiedmann and Minx (2008), the carbon footprint is a "measure of the total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product", usually quantified in tons of emissions (tCO_2-eq) per year. Carbon dioxide equivalent[12] (CO_2-eq) is calculated from the Global Warming Potential (GWP), i.e. the heat absorbed by any greenhouse gas in the atmosphere; it is the amount of CO_2 which would warm the earth as much as the amount of another gas. Considering that GWP is 1 for CO_2, if for example a gas has GWP of 100, two tons of that gas have CO_2-eq of 200 tons.

In addition to carbon dioxide (CO_2), in fact, in accordance with the Kyoto Protocol, other five greenhouse gases have to be considered: methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6) and perfluorocarbons (PFCs)[13].

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[11] https://sphera.com/insights/what-is-an-environmental-footprint
[12] Wikipedia, s.v. "Global Warming Potential", https://en.wikipedia.org/wiki/Global_warming_potential
[13] https://www.minambiente.it/pagina/cose-la-carbon-footprint

In general, across the value chain of a product (good and/or service), it is possible to classify direct and indirect GHG emissions of a company into three types, corresponding to the GHG Protocol "scopes" for accounting and reporting emissions (WRI and WBCSD, 2011) (see *Figure 9*):

- *direct* or *scope 1 emissions*: emissions from operations that are owned or controlled directly by the company;
- *indirect* or *scope 2 emissions*: emissions generated by the purchased or acquired electricity, steam, heating or cooling consumed by the company;
- *indirect* or *scope 3 emissions*: all upstream (from material acquisition and pre-processing) and downstream emissions (from distribution and storage, use and end-of-life treatments) that occur in the value chain of the company.

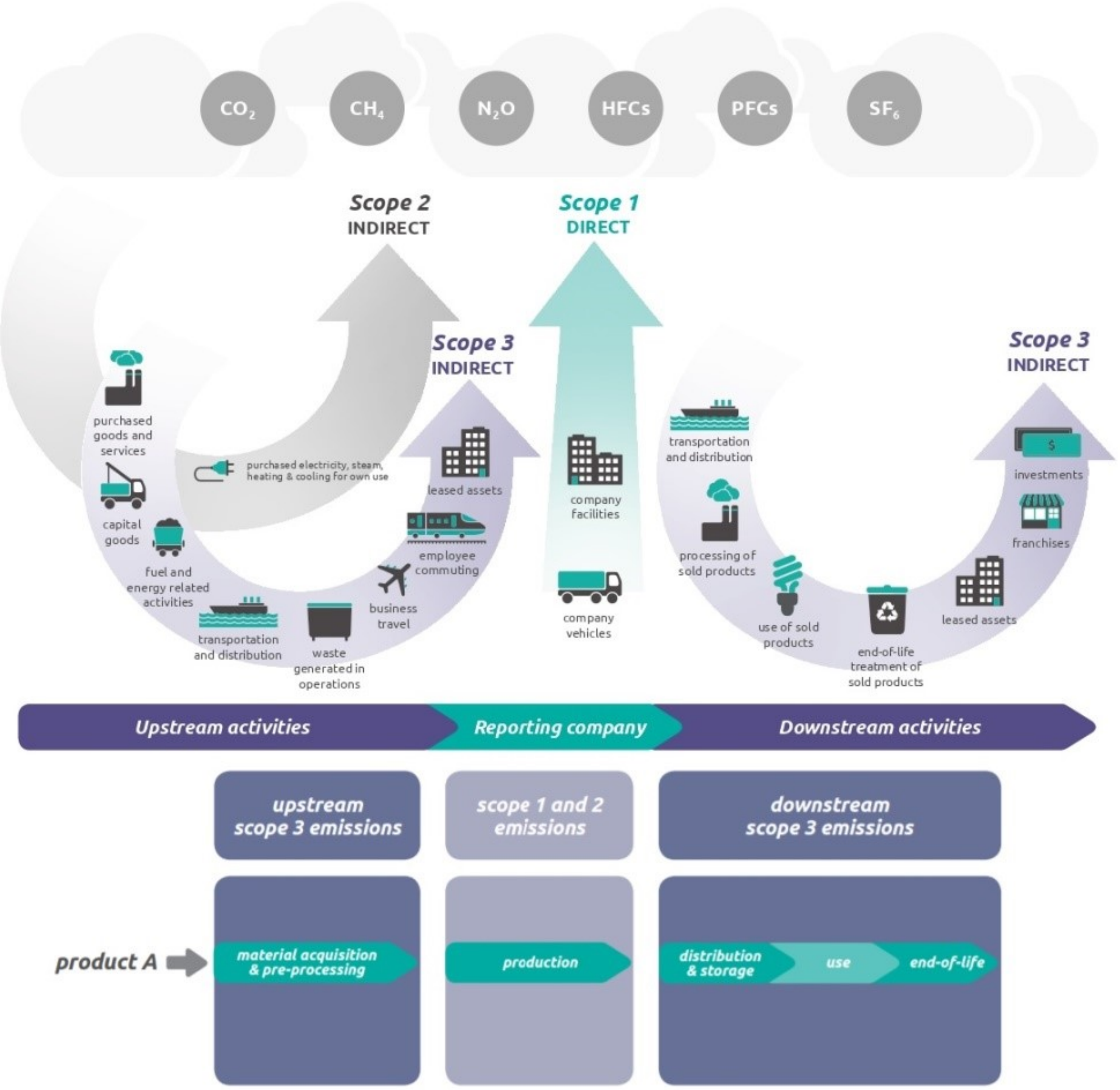

Figure 9 - Overview of GHG Protocol scopes and emissions across the value chain
Source: WRI and WBCSD, 2011

2.2 The transition to digital: rethinking positive and negative effects

ICT (Information and Communications Technology) is undoubtedly what lies behind the transition to digital.

ICT is a broader term for Information Technology (IT). There is no single, universal definition of ICT because it is a constantly evolving concept, but it is used as an umbrella term to indicate "all technologies that, combined, allow people and organizations to interact in the digital world" (Rouse et al, 2005) and to access, store, transmit, and manipulate information[14]. These technologies fall mainly in two categories (Belkhir and Elmeligi, 2018; Malmodin and Lundén, 2018; Ericsson, 2020):

- *user electronic devices* (e.g., smartphones, tablets, desktop and laptop PCs, connected devices);
- *infrastructural facilities* such as communication networks (fixed and mobile for telephony and broadband connectivity) and data centers (including servers, networking gear and cooling and power systems).

At the base of these technologies there is obviously the Internet, which acts as a sort central nervous system or backbone of our digital-based economy (Greenpeace, 2017). According to Internet World Stats[15], in the period 2000-2020 the growth of the world Internet usage amounted to 1,266%, with an estimated 4.9 billion people using the Internet and a global penetration rate of 63.2% in the third quarter of the year 2020.

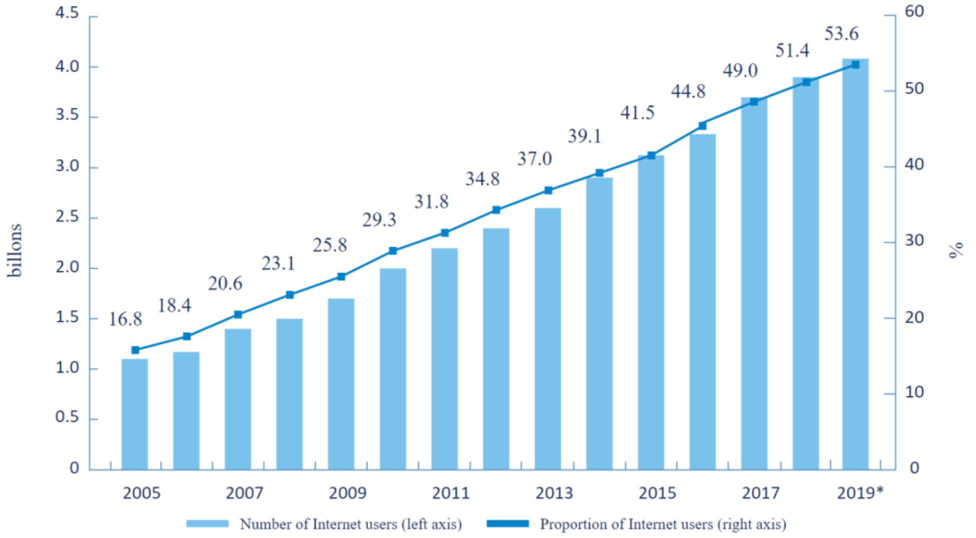

Figure 10 - Individuals using the Internet 2005-2019 - Source: ITU, 2020

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[14] Wikipedia, s.v. "Information and communications technology", https://en.wikipedia.org/wiki/Information_and_communications_technology

[15] https://www.internetworldstats.com/stats.htm

With its widespread diffusion year after year (see *Figure 10*), Internet has also led to an exponential growth in the use of the above mentioned devices and infrastructures. According to the Annual Internet Report (2018–2023) by Cisco (2020), the number of internet-connected ICT devices will be more than triple that of the global population by 2021.

Certainly, the proliferation of ICT devices and services resulted in changes in the way we work, travel and communicate (Van Heddeghem et al., 2014; Belkhir and Elmeligi, 2018), but not only that.

Even if we often do not realize it, everything that is digital has a physical counterpart. If we start from this assumption, it is almost impossible not to think about the possible effects of digital technologies on the environment.

The first framework with the aim to distinguish the different ways in which ICT impacts on environment was introduced by Berkhout and Hertin (2004) and further developed by Hilty (2008) (see *Figure 11*). Accordingly, the effects of ICT on the environment can be classified as follows:

- *first order* or *direct effects*: negative effects that stem from the physical existence of ICT, referred to the environmental costs of production, use and disposal of ICT (i.e., life-cycle emissions and energy/materials demand);
- *second order* or *enabling effects*: indirect impacts created by the use of ICT-based solutions; two are attributed to the “problem” side (induction effect and obsolescence effect), two to the “solution side” (optimization effect and substitution effect);
- *third order* or *systemic effects*: indirect long-term behavioral and economic processes of change due to the availability of ICT; on the positive side ICT can support sustainable patterns of production and consumption, while on the negative side, despite decoupling[16], ICT can limit the reduction of resource use by transforming efficiency improvements into further consumption (rebound effect).

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[16] When resource use or some environmental pressure either grows at a slower rate than the economic activity that is causing it (relative decoupling) or declines while the economic activity continues to grow (absolute decoupling) (IRP, 2017)

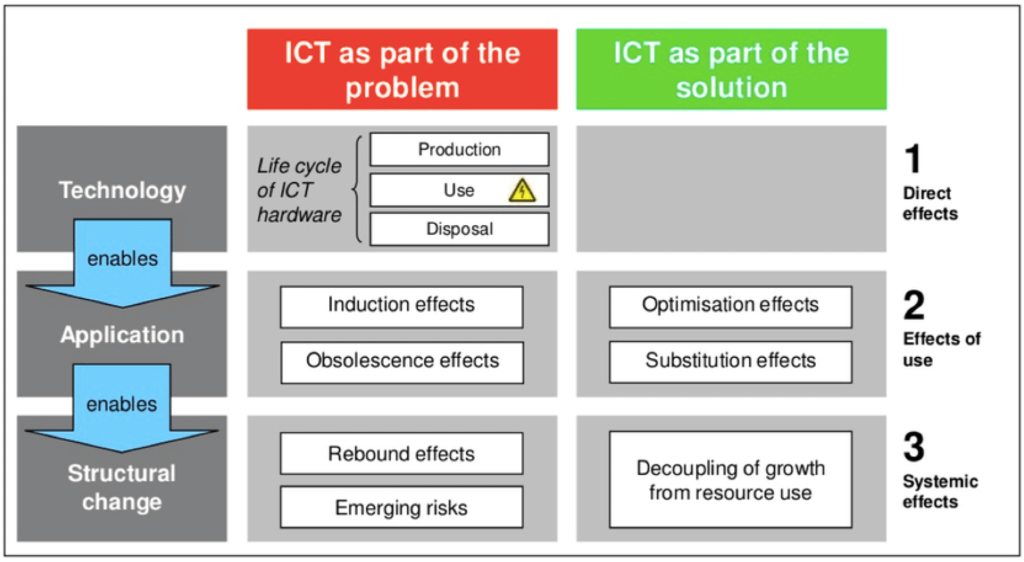

Figure 11 - Conceptual framework of the impact of ICT on the environment
Source: Hilty, 2008

First order or direct effects

Direct impacts of ICTs on the environment refer to "negative impacts due to the physical existence of ICT products (goods and services)" (Mickoleit, 2010). The origins of these impact are ICT producers and final consumers and users.

ICT producers affect the environment during the phase of production of ICT through their operations, while consumers and users determine an increase in the direct environmental footprint through purchase, use and end-of-life treatments.

Examples of actions triggering a potential direct effect during the life-cycle of ICTs are:

- software-induced hardware obsolescence;
- water and energy consumption in the manufacturing phase;
- energy used by ICT devices and infrastructures or for cooling servers and data centers;
- incorrect disposal of hazardous substances in ICT devices that pollute air, water and soil.

Second order or enabling effects

Enabling effects of ICTs stem from the fact that ICTs can modify the way in which other products are designed, produced, consumed, used and disposed in four ways (Mickoleit, 2010):

- *induction effect* if ICT products boost the demand for other products;
- *obsolescence effect* when ICT products make other products no more up to date and so increasing the demand for new products;

- *optimization effect* if ICT products help to reduce the environmental impact of other products;
- *substitution effect* when improvements in ICTs facilitate the replacement of physical products and processes with digital products and processes.

Examples of ICTs applications triggering a positive potential enabling effect are:

- computer-aided design, 3D printing, computer-integrated manufacturing, "smart" technologies such as intelligent heating, cooling and ventilation, electricity distribution, supply-chain management (*optimization effects*);
- digital music and movies replacing purchases of physical CDs and DVDs or smart working in substitution of commutes (*substitution effects*).

Instead, an example of ICTs applications generating a negative potential enabling effect is the development of a new software making PCs more energy demanding or requiring new hardware (*induction and obsolescence effects*).

Third order or systemic effects

Systemic effects of ICTs are those including behavioral and economic changes due to intended and unintended outcomes of the widespread application of ICT-based solutions. ICT have systemic effects in a number of ways, but the main ones are (Mickoleit, 2010):

- *changing technologies impacting consumer and user behavior*: the progresses and evolution in technology change consumer preferences, with major effects on raw material exploitation and power use; for instance, digital music is preferred over CDs, Internet communications and social networks are getting more popular than social affair, and teleconferencing technologies are reducing business travel;
- *triggering rebound effects*: greater efficiencies at the micro level do not always result in equivalent savings at the macro level due to a higher aggregate levels of consumption and use; for example, a high energy saving semiconductor has to contend with the very rapid increase in the number of ICT products embodying this component.

2.2.1 Information and Communications Technology for Sustainable Development (ICT4SD): the bright side of the coin

The study related to the Three-Levels Model by Hilty (2008) was only the first of many researches aimed to better understand environmental effects caused by ICT.

What came afterwards was a growing emphasis on the positive enabling effects that, together with the growing attention to the issue of sustainability, led to the belief in some that digital technologies could foster the achievement of a sustainable development as well.

The field of *Information and Communication Technologies for Sustainable Development* (ICT4SD) thus become the subject of a broad range of literature and reports (Rothe, 2020). According to the International Telecommunication Union (ITU), in fact, ICTs are capable to favour and accelerate the achievement of all 17 Sustainable Development Goals (SDGs), with an high impact on 7 of them (Dinana, 2019) (see *Table 2*).

SDG	**ICT Role in achieving the SDG**	**ICT Impact**
Goal 1: End poverty	ICT provide opportunities for businesses to become part of formal economy; mobile banking provides easy access to loans and mobile credit services.	High
Goal 2: Zero hunger	Smart agriculture system allows farmers to monitor the soil and weather conditions hence increasing productivity and reducing the use of water resources. Efficient crop management techniques can retain soil condition and leads to more sustainable agriculture.	High
Goal 3: Good health and well-being	The use of IoT applications in the delivery of health care services allow intelligent monitoring and diagnosis of diseases. Further, Big Data analytics allow timely forecast of diseases.	High
Goal 4: Quality education	ICT have enabled the access to online educational resources. Big Data analytics have assisted educators to identify learning challenges and deliver more personalized and tailored education training.	High
Goal 5: Gender equality	ICT increases women access to information and services including microfinance and banking services.	Low
Goal 6: Clear water and sanitation	Smart water management techniques have reduced water wastage and enhance water safety.	Low
Goal 7: Affordable and clean energy	Smart metering techniques allow better energy management, smart grids have allowed for sustainable energy supply while reducing the carbon footprint.	Low
Goal 8: Decent work and economic growth	Application of IoT and artificial intelligence possess great amount of potential to improve the production processes and leads to substantial economic growth. These technologies can also reduce the emission of GHG gases.	High

Goal 9: Industry, innovation and infrastructure	Integration of ICT, Big Data, IoT and artificial intelligence into the industrial processes have allowed for better fault tolerance techniques and continuous monitoring of industrial process.	High
Goal 10: Reduced inequalities	Advance ICT will allow for localized production and will lead to lower income inequalities.	Low
Goal 11: Sustainable cities and communities	IoT applications can transform the ideas of smarter and efficient cities into reality. Artificial intelligence and Big Data analytics can create better transportation systems and will enhance the transparency within the government processes.	High
Goal 12: Responsible consumption and production	IoT, Big Data analytics and artificial intelligence can significantly improve the coordination between producer and consumer, thus increasing efficiency and sustainability.	Low
Goal 13: Climate action	ICT can help reduce the carbon footprint and greenhouse gas emissions by making the production processes more efficient.	Low
Goal 14: Life below water	Use of new sensor and monitoring techniques can track oceanic resources. In addition, it allows for better resource management and early warning systems.	Low
Goal 15: Life on land	ICT enabled efficient monitoring of land resources, soil conditions and deforestation can help in the preservation of natural resources.	Low
Goal 16: Peace, justice and strong institutions	Use of open data policies can empower citizens; Big Data and blockchains can increase the government transparency.	Low
Goal 17: partnerships for the goals	ICT will enable in the formation of new communities of engaged citizens; Artificial intelligence will allow advance modelling of development that can be shared widely and rapidly.	Low

Table 2 - ICT Role in Achieving SDGs
Source: Dinana, 2019

With respect to the environmental question, studies and researches have highlighted how through the "*enabling effects*" (GeSI, 2008; GeSI, 2012; Ericsson, 2020), digital technologies can reduce the environmental footprint of numerous sectors and industries (Wu et al., 2018; Dinana, 2019; Ericsson, 2020).

Hence, the ICT sector could play a dominant role in facing climate change providing technologies to enable energy efficiency in other sectors or replacing goods and services with virtual equivalents with the aim to create a low environmental impact society.

In fact, as stated by Malmodin and Lundén (2018) and Ericsson (2020), ICT has an estimated potential to reduce global carbon emissions by up to 15 percent in other sectors.

Previously, GeSI researches (2008) found instead that ICT solutions to enhance efficiency in industry, transport, buildings and power sectors could abate global carbon emissions by 7.8 GtCO2-eq, with savings from avoided electricity and fuel consumption of €600 billion. From the updated report “SMARTer 2020”, also by GeSI (2012), resulted that the adoption of ICT can contribute to an important reduction of GHG emissions not only in the already analyzed sectors but also in other two: agriculture and consumer and service. Thus, the total reductions are predicted to be equal to 9.1 GtCO2-eq, a 16% higher than calculated in the preceding report.

According to Malmodin and Bergmark (2015), finally, from the implementation of ICT, the projections indicate a total GHG emission reduction by 2030 of about 8 GtCO2-eq or 12% of the global GHG emissions in a high reduction potential scenario, and of about 4 GtCO2-eq or 6% in a medium reduction potential scenario.

2.2.2 ICTs side-effects: the other side of the coin

Despite the evidences presented in the previous paragraph, not all that glitters is gold.

As we have seen, the sphere of Information and Communication Technologies for Sustainable Development (ICT4SD) is moved by the principle that ICTs can be adopted to foster sustainable development (Rothe, 2020), and of consequence to achieve Sustainable Development Goals (SDGs).

In relation to the SDGs, a central notion is the *Policy Coherence for Sustainable Development* (PCSD). It features under Goal 17 “Strengthen the means of implementation and revitalize the global partnership for sustainable development”, Target 14 “Enhance policy coherence for sustainable development”[17]. Even if PCSD is not clearly defined in the 2030 Agenda, according to OECD it is an approach aimed to ensure that development efforts to achieve a certain goal do not undermine the achievement of the other goals, so that all the efforts are coherent with the overall 2030 Agenda SDGs (Mackie et al., 2017).

Given that SDGs represent a complex network of interdependent objectives (Le Blanc, 2015), if we think about the notion of coherence applied onto the field of ICT4SD, what opens up is a rather important discourse.

