Stefano Fantoni · Nicola Casagli ·
Cosimo Solidoro · Marina Cobal *Editors*

Quantitative Sustainability

Interdisciplinary Research for Sustainable Development Goals

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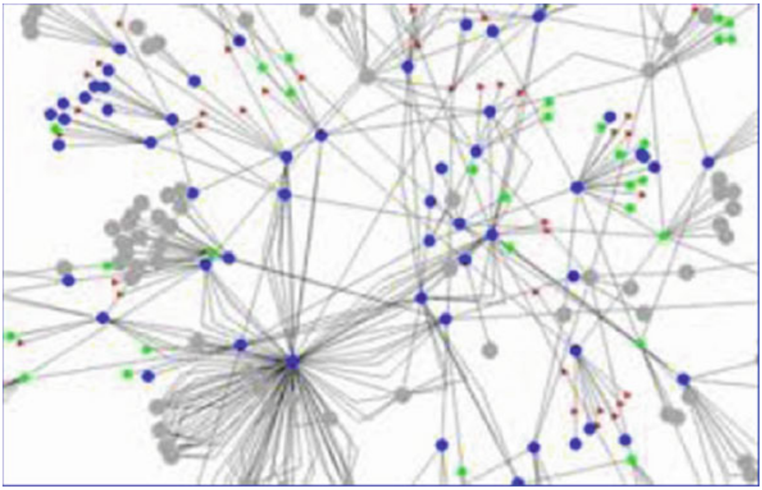

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Foreword

Why Interdisciplinarity for Sustainability

Sustainability. The best definition of sustainable development is still the one proposed for the first time by the United Nations Brundtland Commission Report "Our Common Future": *meeting the needs of the present without compromising the ability of future generations to meet their own needs*. However, when you start digging, many questions arise: which needs? how far in the future? is there a science? is it possible?, etc. For example, one of the questions I ask myself as a chemist is whether Earth is a closed system relative to the Universe, if it reached thermal equilibrium, or if entropy continues to increase. Apparently, there is quite a bit of entropy around, most of which is created by us, but is there a relation between entropy and sustainability?

Several of these questions are first of all philosophical, but most of them are scientific. Until now, we don't seem to have definitive answers, so the only possible sustainable strategy is to minimize the production of entropy by making processes more efficient. It is not clear whether we have already passed the point where the future can no longer support the flourishing of humans and other forms of life, but we must consider the possibility of abrupt, non-linear changes in the near future.

Complexity. One of the reasons we still know so little is that the subject is enormously complex, due to the interdependence of hyper-complex and intertwined systems like the society, the economy, and the environment. Complex systems are not linear and behave in a non-predictable way. Hence, any attempt to manage sustainability with a reductionist approach is doomed to fail. Only a systemic and, consequently, interdisciplinary approach can prevent failures. Social and natural sciences must go hand in hand, and this makes the problem of interdisciplinarity even more difficult.

Because of complexity, knowledge is not expected to be produced in a linear and cumulative way; only empirical and observational relationships can be detected with powerful tools, such as those provided by artificial intelligence (machine learning, digital twins, etc.). This approach creates the problem of access to big data sets containing all relevant measurables and with good quality information. Most of these measurables have not been identified yet or are not available, and this determines a catch-22 situation.

Cognitive Gap. Extreme complexity makes it difficult for people to understand the challenges ahead and their solutions. Pre-crisis symptoms were very clear half a century ago, but the slow pace of changes made society live within a "boiled frog syndrome" situation. Now that the climate crisis reached emergency levels, we are experiencing stages of the grief cycle, from denial to anger, bargaining, and depression, which are not constructive because they trigger resistance to change as well as irrational and selfish behaviors.

Externalities like pandemics, wars, inflation, and social unrest, are on one side natural consequences of the chaos induced by the unsustainable world we have created, but, on another side, also big distractions from the urgency to solve the problem. As a matter of fact, planetary sustainability can be hardly pursued with conventional governance models, because the necessary conditions for consistent and right decisions, along with good execution-which include highly ethical and competent leadership, long-term mandates, and global scope-in practice do not exist in our world. Countries are not ready to limit their sovereignty for a global cause. The resulting short-termism, opportunism, cynicism, misinformation, instability, and inconsistency driven by gigantic financial speculation are not the right conditions to pull people and businesses out of their comfort zones to reduce their ecological footprint. Under such governance conditions, the tragedy of the commons is still the most likely scenario.

Understanding Our World. Studying sustainability starts with understanding our world, i.e., the birth of the planet, the origin and evolution of life, the mechanisms regulating the biosphere, the human impact, and many others. We shall start from the universal picture: if it is true that all the energy originates directly or indirectly from the sun and that life originated from chaos, that heterotrophic organisms appeared to clean the excess of oxygen that was intoxicating the primordial anaerobic biosphere, that the course of climate change can be abruptly changed by many possible co-factors, then interesting new surprises could change the situation.

As omnivores capable of moving resources around and exploiting them, rather than moving themselves towards resources, humans completely disrupted the natural equilibrium and exploited every ecosystem on Earth. Technological development, coupled with unimaginable solutions to protect human health and safety, has made the human civilization outnumber every species with a comparable body mass by a factor that can be estimated in more than 10,000. Moreover, contrary to any other species that ever existed, humans do not limit their activities to basic biological needs, but have developed all kinds of anthropic (i.e., beyond physiological) activities, which are responsible for a per capita energy consumption 18x higher than that corresponding to sheer food calories. The combined effect is that human ecological footprint can be estimated to be tens of thousands of times higher than any species, and the resulting planetary transformation has been so disruptive to be associated with an ecological era, *Anthropocene.*

For sure, it is not the biosphere to be endangered by humans, but the opposite. Natural systems adapt and evolve quickly, driven by the exponential growth of cellular replication, until conditions are favorable. Resource scarcity, diseases, competition, difficult environment, etc., are limits to growth, which cause populations to level off or to decline, paving the road to new species, and thriving on the new situation. *Homo sapiens* is still in the exponential growth phase, so we still have time to figure out whether we will be capable to adapt to the new biosphere inadvertently created by us, or if some catastrophic event will wipe us off the planet. Interestingly enough, removing the above-mentioned limitations would immediately reboot population growth. Because sustainable development depends on the same factors, sustainability paradoxically drives demographic increase, which has been the trigger of the climate crisis. Is there a vicious circle or even a paradox?

Assessing Our Development Model. The problem with sustainability started with the industrial revolution and its extractive and linear model. Since then, over a century and a half ago, our economy has kept depleting natural resources like they were infinite and producing an unlimited amount of pollution and littering at the end of the product lifecycle. Progress triggered super-exponential growth: to cope with the demographic explosion, energy consumption rose from ca. 12,000 TW in 1900 to 28,000 TW in 1950 (cagr 1.7%), ca. 120,000 TW in 2000 (cagr 3%), with nearly 80% of energy still coming from fossil sources. Total food consumption went from ca. 3.15 trillion kilocalories in 1969 to ca. 8.5 trillion kilocalories in 2019 (cagr 2%). The soil used for agriculture reached 50% of habitable land (twice as much as one century ago), at the detriment of forests, which now represent only 37% of the terrestrial surface. Arable land per person halved in the last 60 years from 0.36 ha/pp to 0.18 and cannot be increased due to saturation of suitable land.

So, are we running out of resources? There are probably still more detractors than supporters of the limits to growth theory presented by the Club of Rome 50 years ago. It is true that, since then, many production limits have been crossed thanks to productivity increases, but the impact is under our eyes.

Burning mineral carbon, sequestered and stored millions of years ago under the terrestrial crust, caused greenhouse gas emissions to exceed Nature's capacity to re-absorb carbon, resulting in an increased concentration in the atmosphere and climate change. Global warming might become irreversible and self-feeding once a redline of carbon dioxide in the atmosphere is reached. Agricultural production increased, thanks to improved agronomical practices, but at the detriment of other ecosystem services. Currently, agriculture is the second source of greenhouse gas emissions and the first cause of biodiversity loss, with a severe impact on the biogeochemical cycles. Finally, pollution caused by most economic activities accumulates in waters and soils, intoxicating the biosphere and hindering its spontaneous regeneration.

At present, we consume 1.7 times Earth's equivalent resources per year, depleting natural capital while endangering medium/long term food security and necessary ecosystem services continuity.