If on the one hand we have, in fact, the potential of using ICTs to support various areas of sustainable development, on the other hand we have also to consider ICTs negative implications. Some questions that emerge are, for example: what impact do pervasive information and communication technologies have on global warming? Is it a sector that will hinder our fight against dangerous climate change?

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[17] https://sdgs.un.org/goals/goal17

ICTs are, as mentioned above, associated also with some undesired effects on the environment (Berkhout and Hertin, 2004; Hilty, 2008), that make the ICT sector itself highly unsustainable, especially if we take into account the entire life-cycle, and that is exactly why that paradoxes and incoherencies with the underlying principle of ICT4SD and with the principle of coherence of SDGs arise.

In fact, given that increasing the access to digital technologies is an important part of the SDGs (examples are SDG 5 Target 5.8 "Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women" or SDG 9 Target 9.c "Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020"), it is necessary to consider how the results of the successful implementation of these SDGs impact on the other goals.

If, for instance, we think about the increased production of laptops to achieve SDG 5 and SDG 9, we know that their production, and at the end of their life-cycle also their disposal, could cause consequences on climate action (SDG 13) and, in turn, on life on land (SDG 14) and life below water (SDG 15).

2.3 Focus on negative environmental impacts of ICTs solutions: a literature review

The existing literature shows heterogeneous consequences of ICTs solutions.

According to the report by The Shift Project (2019), the indirect beneficial impacts (optimization effects, substitution effects and decoupling) are often overestimated, essentially because direct and indirect negative impacts are not take into consideration.

In fact, while the ICTs potential is subject of a vast literature estimating the value of these positive impacts and how to take full advantage of them, much less attention seems to be paid to the potentially harmful side-effects of ICT and so to the increase in the environmental footprint (Verdecchia et al., 2017; Khan et al., 2020; Lucivero, 2020; Rothe, 2020) (see *Figure 12*).

This is why we should investigate more about these effects and about the increase in environmental impact which may depend on them, especially in the case of ICT, but not only because of this. There are some other reasons (Intellect, 2012):

- ICT sector is large, constantly and rapidly growing, so the impact can be significant;
- ICT sector is disruptive, pervasive and hard to delimit, so it is difficult to determine and assess emissions ascribable to ICT as opposed to those referable to other sectors;
- ICT is a sort of "iceberg" as often its main impact is invisible, in particular after the advent of *cloud* that strengthened the intangibility and imperceptibility of ICT.

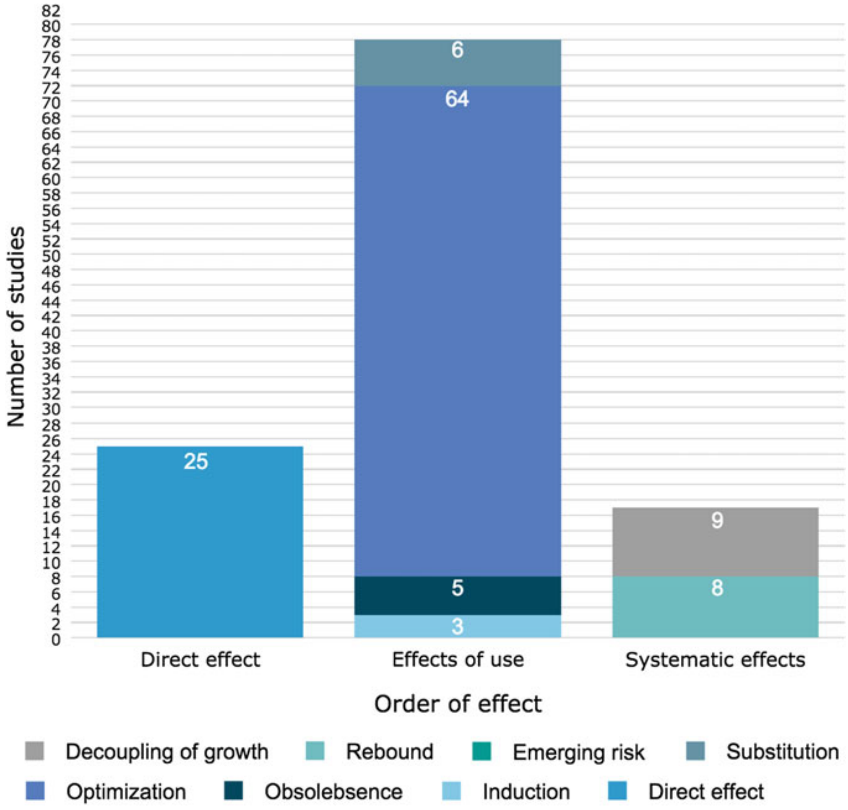

Figure 12 - Number of studies categorized by effect
Source: Verdecchia et al., 2017

2.3.1 Rare metals extraction and e-waste disposal

The metal content of digital equipment is one of the causes of natural resources depletion. Malmodin et al. (2018) found that ICT sector has a material resource depletion potential that can vary between 13% and 48%.

Digital equipment producers, in fact, are the largest consumers of metals, some of which are rare or whose reserves, at current cost and with current technologies, are not fully accessible (Mickoleit, 2010; Malmodin et al., 2018; The Shift Project, 2019).

The fundamental metals used in ICT goods manufacturing are aluminum, beryllium, cadmium, cobalt, copper, gallium, germanium, gold, indium, lithium, nickel, palladium, platinum, silver, tantalum and tin. Although some of them are used in minimum percentage, for others instead the ICT sector represents the major user (The Shift Project, 2019).

For example, gallium and tantalum are used in ICT production for 90 and 80 percent of the overall production respectively (Malmodin et al., 2018).

Moreover, the extraction and manufacturing processes of these metals increase carbon, water and energy footprints, triggering human and ecosystem toxicity (*ibidem*).

In addition to reducing the availability of reserves, the increase in the number of digital equipment also poses the problem of how to recycle them because of the presence of hazardous materials. Since 2010, worldwide volume of e-waste generated has been regularly growing (Forti et al., 2020). In 2019, around 53.6 million metric tons was produced, with an increase of 44.4 million metric tons in just five years. Of this, only the 17.4 percent was collected and properly recycled (*ibidem*).

2.3.2 Energy consumption growth

Although ICT can bring improvements in energy efficiency, one of the ICT sector itself primary problems is related to the energy consumption.

As reported by Lange et al. (2020), the relationship between digital technologies and energy consumption is crucial to establish whether the worldwide growing ICT sector is helping or hindering environmental sustainability, in particular regarding climate change.

In the ICT sector what most affects electricity consumption is the use of devices, networks and data centers, sometimes defined the “energy hungry factories of the digital age”, and their manufacturing (Greenpeace, 2011; Greenpeace, 2017) (see *Figure 13*).

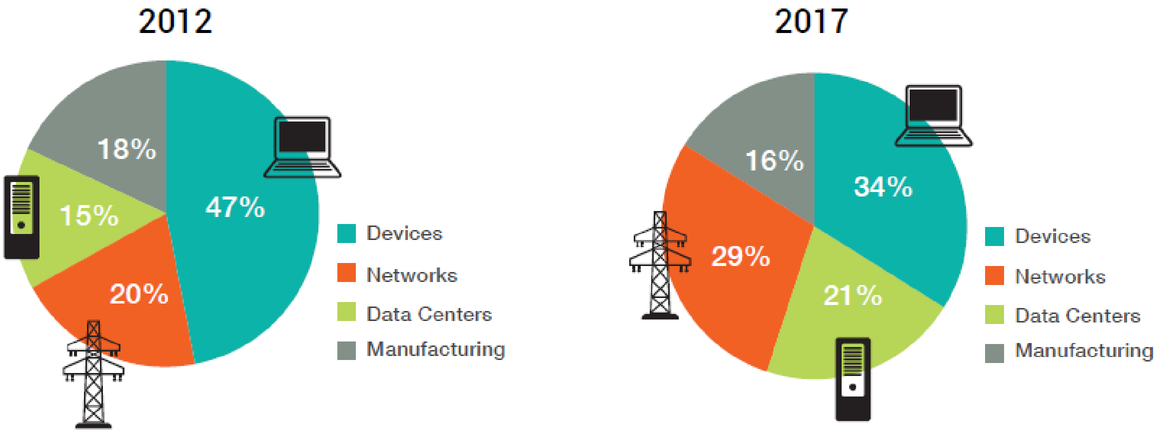

Figure 13 - Main components of electricity consumption for the ICT sector
Source: Greenpeace, 2017 (Adapted from Corcoran and Andrae, 2013)

Though most agree on the increase in electricity consumption derived from ICT, not everyone agrees on the amount of this increase and the resulting GHG emissions.

Malmodin et al. (2010) estimated that in 2007 the ICT sector contributed to the global electricity use for 3.9%, resulting in GHG emissions equal to 1.3% of the global emissions.

Subsequently, the findings of Van Heddeghem et al. (2014) indicated that the combined electricity consumption of personal computers, communication networks and data centers was growing at a rate of circa 7% per year, with a trend that doubled every 10 years, and an absolute operational power consumption grown up from 658 TWh in 2007 to 900 TWh in 2012 (an increase in the share of ICT in global electricity consumption from 3.9% to 4.6%).

Another research by Corcoran and Andrae (2013) estimated that in 2012 the ICT sector consumed over 7% of global electricity, with a projection exceeding 12% for 2017, and a annually growth of at least 7% through 2030.

Moreover, including manufacturing, in 2012 comparing the total electricity consumption of the ICT sector with the total electricity consumption of various states in the world, the global ICT sector electricity consumption ranks third, behind China and United States of America (Corcoran and Andrae, 2013) (see *Figure 14*).

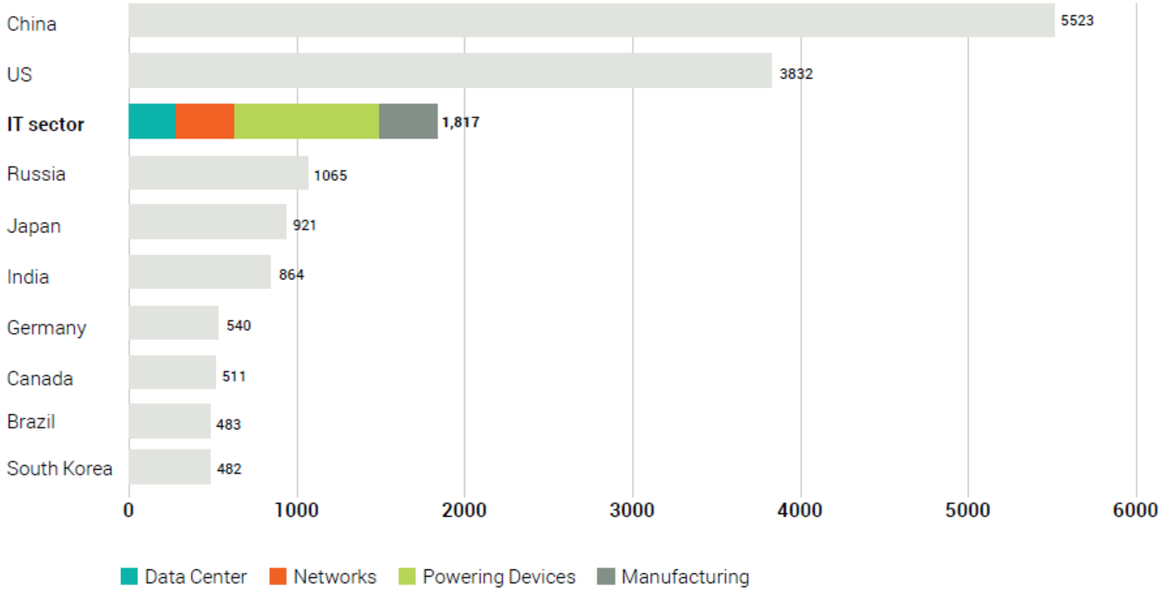

Figure 14 - 2012 Electricity Consumption; Countries Compared to IT Sector in billion kWh
Source: Greenpeace, 2017 (Adapted from Corcoran and Andrae, 2013)

A later study by Andrae and Edler (2015) tried to estimate global electricity usage (TWh/year) attributable to ICT sector (production and usage of consumer devices, communication networks and data centers) between 2010 and 2030, setting up also three different scenarios (best, expected and worst case) (see *Figure 15*).

What emerged, regardless the scenario, was that a proportion of use-stage electricity consumed by consumer devices will decrease and will be transferred to networks and data centers (Andrae and Edler, 2015).

The analysis then showed that, if it will not be possible to make further improvements to the efficiency of networks and data centers (worst-case scenario), ICT sector could consume up to 51 percent of worldwide electricity in 2030 and so contribute as much as 23 percent of the globally released GHG emissions in 2030, with devastating effects on the environment.

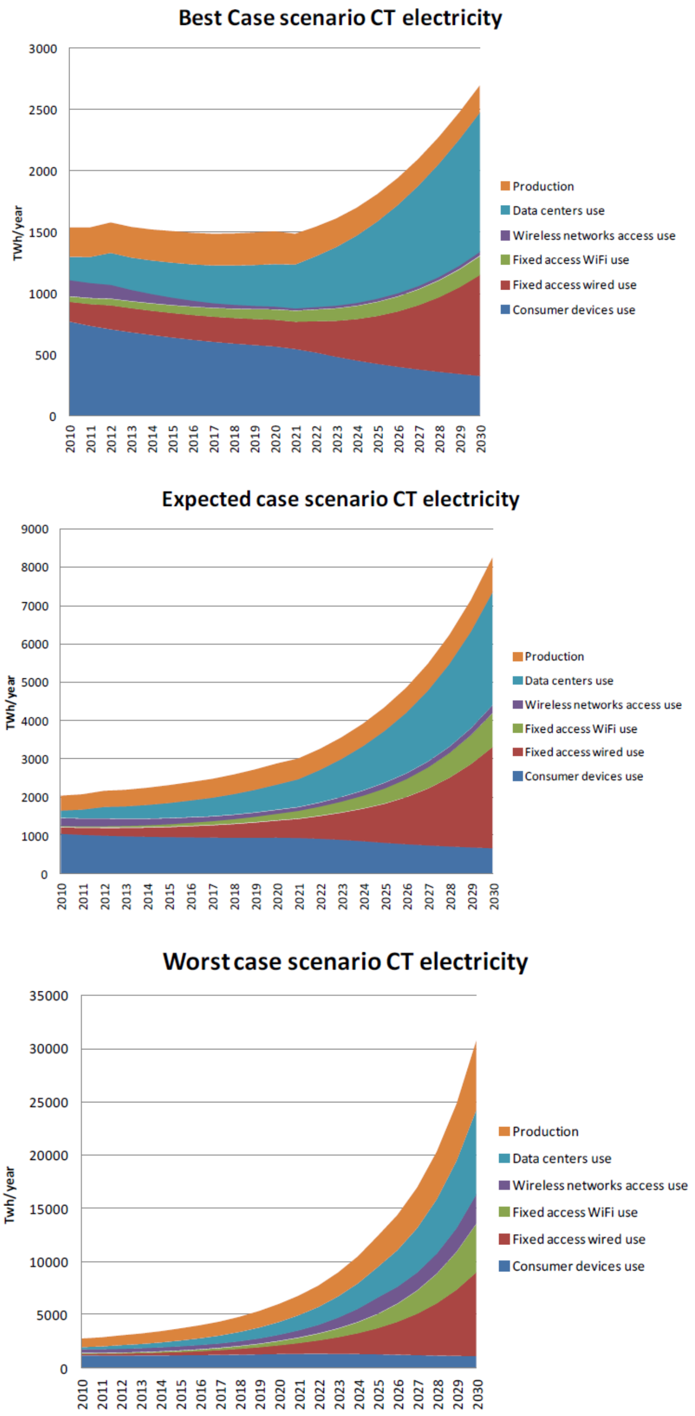

Figure 15 - Trends per ICT category for best, expected and worst case in global electricity usage 2010–2030
Source: Andrae and Edler, 2015

A more recent research by Belkhir and Elmeligi (2018) confirmed that the emissions from ICT industry, and therefore the environmental impact and the carbon footprint, come mainly from the production and operational energy consumption of ICT devices (consumer devices, data centers and communication networks).

This research had the purpose to assess the global carbon footprint of the ICT sector and compare it with the overall GHG emissions. With regard to the contribution of ICT to the total carbon footprint, it has grown from a 1-1.6% in 2007 to 3-3.6% in 2020 (estimated) (see *Figure 16*).

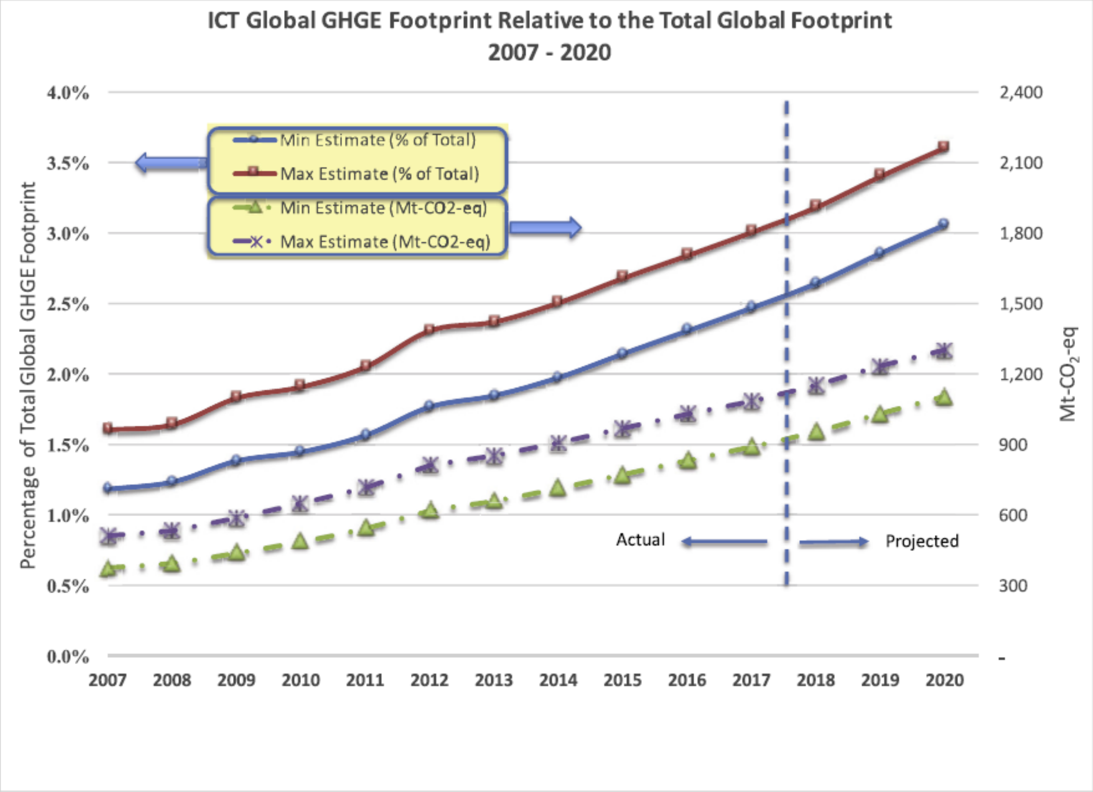

Figure 16 - ICT global GHGE footprint as a percentage of total global footprint (primary axis), and in absolute values in MtCO$_2$-eq on the secondary axis
Source: Belkhir and Elmeligi, 2018

Unlike what emerges from the elaboration of Corcoran and Andrae (2013) in *Figure 13*, from the analysis of what are the major ICT components that impact on the electricity consumption by Belkhir and Elmeligi (2018), subdividing the main category of devices into desktops, notebooks, displays, tablets and smartphones, it is interesting to note that the relative GHG footprint contribution of smartphone has almost tripled in the time span 2010-2020, exceeding the individual contribution of desktops (6%) and laptops (7%). However, the relative impacts of data centers (45%) and communication networks (24%) remain those that contribute most to the total footprint (see *Figure 17*).

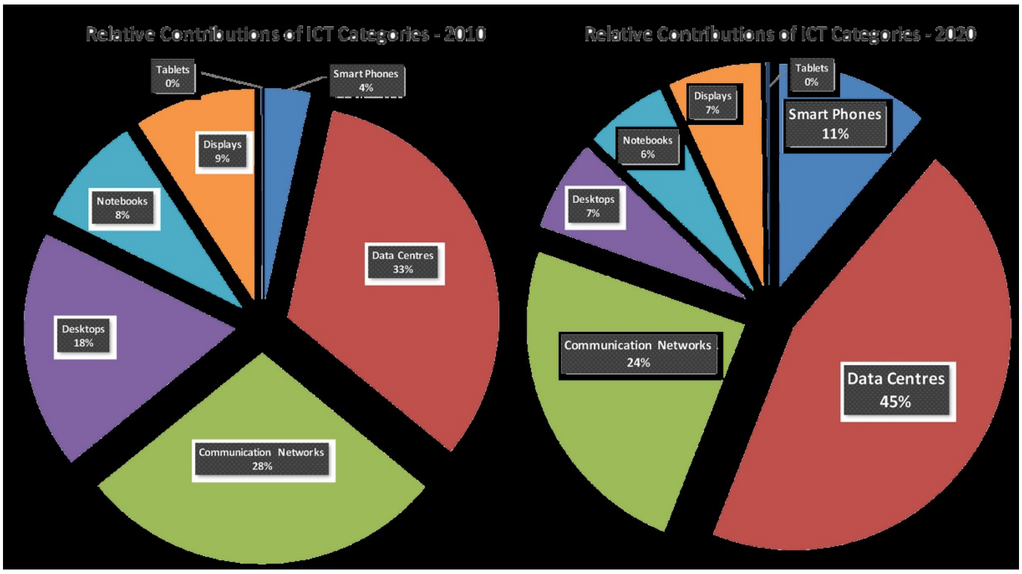

Figure 17 - Relative contribution of each ICT category in 2010 and 2020
Source: Belkhir and Elmeligi, 2018

Moreover, they performed both a linear and exponential fit to the data to predict the variations of ICT footprint as a percentage of total footprint (see *Figure 18*). Both linear and exponential forecasting predicted that by 2040 the ICT carbon impact could exceed circa 14% of the overall 2016 GHG footprint, with an annual growth fluctuating between 5.6% to 6.9%, value that could seriously undermine the efforts made so far to combat GHG worldwide emissions.

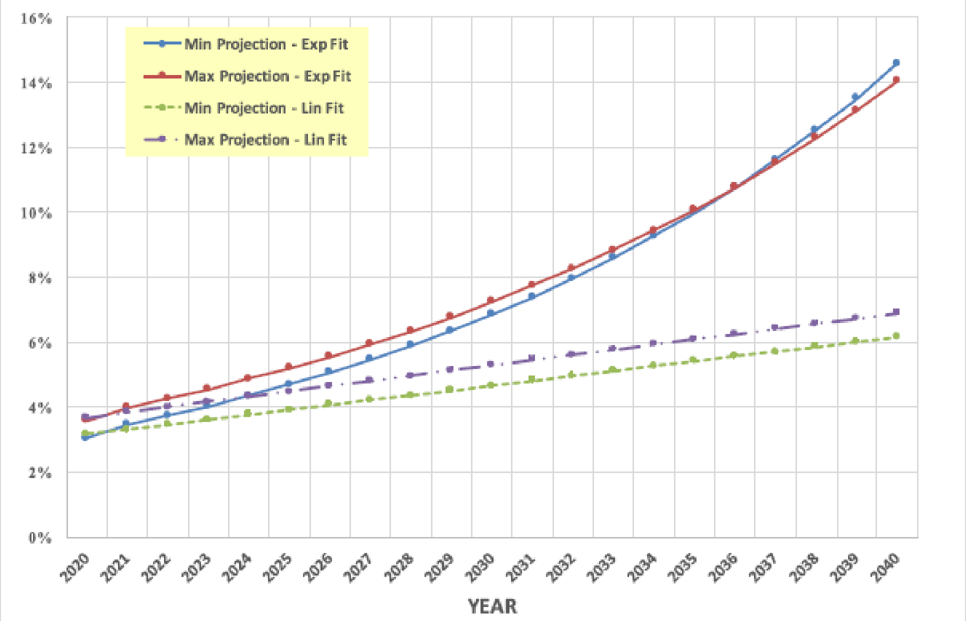

Figure 18 - ICT footprint as a percentage of total footprint projected through 2040 using both an exponential and linear fits Source: Belkhir and Elmeligi, 2018

A partially different scenario however emerges from a very recent report by Ericsson (2020), According to them, the total life cycle[18] carbon footprint of the ICT sector is approximately 730 Mt CO_2-eq (1.4 percent of the total GHG emissions), but it will be expected to remain almost constant in the coming years. The reasons behind this statement are related to the fact that, for understanding future trends, they analyzed the historical development of carbon footprint of ICT compared to the development of data traffic.

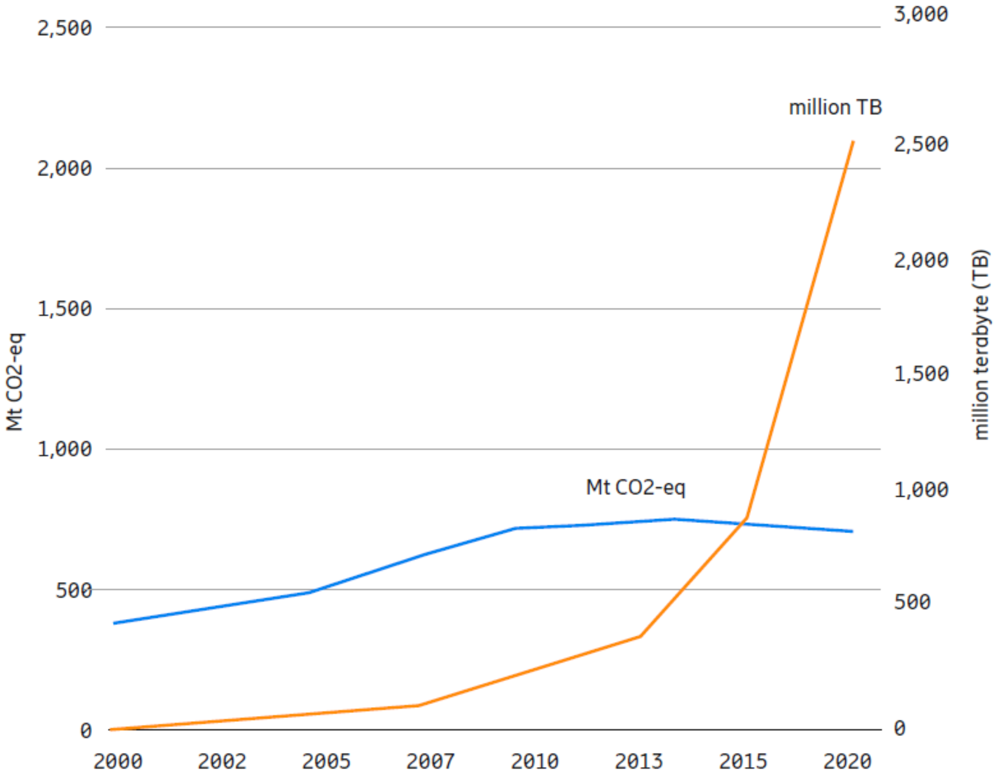

Figure 19 - Carbon footprint of ICT and data traffic development
Source: Ericsson, 2020

As you can see from *Figure 19* above, since 2010, the carbon footprint of the ICT sector have no longer followed the same trends as data traffic. In fact, starting from that point, total data traffic has increased approximately tenfold, while carbon emissions for the ICT sector remained nearly steady (Ericsson, 2020).

An even more up-to-date study by Lange et al. (2020) concluded that the reliance and trust placed in digitalization as a means to reduce energy consumption have not yet been validate.

In fact, instead of saving energy, ICT sector expansion has caused additional energy consumption. Furthermore, even if ICT could actually increase energy efficiency, it is still not

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[18] Not only the electricity used by all equipment in the system during their use, but also all other parts of the life cycle, like the manufacturing of networks, data centers, phones, computers and other user equipment

clear the overall effect on energy consumption due to rebound effects. However several authors, including Gossart (2015) and Coroamă and Mattern (2019), argue that the ICT sector is remarkably predisposed to high rebound effects.

2.4 Conclusion

In brief, the reasons why the ICT sector is to be kept under observation go well beyond helping the "go green" process of other sectors.

Although the relationship between ICT and environmental sustainability is in some ways still ambiguous and inconclusive (Khan et al., 2020; Lucivero, 2020), according to Santarius et al. (2020) it is also true that:

- ITC has a positive impact on economic growth and this makes reductions in energy and resource consumption very difficult;
- absolute resource and energy use by ICT sector is growing day-by-day;
- expectations that ICT helps the environment through decoupling effect seems not probable, given that the latter probably will be counterbalanced by rebound effects and economic growth.

Hence, it is necessary to investigate more on the role of ICTs in climate change and in the increasing carbon footprint, so that the industry will be able to take corrective actions while continuing to help and increase efficiency in other sectors.

- In Chapter 3 we will make an analysis to estimate the environmental footprint of cryptocurrencies compared to the environmental footprint of cash.

CHAPTER 3

COMPARATIVE ANALYSIS OF THE ENVIRONMENTAL IMPACT OF DIFFERENT PAYMENT SYSTEMS: AN LCA-BASED APPROACH

3.1 The evolution of payments

Since the dawn of trade, the payment methods with which to exchange goods and services have been subject to continuous evolution: from barter to the earliest forms of metal currencies from 1000 b.C., from the rise of the first banknotes in the middle of the 19th century to debit and credit cards from 1950s (Deutsche Bank Research, 2020a).

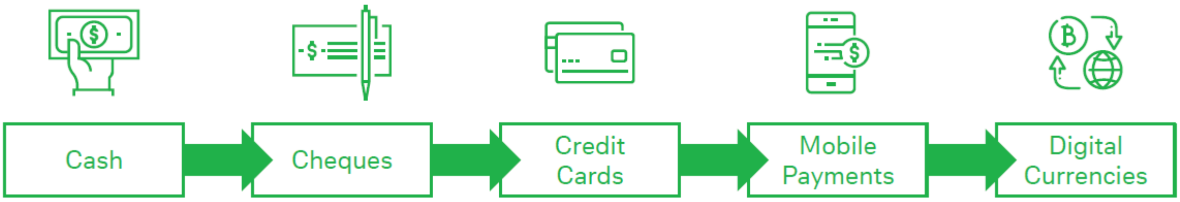

Figure 20 - A Century of Innovative Disruptions
Source: Deutsche Bank Research, 2020a

The advent of digital technologies has once more changed the world of payments, rapidly reducing the use of cash in transactions, and introducing new payment methods (Boshkov, 2018; Fiedler et al., 2019) (see *Figure 20*).

The increase in the digital payment adoption rate began with the proliferation of smartphones. The great expansion of these "one size fits all" devices opened the doors to a wide range of possibilities, including the opportunity for anyone to use phones for carrying out financial transactions (Deutsche Bank Research, 2020b). This, in turn, brought to the development of online and mobile banking/fintech[19] applications and carried new players, such as Apple, Google and Samsung, into the financial sector. They allow users to create digital wallets, on mobile phones, with personal and financial information traditionally stored on cards, so dematerializing payments.

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[19] Financial technology (Fintech) is used to describe new tech that seeks to improve and automate the delivery and use of financial services. More precisely, it describes a variety of financial activities, such as money transfers, bypassing a bank branch to apply for credit, raising money for a business startup, or managing investments, generally without the assistance of a person. [https://www.investopedia.com/terms/f/fintech.asp]

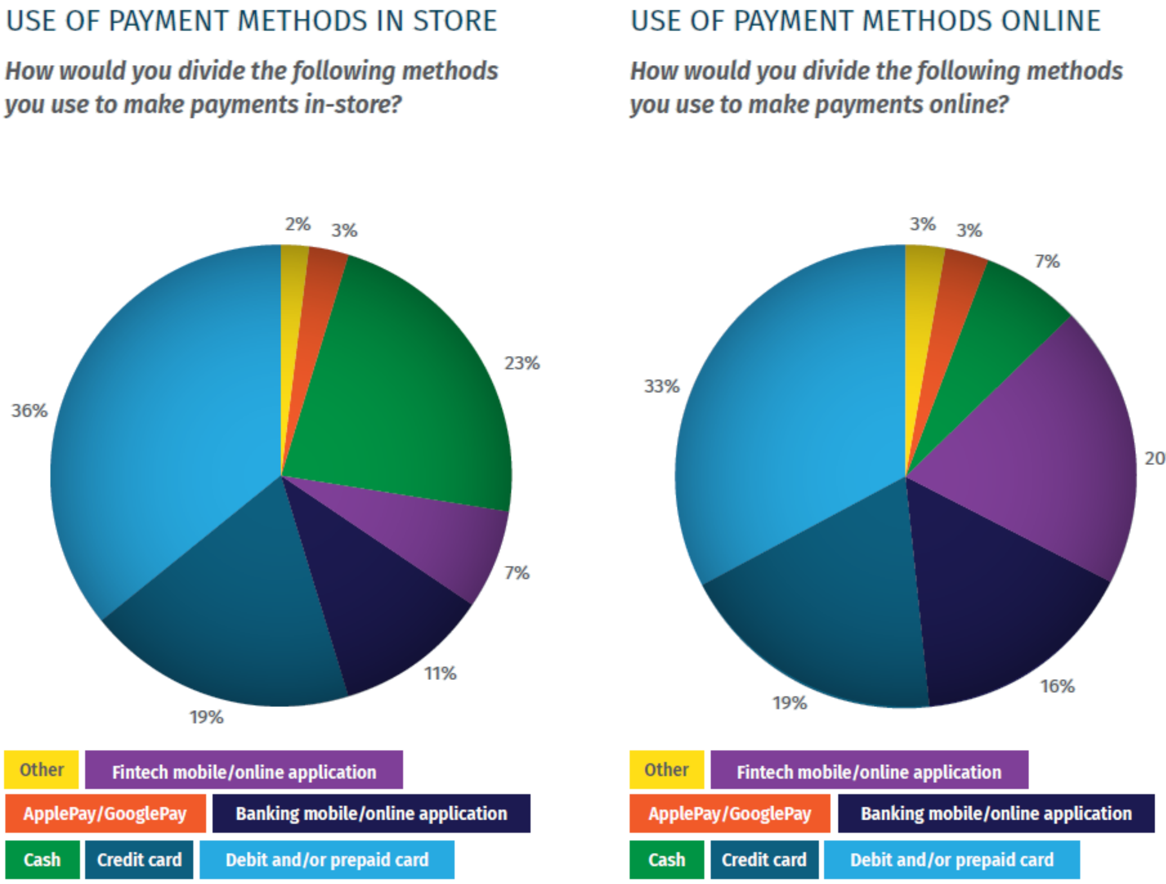

Figure 21 – The evolving European payments landscape
Source: Payments Europe and FTI Consulting, 2019

As we can see from *Figure 21*, the access to multiple payment methods has revolutionized the payments landscape, and the use of banking/fintech applications as ways of paying is becoming even more common, at least online.

However, technological advancement has not stopped and further changes are taking place in the financial sector, especially after that digital currencies have spawned. Digital currencies, as opposed to the so-called fiat currencies, are currencies that are available only in digital or electronic form, and not in physical and tangible form[20]. Examples include virtual currencies and the most famous cryptocurrencies.

Digital currencies are one of the most active areas of fintech innovations and have the potential to radically change payments (Deutsche Bank Research, 2020c). In fact, despite digital currencies was never meant to replace fiat currencies, they have already been adopted by millions of people worldwide and, in the long run, they could ultimately substitute cash (Deutsch Bank Research, 2020c; Gibbs, 2020).

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[20] Investopedia, s.v. “Digital Currency”, https://www.investopedia.com/terms/d/digital-currency.asp

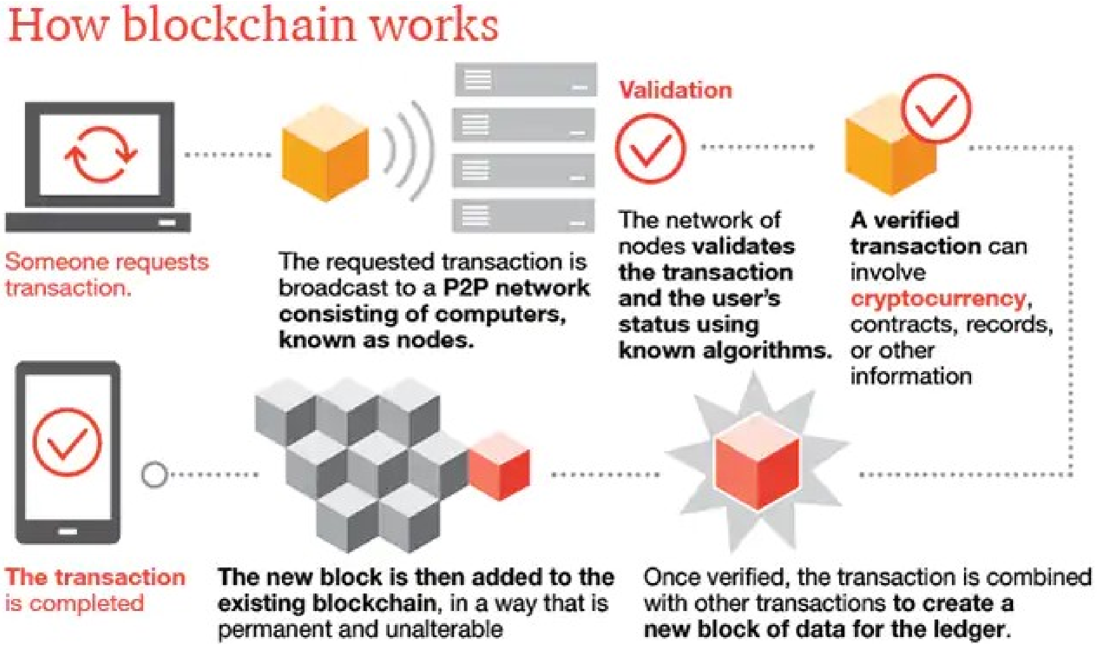
3.1.1 Cryptocurrencies and blockchain

Among digital currencies, those that are most talked about in recent years are cryptocurrencies. Even if cryptocurrencies have been around for about a decade, they were for the majority of people unknown until late 2017, when the Bitcoin's price went on a hair-bending rise and hit a peak of $19,783[21].

Cryptocurrencies, of which Bitcoin is the most prominent, are digital representations of value traded on global platforms, exchanged peer-to-peer[22], secured by cryptography and whose validity is provided by a blockchain (Houben and Snyers, 2018; World Bank, 2018; Frankenfield, 2020).

A blockchain is a database based on the distributed ledger technology (DLT), a way of recording data across multiple ledgers, containing exactly the same information, managed and controlled by a decentralized peer-to-peer network of servers, known as nodes (PwC, 2018).

So, blockchain can be viewed as a continuously growing database where transactions are recorded with a cryptographic signature, called hash, and once verified grouped in blocks. Each block is linked to the previous one by a hash pointer that chain them together in a verifiable and permanent way (see *Figure 22*) (Zheng et al., 2017; Houben and Snyers, 2018).



Someone requests transaction.

The requested transaction is broadcast to a **P2P network consisting of computers, known as nodes.**

The network of **nodes validates the transaction and the user's status using known algorithms.**

A verified transaction can involve cryptocurrency, contracts, records, or other information

Once verified, the transaction is combined **with other transactions to create a new block of data for the ledger.**

The new block is then added to the existing blockchain, in a way that is permanent and unalterable

The transaction is completed

Figure 22 - How blockchain works
Source: PwC, 2018

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[21] Investopedia, s.v. "Bitcoin's Price History", https://www.investopedia.com/articles/forex/121815/bitcoins-price-history.asp

[22] Without third parties such as governments, central banks and commercial banks working as intermediaries; the transaction takes place directly between the exchangers

The process of verification of the transaction is based on the consensus mechanism called Proof-of-Work (PoW). Following this system, network participants have to solve "cryptographic puzzles" of increasing complexity as time goes by in order to be allowed to add new blocks to the blockchain (World Bank, 2018). This puzzle-solving activity is commonly referred to as *mining* and is an open source process, given that anyone on the network can confirm the transaction to be added to the ledger.

In the case of cryptocurrencies, when a network participant or groups of participants, whether or not they are a cryptocurrency users, solve the puzzle, they are rewarded with a newly mined coin that can be sold for fiat currency or for other cryptocurrencies.

Apart from the Bitcoin, the cryptocurrency launched in 2009 by the mysterious Satoshi Nakamoto after the publication of his pioneering whitepaper "Bitcoin: A Peer-to-Peer Electronic Cash System" (2008), according to CoinMarketCap, there are more than 7,900 cryptocurrencies on the market[23]. The top five by market capitalization (see also *Figure 23*), as at January 15, 2021, are:

- Bitcoin (BTC): market cap $715,502,327,425; circulating supply 18,600,981 BTC;
- Ethereum (ETH): market cap $140,474,904,805; circulating supply 114,260,225 ETH;
- Ripple (XRP): market cap $13,310,397,893; circulating supply 45,404,028,640 XRP;
- Litecoin (LTC): market cap $9,915,848,667; circulating supply 66,283,191 LTC;
- Monero (XMR): market cap $2,943,163,308; circulating supply 17,813,650 XMR.

The so-called market capitalization of a cryptocurrency (i.e., the product between the market price of a cryptocurrency and its circulating supply) is a purely theoretical data. In fact, in the hypothetical case in which someone decides to sell all the BTC, or ETH, in exchange for US dollars or Euro, it is nearly impossible that he would get in exchange an amount equal to the market capitalization of Bitcoin or Ethereum.