Developing a New Regenerative Model. Economic, Environmental, and Social sustainability are all reciprocally interdependent and equally indispensable. Environmental sustainability requires a new development model, which must correct the secular mistake that made the extractive model systemically unsustainable. In the combination 'Nature/Culture', the conjunction in the extractive model is 'or', assuming that science and technology could eventually free us from our dependence on Nature. Since, in reality, whatever we need for living—air, water, food, health— is 'Made in Nature', we must change the conjunction into 'and'. 'Nature & Culture' doesn't only mean a codevelopment of people and planet, but also using social and natural sciences to restore and heal the biosphere from the damages of the past. Social sustainability must take into account the projected population in the decades ahead and pursue poverty eradication through education. Economic sustainability needs growth as a prerequisite to payback investments. However, in this new model growth, which is a quantitative metric, must go along with development, which is a qualitative criterion.

The Regenerative Society Foundation, which I have the privilege to co-chair with Professor Jeffrey Sachs, adopted a framework made of three macro factors—Well-being, Circularity, Biosphere—and their mutual interactions. The goal is to rebuild the carbon stock, which until now is the only way to decarbonize the atmosphere, as well as to restore biodiversity, which is responsible for ecosystem's resilience and health. Consistently with the one health approach, which makes it clear that our health depends upon biodiversity, human health is the co-benefit pursued by this framework.

The foreseen dynamic is that healthy and happy people, conscious that their well-being depends primarily on the ecosystems where they live, reduce their ecological footprint through circularity; circularity minimizes resource depletion and avoids pollution, detoxifying the biosphere; spontaneous regeneration heals the biosphere, paying the dividend with better ecosystems.

The ecological transition from extractive to regenerative is a titanic endeavor, which will result from thousands of learning curves contributing to the energy transition (from fossil to renewable sources), the agro-ecological one (from conventional to regenerative agriculture), and the industrial one (from linear to circular economy). It must be approached in a systemic way, in order to understand, for instance, the completely different planet setting of our times compared to *Holocene*, the complexity and path dependency of the transition, and the balance between the given biocapacity, the human appropriation of the net primary production and the need to restore ecosystems. The waterfall impact of the transition will change our lifestyle. For instance, livestock consumes 70% of agricultural resources, and a diet too rich in animal-derived food also represents a risk to health. We will, therefore, need to change our diet to a more vegetable-based and a much more varied one. This is a challenge in the challenge because, although there are thousands of edible plants, nearly half of the world calories intake derives from only three crops (which is also one of the main causes of biodiversity loss).

An educated guess is that less than 50% of the necessary technologies for the transition to the regenerative model are already available and most of them are not mature yet. So, at present, we cannot even calculate their regenerative capacity. Exit barriers from the inherited extractive infrastructures, as well as the entry barriers to develop new regenerative ones, will make the phase in/phase out quite difficult and hopefully not too slow. To mention just a few of them: the new supply chains for solar energy need conversion and stocking technologies with capacity and energy density at least comparable to fossil fuels; most technologies underlying the production of goods and services must be redesigned to be powered with renewable energy; to ensure food security, in addition to reducing waste and making food systems more efficient, artificial food production should also be considered; waste becoming critical resources, they require reinventing reverse supply chains and infrastructures, as it happened for example with the development of sewage systems; reaching carbon neutrality requires developing carbon capture and storage as a brand new industry.

What the Trieste Laboratory in Quantitative Sustainability Can Do. The road towards the ecological transition is bumpy and we are still lagging. The impact of the climate crisis on environment, society, and economy is devastating and exponentially increasing. Mitigation, preparedness, response, and recovery are the four stages needed to manage the crisis. Robust public–private preparedness programs directed to citizens and businesses would increase the level of perception and anticipate response. Every organization and individual, with no exception, must mobilize. Businesses, in particular, are the most important stakeholders because everything in society is made by a company and because the private sector represents on average half of the GDP. Therefore, collectively they have an enormous power and economic advantage in embracing the cause.

After more than fifty years, notwithstanding the enormous work made by a plethora of governmental, intergovernmental, non-governmental, and private institutions, we still don't seem to agree on the definitive framework, methodology, and measures for sustainability. We desperately need to quantify the fundamental dimensions of sustainability and embed them into the economic value of goods and services.

Considering the interdisciplinarity of this process and the scientific humus existing in Trieste, with the relevant institutions dedicated to theoretical physics, advanced mathematical studies, biotechnology, oceanography, astrophysics, medical sciences, a Science park, a synchrotron, data science and artificial intelligence institute, and the coordination of all of them by the Trieste International Foundation, the TLQS can give a significant contribution in driving and accelerating the transition.

As far as more specific research is concerned, besides the terrestrial ecosystems to be regenerated (natural, rural, industrial, and urban), the aquatic ones are the most important and still neglected. With 70% of the oxygen produced and about 35% of the carbon sequestered, oceans are among the largest contributors to ecosystem services but, due to increased acidity and lower dissolved oxygen, are endangered by both the causes and effects of climate change. If we exclude marine protected areas and fishing regulations, there seem to be very few effective sustainable strategies for ocean conservation. OGS, as the main promoter of the TLQS, could strive to lead international research supporting the future blue economy for sustainability, in areas such as carbon capture and storage, renewable energy production, innovative raw materials, ecosystems conservation and restoration, marine biodiversity, and others.

June 2023

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Preface

Let us begin with a citation taken from the prologue of the book "*The lunar men*" [1] by Jenny Uglow which tells about the stories of a group of friends belonging to *the Lunar Society of Birmingham* in the eighteen century. In a way, our laboratory is inspired by the innovation spirit of these men.

> The earth turns and the curving shadow sweeps round the globe. The sun sets, the moon rises, and all that is familiar feel suddenly strange. In an age before street lights, link-boys carry torches to see city-dwellers home, while in the countryside starlight and moonlight are the only guides… And in the eighteen century clubs are everywhere: clubs for singing, clubs for drinking, clubs for farting; clubs of poets and padding-makers and politician. One such gathering of like-minded men is the Lunar Society of Birmingham. They are a small, informal bunch who simply try to meet each other's house on the Monday nearest the full moon to have light to ride home (hence the name) and like other clubs they drink and laugh and argue into the night. But the Lunar men are different-together they nudge their whole society and culture over the threshold of the modern, tilting it irrevocably away from the old patterns of life towards the world we know today.

We still do not know towards which patterns of life we are going to *nudge our whole society*, but certainly we are aiming at a quantitative understanding of the modern sustainable development. Like the lunar men, we need to escape from the disciplinary barriers of sciences inside which we operate today, towards new and largely unknown borders based on an interdisciplinary approach.

Our interdisciplinary laboratory on Quantitative Sustainability is growing in the right place and at the right time. Friuli Venezia Giulia is a small region, but very rich in *Science and Technology*, located at the centre of the North-Adriatic area, a lively land of culture and innovation.

Trieste is the flagship of this innovation harbour, with a density of people doing research which is the highest in Italy and among the highest in Europe. The high standard of the research produced is the fruit of the settlement of three major national Universities and of most of the existing national Research centres, like for instance the National Institute of Oceanography and Applied Geophysics (OGS), together with the presence of prestigious international research Institutes: the International School for Advanced Studies (SISSA), one of the six Italian Advanced Schools, two international institutes for the promotion of science in developing countries, the *Abdus Salam* International Centre for Theoretical physics (ICTP) and the International Centre for Genetic Engineering and Bio-technologies (ICGEB), with one of the highest percentages in Italy of foreign students. There is the largest national scientific district for innovation, the Area Science Park, which hosts a large European synchrotron radiation facility, ELETTRA, and one of the most powerful free electron lasers in the world, the FERMI.

All this, generated already in the fifties by the strategic view of a man, Paolo Budinich, a champion not only in Theoretical Physics, but also in Science Diplomacy, has become a splendid network of science and technology, well known worldwide, which has recently been awarded with the nomination by Euro-Science of Trieste as *European city of Science* for the years 2018–2020. A strong message given by the participants at the *Euro-Science Open Forum (ESOF2020)*, the final international event, organized by the Trieste International Foundation (FIT) in September 2020, has been the development of a North-Adriatic Summer Institute on Sustainability, of which our laboratory is the premise.

The fallout effects of the rapid growth of the research activity, together with the presence of important industrial settlements, like Fincantieri and IllyCaffè as well as important Insurance companies, like Generali and Allianz, have generated a rate of qualified employment growth in Trieste, particularly in the innovation sector which in 2017 reached the highest provincial percentage at a national level of innovation start-ups.

Not to forget the high level of science journalism, initiated by SISSA, with its Master in science communication and the organization of several science festivals.

This creative environment, most favourable to the birth of moving ideas, takes also the advantage of the social atmosphere, that pervades the city. The writer Jan Morris [2] described Trieste as *the Nowhere city …. not just as a city but an idea of city*, *and it appears to have a particular influence upon those of us with a weakness for allegory—that is to say*, *as the Austrian Robert Musil once put it*, *those of us who suppose everything to mean more than it has any honest claim to mean.* The people in Trieste never look surprised by anything, and at the same time is curious to know the new, the paradox, the unimaginable.

The figure in the back cover shows a long and beautiful pier in Trieste, just in front of Piazza dell'Unità, which points in a sort of nowhere, towards a *Leopardian infinity*, the unknown that we wish to reach.

The right place for Lunar Men, like us, looking at the science of sustainability.

Trieste, Italy — Nicola Casagli
Udine, Italy — Marina Cobal
Trieste, Italy — Stefano Fantoni
Trieste, Italy — Cosimo Solidoro

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1. Jenny Uglow, *The Lunar men*, Faber & Faber Limited, 2002.
2. Jan Morris, Trieste *and the meaning of nowhere*, Simon and Schuster, New York, 2001.

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Contents

Part I
Laboratory Structure

In this part, we present and discuss the structure of The Laboratory on Quantitative Sustainability (TLQS). This is made of seven research groups, each addressing one or more different tasks pertaining to the seventeen UN 2030 Sustainable Development Goals (SDGs) [1].

Every group is composed of a coordinator, accompanied by two deputy coordinators, and a number of members, working at academies, research institutes, industries, business companies, science and technology journals.

The seven coordinators seat in the Scientific Council of the Laboratory together with the Director and two other external members, who are supposed to cover transversal issues to all the research groups, like for instance, science communication and sustainable economy. The Scientific Council acts as the governing board of the Laboratory, making the final decisions on the tasks assigned to the various groups and on the events to be organized.

An international advisory committee supervises the activities of the Laboratory and suggests new ideas and new tasks.

The research areas covered by the seven groups are given in the following, with, in parenthesis, the corresponding SDGs.

1. The blue planet for the sustainability of the sea economy (6 and 14)
2. Food and biodiversity for the health of the planet and its inhabitants (1,2,3 and 12)
3. Climate changes and the environment (11,13 and 15)
4. The new data science for sustainability and human ecology (9,10,13,14 and 15)
5. The energy transition and the industrial processes (7,9 and 11)
6. Sustainability frames, social equity and the right to sustainability (1,7,10,16 and 17)
7. Monitoring the terrestrial habitat from the Space. Prevent the Space Weather extreme conditions (9,11,13 and 15).

It is useful to represent the laboratory structure with a complex network, in which the various researchers are weighted nodes and their documented collaborations are weighted lines. The coordinator nodes are white dots, whereas all the other members of the seven groups are black dots. Since the coordinators are linked to all the members of their own groups, and, in addition, they are fully linked amongst themselves, the network is of the small world type [2] with only three separation degrees for the various nodes to reach each other.

Such a representation is given and discussed in the following Chap. 1, Sustainability Complex Network, by S. Fantoni.

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1. Brundtland Commission, Our *Common Future*, Oxford University Press, Oxford, 1987.
2. Duncan J Watts and Steve H. Strogatz, *Collective dynamics of small-world networks*, NATURE, 393, 440-442, 1998.

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Chapter 1
Sustainability Complex Network

S. Fantoni

Abstract We introduce the concept of *quantitative evaluation* of a complex network made up of researchers operating in different disciplines and different sectors belonging to life and hard sciences or social science and humanities or industrial and entrepreneurial activities, which, in addition to their disciplinary research, interact within each other in interdisciplinary scientific collaborations on sustainability projects. The complex network that we consider in this paper is of the *small-world* type, which has been already used in the study of several other biological, technological and social complex systems. This kind of network has a flexible structure which is in between those of the completely regular and the completely random networks. Similarly, the increase of interdisciplinary collaborations amongst scholars having a large and recognized experience in a given disciplinary sector may be favoured by random links arising in facing up specific issues of sustainability. Numerical results are given for a few unweighted networks having up to ten research groups with up to hundred researchers each.

Introduction

In this paper we address the problem on how scientific methodologies can help policy makers, industrial managers, entrepreneurs to handle in the best possible way and soon the seventeen UN 2030 Sustainable development Goals (SdGs), which for better clarity are reported and discussed in Appendix "Sustainable Development Goals and Disciplinary Sectors".

Given the fact that each SDG is strongly interdisciplinary if not trans-disciplinary, the question we try to answer is whether one should promote interdisciplinary research from being only instrumental of the traditional one to become the base of these scientific methodologies when dealing with sustainability issues.

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The answer we give to this question is somewhat intermediate between the full disciplinary science which provides blindly the instruments to be used by sustainability makers and a full interdisciplinary science whose individual researchers are characterized more by the soft skills necessary to create collaboration networks in macro-areas, rather then the capability of deepening specific scientific problems.

On one side it should not be forgotten the extraordinarily successful results obtained so far by the traditional disciplinary research, which has led to a deeper and deeper understanding of each single discipline. Let us quote a sentence declared by Abdus Salam during his Nobel Lecture on the eight December 1979

Scientific thought and its creation are the common heritage of mankind

At the same time, however, these successful results have also led to higher and higher specializations, giving rise to sub-disciplines, sub-sub-disciplines, and so on. Today, according to the Italian academical system, Life and Hard Sciences (LHS) and Social Sciences and Humanities (SSH) are divided all together into 15 disciplinary Areas, each of them is subdivided into several disciplinary sectors, for a grand total of about 370 disciplinary sectors [1]. Not to forget the applied research which is carried out by various industrial areas, which introduces other disciplinary sectors.

On the contrary interdisciplinary research requires the collaboration of scholars belonging to different disciplinary sectors. At present, such type of research is only an extremely small percentage of the whole research output, and, what is more important, it has never been planned in a methodological way, except for very few cases.

What we have in mind is a Laboratory made of *disciplinary researchers* who address problems which need to be solved by wide collaborations. In such a Laboratory, which may be viewed as a virtual Institute, the *disciplinary researchers* are grouped in N_C *macro-area Clusters*, which in turn interact amongst themselves. Therefore, in such *interdisciplinary laboratory* there is a first level of interactions, namely the *neighbouring interactions* between the members of the same *macro-area Cluster*, and a second one between the Clusters. These second kind of interaction is either of the *global* type between the coordinators of the clusters or of the *random* type between two individual researchers belonging to different Clusters.

We represent such a interdisciplinary laboratory, as a complex *small-world* network [2–7], that we denote as *Sustainability Complex Network (SCN)*.

The structure of a generic complex *small-world* network is presented on the next section, whereas section “The Sustainability Complex Network” is devoted to define the SCN structure.

Results on the characteristic path length and the clustering coefficient of large regular and random SCNs are presented and discussed on section “From a Small to Large Networks”.

The goal of the present study is to develop an operational platform to evaluate the efficiency of the SCN, and correspondingly that of the interdisciplinary Laboratory, at any given time of its functioning in terms of both the creation of new links and the response given to a specified task. Section “From Unweighted to Weighted SCN” presents the theoretical scheme to build up such platform.

A discussion of the perspectives of the present study and conclusive remarks are left to section "Conclusions and Perspectives".

The Small–World Complex Network

Any complex system in nature can be modeled as a network, where vertices or nodes are the elements of the system and links represent the interactions between them. Coupled biological and chemical systems, neural networks or the Internet are just a few of such examples [8]. The characterization of the structural properties is of fundamental importance to understand the complex dynamics of these systems. In a recent paper [2] it has been shown that the connection topology of some biological and social networks is neither completely regular nor completely random. These networks have been named *small–world* from the concept of *small–world* phenomenon developed in social psychology [9] in the sixties. They are highly clustered as the regular lattices in spite of having characteristic path lengths like random graph. In several examples they have been shown to be both locally and globally efficient.