While it is merely theoretical, the purpose of calculating market capitalization of a cryptocurrency is the same of calculating market capitalization of publicly traded companies: make comparisons, not only between different cryptocurrencies, but also between a cryptocurrency and for example a stock. For example, as at January 15, 2021, the market capitalization of Bitcoin (circa $715 billion) is higher than the market capitalization of

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[23] https://coinmarketcap.com/

Facebook (circa \$699 billion)[24]. Another type of comparison can be made between changes over time in the market capitalization of a single cryptocurrency.

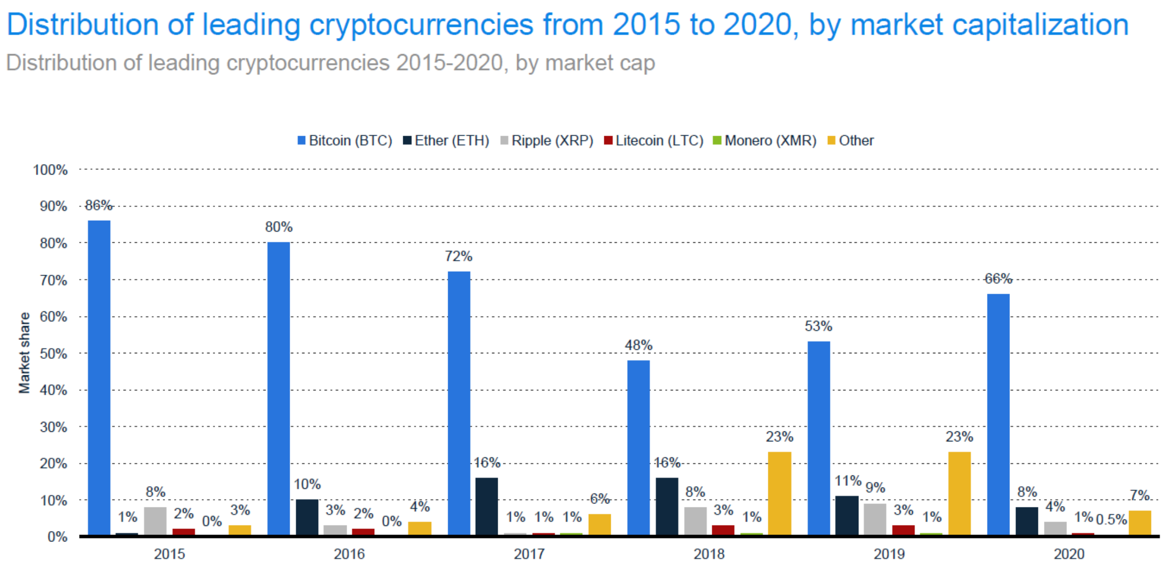

Figure 23 - Distribution of leading cryptocurrencies from 2015 to 2020, by market capitalization
Source: De Best, 2020 (Elaborated from Cambridge Judge Business School; CoinMarketCap; Various sources)

Although cryptocurrency is currently not widely accepted as a means of payment, adoption rates will certainly change in the near future. If they could be legitimized in the eyes of governments and regulators, thanks to the advantages they bring, including high security, they could really jeopardize the future of cash.

According to Deutsche Bank (2020c), cryptocurrencies adoption rate would mirror that of the Internet, indicating that the growth of the cryptocurrencies and of the Internet go almost hand in hand, even if cryptocurrencies user numbers are an order of magnitude smaller (see *Figure 24*).

Analysts of the Deutsche Bank tracked the adoption rate by the number of users embracing the Internet and Bitcoin since each went public. The Internet has been around since the 1980s but went public in 1991, while Bitcoin was launched in 2009 but was publicly accepted in 2011. So, year one for the Internet is 1991 and for Bitcoin is 2011.

To predict the number of blockchain wallet users, they applied the growth rate of the number of Internet users. What emerged is that the Internet, after 8 years of its existence, counted 500 million users, while the number of users of cryptocurrencies during the same time frame is currently 10 times smaller and counts about 50 million users.

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[24] https://finance.yahoo.com/

The predictions says that, if current trends continue, cryptocurrencies adoption will encompass about 200 million users by 2030.

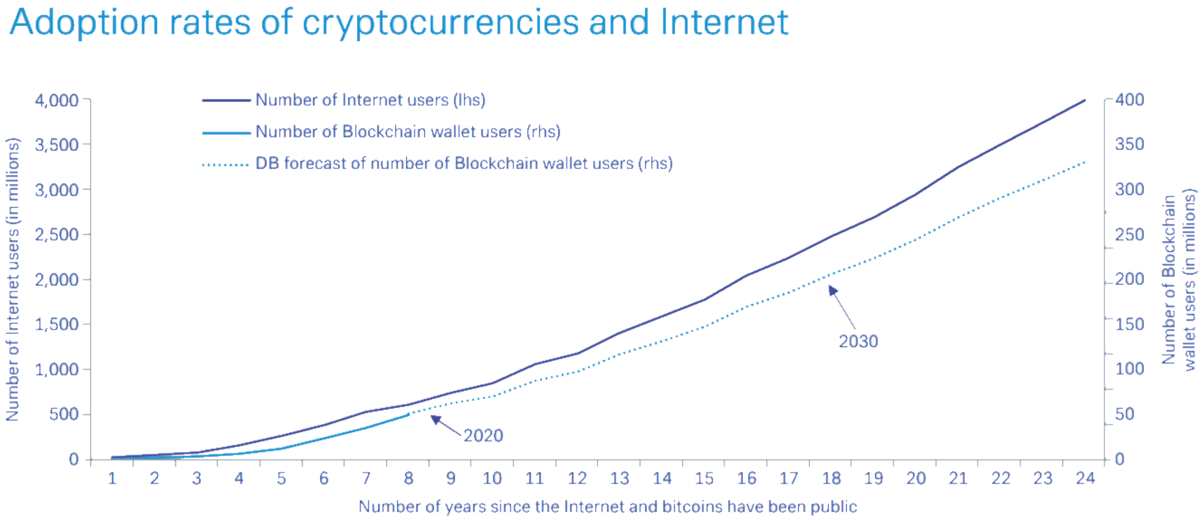

Figure 24 - Adoption rates of cryptocurrencies and Internet
Source: Deutsche Bank, 2020c

From the graph above, the expected growth of cryptocurrencies might not seem so impressive, but since precisely this is a prediction, at the moment we can interpret it more as an acceptance rate than an adoption rate.

In fact, a fairly broad acceptance could be the trigger for a subsequent widespread adoption of cryptocurrencies.

The general sentiment that cryptocurrency adoption rates are expected to rise is echoed by other researchers as well. According to a report by market intelligence and consulting firm Mordor Intelligence, the market for cryptographic hardware wallet[25] is likely to grow at a rate of 24.93 percent in the coming five years (Frost, 2020). This is supported by another report from P&S Intelligence which found that the projected market for cryptographic devices (hardware wallets in particular) will reach $23.5 billion by 2030, a whopping 7,700% increase (*ibidem*).

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[25] A crypto wallet is a tool used to interact with a blockchain network. It is possible to distinguish three groups of wallets: software, hardware, and paper wallets.
Software wallets can in turn be divided into web, desktop, and mobile wallets. Web wallets are browser-based wallet accessible without having to download or install anything. Desktop wallets imply the download of a software to be executed locally on the computer. Mobile wallets are instead smartphones applications.
Hardware wallets (the most secure alternative) are physical, electronic devices that use a random number generator to generate public and private key in order to perform transactions and that don't require Internet connection.
Paper wallets are piece of paper on which a crypto address and its private key are physically printed out in the form of QR codes that can then be scanned to execute transactions. [https://academy.binance.com/en/articles/crypto-wallet-types-explained]

3.2 Research scope and methodology

As we have seen, the payment market has evolved a lot. While in the past only cash and cards were competing, now there are new ways of paying.

As commerce is progressively moving to the online world, consumers and businesses are offered more and more choices. Each payment method has different features and everyone chooses the payment type that best fits him, or the specific purchase he needs to make.

In practice, consumers and businesses have ample freedom of choice in deciding how to make payments and what forms of payments to accept, but different payment methods correspond to different benefits and costs for the payer and the payee (Angel and McCabe, 2015; Payments Europe and FTI Consulting, 2019).

But that's not all. In fact, there are also social costs involved with each payment system, including the often underestimated environmental costs.

If we think for example about cryptocurrencies, a source of concern related to the environment is the one regarding the astonishing amount of electrical energy required for "mining" them (Belkhir and Elmeligi, 2018; Deutsche Bank Research, 2020c), and that certainly weighs heavily on the environmental impact of this emerging payment method.

Why does cryptocurrencies use energy? Because the lack of third parties working as trusted intermediaries makes the presence of a consensus mechanism (the above-mentioned Proof-of-Work) necessary. The idea for Proof-of-Work (PoW) was initially invented by Cynthia Dwork and Moni Naor in 1993, but the term was first used and formalized in 1999, in a paper by Markus Jakobsson and Ari Juels (Hooda, 2019).

According to Jakobsson and Juels (1999), in a typical cryptographic scenario, PoW is a protocol in which "one party, the prover, aims to convince another party, the verifier, that it possesses a secret of a certain form, or that a certain mathematical statement hold true" and that "he has expended a certain level of computational effort in a specified interval of time".

More simply, PoW is based on the principle for which the prover has to find a solution, that is in se difficult to discover, but easy to verify for the verifier (Hooda, 2019).

In a blockchain, and therefore also in the context of cryptocurrencies, Proof-of-Work is a consensus algorithm used to confirm transactions and add new blocks to the chain (Tar, 2018; Hooda, 2019). For a block to be accepted, in fact, *miners* (special computers on the network) have to perform computations, competing each other, in order to solve a complex "mathematical puzzle" that, with time, becomes even more complex (*ibidem*).

With regard to cryptocurrencies, the "mathematical puzzle" is generally a *hash function* – a function concerning the finding of an input knowing the output – that requires a lot of computational power to be solved, while the answer to the PoW problem is called *target hash*, a string of 64 chars or numbers.

To find the target hash, miners have at disposal the hash of the previous block and the hash of the current block of transactions (*Merkle root*) to verify. So, miners take that hash, add the Merkle root and then take a *nonce* ("number only used once"), a random string of number, and add it to the end of the string (Tar, 2018; Huskanović, 2018; Hooda, 2019).

After that, miners continue testing different nonces until they find the one for which the target hash of the block, according to the cryptographic protocols used, meets the requirements and solves the problem, allowing to add the block into the blockchain (see *Figure 25*).

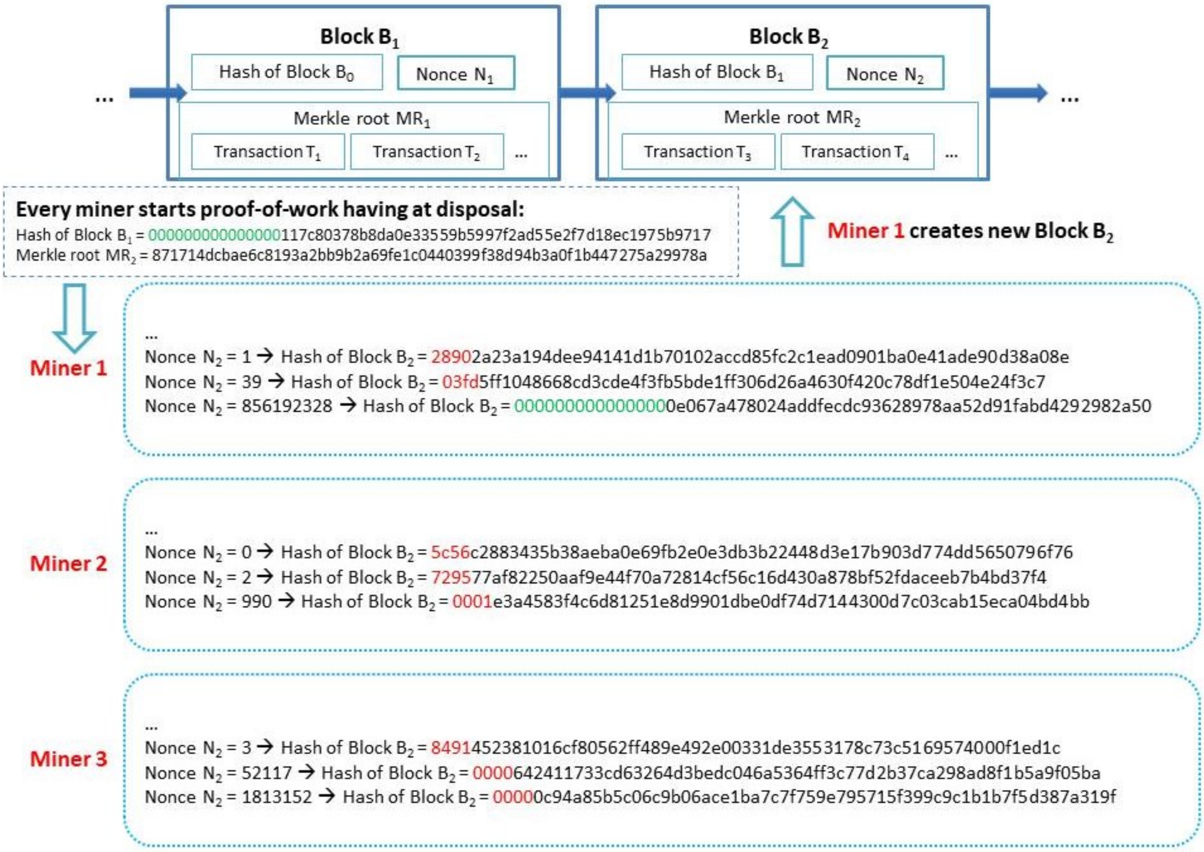

Figure 25 - An example of the nonce mechanism for the proof-of-work
Source: Personal elaboration

In practice, PoW is a trial-and-error process that ends when a miner find the hash string starting with a predefined number of leading zeroes (*target*) (at least the same of the hash string of the precedent block) (Huskanović, 2018). At that moment, the first miner that successfully completed the proof-of-work has the privilege to create the new block and is rewarded for his work, while the other competing miners stop the proof-of-work.

So, how does cryptocurrencies use energy? The energy use of the cryptocurrencies network is a function of some mutually dependent factors (Kamiya, 2019):

- hardware specifications of miners, in particular power consumption and hashrate (i.e., the processing power);
- network hashrate, or the combined processing power at which all miners on the network are simultaneously guessing the solution to the "mathematical puzzle"[26];
- difficulty of solving the puzzle, that adjusts approximately once every 2 weeks;
- energy consumption by other infrastructures, such as cooling and lighting ones.

Some of these factors increase proportionally with the cryptocurrencies market valuation given that miners are rewarded with newly mined coins, so the higher the market valuation of the cryptocurrency, greater the incentive for the miner to enhance hardware and infrastructures in order to be the first to find the solution to the "mathematical puzzle" and be rewarded for its effort, also at the expense of increased electricity use.

Summarizing, the energy consuming part is the one related to the resolution of the "mathematical problem" while performing the PoW, not in itself the verification or the addition of a new block to the blockchain (Hooda, 2019).

Given that, as previously said, cryptocurrencies have the potential to replace cash within the next 10 years (Deutsch Bank Research, 2020c; Gibbs, 2020) and, in recent times, seem also to be able to become the world's preferred safe-haven investment[27], the aim of this thesis is to make a comparative analysis between cash payment system and cryptocurrencies payment system, in order to estimate their environmental impact and evaluate whether or not the advances introduced by new digital technologies are environmentally beneficial.

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[26] e.g., a hashrate of 1 Th/s (Tera Hashes per second), indicates that the network is capable of performing 1,000,000,000,000 (one billion) calculations per second

[27] https://www.coindesk.com/tag/bitcoin-as-safe-haven
https://finance.yahoo.com/news/millennials-twice-likely-buy-bitcoin-221520470.html

Starting from this goal of comparing the environmental impact of a traditional (and analog) payment method such as cash with a digital payment method such as a cryptocurrency, we performed some preliminary research in the literature.

What emerged is that, in order to estimate the environmental impact of processes, products or activities, the Life Cycle Assessment (LCA) methodology is often used. In particular, this methodology had already been previously adopted to estimate the environmental impact of cash payment systems:

- Shonfield (2013), commissioned by the Bank of England, undertook an LCA study to calculate and compare the environmental impacts of conventional cotton paper banknotes and polypropylene banknotes for all UK banknote denominations;
- Luján-Ornelas et al. (2018) reported on comparing the environmental performance of Mexican banknotes printed on high-durability cotton paper and banknotes printed on thermoplastic polymer through a Life Cycle Assessment to evaluate the environmental impacts from raw materials extraction to the final banknotes disposal;
- Hanegraaf et al. (2020) quantified the impact of the Dutch cash payment system on the environmental and climate change using LCA, examining both the impact of banknotes and of coins.

Hence, the idea of using also for our analysis the LCA methodology, so as to be able to easily compare the results obtained with those obtained in previous studies.

We therefore decided, as a first step, to analyze the Euro cash payment system at a Eurozone level. Subsequently, although the LCA methodology was born and is generally used for the analysis of environmental impacts related to physical products, on the basis of what already done previously and in order to achieve our goal, we decided to try to adapt this methodology also to a digital product such as a cryptocurrency (the Bitcoin).

Generally, in order to develop LCA analysis, software like SimaPro[28] or GaBi[29] are used. These software tools enable to model and analyze complex life cycles, assess the environmental impacts of products and services at all stages of the life cycle, and detect hot spots at every link in the supply chain, from raw materials extraction to manufacturing, distribution, use, and disposal.

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[28] https://simapro.com/

[29] http://www.gabi-software.com/international/index/

Moreover, at the base of the functioning of these software there are datasets providing access to life cycle inventory data on energy supply, resource extraction, material procurement, chemicals, metals, agriculture, waste management services, transportation services etc. Among the available databases, Ecoinvent[30] is certainly the most complete, consistent and transparent.

Because of the high cost of licenses to use these commercial LCA software and datasets, in order to perform our analysis, we opted for an open source and free software (openLCA 1.10.3[31]), that plays the same league as commercial LCA software, and free databases[32] (IMPACT World+, Agribalyse, NEEDS, ELCD, bioenergiedat, openLCA LCIA methods, Ecoinvent LCIA methods).

Always with the aim of making our results comparable with the findings of previous studies, we chose the ReCiPe 2008 (H) as impact assessment method. ReCiPe is a methodology that consists of 18 midpoint impact categories (agricultural land occupation, climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, marine ecotoxicity, marine eutrophication, metal depletion, natural land transformation, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity, urban land occupation and water depletion) and three endpoint categories (human health, ecosystem and resources) (Goedkoop et al., 2009). These three endpoint indicators are then weighted into a single environmental indicator expressed in ecopoints (Pt).

All midpoint and endpoint indicators are available in three versions taking into account three different cultural perspectives (*ibidem*):

- individualist (I) is based on short-term interest and on the optimism that technology can avoid future problems deriving from the human behavior;
- hierarchist (H) is considered the default model;
- egalitarian (E) takes into account long-term interest and is based on a precautionary perspective.

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[30] https://www.ecoinvent.org/home.html
[31] https://www.openlca.org/
[32] https://nexus.openlca.org/databases

3.2.1 Life Cycle Assessment (LCA) methodology

LCA is a structured and comprehensive technique, internationally standardized according to environmental management standards ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), developed as a consequence of the increased awareness of the importance of environmental protection.

In the introductory part of ISO 14040, LCA is defined as a tool that "addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave)" (ISO, 2006a).

Generally, LCA is used to quantify and inform about emissions, resources consumption, and environmental impacts associated with processes, products or activities, and for identifying opportunities to improve the environmental performance at various points in their life cycle (ISO, 2006a; Klöpffer and Grahl, 2014).

In more detail, LCA methodology can be used to (Intellect, 2012):

- identify which points or stages in the lifecycle of a product/process have a high environmental impact, and so identify where efforts should be focused;
- estimate changes in environmental impact of a product/process over time;
- make comparative analysis regarding impacts among different industries;
- compare different supply chains for the same products/processes;
- compare products/processes that perform the same function but rely on different technologies.

An LCA framework is divided into four phases (ISO, 2006a; Klöpffer and Grahl, 2014) (see *Figure 26*):

- Goal and Scope Definition;
- Life Cycle Inventory (LCI) Analysis;
- Life Cycle Impact Assessment (LCIA);
- Interpretation.