Let us reexamine the original formulation of *small–world* network given by Watts and Strogatz [2].

In that paper the authors consider a generic graph $\mathbf{G}$ with K links and N nodes, which has the following properties:

unweighted graph: the links are all equal;
sparse graph: $K \ll K_{MAX}$, with $K_{MAX} = \frac{N(N-1)}{2}$;
connected graph: there exists at least one path connecting any two nodes with a finite number of steps;
regular and random graphs: a regular graph is a graph where all the nodes R_α have the same *degree* k_α which is defined as the number of links $l_{\alpha\beta}$ with $\beta \neq \alpha$. A random graph is obtained by applying to a regular one a random rewiring procedure to a limited number r of links. The fraction $\rho = \frac{r}{K}$ measures the randomness. If $\rho = 1$ the graph is completely random;
links matrix: the graph representation is given by the matrix $[a_{\alpha\beta}]$, where $a_{\alpha\beta}$ is equal to 1 or 0 weather or not it exists the link $l_{\alpha\beta}$ or not.

The average of the node degrees is given by

$$\langle k_\alpha \rangle \equiv k = \frac{2K}{N}. \tag{1.1}$$

Given the links matrix $[a_{\alpha\beta}]$ one can calculate the shortest path length $[d_{\alpha\beta}]$. Since $\mathbf{G}$ is connected, $d_{\alpha\beta}$ is always positive and finite for any $\alpha \neq \beta$.

Let us introduce, as in Ref. [2], the **characteristic path length** L and the **clustering coefficient** C

$$L = \frac{1}{N(N-1)} \sum_{\alpha \neq \beta} d_{\alpha\beta} = \frac{1}{N} \sum L_\alpha, \tag{1.2}$$

where

$$L_\alpha = \frac{1}{N-1} \sum_{\beta \neq \alpha} d_{\alpha\beta}. \tag{1.3}$$

The quantity L can be viewed as the average distance between any two nodes.

$$C = \frac{1}{N} \sum_\alpha C_\alpha, \tag{1.4}$$

where C_α is defined as number of links existing in $\mathbf{G}_\alpha$, which is the sub-graph of the neighbors of α normalized with its maximum possible number given by $\frac{k_\alpha(k_\alpha-1)}{2}$.

The Sustainability Complex Network

The Sustainability Complex Network (SCN) is a complex network of the *small–world* type having N_C clusters, each addressing a given Cluster Sustainability Task T_i with $(i = 1, \ldots, N_C)$. Each task T_i refers to a subset $S_i = [t_1, \ldots, t_{S_i}]$ of the full set of the disciplinary sectors $S = [t_1, \ldots, t_S]$ as discussed in Appendix.

A given cluster C_i is made of M_i nodes with

$$M_T = \sum_i^{N_C} M_i \tag{1.5}$$

being the total number of nodes. Each node R_{ij} is associated with an individual researcher, with $(i = 1, N_C)$ and $j = (1, M_i)$, and carries a weight function $W_{ij}[S]$, obtained by the evaluation of both his disciplinary research and other interdisciplinary works, addressing one or more t_m of the set $[S]$. The weight functions W_{ij} depend on the N_S disciplinary sectors t_m, and is given by a set of N_S values, $W_{ij}(t_m)$, one for each t_m, ranging from 0 to 1. The way this value is calculated is explained in section "From Unweighted to Weighted SCN".

Each Cluster C_i has a *central node* R_{i1} graphically represented by a white dot (a small circle) which is directly linked with the remaining nodes of the Cluster, each of them represented by black dots. The white nodes correspond to the coordinators of the Cluster.

Any two black dots R_{ij} and R_{kl}, with $(ij) \neq (kl)$ are connected with a link $L_{ij;kl}$ if and only if the two corresponding researchers have a documented common interest in one or more disciplinary sectors or, equivalently, if the link weight function $W_{ij;kl}(t_m)$ given by

$$W_{ij;kl}(t_m) = W_{ij}(t_m) \times W_{kl}(t_m), \tag{1.6}$$

for all the disciplinary sectors variables t_m of the set $[S]$, is not the null function.

The N_C white dots R_{i1}, besides having their own weight function, are also associated with the weight functions $W_i^C[S]$ of their own Clusters C_i, given by the normalized sum of the weight functions of all of their nodes, namely

$$W_i^C(t_m) = \sum_{j=1}^{M_i} W_{i,j}(t_m). \tag{1.7}$$

The sub-graph constituted by the white dots is intrinsically fully connected trough its own $\frac{N_C}{N_C-1}$ links, because it represents the coordination committee and two any members R_{i1} and R_{j1} need to directly interact within each other.

There are three types of link:

cluster link a link between two black dots of the same cluster.
coordinator link a link between white dots.
random link a link connecting a black or a white dot of a cluster with another black dot of a different cluster.

In the following, for the sake of simplicity, we may use Greek letter, $\alpha, \beta, \cdots$ to label the nodes R_{ij}. The various graph elements of a SCN obey the following rules

rule 1 The white dots, are all linked among each other through *coordinator links*.
rule 2 The white dots are connected with all the black dots of its cluster through *cluster links*.
rule 3 Any connection of a black or a white dot with a second black dot of a different cluster is of the random type
rule 4 A network with no random links is defined as a **regular SCN**. Note that such definition of regularity differs from that given in section "The Small–World Complex Network". In fact, the degree k_α of the node α, giving the number links incident with it cannot be equal within each other, because the white dots must obey rules 1 and 2.
rule 5 A *generic SCN* is denoted as $SCN_m^{(r)}$, where the subscript m labels the generic network structure and the upper-script (r) gives the number of its random links. Characteristic properties are the number of cluster N_C, the number M_i of nodes of each clusters, where i runs from 1 to N_C, the total number of links K, the total number of random links l.
rule 6 The random links are obtained by reconnecting a cluster link of a given cluster of the underling regular $SCN_m^{(0)}$ to a different node belonging to a different cluster. The reconnecting procedure leaves the total number of links unchanged. The rewiring is done satisfying periodicity,

Let us first consider in Fig. 1.1, just for the sake of clarifications of the above rules, an example of SCN with a very simple structure. The network considered is of

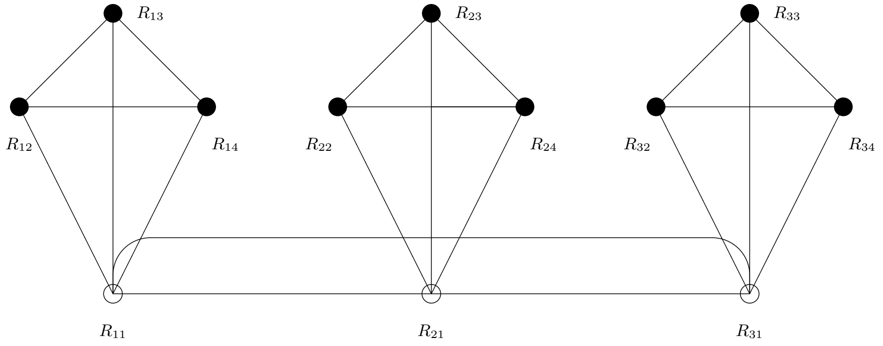

Fig. 1.1 Example of a network having three 4-node clusters. The three white dots represents the coordinators of the clusters. Each coordinator is linked to all the other members (black dots) of his own cluster and amongst themselves. The graph is denoted in the test as $SCN^{(0)}_{Fig}$. It has $N_C = 3$ and $M_T = 12$ and $K = 21$

the regular type, having three clusters, each with 4 nodes, which will be denoted as $SCN^{(0)}_{Fig}$. The three white dots R_{11}, R_{22} and R_{33} are connected within each other and characterizes the coordination of the network. The total number of nodes is $M_T = 12$. Each cluster is connected to the graph only through its own white dot (rule 2). As a consequence, the white dots are separability points of the graph which therefore is *separable*. The total number of links is $K = 21$.

In Fig. 1.2 we show one of the possible random networks, denoted as $SCN^{(3)}_{Fig}$, where we have introduced three random links, the first one connecting R_{14} with R_{22} in place of R_{13}, the second one connecting R_{24} with R_{32} in place of R_{23} and last one connecting R_{34} with R_{12} in place of R_{33}. The randomness is of the periodical type, as required by *rule 6*. Moreover, the white dots are no more separability points, which makes the graph *not separable*.

Moreover, we assume that the two graphs of Figs. 1.1 and 1.2 are unweighted, namely that the connection matrix elements $[a_{\alpha\beta}]$ are either 1 or 0, depending whether there a link $l_{\alpha\beta}$ exists or not. One can easily verify that, in the case of the regular network, each of the 3 white dots has the same degree, given by 5. The remaining nodes have all degree 3 for an average degree $\langle k \rangle$ given by 3.5, in accordance with the equality $\langle k \rangle = \frac{2K}{N}$.

It is worth noticing that, the example presented in this Section is not completely representative of the more general case of the SCN we are proposing in this paper for two following main reasons. The first one is that the number $M_\alpha = 4$ of nodes is too small for being representative of our general case. We will see that the minimum number of nodes is 6, one more of that given by the white dot, plus the two next neighbouring nodes and plus the other two next to next neighbouring nodes. This will be discussed in length in the next Section. The second reason is this network is unweighted. How to include weight to the links will be discussed further on in section "From Unweighted to Weighted SCN".

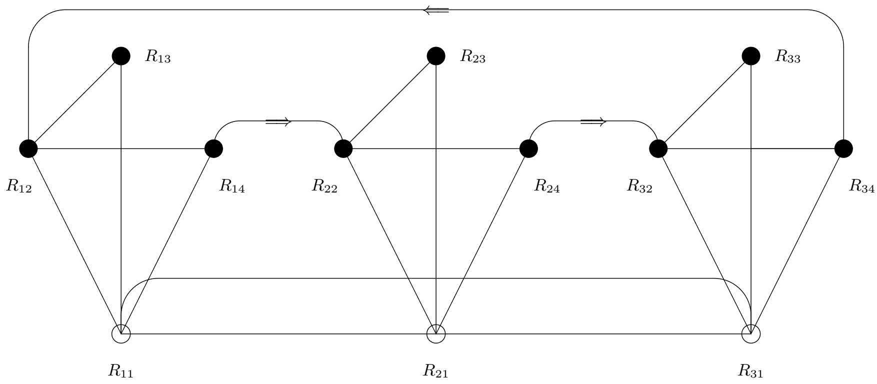

Fig. 1.2 Example of a $SCN^{(3)}_{Fig}$ having three 4-node clusters and three random links between the three clusters. The basic structure of the graph is given by $SCN^{(0)}_{Fig}$. The random links are $l_{14,22}$ and $l_{24,32}$ and $l_{34,12}$. The total number of links is $K = 21$, the same as for $SCN^{(0)}_{Fig}$

Table 1.1 Results for the characteristic path length L_α of the four nodes of the cluster 1. Clusters 2, and 3 provide similar results. In the left part of the Table, 1-p, 2-p and 3-p count the number of paths with 1, 2, and 3 links respectively for the regular graph, with Reg giving L_α. Analogously, the central part of the Table displays the results for the random graph *Ran1* ($\rho = 0.14$), whereas the left part is reserved to a random graph *Ran2* having the double of random links $\rho = 0.28$. The extra random links are the following: $l_{13;12} \to l_{13;23}$, $l_{23;22} \to l_{23;33}$ and $l_{33;22} \to l_{33;13}$

α	*1-p*	*2-p*	*3-p*	*Reg*	*1-p*	*2-p*	*3-p*	*Ran1*	*1-p*	*2-p*	*3-p*	*Ran2*
R_{11}	5	6	0	$\frac{17}{11}$	5	6	0	$\frac{17}{11}$	5	6	0	$\frac{17}{11}$
R_{12}	3	2	6	$\frac{25}{11}$	4	4	3	$\frac{21}{11}$	3	5	3	$\frac{22}{11}$
R_{13}	3	2	6	$\frac{25}{11}$	2	4	5	$\frac{25}{11}$	3	4	4	$\frac{23}{11}$
R_{14}	3	2	6	$\frac{25}{11}$	3	6	2	$\frac{21}{11}$	3	5	4	$\frac{22}{11}$

Let us give the results of the calculations of the quantities L_α, defined in Eq. 1.2, and $C\alpha$, defined in Eq. 1.4 for both the regular and random graphs displayed in Figs. 1.1 and 1.2 respectively. Let us first consider the characteristic path length L. The results for L_α are given in Table 1.1.

The results for the clustering coefficient C_α are given in Table 1.2.

In Table 1.3 we give the results for the characteristic path length L and the clustering coefficient C. As already mentioned in section "The Small–World Complex Network", L measures the typical separation between two nodes in the graph, *which is a global property*. On the contrary, the clustering coefficient measures the cliquishness of a typical neighborhood, *which is a local property*. For researcher networks we may give to the two quantities the following meanings: L is the average number of collaborations or common interests in the shortest chains connecting any two researchers; instead, C_α reflects the extent to which the collaborators of α collaborates with each other. The quantity C is an average of C_α and is defined in Eq. 1.4.

Table 1.2 Results for the clustering coefficient C_α of the four nodes of cluster 1. Clusters 2, and 3 provide similar results. In the left part of the Table, the three columns display the results for the regular graph *Reg* of the degree k_α, the number of links in the sub graph $\mathbf{G}_\alpha$ and the clustering coefficient C_α respectively. Analogous results are provided on the central part of the Table for the random graph *Ran1*, and on the left part for *Ran2*. See also the caption in Fig. 1.1

α	k_α^{Reg}	G_α^{Reg}	C_α^{Reg}	k_α^{Ran1}	G_α^{Ran1}	C_α^{Ran1}	k_α^{Ran2}	G_α^{Ran2}	C_α^{Ran2}
R_{11}	5	4	0.40	5	3	0.30	5	2	0.20
R_{12}	3	3	1.00	4	1	0.17	3	1	0.33
R_{13}	3	3	1.00	2	1	1.00	3	1	0.33
R_{14}	3	3	1.00	3	1	0.33	3	1	0.33

Table 1.3 Results for the characteristic path length L and the clustering coefficient C of the two graphs of Figs. 1.1 and 1.2. The fourth line gives the ratios of both L and C between the random and the regular graphs

Graph	L	C
Regular	2.09	0.85
Random (0.14)	1.91	0.45
Random (0.28)	1.91	0.30
Ratio (0.14)	0.91	0.52
Ratio (0.28)	0.91	0.35

Note that for a fully connected graph $L = C = 1$. In the case of the graph displayed in Fig. 1.2 $\rho = \frac{3}{21} = 0.14$.

The results of Table 1.3 show that the randomness diminishes both the characteristic path length and the clustering coefficient. The ratios indicates that the effect is significantly larger for C then for L.

From a Small to Large Networks

Let us first proceed in this Section to a first step towards a general, still unweighted SCN of the type proposed and calculated in the previous Section.

We consider an unweighted SCN having N_C clusters, each with $M_1, M_2, \ldots M_{N_C}$ nodes. The Total number of nodes, M_T is given by Eq. 1.5. The structure of each cluster is the same as that of Fig. 1.1 for the case of the regular network, namely that of a ring, with the white dot linked to all the black points. In addition the two neighbouring black dots of the white one are linked between themselves.

The randomness is done in the same way as in Fig. 1.2, namely the link $l_{1M_1;1(M_1-1)}$ is opened up towards the node R_{22}, the link $l_{2M_2;2(M_2-1)}$ is opened up towards the node R_{32}, ..., the link $l_{N_C M_{N_C};N_C(M_{N_C}-1)}$ is opened up towards the node R_{12}. See Fig. 1.3 for an example of such random graph.