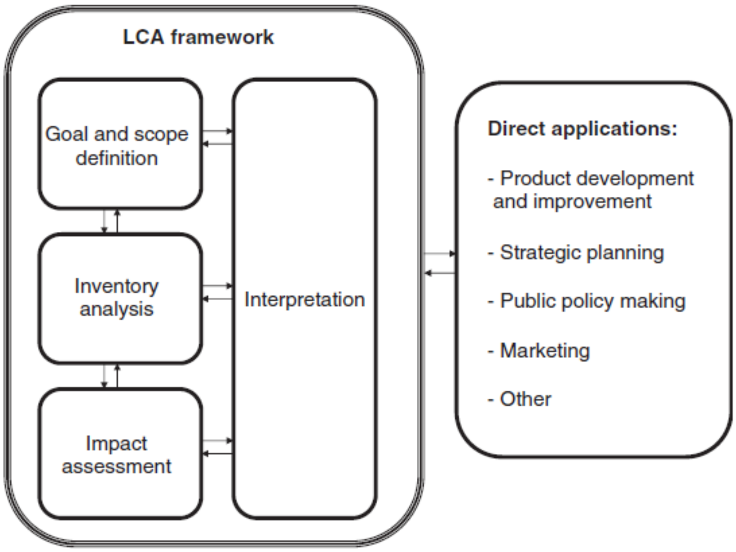

Figure 26 - LCA phases according to ISO 14040:1997/2006
Source: ISO, 2006a; Klöpffer and Grahl, 2014

As it is possible to observe from the arrows connecting the various phases of the framework above, LCA is an iterative technique because each phase use the results of the other phases. This iterative approach within and between the phases contributes to the development of the analysis according to the principles of comprehensiveness, consistency and transparency required from the ISO 14040 and ISO 14044 (*ibidem*).

Goal and Scope Definition

During the "Goal and Scope Definition" phase of the LCA, the objectives of the study shall be clearly defined, including the product/process system to be studied, the function of the product/process system and the functional unit with the reference flows, the system boundaries, and any other information necessary to achieve the purpose (ISO, 2006a; ISO, 2006b; Klöpffer and Grahl, 2014).

A product/process system is usually best described with a flow chart indicating processes (usually represented by boxes) of each life cycle stages and their interrelations. Then, given that a system may have a number of possible functions, the functional unit defines the selected one(s) to be studied in accordance with the goal and scope of the LCA.

After that, system boundaries are set to determine which unit processes should be included within the LCA (e.g., acquisition of raw materials, distribution and transportation, production and use of fuels/electricity/heat, use and maintenance of products, disposal). Given that LCA is aimed at providing a life cycle perspective, it is important to opt for wide boundaries to avoid an incorrect and/or incomplete analysis (Čuček et al., 2015).

The choice of which boundaries to put can fall among various possibilities (*ibidem*):

- *cradle-to-cradle*, from raw materials extraction to recycling or producing a new product (i.e., no waste);
- *cradle-to-grave*, from resource extraction to disposal;
- *cradle-to-gate*, from raw materials extraction to the factory gate (i.e., no use and disposal phase):
- *gate-to-gate*, related to only one process within the entire life cycle.

In the end, also geographical and temporal system boundaries are selected.

Life Cycle Inventory (LCI) Analysis

The second phase of Life Cycle Assessment involves data collection and calculation procedures to quantify inputs and outputs of a product/process system within the functional unit and boundaries defined during the first phase (ISO, 2006a; ISO, 2006b; Klöpffer and Grahl, 2014).

Data collected can be classified under macro-categories, including:

- energy inputs, raw material inputs and other physical inputs;
- products and wastes;
- emissions to air, releases to water and soil;
- other environmental aspects.

Life Cycle Impact Assessment (LCIA)

The phase of Life Cycle Impact Assessment (LCIA) is aimed at evaluating and classifying the significance of potential environmental impacts for the product/process system, that are afterwards assigned to specifically selected impact categories such as global warming potential (GWP), acidification potential, carbon footprint etc., in order to estimate the total environmental footprint (ISO, 2006a; ISO, 2006b; Klöpffer and Grahl, 2014).

Interpretation

Interpretation is the last phase of the LCA and it is the phase in which all the results from the previous analysis are considered together. These findings are then used to make comparative analysis and draw conclusions (ISO, 2006a; ISO, 2006b; Klöpffer and Grahl, 2014).

3.3 Cash payments from an LCA perspective

3.3.1 Goal and Scope Definition

Money makes the world go round and banknotes and coins are their physical expression.

In 2020, there were approximately 25.7 billion euro banknotes and 137.8 billion euro coins in circulation in the Euro area, with a total worth of 1,439 billion euro (ECB, 2020a).

The aim of this analysis is to provide a basic LCA in order to estimate the environmental impact of the main energy and material intensive processes involved within the cash payment system, from raw material production, to manufacturing and distribution of banknotes and coins, to ATMs use.

The functional units selected for the assessment are: "*Provision and use of cash (banknotes and coins) in 2020 in the Eurozone*[33]" and "*Provision and use of cash for an average cash payment (one banknote and one coin) in 2020 in the Eurozone*".

Product system to be analyzed

This study try to assess the life cycle environmental impacts associated with euro banknotes and coins, which main physical characteristics are provided in *Table 3* and *4* below.

Denomination	Material	Dimensions (mm)	Weight (g)
€ 5	Pure cotton fiber	120 x 62 x 0.12	0.6
€ 10	Pure cotton fiber	127 x 67 x 0.12	0.7
€ 20	Pure cotton fiber	133 x 72 x 0.12	0.8
€ 50	Pure cotton fiber	140 x 77 x 0.12	0.9
€ 100	Pure cotton fiber	147 x 77 x 0.12	1.0
€ 200	Pure cotton fiber	153 x 77 x 0.12	1.1
€ 500	Pure cotton fiber	160 x 82 x 0.12	1.1

Table 3 - Physical properties of Euro banknotes
Source: Personal elaboration on data from ECB, 2014; ECB, 2020b

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[33] The Eurozone, officially called Euro area, is a monetary union of 19 member states (Austria, Belgium, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Slovenia, Spain) of the European Union (EU) that have adopted the euro (€) as their primary currency and sole legal tender. [https://en.wikipedia.org/wiki/Eurozone]

Denomination	**Material**	**Diameter; Thickness (mm)**	**Weight (g)**
€ 0,01	94.35% steel, 5.65% copper	16.25; 1.67	2.30
€ 0,02	94.4% steel, 5.6% copper	18.75; 1.67	3.06
€ 0,05	94.35% steel, 5.65% copper	21.25; 1.67	3.92
€ 0,10	89% copper, 5% aluminum, 5% zinc, 1% tin	19.75; 1.93	4.10
€ 0,20	89% copper, 5% aluminum, 5% zinc, 1% tin	22.25; 2.38	5.74
€ 0,50	89% copper, 5% aluminum, 5% zinc, 1% tin	24.25; 2.38	7.8
€ 1	Inner 75% copper, 25% nickel clad on nickel core; Outer 75% copper, 20% zinc, 5% nickel	23.25; 2.33	7.5
€ 2	Inner 75% copper, 20% zinc, 5% nickel clad on nickel core; Outer 75% copper, 25% nickel	25.75; 2.20	8.5

Table 4 - Physical properties of Euro coins
Source: Personal elaboration on data from ECB, 2014; ECB, 2020b

So, the Euro cash payment system consists of both euro banknotes and euro coins, which have different life cycles. To better understand how this system works it is possible to draw a flow chart (see *Figure 27*).

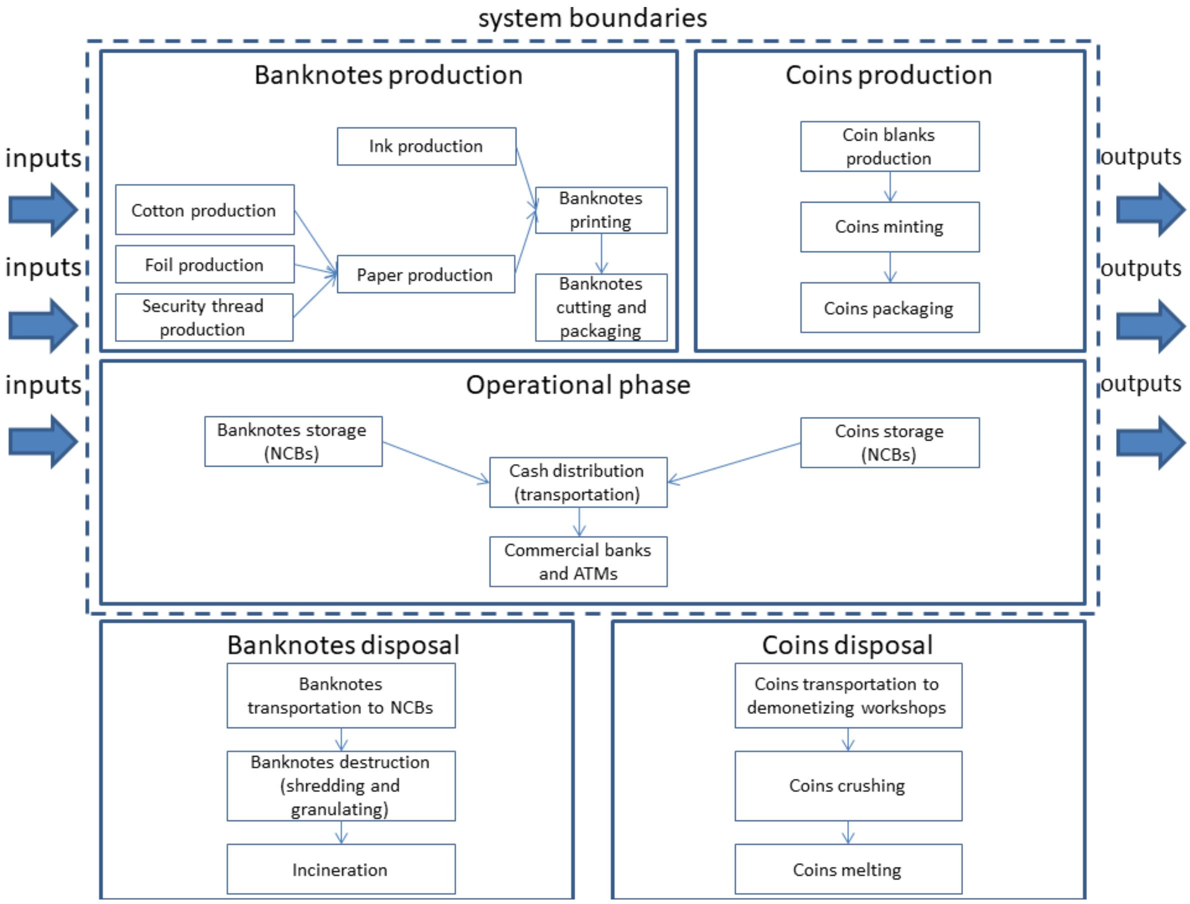

Figure 27 - Flow chart of the cash payment system with system boundaries and processes
Source: Personal elaboration (adapted from Hanegraaf et al., 2020)

Description of Euro banknotes life cycle

The life cycle of euro banknotes starts with their production thanks to the combined effort by national central banks (NCBs) and the European Central Bank (ECB). The number of banknotes required each year is forecasted by NCBs and ECB, considering how much banknotes are needed to replace unfit (poor-quality) banknotes returning from circulation and to meet expected (i.e., seasonal fluctuations) and unexpected increases in demand (ECB, 2020c).

The production process starts with paper making. Euro banknotes are printed on pure cotton-fiber paper, that gives them their special crispness and makes them resistant to wear and tear. At this stage, a watermark and a high-tech security thread are embedded in the paper, and a metallic foil is applied to the paper using pressure and heat. At the end of the production process, the paper is cut into sheets and transported from the paper mills to the printing works.

The printing of banknotes is performed by 11 different high-security printing works in Europe in order to achieve efficiency (*ibidem*). There are four stages to the printing process. The first stage is called offset printing and at this stage a multi-colored background is printed simultaneously on both sides of the paper. Then comes the silkscreen printing that is the applying of the number to the front of the banknote: the shiny ink contains special high-tech pigments which allow the number to change color when the banknote is tilted. The third stage is the intaglio printing where the ink high pressure application to the paper takes place. The last stage is the letterpress printing: the numbering press prints a serial number (a unique combination of two letters and ten digits) on the back of the notes.

After that, but also throughout the production process, randomly-chosen sheets of banknotes undergo strict quality checks and are thoroughly inspected by both machines and humans to ensure a uniform standard regardless of where they have been printed.

The printed sheets are then moved on to the finishing process. In this step, high-precision cutting machines slice piles of sheets into strips and then again into stacks of banknotes.

After being checked and counted once more, notes are wrapped in self-sealing plastic film, neatly stacked in cardboard containers and then either stored in high security vaults or shipped to commercial banks (ECB, 2020d).

Each bank should have enough banknotes for its customers, who withdraw the banknotes and make purchases with them. Later, banknotes circulate between shops, customers and banks and the ones that become dirty or worn are returned to NCBs, where unfit banknotes are destroyed and replaced with freshly printed ones.

Description of Euro coins life cycle

The production of Euro coins is carried out using advanced technologies that make their counterfeiting very difficult (ECB, 2014).

The design is the basis of each coin. This design is contained in a 3D digital file and, based on it, the metal dies are engraved.

The next step in the coins production is the minting. The various metals for the coins (i.e., copper, nickel, aluminum, zinc, tin) are first pressed to produce coin blanks (metal plates ready to receive the impressed design) and then punched according to the engraving to do.

Coins of any specific value must always have the same weight, therefore a weight check is performed. After that, minted coins are packed and placed in rolls and boxes, either stored or shipped, and then put into circulation.

In the case of obsolete or worn circulating coins, these are sent to the denaturating/demonetizing laboratory, in which their nominal value is erased by pressing the faces of the coins. They thus once again become mere sheets of metal that can be molten and used to strike new coins.

System boundaries

With regard to the system boundaries, the aspects considered for this assessment are:

- production of raw materials;
- transport of main raw materials;
- manufacturing of intermediate products;
- printing of banknotes;
- banknotes cutting and packaging;
- coins minting;
- coins packaging;
- distribution from NBCs cash centers to commercial banks and ATMs;
- impacts associated with the use of ATMs.

The aspects excluded from this assessment, instead, are:

- cultivation and/or extraction of raw materials;
- banknotes and coins storage at NBCs;
- impact of the banking system (bank branches);
- impact due to utilities such as lighting and HVAC (Heating, Ventilation and Air Conditioning) systems;
- transport and final disposal of unfit banknotes;
- transport and final disposal of obsolete or worn coins;
- use of cash by retailers (e.g., cash registers) and public (e.g., transports impact);
- construction of capital equipment for producing raw materials, intermediate products, banknotes and coins;
- packaging materials associated with the delivery of raw materials and similar.

Geographical boundary

The geographical boundary of the study is the Eurozone, but some raw materials are produced in other areas of the world depending upon the location of the manufacturing plants.

Temporal boundary

The temporal boundary is the year 2020 with regard to the quantities of cash produced, but information about raw materials, energy use, fuels etc. can be based on data collected at an earlier time.

3.3.2 Life Cycle Inventory (LCI) Analysis

Banknotes production

As we have seen, euro banknotes are produced in seven different denominations: EUR 5, EUR 10, EUR 20, EUR 50, EUR 100 and EUR 500.

In total, in 2020, 5,725 million banknotes has been produced (ECB, 2020b), equal to a value of 205,040 million euro.

Starting from weight and quantity of banknotes produced in 2020 (see *Table 5* below), and running the weighted average, it is possible to calculate the average weight of a fictional banknote (0.81 g), in order to facilitate subsequent calculations.

Denomination	Weight (g)	Quantity produced in 2020 (million)	Total weight (tonnes)
€ 5	0.6	752	451
€ 10	0.7	1,186	830
€ 20	0.8	1,271	1,017
€ 50	0.9	1,752	1,577
€ 100	1.0	764	764
€ 200	1.1	0	0
€ 500	1.1	0	0
		TOTAL	**4,639**

Table 5 – Weight and quantity of banknotes produced in 2020
Source: Personal elaboration

Assuming that each banknote is 87% cotton, 8% ink, 4% metallic foil and 1% security thread, the fictional banknote contains 0.705 g of cotton, 0.065 g of ink, 0.032 g of metallic foil and 0.008 g of thread.

Cotton yarns production

Cotton fibers are the main raw material used to produce banknote paper. ECB is strongly committed in improving sustainability of euro banknotes by gradually increasing the amount of sustainable (organic) cotton (in 2018, 15% were certified as originating from a sustainable source in environmental and social terms) in euro banknotes, in any case "requiring that all the companies involved in the production process are in full compliance with the ISO 14001 international standard"[34].

The cotton's country origin is unknown, but it is conceivable that the fiber production occurs in the largest cotton-producing regions: United States, India and China for traditional cotton[35] and India, Turkey and Syria for organic cotton[36].

Taking the Bundesdruckerei, a banknotes factory in Berlin (Germany), as middle point among all European banknotes factories, the approximate as the crow flies distance is 7,930 km from US, 6,558 km from India, 6,972 km from China, 2,350 km from Turkey and 2,856 km from Syria. So, on average, traditional cotton has to be transported for 7,153 km to reach European banknotes factories, while organic cotton has to travel for 4,059 km. The assumption is that cotton is transported by freight ships.

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[34] https://www.ecb.europa.eu/euro/banknotes/environmental/html/index.en.html

[35] Wright S., 2020. *Top Cotton Producing Countries in the World* [https://www.worldatlas.com/articles/top-cotton-producing-countries-in-the-world.html]

[36] Organic Trade Association, 2020. *Get the facts about Organic Cotton* [https://ota.com/advocacy/organic-standards/fiber-and-textiles/get-facts-about-organic-cotton]

The LCI inputs for cotton yarns production include cotton fibers (in our case 85% conventional and 15% organic; from 1 kg of raw fibers usually 700 g of yarn is obtained), electricity (avg. 3.50 kWh/kg[37]) and transports.

Metallic security foil production

Special metallic security foils are used to makes difficult to reproduce banknotes using common counterfeiting techniques. They are Optically Variable Devices (OVDs) applied to the substrate of banknotes, which have different metallic effects with holographic elements.

The LCI inputs of these foils are thermoplastic polyester films (PET)(25%), from which holographic effects are transferred on aluminum foils (75%), and electricity (for simplicity, we assume the same electricity usage of aluminum production, i.e., 15 kWh/kg[38]).

Security thread production

Security threads are made of thin aluminum coated and partly de-metallized polyester film thread with micro printing incorporated in banknotes to avoid fake duplications[39].

Of consequence, the LCI inputs for security thread production include aluminum, polyester films (PET), and electricity (for simplicity, we assume the same electricity usage of aluminum production, i.e., 15 kWh/kg).

Cotton paper production

The paper intended for the manufacturing of banknotes is formulated with cotton linters and cotton combers as base materials, that are then mixed in water with specific additives and chemicals to make a sort of pulp. During the manufacturing process, this pulp is distributed onto a moving continuous screen that allow water to drain by gravity. Then, the wet paper sheet goes through presses to be dried, and finally is rolled into large rolls[40].

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[37] Koç E., Kaplan E., 2007. An Investigation on Energy Consumption in Yarn Production with Special Reference to Ring Spinning. *Fibers & Textiles in Eastern Europe*, October/December 2007, vol. 15, No. 4 (63), http://www.fibtex.lodz.pl/63_08_18.pdf

[38] According to Alcoa (Aluminum Company of America) the best smelters use about 13 kilowatt hours of electrical energy to produce one kilogram of aluminum; the worldwide average is closer to 15 kWh/kg [https://www.alcoa.com/global/en/home]

[39] Wikipedia, s.v. "Security Printing", https://en.wikipedia.org/wiki/Security_printing

[40] Wikipedia, s.v. "Papermaking", https://en.wikipedia.org/wiki/Papermaking

So, the LCI inputs for paper production are water (for simplicity, we assume the same water usage of normal paper production, i.e., about 50 l/kg[41]), electricity (about 3 kWh/kg[42]), and additives and chemicals, in particular alum sulphate (2 g per kg of paper produced) to give the paper resistance to wetting and partial water repellency and carboxymethylcellulose (10 g per kg of paper produced) to increase its dry strength.

Ink production

The composition of security ink (including color-shifting ink and ultraviolet ink) with anti-duplication and anti-alteration characteristics is not disclosed for obvious reasons, so we can assume that the LCI inputs are the same of a traditional ink: 70% water, 10% dyes and pigments, and 20% additives (Isopropyl alcohol) and solvents (2-Pyrrolidone and Polyethylene glycol 200) that are then mixed together, plus electricity (1 kWh per kg of ink produced[43]).

Banknotes printing

As for the printing process, simplifying, it is possible to assume that the main LCI input is electricity (avg. 8 kWh/thousand banknotes[44]).

Banknotes cutting and packaging

With regard to the processes of cutting and packaging, LCI inputs include electricity (8kWh/160,000 banknotes[45]), polyester films (PET) and board boxes (avg. weight 400 g, containing max 10 kg).

Coins production

Euro coins are produced in eight different denominations: EUR 0.01, EUR 0.02, EUR 0.05, EUR 0.10, EUR 0.20, EUR 0.50, EUR 1 and EUR 2.

In total, in 2020, 13,152 million coins has been produced (ECB, 2020a), equal to a value of 4,211 million euro.

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[41] Wires&Fabriks, 2012. *Water – Meeting Paper's need*, https://paperonweb.com/Articles/Snapshot_Wateruse_2013_WireFabric.pdf

[42] https://www.statista.com/statistics/713287/energy-consumed-by-paper-production

[43] Marabu, 2013. *Marabu Environmental Report – Printing Inks*, https://www.marabu.de/fileadmin/content_Portalseite/pdf/Environmental_Report_Tamm_1426_Endfassung.pdf

[44] Average data derived from the declared consumption of various world mints

[45] https://www.gi-de.com/en/currency-technology/solutions/cash-processing-solutions/

Starting from weight and quantity of coins produced in 2020 (see *Table 4* below), and performing the weighted average, it is possible to calculate the average weight of a fictional coin (4.61 g), in order to facilitate following calculations.

According to the material composition of each coin as reported by ECB (2014), it is possible to calculate, approximatively, the quantities needed for each raw material (see *Table 6* below).

Denomination	Weight (g)	Quantity produced in 2020 (million)	Total weight (tonnes)
€ 0.01	2.3	2,505	5,762
€ 0.02	3.06	2,712	8,299
€ 0.05	3.92	1,777	6,966
€ 0.10	4.1	1,433	5,875
€ 0.20	5.74	1,727	9,913
€ 0.50	7.8	972	7,582
€ 1	7.5	984	7,380
€ 2	8.5	1,042	8,857
		TOTAL	**60,633**

Table 6 – Weight and quantity of coins produced in 2020
Source: Personal elaboration

Assuming that each coin is 52% copper, 38% steel, 5% nickel, 4% zinc, 0.8% aluminum and 0.2% tin, the fictional coin is made of 2.397 g of copper, 1.752 g of steel, 0.231 g of nickel, 0.184 g of zinc, 0.037 g of aluminum and 0.009 g of tin.

Coin blanks production

For coin blanks manufacturing are used steel, copper, aluminum, zinc, tin and nickel. The biggest producers of coin blanks for Euro coins are based in South Korea, Germany and Greece, so taking the Bundesdruckerei, a coins factory in Berlin (Germany), as middle point among all European coins factories, the approximate as the crow flies distance is 8,313 km from South Korea, 230 km from Germany and 1,642 km from Greece. So, on average, coin blanks have to be transported for 3,395 km to reach European coins factories. The assumption is that coin blanks are transported in part by freight ships (70%) and in part by freight trucks (30%).

The LCI inputs include steel, copper, aluminum, zinc, tin and nickel, electricity (2 kWh per kg of metal), water (0.5 liters per kg of metal), lubricating oil (0.5 kg every liter of water) and transports[46].

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[46] Cooper D.R., Rossie K.E., Gutowski T.G., 2017. An Environmental and Cost Analysis of Stamping Sheet Metal Parts, *Journal of Manufacturing Science and Engineering*, https://core.ac.uk/download/pdf/83232471.pdf

Coins minting

With regard to coins minting, it is possible to suppose that the only LCI input is the electricity (4 kWh/thousand coins[47]) used to engrave coin blanks.

Coins packaging

With regard to the processes of coins packaging, LCI inputs are electricity (7 kWh/210,000 coins[48]), polyester films (PET) for wrapping them and board boxes (avg. weight 400 g, containing max 10 kg).

Operational phase

The operational phase involves different processes: cash distribution and ATMs use.

Cash distribution

After being produced, banknotes and coins start to be distributed from NCBs cash centers to commercial banks branches and ATMs.

Not having available data on CIT (Cash-In-Transit) transports, we assume the same average distance on which goods are carried in international road freight transport in the EU in 2018 (581 km)[49]. For this process, the only LCI input is the transport.

ATMs use

According to the European Association for Secure Transactions (EAST), currently in Europe there are 378,750 ATMs[50]. ATMs are mainly used to withdraw money: between 2015 and 2018, on average, 11,995 million of withdrawals per year has been carried out in European Union[51], which results in an average of 86 transaction per ATM per day.

The main LCI input for ATMs is the electricity used, given that they are turned on 24/7. Every ATM has an average daily consumption of 3 kWh[52](it is not considered that when the temperature drops below zero Celsius a heater is required for ATMs, that significantly would increase energy consumption).

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[47] Average data derived from the declared consumption of various world mints

[48] http://www.scancoin.com/

[49] https://ec.europa.eu/eurostat/statistics-explained/index.php/Road_freight_transport_by_journey_characteristics

[50] https://www.association-secure-transactions.eu/industry-information/atm-numbers-europe/

[51] https://www.statista.com/statistics/1132870/number-of-money-withdrawal-at-cash-machines-european-union/

[52] https://www.deltapowersolutions.com/en/mcis/white-paper-uninterruptible-power-supplies-in-banking-and-finance-sectors.php

Data overview

In *Table 7* below is provided an overview of all inventory inputs per single banknote and/or coin, divided per process.

Due to the sensitivity of the data regarding the production of euro banknotes and coins, the majority of the data reported in the table below are the result of assumptions made in accordance with the information retrieved and described in the Life Cycle Inventory (LCI) Analysis, given that the real data are obviously not disclosed or are contained in confidential reports.

Process	Amount	Inventory input per banknote/coin
Cotton yarns production	0.856 g	Cotton fibers (traditional)
	0.151 g	Cotton fibers (organic)
	0.004 kWh	Electricity
	0.006 tkm[53]	Transport (traditional cotton)
	0.00061 tkm	Transport (organic cotton)
Metallic security foil production	0.008 g	Polyester films (PET)
	0.024 g	Aluminum foils
	0.00048 kWh	Electricity
Security thread production	0.006 g	Aluminum
	0.002 g	Polyester films (PET)
	0.00012 kWh	Electricity
Cotton paper production	0.037 l	Water
	0.002 kWh	Electricity
	0.0015 g	Alum sulphate
	0.0075 g	Carboxymethylcellulose
Ink production	0.045 l	Water
	0.006 g	Dyes and pigments
	0.006 g	Isopropyl alcohol
	0.003 g	2-Pyrrolidone
	0.003 g	Polyethylene glycol 200
	0.000065 kWh	Electricity
Banknotes printing	0.00799 kWh	Electricity
Banknotes cutting and packaging	0.000049 kWh	Electricity
	0.00002 g	Polyester films (PET)
	0.0324 g	Board boxes

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[53] Unit of traffic measurement that indicates the transport of one ton of goods for one kilometer of road; tkm are calculated as the product between the quantity transported and the kilometers traveled

Coin blanks production	1.752 g	Steel
	2.397 g	Copper
	0.037 g	Aluminum
	0.184 g	Zinc
	0.009 g	Tin
	0.231 g	Nickel
	0.0092 kWh	Electricity
	0.0023 l	Water
	0.00115 g	Lubricating oil
	0.01565 tkm	Transport
Coins minting	0.004 kWh	Electricity
Coins packaging	0.000033 kWh	Electricity
	0.00002 g	Polyester films (PET)
	0.1844 g	Board boxes
Cash distribution	0.00049 tkm	Transport (banknotes)
	0.00028 tkm	Transport (coins)
***ATMs use* (only for banknotes)**	0.0724 kWh	Electricity[54]

Table 7 - Material and resources inventory inputs for each process
Source: Personal elaboration

3.3.3 Life Cycle Impact Assessment (LCIA) and interpretation of the results

The environmental impact of the entire Eurozone cash payment system in 2020, estimated using the ReCiPe Endpoint (H) v. 1.13[55] method, is of 59.98 MPt (million ecopoints).

The climate change impact, instead, calculated as the global warming potential (GWP), results in 478.4 million kg CO_2-eq, which corresponds to 0.014% of total CO_2 emissions in the EU (3,320.3 million tons CO_2 in 2019[56]).

In *Figure 28* we can see the environmental impact of each macro-process divided per endpoint category. The highest impacts are relative to the coins production phase (21.12 MPt) and to the operational phase (32.79 MPt), while the production of banknotes has a relative low impact (6.07 MPt).

Figure 29 provides an overview of the total environmental impact broken down in midpoint categories, outlining the areas that account mostly to the environmental footprint of the cash payment system. The midpoint category with the largest contribution is fossil depletion (24.98%), while climate change human health and metal depletion affect the total impact for

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[54] To determine environmental impact of electricity use, the European Union's electricity mix was considered

[55] This version was used, although it is currently outdated, to make the analysis comparable with analyses performed in previous studies

[56] https://www.statista.com/statistics/450017/co2-emissions-europe-eurasia/

14.35% and 17.11% respectively. Climate change ecosystems midpoint category accounts for 8.46%, agricultural and land occupation for 8.07%, particulate matter formation for 7.31%, and human toxicity for 2.24%. The other midpoint categories together contribute for the 1.09% to the total environmental impact.

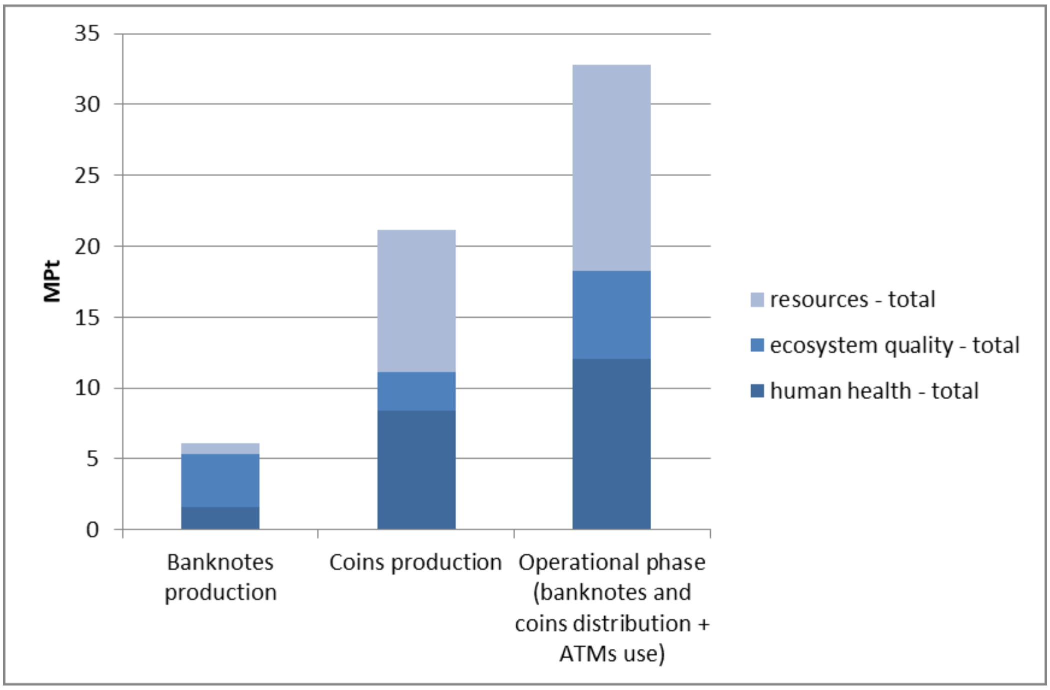

Figure 28 - Environmental impact of each macro-process per endpoint category
Source: Personal elaboration

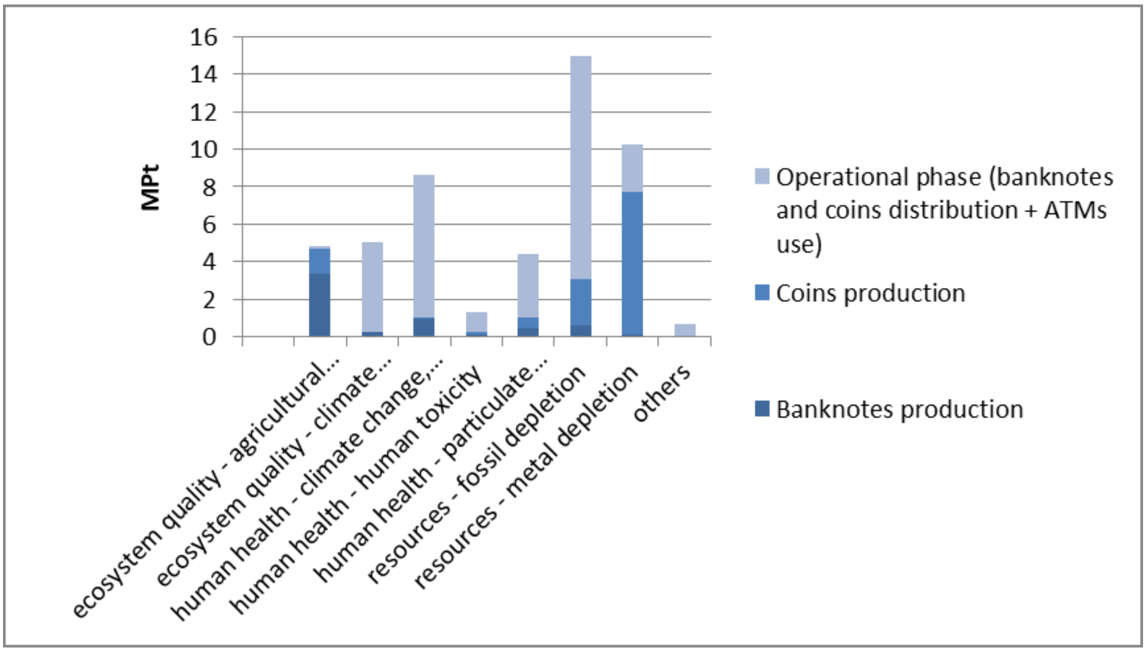

Figure 29 - Environmental impact of each macro-process per midpoint category
Source: Personal elaboration

With regard to the fossil depletion, the operational phase is the one with the greatest impact because of cash distribution (transport) and ATMs electricity use derived from non-renewable energy sources, that affect also climate change midpoint categories.

Metal depletion, instead, stems primarily by the use of metals (copper, steel, aluminum etc.) during coins production, while the particulate matter formation into the air is caused by the combustion of fossil fuels by the armored vehicles for transporting cash.

Despite the complexity of the studied system and the unavailability/scarcity of official data because of confidentiality issues, and although free software and databases have been used to perform this analysis, all these findings seems to be quite in line and consistent with those of Shonfield (2013), Luján-Ornelas et al. (2018) and Hanegraaf et al. (2020).

In particular, with regard to the results obtained by Hanegraaf et al. (2020), they found that the environmental impact of the Dutch cash payment system in 2015 was 2.42 MPt, with emissions equal to 19 million kg CO_2-eq.

Considering that the Eurozone economy (GDP 2019 equal to 13,361 US$ billion) is almost 15 times bigger than the Dutch economy (GDP 2019 equal to 907 US$ billion)[57], and that the Netherlands produce only a small part of the total Euro banknotes and coins (in 2015, the Netherlands mint produced about 4.4% of the total Euro banknotes, while in 2020 only the 2.47%[58]), it is credible that the environmental impact of the Eurozone cash payment system is several times bigger. If we compare the two, in fact, it emerges that the environmental impact of the Eurozone cash payment system is about 25 times bigger than the one of the Netherlands.

Also with respect to the environmental impact of an average cash payment our results are sufficiently coherent with those of Hanegraaf et al. (2020). Their findings showed, for an average single-cash transaction in the Netherlands in 2015, an environmental impact calculated as 654µPt (millionths ecopoints) and a carbon footprint of 5.1 g CO_2-eq, while our findings for an average cash payment (intended as a payment using one banknote and one coin) in 2020 in the Eurozone results in 516µPt and carbon emissions equal to 4.05 g CO_2-eq.

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[57] https://www.imf.org/en/Publications/WEO/weo-database/2020/October

[58] https://www.ecb.europa.eu/stats/policy_and_exchange_rates/banknotes+coins/production/html/index.en.html

3.4 Cryptocurrencies from an LCA perspective

3.4.1 Goal and Scope Definition

Among cryptocurrencies, Bitcoin is definitely the best known.

At the end of 2020, there were approximately 18.5 million BTC mined in circulation, for a total worth of circa 506 billion USD[59] (412 billion €).

The aim of this analysis is to provide a basic LCA in order to estimate the environmental impact of the Bitcoin payment system.

The functional units selected for the assessment are: "*Th computed for all the Bitcoins mined in 2020*" and "*Th computed for one Bitcoin mined in 2020*".

Product system to be analyzed

The Bitcoin payment system works as follows[60] (see also *Figure 30*):

1. Sender opens his Bitcoin wallet, scans the code containing the Receiver's address, fills the amount and creates the transaction;
2. Bitcoin wallet validates the new transaction and sends it to the Mempool (Memory Pool); the Mempool is where all valid transactions stay until they are added to a new block;
3. Subsequently, miners get the block including also Sender's transaction awaiting confirmation and start mining using the Proof-of-Work (consensus algorithm);
4. When the block is fully mined, it is added to the blockchain, a public ledger of Bitcoin transactions in chronological order used to verify Bitcoin transactions and to prevent double spending;
5. After the blockchain validates the new block, finally Receiver get the amount sent by the Sender.

New Bitcoins are created each time a new block is validated and added to the blockchain. In fact, for each block mined, the miner receives a reward, that represents also the number of new Bitcoins created. So, in the case of cryptocurrencies, the productive phase is the mining one.

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[59] https://www.blockchain.com/
[60] https://dev.to/gmfcastro/the-bitcoins-lifecycle-overview-1fld

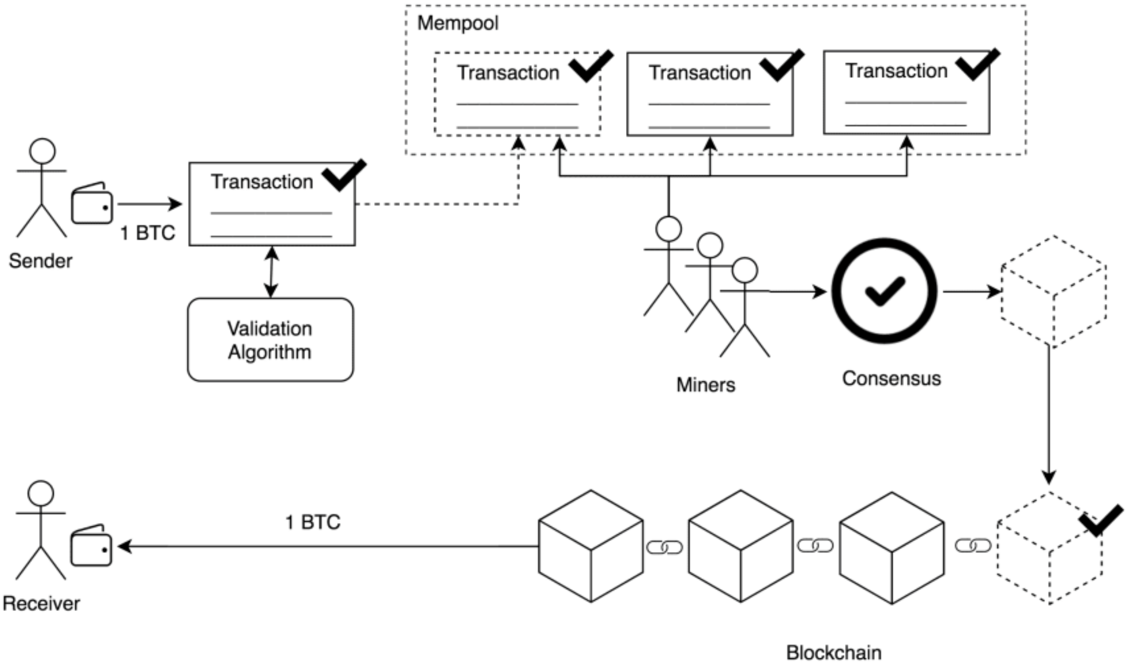

Figure 30 - The Bitcoin payment system
Source: https://dev.to/gmfcastro/the-bitcoins-lifecycle-overview-1fld

In 2008, after the mining of the Bitcoin Genesis Block (Block 0) containing 50 Bitcoins, the initial reward per block was set to 50 BTC. This quantity was programmed to decrease over time according to a geometric progression with a *halving* of the premium every 210,000 blocks, or approximately every 4 years. Thus sized, this series implies that a total of about 21 million bitcoins will be created until 2140, when the mining reward will drop below 10^{-8} BTC, which is the minimal unit of Bitcoin (Vranken, 2017).
The reward has thus decreased to 25 BTC per block on November 28, 2012, to 12.5 BTC per block on July 9, 2016, and is currently equal to 6.25 BTC per block from May 11, 2020[61].

To better understand the way in which a block is mined, and so the way in which new Bitcoins are created, it is possible to draw a flow chart (see *Figure 31*).

System boundaries

With regard to the system boundaries, the only aspect considered for this assessment is the impact associated with the electricity used by mining hardware equipment for the mining phase, since, as mentioned earlier, the energy consuming part is the one related to the performing of the PoW.

The aspects excluded from this assessment, instead, are mining hardware equipment production and disposal, impacts due to cooling systems and other energy requirements.