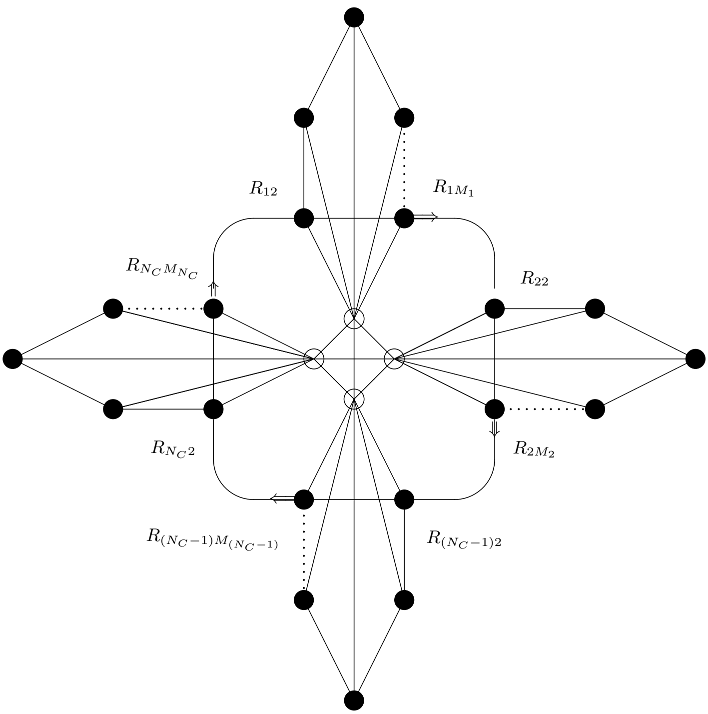

Fig. 1.3 Scheme of a generic $SCN^{(N_C)}$ having N_C clusters and N_C random links between them. The basic structure of the graph is the same of the graphs shown in Figs. 1.1 and 1.2. The clusters $3 \cdots N_C - 2$ are omitted to make the figure as simple as possible without loss of clarity. The dotted lines in the random graph are rewired into the corresponding oval links

The randomness is shown in the figure by a transversal ring of links, where the oval links are the rewiring of the dotted ones. One can imagine a third, a fourth, $\cdots$, rings of randomness to increase ρ.

The rationale of the network structure is the following. The set of SCN agents is made of experts in disciplinary sectors of LHS, SSH and Science Diplomacy, joined with components from industries, all working in a quantitative and trans-disciplinary way on themes regarding sustainability. The agents are grouped in a number of clusters each having a *coordinator agent* (the white dots) and two deputy coordinators. The coordinators of the various clusters interact between each other. They are stable members of the scientific committee of SCN. They meet periodically and take decisions together, reporting the outcome of their cluster and defining new tasks for the network. Each coordinator and his two deputy coordinators interact each other as an internal coordination committee. Therefore they are linked together. The coordinators are linked to all the agents of their own clusters.

The topological structure of each cluster is that of ring of nodes, with the first and the last black dots of the ring also joined between themselves, and the white dots $R_{\alpha 1}$

represented by a fully connected sub-graph. The ring topology is suggested by the fact the (i) collaborations between researchers are mainly pairwise; (ii) the first and the last black dots of the ring constitute an executive committee of the cluster group and (iii) the second and the last but one black dots are influenced by the rewiring procedure. For this reason the minimum number of nodes in a cluster is 6.

Such a structure allows, already in its regular form, that no more than three direct links are necessary to a given agent to reach any other agent in three steps Because of this the proposed SCN structure has to be considered of the *small world network type*. The introduction of randomness leads to a diminishing of both the characteristic path length L and the clustering coefficient C.

The number K of links, which is the same for both the regular and the random networks, is given by

$$K = \frac{N_C(N_C-1)}{2} + M_T - N_C + \sum_{i=1}^{N_C}(M_i - 1) = \frac{1}{2}(N_C^2 - 5N_C + 4M_T), \quad (1.8)$$

which has to be confronted with maximum number of links, given by $K_{MAX} = \frac{M_T(M_T-1)}{2}$. The ratio p between K and K_{MAX} measure how sparse is the network. In the case of $N_C = 3$ and $M_T = 12$, $K = 21$, $p = 0.32$.

Let us calculate the characteristic path length L and the clustering coefficient C for both the regular and random graphs of Fig. 1.3. The regular graph is obtained by considering the dotted links rather then the oval links. Because the four neighbouring black dots of a given white dots $R_{\alpha 1}$, $R_{\alpha 2}$, $R_{\alpha M_\alpha}$, $R_{\alpha 3}$ and $R_{\alpha(M_\alpha-1)}$ have different counting properties after the randomization assumed in this paper. Obviously, if we want to proceed to further levels of randomization, the minimum number of $m + M_\alpha$ has to grow to 8, 10, $cdots$.

Regular Graph

Let us give in this section the results of the lengths L_α for the regular graph of Fig. 1.3, namely the one with the dotted links and without the oval ones.

$$\begin{aligned} L_{11} &= L_{21} = \cdots = L_{N_C 1} = 2M_T - N_C - M_1, \\ \Sigma_C &= \sum_{\alpha=1}^{N_C} L_{\alpha 1} = 2N_C M_T - N_C^2 - M_T, \end{aligned} \quad (1.9)$$

$$
\begin{aligned}
L_{12} &= L_{13} = \cdots = L_{1M_1} = 3M_T - N_C - M_1 - 4, \\
\Sigma_1 &= \sum_{\beta \neq 1}^{M_1} L_{1\beta} = (M_1 - 1) L_{12}, \\
L_{22} &= L_{23} = \cdots = L_{2M_2} = 3M_T - N_C - M_2 - 4, \\
\Sigma_2 &= \sum_{\beta \neq 1}^{M_2} L_{2\beta} = (M_2 - 1) L_{22},
\end{aligned}
\tag{1.10}
$$

and similarly for $\Sigma_3, \cdots, \Sigma_{N_C}$.

Putting all together we get the following expression for the characteristic path length L

$$
\begin{aligned}
L &= \frac{1}{M_T(M_T-1)} \left(\Sigma_C + \sum_{\mu=1}^{N_C} \Sigma_\mu \right) \\
&= \frac{1}{M_T(M_T-1)} \left(3M_T^2 - 2M_T N_C - 4(M_T - N_C) - \sum_{i=1}^{N_C} M_i^2 \right).
\end{aligned}
\tag{1.11}
$$

In the case of $N_C = 3$ and $M_1 = M_2 = M_3 = 4$ one gets $L = 2.09$, in accordance with the results displayed on Table 1.3.

In order to calculate the clustering coefficient one needs to compute the degree k_α of each node R_α, which is given by

$$
\begin{aligned}
k_{\alpha 1} &= (N_C - 1) + (M_\alpha - 1), \quad (\alpha = 1, N_C), \\
k_{\alpha\beta} &= 3, \quad (\beta \neq 1).
\end{aligned}
\tag{1.12}
$$

The number $c_{\alpha\beta}$ of the links in the sub-graph $\mathbf{G}_{\alpha\beta}$ of the neighbours of $R_{\alpha\beta}$ is given by

$$
\begin{aligned}
c_{\alpha 1} &= (M_\alpha - 1) + \frac{(N_C - 1)(N_C - 2)}{2}, \quad (\alpha = 1, N_C), \\
c_{\alpha\beta} &= 2, \quad (\beta \neq 1),
\end{aligned}
\tag{1.13}
$$

with the exception of the case $M_i = 4$, for which $c_{i\beta} = 3$, with $\beta \neq 1$. Using Eqs. 1.12 and 1.13 on gets the following result for $C_{\alpha\beta}$

$$
\begin{aligned}
C_{\alpha 1} &= \frac{2(M_\alpha - 1) + (N_C - 1)(N_C - 2)}{(N_C + M_\alpha - 2)(N_C + M_\alpha - 3)}, \quad (\alpha = 1, N_C), \\
C_{\alpha\beta} &= \frac{2}{3}, \quad (\beta \neq 1),
\end{aligned}
\tag{1.14}
$$

with the exception of the case $M_i = 4$, for which $C_{i\beta} = 1$, with $\beta \neq 1$. Using the above equation Eqs. 1.12 and 1.13 on gets for $C_{\alpha\beta}$ the following result for the average clustering coefficient C

$$C = \frac{1}{M_T}\left\{\frac{2}{3}(M_T - N_C) + \sum_{\alpha=1}^{N_C}\frac{2(M_\alpha - 1) + (N_C - 1)(N_C - 2)}{(N_C + M_\alpha - 2)(N_C + M_\alpha - 3)}\right\}. \quad (1.15)$$