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[61] Wikipedia, s.v. “Bitcoin”, https://en.wikipedia.org/wiki/Bitcoin#Supply

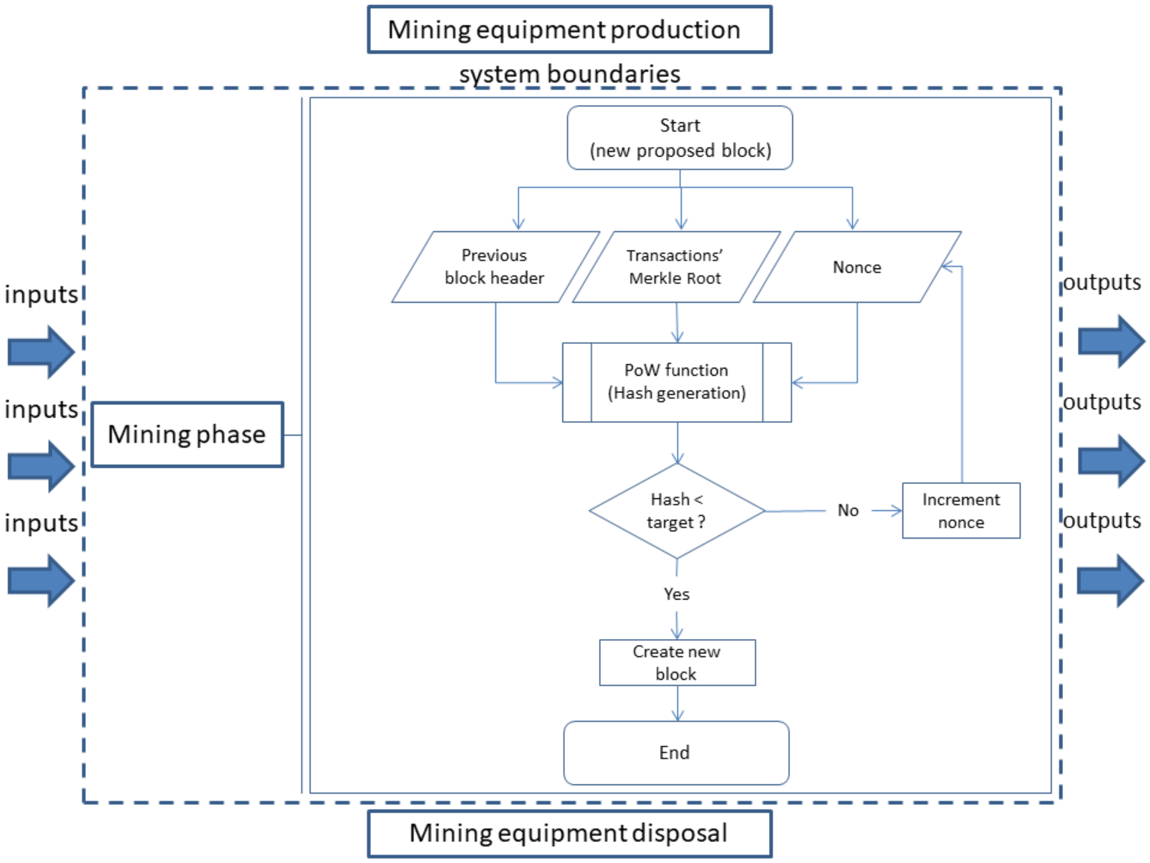

Figure 31 - Flow chart of Bitcoin mining with system boundaries and processes
Source: Personal elaboration

Geographical boundary

By definition, digital technologies know no geographical boundaries, and so it is with cryptocurrencies as well. However, for the purposes of our assessment, we can analyze the geographical distribution of miners around the world.

Although the mining process is permissionless, and so in theory anyone in the world can start mining blocks by himself, a single miner could operate several ASICs at high power and would still only be a drop in the ocean of Bitcoin mining, with a odds of finding a block that is pretty slim, even if he has spent a lot of money in hardware and electricity to run it.

In fact, a good hardware is only useful up to a point. To bypass this problem, miners begun to combine their computational resources to strengthen the probability to successfully mine a block and receive the reward, creating the so-called *mining pools* and splitting the reward equally, based on their contribution and effort in finding the block.

According to the information provided by BTC.com[62], the distribution of the mining pools calculated by number of blocks mined was as represented below by *Figure 32*.

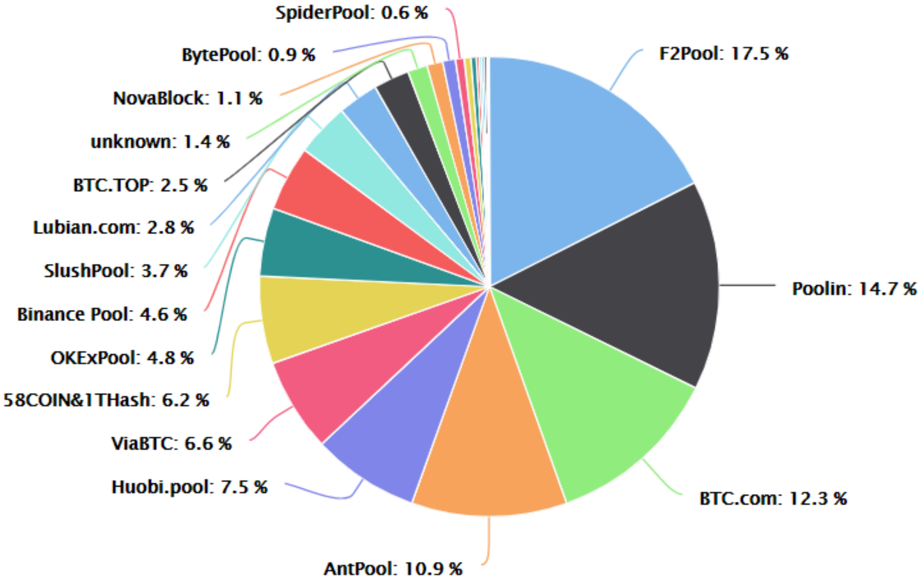

Figure 32 - Mining pools distribution in 2020
Source: https://btc.com/stats/pool?percent_mode=2020#pool-history

Dropping out mining pools contributing less than 2% and unknown miners, the distribution becomes as follows (see *Table 8*):

Mining pool	Share 2020
F2Pool	18.62%
Poolin	15.62%
BTC.com	13.03%
AntPool	11.60%
Huobi.pool	7.98%
ViaBTC	6.97%
58COIN&1Thash	6.53%
OKExPool	5.10%
Binance Pool	4.88%
SlushPool	3.98%
Lubian.com	3.02%
BTC.TOP	2.67%
	100%

Table 8 - Distribution of Bitcoin miners based on mining pools data for 2020
Source: Personal elaboration on data from https://btc.com/stats/pool?percent_mode=2020#pool-history

To determine the geographic distribution of miners, for the twelve pools making up the distribution, we will search information about their location.

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[62] https://btc.com/stats/pool?percent_mode=2020#pool-history

F2Pool

F2Pool is currently the largest mining pool on the entire planet. F2Pool is a geographically distributed mining pool, with the headquarter in Beijing (China). The mining farms used by the users of F2Pool are located in the following areas[63]:

- Kirishi and Nadvoitsy (Russia);
- Reykjanesbær, Keflavik (Iceland);
- Xinjiang, Sichuan, Yunnan and Inner Mongolia (China).

Poolin

Poolin is a mining pool headquartered in Hong Kong (China). Not finding other information, it is assumed that all Poolin miners are located in China.

BTC.com

BTC.com is a mining pool operated by the Chinese company Bitmain. Information about the region a miner of a block is located at can be found on their website[64]. The majority of miners within the BTC.com pool is located in Shenzen and Beijing (China), while the remaining are in EU (Norway) and US (Georgia).

AntPool

AntPool is also run by the Chinese company Bitmain. No information about where blocks have been mined, so it is assumed that all AntPool miners are located in China.

Huobi.pool

Huobi.pool is a Chinese mining pool. Their homepage is only available in Chinese. Therefore, we assume that all miners are located in China.

ViaBTC

ViaBTC has its main office in Shenzen (China). According to its website, the mining farms used are located in the following areas[65]:

- Russia;
- Xinjiang, Hami and Sichuan (China);
- Kazakhstan;
- Dalton (Georgia, US), Marble (North Carolina, US) and Calvert (Kentucky, US).

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[63] https://www.f2pool.com/farms
[64] https://pool.btc.com/pool-stats
[65] https://www.viabtc.com/farms

58COIN&1Thash

58COIN&1Thash is operated out of China and no other information are available. Therefore, it is assumed that all their miners are located in China.

OKExPool

OKExPool is run by a company with headquarter in Malta, but all their miners are located in China.

Binance Pool

Binance Pool is also operated by a company with headquarter in Malta, but their miners are located in China and Japan.

Slush Pool

Slush Pool is a Czech mining pool. The majority of its miners is located in Iceland and US, while the rest is located in Canada, China and Japan[66].

Lubian.com

Lubian.com is a Chinese mining pool. Given that their website is only available in Chinese, we assume that all miners are located in China.

BTC.TOP

BTC.TOP is also a Chinese mining pool. No much information about them. It is thus assumed that all BTC.TOP miners are located in China.

From these information about mining pool shares and mining pool locations, it is possible to derive the geographical distribution of miners (see *Table 9*). For mining pools located in more than one location, we assume that the miners are equally distributed among those locations.

It is no coincidence that miners are concentrated in more or less the same countries. In fact, all those countries satisfy some of the most important factors used for assessing the suitability of a location for mining facilities (Rauchs et al., 2018):

- access to ample and low-cost electricity supply;
- good Internet connectivity;
- cold climate;
- friendly regulatory environment.

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[66] https://slushpool.com/home/

Location[67] Pool	CN	RU	IS	NO	US	JP	KZ	CA
F2Pool	6.21%	6.21%	6.21%					
Poolin	15.62%							
BTC.com	4.34%			4.34%	4.34%			
AntPool	11.60%							
Huobi.pool	7.98%							
ViaBTC	1.74%	1.74%			1.74%		1.74%	
58COIN&1Thash	6.53%							
OKExPool	5.10%							
Binance Pool	2.44%					2.44%		
SlushPool	0.80%		0.80%		0.80%	0.80%		0.80%
Lubian.com	3.02%							
BTC.TOP	2.67%							
Total	**68.05%**	**7.95%**	**7.01%**	**4.34%**	**6.88%**	**3.24%**	**1.74%**	**0.80%**

Table 9 - Geographical distribution of miners
Source: Personal elaboration

Temporal boundary

The temporal boundary is the year 2020.

3.4.2 Life Cycle Inventory (LCI) Analysis

Given that each block takes circa ten minutes to be mined (*block time*)[68], on average 144 Bitcoin blocks per day are mined. In 2020, due to halving, until May 10, 12.5 new Bitcoins were created per block, while since May 11, 6.25 new Bitcoins have been created per block. This means that, totally, in 2020, 445,500 new Bitcoins have been mined.

To perform Proof-of-Work, and of consequence create also new Bitcoins, miners initially used general-purpose computers, but then quickly switched to more dedicated mining hardware equipment to achieve higher performance.

In few years, there has been an evolution that has seen four generations of different hardware types (Vranken, 2017; Rauchs et al., 2018):

- Central Processing Unit (CPU): although Bitcoin mining was first performed using CPUs of simple computers, they were not optimized for mining activities; they were not powerful enough, nor efficient;

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[67] CN = China; RU = Russia; IS = Iceland; NO = Norway; SE = Sweden; US = United States of America; JP = Japan; KZ = Kazakhstan; CA = Canada

[68] Investopedia, s.v. "Block Time", https://www.investopedia.com/terms/b/block-time-cryptocurrency.asp

- Graphic Processing Unit (GPU): originally designed to perform complex graphics calculations, from the late 2010 GPUs were a good step forward for miners; they offered superior efficiency and processing speed;
- Field Programmable Gate Array (FPGA): in mid-2011, some miners started to look for even more powerful and more efficient alternatives; FPGAs are particular hardware devices which allowed to increase hash rates even further, but at the same time to maintain lower power consumption;
- Application-Specific Integrated Circuit (ASIC): the fourth generation appeared in early 2013 with the introduction of ASICs, customized hardware chips specifically designed to perform hashing computations as efficiently as possible, which determined the end of FPGA-based mining.

According to the estimations of Bendiksen and Gibbons (2019), the distribution of ASICs equipments for Bitcoin mining is as follows (see *Table 10*):

Product	Mining units	Distrib.%	Thashes/s (hashrate)	kWh/day	kWh/Thash
Bitmain AntMiner S9	1,800,000	51.41%	14	32.93	0.0000272
Bitmain AntMiner S17	525,000	14.99%	56	60.48	0.0000125
Canaan AvalonMiner 841	468,500	13.38%	13.6	30.96	0.0000263
Ebang Ebit10	200,000	5.71%	18	39.60	0.0000255
Canaan AvalonMiner 921	163,000	4.66%	20	40.80	0.0000236
Bitmain AntMiner S15	120,000	3.43%	28	38.30	0.0000158
MicroBT WhatsMiner M10	105,000	3.00%	33	51.48	0.0000181
Canaan AvalonMiner 1047	57,000	1.63%	37	57.12	0.0000179
Halong DragonMint T1	25,000	0.71%	16	35.52	0.0000257
GMO Miner B3	16,000	0.46%	33	82.01	0.0000288
Innosilicon T2 Turbo	10,000	0.29%	24	47.52	0.0000229
Innosilicon T3 Turbo	10,000	0.29%	50	74.40	0.0000172
Bitmain AntMiner S7	1,000	0.03%	4.73	31.03	0.0000759
Bitfily Snow Panther B1+	1,000	0.03%	24.5	50.40	0.0000238
	3,501,500	**100%**			

Table 10 – Distribution and technical specifications of the most popular ASICs
Source: Personal elaboration on data from Bendiksen and Gibbons, 2019; https://www.asicminervalue.com/miners

Running the weighted average, it is possible to calculate the average Thashes/s (22.41), kWh/day (39,09) and kWh/Thash (0.0000202) of a fictional mining equipment.

In 2020, the hashrate of the entire Bitcoin network ranged from around 90 to 146 million Tera hashes per second (Th/s)[69]. Using the data provided by Blockchain.com about the average

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[69] https://www.blockchain.com/charts/hash-rate

hashrate of the Bitcoin network, it is possible to calculate the total number of Tera hashes generated in 2020, that is equal to 3,763,662,734,304,180 Th. If we divide this number by the total number of Bitcoin created in 2020, we can find that on average 8,448,176,732 Th were needed to mine one single Bitcoin.

Now, given that clearly the main LCI input for ASICs mining equipment is electricity, it is necessary to analyze which type of electricity mixes are used to run these equipment. According to the information provided by F2Pool and ViaBTC, it is possible to basically delineate which electricity type is employed by the different mining pools, based on their geographical distribution (see *Table 11*).

Location[70] **Electricity**	**CN**	**RU**	**IS**	**NO**	**US**	**JP**	**KZ**	**CA**	**Total**
Hydro	*50%* **34.03%**	*100%* **7.95%**	*50%* **3.51%**	*100%* **4.34%**		*50%* **1.62%**		*100%* **0.80%**	**52.25%**
Geothermal	*20%* **13.60%**		*50%* **3.51%**		*50%* **3.44%**	*10%* **0.32%**	*100%* **1.74%**		**22.61%**
Coal	*30%* **20.42%**				*50%* **3.44%**	*40%* **1.30%**			**25.16%**
									100%

Table 11 - Electricity mixes used based on geographical distribution of mining pools[71]
Source: Personal elaboration on data from https://www.f2pool.com/farms; https://www.viabtc.com/farms

Lastly, we can establish how many of the kWh/Thash consumed by a fictional mining equipment calculated above (0.0000202) come from hydroelectricity, geothermal electricity and electricity from coal (see *Table 12*).

Process	**Amount**	**Inventory input per Thash**
Bitcoin mining	0.0000105545 kWh	Hydro electricity
	0.0000045672 kWh	Geothermal electricity
	0.0000050823 kWh	Coal electricity

Table 12 - Inventory inputs for the mining process
Source: Personal elaboration

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[70] CN = China; RU = Russia; IS = Iceland; NO = Norway; SE = Sweden; US = United States of America; JP = Japan; KZ = Kazakhstan; CA = Canada

[71] In italics the absolute percentage, in bold the relative percentage based on the geographic distribution of miners

3.4.3 Life Cycle Impact Assessment (LCIA) and interpretation of the results

The environmental impact of the entire Bitcoin network in 2020, estimated using the ReCiPe Endpoint (H) v. 1.13 method, is of 1358.41 MPt (million ecopoints).

A fictional mining equipment consumes 0.0000202 kWh/Thash. That means that in 2020, for the total number of Tera hashes (3,763,662,734,304,180 Th) generated for the Bitcoin network, the energy consumption was 76.03 TWh.

The climate change associated to this, instead, calculated as the global warming potential (GWP), results in 19.9 million tons CO_2-eq, which corresponds to 0.60% of total CO_2 emissions in the EU (3,320.3 million tons CO_2 in 2019) and to 0.058% of total CO_2 emission in the world (34,169 million tons CO_2 in 2019[72]).

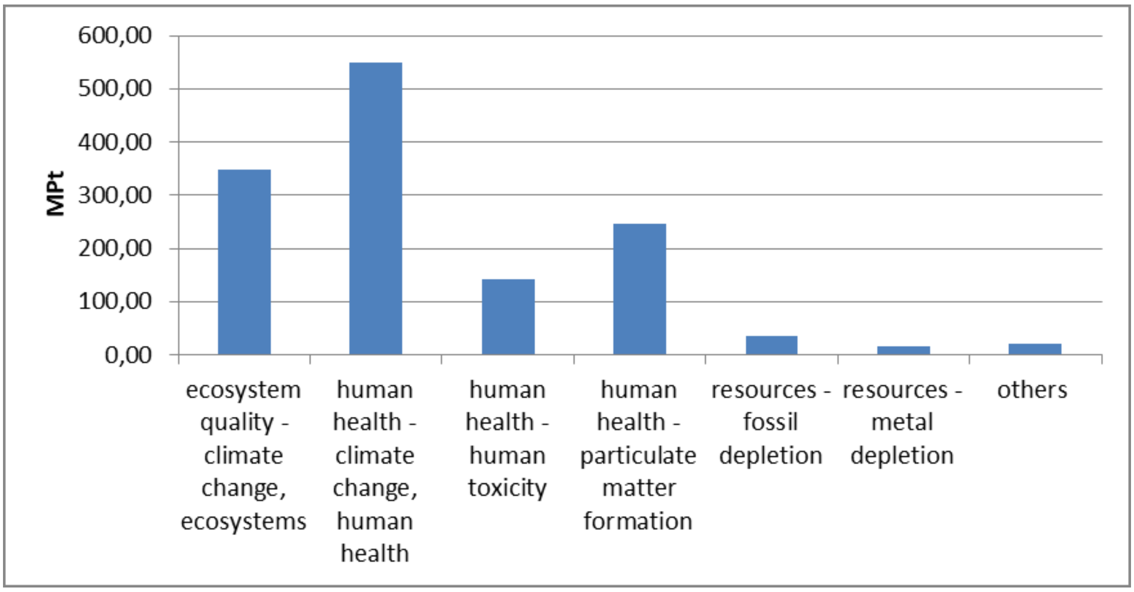

Figure 33 - Environmental impact of Bitcoin mining process per midpoint category (expressed in MPt)
Source: Personal elaboration

In *Figure 33* and *34* we can see an overview of the total environmental impact broken down in midpoint categories. The areas that account mostly to the environmental footprint of the Bitcoin payment system are climate change human health (549.97 MPt) and climate change ecosystems (347.62 MPt), that impact for 40.49% and 25.59% respectively.

Following we find particulate matter formation (245.75 MPt; 18.09%) and human toxicity (142.43 MPt; 10.49%%). Fossil depletion midpoint category, instead, accounts for 2.63% (35.69 MPt), metal depletion for 1.19% (16.15 MPt), while the other categories together contribute for 1.53% (20.81 MPt).