Random Graph

Let us now consider the random graph of Fig. 1.3, in which we switch from the dotted links to the oval ones. The characteristic path length for the white dots, $L_{\alpha 1}^{Ran}$, leads to the same expression as for the case of the regular graph (see L_{11} and $\Sigma_{\alpha 1}$ given in Eq. 1.9)

$$\begin{aligned} L_{11}^{Ran} &= L_{21}^{Ran} = \cdots = L_{N_C 1}^{Ran} = 2M_T - N_C - M_1, \\ \Sigma_C^{Ran} &= \sum_{\alpha=1}^{N_C} L_{\alpha 1}^{Ran} = 2N_C M_T - N_C^2 - M_T. \end{aligned} \quad (1.16)$$

For the two neighbouring black dots of a given white dots $R_{\alpha 1}$, $R_{\alpha 2}$ and $R_{\alpha M_\alpha}$, and the two next neighboring dots $R_{\alpha 3}$ and $R_{\alpha(M_\alpha - 1)}$we get the following results

$$\begin{aligned} L_{12}^{Ran} &= 3M_T - N_C - M_1 - 8, \\ L_{13}^{Ran} &= 3M_T - N_C - M_1 - 5, \\ L_{14}^{Ran} &= = L_{15}^{Ran} = \cdots = L_{1(M_1-2)}^{Ran} = 3M_T - N_C - M_1 - 4, \\ L_{1(M_1-1)}^{Ran} &= 3M_T - N_C - M_1 - 3, \\ L_{1M_1}^{Ran} &= 3M_T - N_C - M_1 - 8, \end{aligned} \quad (1.17)$$

Summing over all the black dots of the various clusters we get the following expressions

$$\Sigma_\alpha^{Ran} = \sum_{\beta \neq 1}^{M_1} L_{1\beta}^{Ran} = (3M_T - N_C - M_\alpha)(M_\alpha - 1) - 24 - 4(M_\alpha - 5) \quad (1.18)$$

with $\alpha = 1, N_C$. Using Eqs. 1.16, 1.17 and 1.18 we get the following result for the average characteristic path L^{Ran}

Table 1.4 Results for the average characteristic path length L of two graphs of the type of from Fig. 1.3 in its regular form (with dotted lines) and in its random form (oval lines). The number of nodes in each cluster for any choice of M_α is taken to be for the sake of simplicity. The randomness parameter of the three random network are, from top-down, $\rho = 0.91$, $\rho = 0.91$ and $\rho = 0.91$, respectively

Graph	N_C	$M_\alpha = 4$	$M_\alpha = 6$	$M_\alpha = 10$	$M_\alpha = 20$	$M_\alpha = 100$
Regular	3	2.09	2.27	2.42	2.55	2.64
Regular	6	2.30	2.47	2.62	2.72	2.81
Regular	10	2.38	2.55	2.69	2.79	2.88
Random	3	1.91	2.19	2.40	2.54	2.64
Random	6	2.22	2.44	2.60	2.72	2.81
Random	10	2.33	2.53	2.68	2.79	2.88

$$
\begin{aligned}
L^{Ran} &= \frac{1}{M_T(M_T-1)}\left(\Sigma_C^{Ran} + \sum_{\mu=1}^{N_C}\Sigma_\mu^{Ran}\right) \\
&= \frac{1}{M_T(M_T-1)}\left(\left(3M_T^2 - 2M_T N_C - 4(M_T+N_C) - \sum_{i=1}^{N_C} M_i^2\right)\right).
\end{aligned} \tag{1.19}
$$

In the case of $N_C = 3$ and $M_1 = M_2 = M_3 = 4$ one gets $L = 1.91$, in accordance with the results displayed on Table 1.3.

The results for the average path length of few regular and random networks are displayed on Table 1.4. The total number of nodes is given by the product of N_C with M_α.

One can see that the characteristic length L slightly increases with the number of clusters. The same effect is observed by increasing M_α. The randomness, as expected, reduces L in a visible away for values of ρ of the order of 1% (see also Table 1.6).

Let us calculate the clustering coefficient. The degrees of the white dots are given by

$$
\begin{aligned}
k_{\alpha 1}^{Ran} &= (N_C - M_\alpha - 2)\,, \quad (\alpha = 1, N_C)\,, \\
k_{\alpha\beta}^{Ran} &= 3\,, \quad (\beta \neq 1 \; and \; (M_\alpha - 1),
\end{aligned} \tag{1.20}
$$

and $k_{\alpha(M\alpha-1)}^{Ran} = 2$ for any value of α.

The numbers $c_{\alpha\beta}^{Ran}$ of the links in the sub-graph $\mathbf{G}_{\alpha\beta}^{Ran}$ of the neighbours of $R_{\alpha\beta}$ are given by

Table 1.5 Results for the *clustering coefficient* C of two graphs of the type given in Fig. 1.3, one regular and the other random. See also capture of Fig. 1.4

Graph	N_C	$M_\alpha = 4$	$M_\alpha = 6$	$M_\alpha = 10$	$M_\alpha = 20$	$M_\alpha = 100$
Regular	3	0.60	0.60	0.62	0.64	0.66
Regular	6	0.61	0.61	0.62	0.64	0.66
Regular	10	0.65	0.63	0.63	0.64	0.66
Random	3	0.49	0.54	0.59	0.62	0.66
Random	6	0.52	0.55	0.58	0.62	0.66
Random	10	0.56	0.57	0.60	0.62	0.66

$$
\begin{aligned}
c_{\alpha 1}^{Ran} &= (M_\alpha - 2) + \frac{(N_C - 1)(N_C - 2)}{2}\,, \\
c_{\alpha 2}^{Ran} &= c_{\alpha(M_\alpha - 1)}^{Ran} = c_{\alpha M_\alpha}^{Ran} = 1\,, \\
c_{\alpha 3}^{Ran} &= c_{\alpha 4}^{Ran} = \cdots = c_{\alpha(M_\alpha - 2)}^{Ran} = 2.
\end{aligned}
\tag{1.21}
$$

By using Eqs. 1.20 and 1.21 on gets the following result for $C_{\alpha\beta}$

$$
\begin{aligned}
C_{\alpha 1}^{Ran} &= \frac{2(M_\alpha - 2) + (N_C - 1)(N_C - 2)}{(N_C + M_\alpha - 2)(N_C + M_\alpha - 3)}\,, \\
C_{\alpha 2}^{Ran} &= C_{\alpha M_\alpha}^{Ran} = \frac{1}{3}\,, \\
C_{\alpha 3}^{Ran} &= \frac{2}{3}\,, \\
C_{\alpha 4}^{Ran} &= C_{\alpha 5}^{Ran} = \cdots = C_{\alpha(M_\alpha - 1)}^{Ran} = \frac{2}{3}\,, \\
C_{\alpha 3}^{Ran} &= 1.
\end{aligned}
\tag{1.22}
$$

Using the above equations one gets the following result for the average clustering coefficient C

$$
C^{Ran} = \frac{1}{M_T}\left\{\frac{2}{3}M_T - N_C + \sum_{\alpha=1}^{N_C}\frac{2(M_\alpha - 2) + (N_C - 1)(N_C - 2)}{(N_C + M_\alpha - 2)(N_C + M_\alpha - 3)}\right\}. \tag{1.23}
$$

Results for the clustering coefficient of regular and random networks are displayed on Table 1.5.

The clustering coefficient C show very minor variations within the various combinations of N_C and M_α considered. The only visible effects come from the randomness, which amount to be of the same order of ρ in percentage.

Table 1.6 Results for the number K of links and, in parenthesis, for the randomness index ρ in connection with various combinations of N_C and M_α. All the graphs considered are random. Regular and random graphs for a given combination have the same value of K

Graph	N_C	$M_\alpha = 4$	$M_\alpha = 6$	$M_\alpha = 10$	$M_\alpha = 20$	$M_\alpha = 100$
Random	3	21 (.14)	33 (.091)	57 (.053)	117 (.027)	597 (.0050)
Random	6	51 (.11)	75 (.080)	123 (.049)	243 (.025)	1203 (.0050)
Random	10	105 (.095)	145 (.069)	225 (.044)	425 (.024)	2025 (.0050)

We display in Table 1.6 the results for the for the quantity K, giving the number of links, and the randomness index ρ.

From Unweighted to Weighted SCN

In this Section we discuss how to give weights to the links of the SCN and how the calculation of the unweighted network given in the previous sections can be generalized to take the into account.