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[72] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/co2-emissions.html

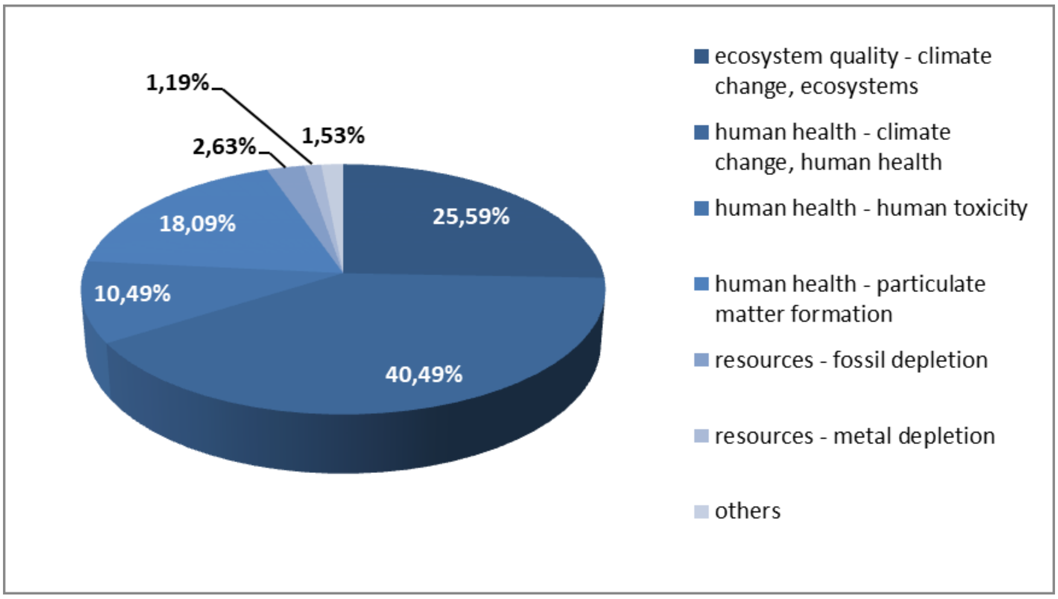

Figure 34 - Environmental impact of Bitcoin mining process per midpoint category (expressed in %)
Source: Personal elaboration

These values are quite consistent with those of previous studies: Rauchs et al. (2018), Stoll et al. (2019), and Digiconomist.net (2020)[73].

In particular, according to Rauchs et al. (2018), the entire Bitcoin network consumes between 40 and 80 TWh/year. For Stoll et al. (2019), Bitcoin's annual electricity consumption adds up to 45.8 TWh, with a corresponding annual emissions range from 22 to 22.9 million tons CO_2-eq.

Lastly, according to Digiconomist.net (2020), the annualized Bitcoin network electrical energy consumption is of 77.78 TWh, with a carbon footprint equal to 36.95 million tons CO_2-eq.

Discrepancies from previous studies are due to the fact that, for example, some calculate their results based on one hashrate value only instead of calculating the total amount of Thashes generated in a year, and also because of the assumptions about energy mixes considered.

Regarding the impact of a single Bitcoin (on average 8,448,176,732 Th needed to mine it), instead, what emerged from our analysis is that its environmental impact is equal to 0.003 MPt. The energy consumption estimated is of about 17.65 MWh, with a climate change impact, calculated as the global warming potential (GWP), that results in 44.75 tons CO_2-eq.

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[73] https://digiconomist.net/bitcoin-energy-consumption/

Interesting is also to see that the entire Bitcoin network consumes more energy and has a carbon footprint higher than a number of countries. If the Bitcoin network was a country, it would rank as shown below.

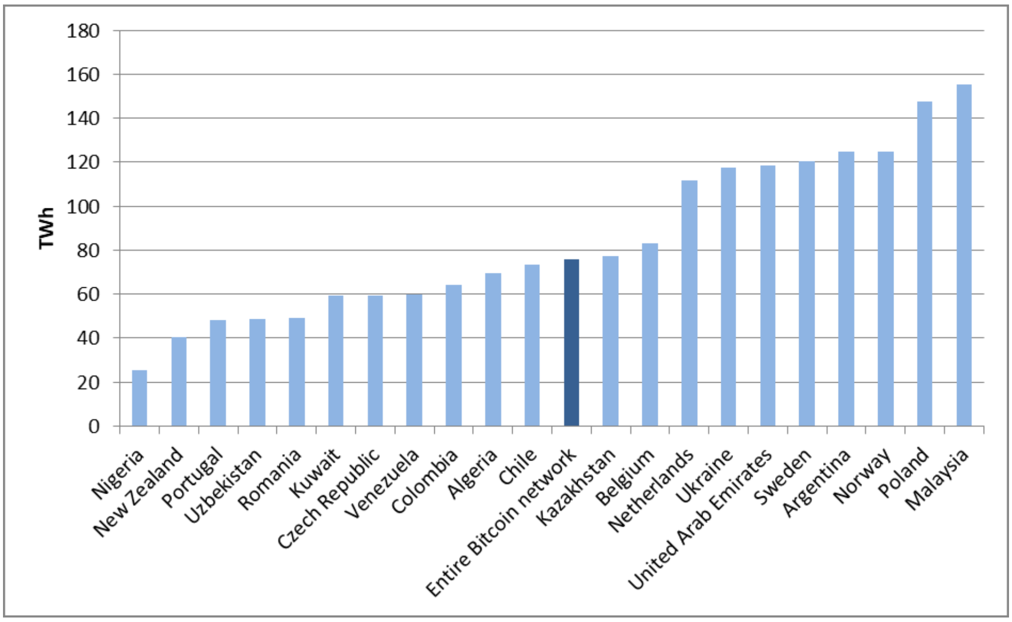

Figure 35 - Energy consumption by country (in TWh/year)
Source: Personal elaboration on data from https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html

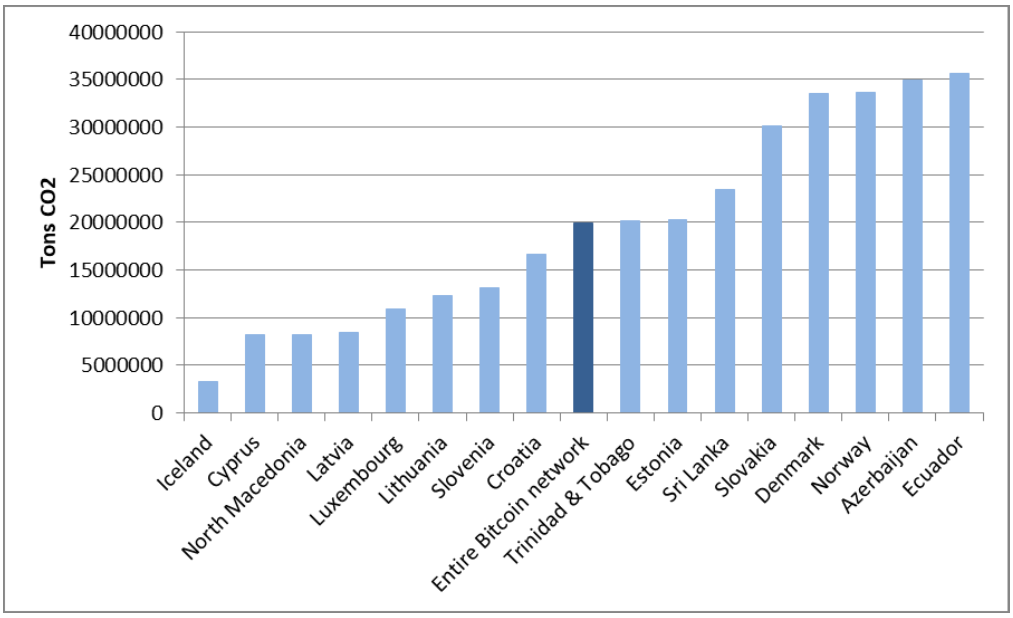

Figure 36 – CO_2 emissions by country (in tons CO_2/year)
Source: Personal elaboration on data from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/co2-emissions.html

In *Figure 35* it is possible to observe how the energy consumptions of the entire Bitcoin network in 2020 are similar to those of Chile and Kazakhstan in 2019, while in *Figure 36* we can note how the CO_2 emissions of the entire Bitcoin network in 2020 are comparable to those of Trinidad and Tobago or Estonia in 2019.

3.5 Comparative analysis

Summarizing:

- an average Euro cash transaction has an estimated climate change impact calculated as 4.05 g CO_2-eq (or 0.000004054 tons CO_2-eq);
- the entire Euro cash payment system has an estimated climate change impact calculated as 478.4 million kg CO_2-eq (or 478,406.09 tons CO_2-eq);
- a single Bitcoin mining has an estimated climate change impact calculated as 44.75 tons CO_2-eq;
- the entire Bitcoin network has an estimated climate change impact calculated as 19.9 million tons CO_2-eq.

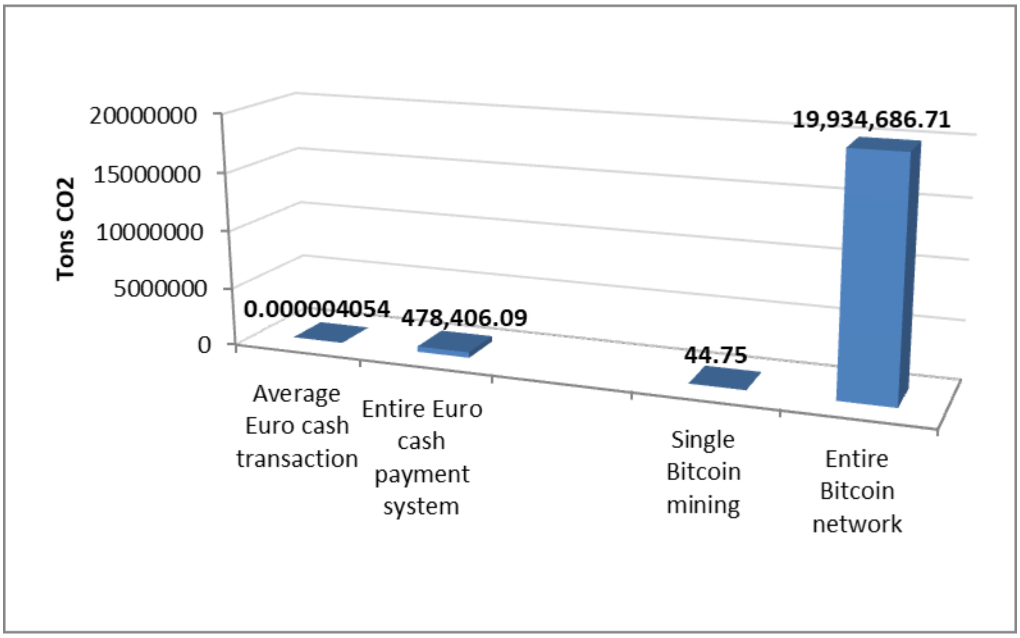

Figure 37 - CO_2 emissions comparison
Source: Personal elaboration

As you can see from *Figure 37*, the difference in the environmental impact between the Euro cash payment system and the Bitcoin payment system is enormous: in one year, the CO_2 emissions of the Bitcoin network are almost 42 times bigger than the CO_2 emissions of the entire Euro cash payment system.

Although currently the impact of the entire Bitcoin network accounts only for the 0.058% of the total CO_2 emissions worldwide, the hashrate of the network is expected to continue growing, given that since the Genesis Block in 2009, showed a steady and consistent exponential growth (see *Figure 38*), so increasing also CO_2 emissions, while the impact of the Euro cash payment system is likely to remain nearly the same.

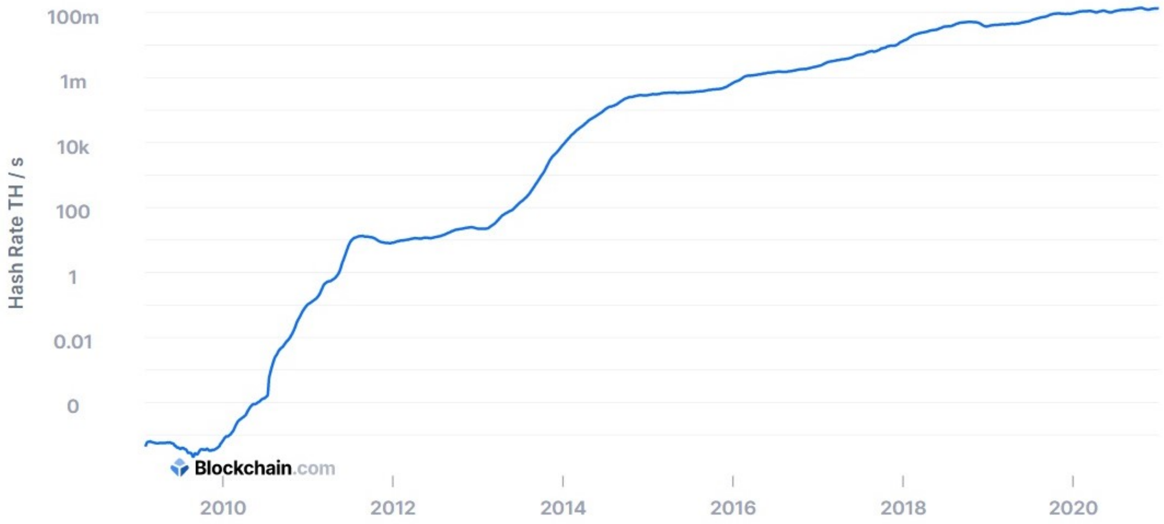

Figure 38 - Bitcoin network Hash Rate 2009-2020 (log scale)
Source: https://www.blockchain.com/charts/hash-rate

Limitations

Limitations to this analysis related to the LCA of cash payments are due to the scarcity of primary data due to confidentiality issues, and so due to the difficulty of finding reliable information. Other limitations, instead, derive from some assumptions:

- for simplicity, the analysis has taken into account only the Euro cash payment system, but to be truly comprehensive it should have included all cash payment systems in the world;
- we focused only to the processes strictly inherent to the production and distribution of banknotes and coins, without considering for example the banking system and the impacts behind it, such as the ones due to utilities (lighting, heating, air conditioning);
- we didn't consider the disposal phase of unfit banknotes and obsolete or worn coins.

Also with respect to the analysis related to the LCA of cryptocurrencies, limitations arise from certain assumptions:

- for simplicity, we considered only one cryptocurrency, the Bitcoin, even if there are more than 8,100 cryptocurrencies in circulation (of these, about 490 cryptocurrencies are comparable to the Bitcoin, i.e. those mineable)[74]; we chose Bitcoin because of its dominance;
- not all other mineable cryptocurrencies in circulation use Proof-of-Work consensus mechanism; the environmental impact of other cryptocurrencies using another

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[74] https://coinmarketcap.com/

consensus mechanism, such as Proof-of-Stake (PoS), is likely to be much lower since no electricity-intensive mining is necessary[75];

- we estimated an electricity mix based on hydrothermal electricity (52.25%), geothermal electricity (22.61%) and coal electricity (25.16%), but in the long run we can expect and hope that miners will use even more renewable energy sources and that the efficiency of mining equipment will increase, so not determining an exponential increase in energy consumptions; moreover, we assumed that miners run ASICs 24/7 throughout the year with constant electricity consumption;
- our estimate doesn't include energy consumption for example required by cooling and lighting;
- we focused only on the mining phase, without considering the Bitcoin network as a whole; Bitcoin's environmental impact related to energy use can be seen as the tip of the iceberg if we consider also the mining equipment production and, especially, the disposal phases. In fact, according to de Vries (2019) and Digiconomist.net (2020)[76], the annualized e-waste generated by obsolete mining equipment would range between 10,948 and 11,210 tons, an amount similar to the total e-waste generated by a country like Luxembourg (12,000 tons) (Forti et al., 2020).

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[75] Proof-of-Stake (PoS) concept states that a person can mine or validate block transactions according to how many coins he or she holds. This means that the more coin owned by a miner, the more mining power he or she has. [https://www.investopedia.com/terms/p/proof-stake-pos.asp]

[76] https://digiconomist.net/bitcoin-energy-consumption

CONCLUSIONS

The purpose of this thesis was to verify whether the advent of new digital technologies is beneficial from the perspective of a sustainable development that also takes into account the environment. In the specific case we dealt with, it is evident how the development of the new blockchain technology, but especially its subsequent application for the creation of cryptocurrencies such as Bitcoin, does not have a positive impact on the environment at all.

However, it would be wrong to conclude from this that blockchains, or more generally ICT solutions, have an exclusively negative impact as far as sustainable development is concerned. It is more accurate to say that digital technologies are helpful, although their environmental impact should not be ignored, but that the magnitude of negative consequences varies according to their use and according to the amount of people who benefit from them.

In the case of Bitcoin, it is estimated that only 1.28 percent of the global population use and benefit from them (around 100 million people)[77]: a huge environmental footprint (19.9 million tons CO_2-eq/year) that benefits only a few, and so source of negative externalities.

In general, Bitcoin aside, the question about cryptocurrencies and digital currencies is a hot topic, much discussed in recent times given their potential to replace cash. Especially in the last year, due to the Covid pandemic and the consequent fear of spreading the virus, the desire for a cashless society has amplified.

Nevertheless, the possibility of replacing all cash in circulation with a mineable cryptocurrency like Bitcoin is inconceivable especially for the socially wasteful electricity use, but also for the lack of regulation.

Regarding the consumption of electricity is to be considered that if a minable cryptocurrency was adopted massively instead of cash would also emerge other issues in addition to those related to CO_2 emissions. Already now, in some countries, further problems are emerging, although the use of cryptocurrency is currently limited.

The most striking and recent example is that relating to Iran where thousands of cryptocurrency farms, many of them illegal, have proliferated across the country, supported by skyrocketing Bitcoin prices during the Covid pandemic. Moreover, Iran's combo of low-cost electricity and high inflation rate has made it a perfect destination for the energy-

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[77] https://www.buybitcoinworldwide.com/how-many-bitcoin-users/

intensive process of mining cryptocurrencies, so much so that the Iranians have established mining farms everywhere, from mosques to actual farms, to make use of the cheaper electricity rate and try to gain rewards from the mining activity.

But the increasing energy requirements due to cryptocurrency mining, coupled with a natural increase in energy demand during an unusually cold winter, has contributed to a shortfall in the supply of natural gas, compelling power plants to burn poor-quality fuel oils to try to meet the country's electricity needs. As a result, many Iranian cities have witnessed blackouts, in addition to the formation of thick layers of toxic smog[78].

As far as the lack of regulations is concerned, although cryptocurrencies have been constructed to function as a means of payment and can be used to pay for goods and services, in practice they are used to a very small extent as such and are mostly used for speculative purposes. Also for this reason, in the event of wanting to replace cash with a digital currency, it is necessary that this is not subject to high price volatility, which is instead what generally characterizes crypto assets.

In an effort to work around the issue of high price volatility, some financial service providers and technology companies have introduced a brand new category of crypto-assets, referred to as stablecoins, which use stabilization mechanisms to keep price fluctuations to a minimum. According to the stabilization mechanism used, stablecoin value can be supported by: money supply; securities and commodities such as gold; crypto-assets; or a mechanism that seek to match supply and demand (i.e., algorithmic stablecoins). However, although stablecoins are less susceptible to speculation due to their reduced volatility, they don't address the environmental problem, particularly if they are pegged to a mineable cryptocurrency.

Therefore, to meet the demand for a cashless society with new innovative and efficient payment methods, it is clear that mineable cryptocurrencies like Bitcoin are not a viable and sustainable solution, either in the short or long term, for the reasons discussed above.

A stable digital currency that provides security, efficiency, and does not require intensive power consumption would be the solution.

To provide security, stability and reliability, a digital currency issued by central banks would be needed.

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[78] https://cointelegraph.com/news/crypto-mining-allegedly-worsening-air-pollution-in-iran

Moreover, this digital currency should meet also the other requirements of money (besides being issued by a national central bank): consist of or be tied to an article with a market value, and function as means of payment, unit of account and store of value. A cryptocurrency like Bitcoin is not issued by a national central bank, is not backed up by a commodity with an independent market value and, although created as a payment method, doesn't fulfil the function of a store of value.

Regarding the main problem we have addressed in this thesis, i.e. the prohibitive environmental costs, it would be necessary a digital infrastructure capable of minimizing the environmental footprint, resulting in having a less or at least the same environmental impact of the entire cash payment system.

In this purpose, it would be advisable to:

- avoid the resource intensive Proof-of-Work (PoW) consensus algorithm and use for example Proof-of-Authority (PoA);
- use a permissioned blockchain in order to have simpler and less time-intensive algorithms for transaction execution.

In contrast to permissionless blockchains based on PoW (like the Bitcoin one), a permissioned blockchain based on PoA involving the existence of one or more pre-selected actors who perform the function of validators in the network would make the transaction execution more performant, faster and less time and resource intensive. Moreover, as only few actors are involved in each transaction, such a blockchain infrastructure would provide a high degree of robustness[79] and scalability[80].

Such a payment system would obviously have a lower impact on the environment, given that it would be based on a digital infrastructure that is much more eco-sustainable than those currently used for cryptocurrencies.

In any case, if hypothetically the possibility of switching from cash to a digital currency were really taken into consideration in the future, it would be recommendable to carry out a thorough and complete analysis to estimate its environmental impact, considering also different energy mixes and without underestimating any aspect, and then compare it with the one of cash.

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[79] Ability of a system to cope with errors during execution and cope with erroneous input

[80] Property of a system to handle a growing amount of work

Summing up, lessons learned from this thesis are:

- although their potential in driving a sustainable development, and their intangibility and imperceptibility, digital technologies, and in general ICT, have an environmental impact to take into account and be aware of;
- switching from analog to digital does not always have benefits;
- in our specific case, pros and cons of a switch from the traditional cash to a cryptocurrency or a digital currency must be studied even more in depth, in order to make a considered decision that also addresses environmental impact problem, which currently appear to be one of the most concerning factor.

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