Let us first consider the function $W_\alpha(t_m)$ associated with node $\alpha \equiv R_{ij}$, where t_m label the macro-sectors defined in Appendix "Sustainable Development Goals and Disciplinary Sectors". The description of the indicators that will be used to evaluate any agent of the network is given in Table 1.7

The function $W_\alpha(t_m)$ can be represented by an Histogram, with N_S bins each corresponding to a given t_m with $0 \leq m \leq N_S$. The height and the width correspond to the evaluation of the disciplinary (x-indicators) and the interdisciplinary research (y-indicators) respectively, both ranging fro 0 to 1. Therefore $W_\alpha(t_m)$ is a two value function given by the height and the width of the mth bin, namely by the pair (h_m, w_m). An example of histogram with only four bins out of the sixty one, is given in Fig. 1.4.

The weight function of link is formally given in Eq. 1.6 which we re-write in the following equation using the Greek labelling for the nodes, namely

$$W_{\alpha\beta}(t_m) = W_\alpha(t_m) \times W_\beta(t_m)\,,$$
$$(h_m(\alpha\beta), w_m(\alpha\beta)) = (h_m(\alpha), w_m(\alpha) \times (h_m(\beta), w_m(\beta)), \qquad (1.24)$$

where α stands for the pair ij and β for kl. The *convolution product of the two vectors* results from the geometrical averages of the heights and the widths, namely

$$h_m(\alpha\beta) = \sqrt{h_m(\alpha)\, h_m(\beta)}\,,$$
$$w_m(\alpha\beta) = \sqrt{w_m(\alpha)\, w_m(\beta)}. \qquad (1.25)$$

Table 1.7 Indicators used in the evaluation of the function $W_\alpha(t_m)$. The x-indicators are for the disciplinary research of type LHS or SSH, or for industrial activity (IA). The y-indicators are for interdisciplinary research

Indicator	Description	Activity area
x_1	Number of papers in journal indexed in Web of sciences or Scopus	LHS
x_2	Number of citations in Web of sciences or Scopus	LHS
x_3	Number of articles and chapters in books with ISDN	SSH
x_4	Number of articles published in in A-rated journals	SSH
x_5	Number of patents with their economical evaluation	IA
x_6	Number of employers	IA
y_1	Number of Google citations	All
y_2	Number of books and of articles on science and technology	All
y_3	Number of interdisciplinary conferences	All
y_4	Number of public events on science and technology	All

The corresponding histogram has the same structure of that shown in Fig. 1.4. The contribution to the weight of the link $l_{\alpha\beta}$ coming from disciplinary sector t_m is given by the modulus of the vector $W_{\alpha\beta}(t_m)$

$$|W_{\alpha\beta}(t_m)| = \sqrt{h_m^2(\alpha\beta) + w_m^2(\alpha\beta)}\,, \tag{1.26}$$

whose maximum value is $\sqrt{2}$ when both the values of h and w are equal to 1. It is convenient to normalize $|W_{\alpha\beta}(t_m)|$ to unity. The weight to the link $\omega_{\alpha\beta}$ is then given by

$$\omega_{\alpha\beta} = \frac{1}{\sqrt{2}N_S}\sum_{m=1}^{N_S}|W_{\alpha\beta}(t_m)|, \tag{1.27}$$

so that its maximum value is 1 when all the h_m and w_m factors have their maximum possible value. It is necessary to fix a cutoff value, ω_{min}, for $\omega_{\alpha\beta}$, below which the link $l_{\alpha\beta}$ does not exist. In fact, this condition substitutes that used for the unweighted

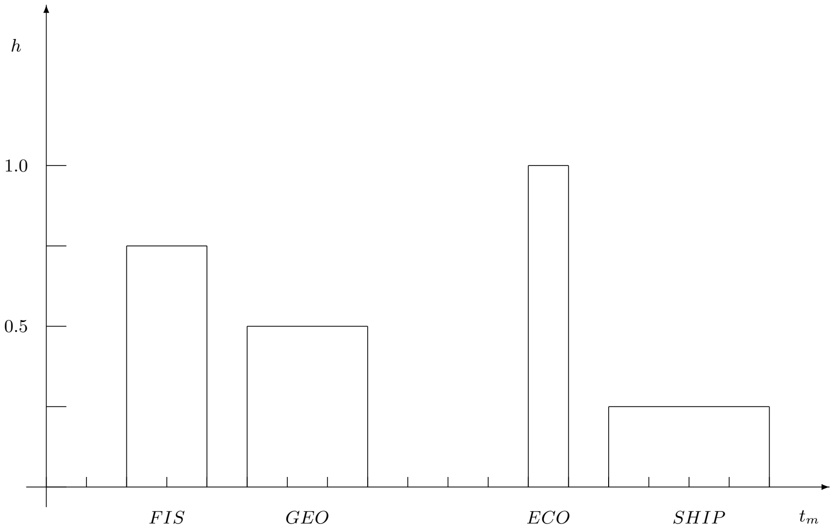

Fig. 1.4 Example of an histogram representing the two-value function $W_\alpha(t_m)$. The y-axis gives the h-value, whose maximum possible value is 1.0. The x-axis displays the width of the bins, providing the w-value, which also has a maximum value of 1.0. The spacing between the tics is 0.25. For instance, the disciplinary sector FIS has $h = 0.75$ and $w = 0.5$

networks for which $d_{\alpha\beta}$ is equal to 0 or 1 and a link can exist if and only if it is equal to 1. One can fix $\omega_{min} = 0.1$.

In the calculation of the minimum path one is faced with a path with one, two or at most three steps. The two- and the three-step paths are made of two links having one node in common, say μ and three links having μ and ν as intermediate nodes, respectively.

One can use the standard procedure to count their contributions, namely summing up the $\omega_{\alpha\mu}$ and the $\omega_{\mu\beta}$ values in the two-step process and the $\omega_{\alpha\mu}$, $\omega_{\mu\nu}$ and the $\omega_{\nu\beta}$ values in the three-step one.

Alternatively, one can consider the following average procedure

$$(h_m(\alpha\mu\beta, w_m(\alpha\mu\beta) = ((h_m(\alpha)h_m(\mu)h_m(\beta))^{1/3}, (w_m(\alpha)w_m(\mu)w_m(\beta))^{1/3}) \tag{1.28}$$
$$(h_m(\alpha\mu\nu\beta, w_m(\alpha\mu\nu\beta) = ((h_m(\alpha)h_m(\mu)h_m(\nu)h_m(\beta))^{1/4}, (w_m(\alpha)w_m(\mu)w_m(\nu)w_m(\beta))^{1/4}).$$

The weights to consider in this case for the two- and the three-steps processes are given by the module of the vectors $W_{\alpha\mu\beta}(t_m)$ and $W_{\alpha\mu\nu\beta}(t_m)$ respectively. This second procedure could be preferable if one wishes to emphasize the feature that, because of dealing with a network made by researchers, the occurrence of multiple links of a path carries a potential better efficiency rather then a loss.

The evaluation of the histograms values for the various nodes can be done by using the methods described in Ref. [1].

The h_m and w_m values for the white nodes may be taken without making a specific evaluation, given the role of the coordinators in the structure of the network, which is mainly of interdisciplinary nature. We may take $w = 1$ for all the t_m, and some median value, say 0.5, for h.

The calculation of the average characteristic length L and of the clustering coefficient C, as well of that of other quantities, like for instance *the efficiency* [3], can be carried out by following the procedure described in this paper for the unweighted network.

The *efficiency* and the *normalized efficiency* of a node are defined as follows

$$e_\alpha = \frac{1}{N-1} \sum_{\alpha \neq \beta} \frac{1}{d_{\alpha\beta}}. \tag{1.29}$$

The global efficiency is given by

$$E_{glob} = \frac{1}{N} \sum_{\alpha} e_\alpha. \tag{1.30}$$

The global efficiency is usually normalized in such a way that the maximum global efficiency is 1, in the case of a perfect efficiency. Such an ideal case is obtained by a completely connected graph with the minimum possible distance, namely $min(d_{\alpha\beta}) = min(\omega_{\alpha\beta}) = \omega_{min}$ for all the pairs $(\alpha \neq \beta)$. The global efficiency of such an the ideal graph is given by $E_{glob}(ideal) = \frac{1}{\omega_{min}}$. Therefore the normalization of the efficiencies is obtained by dividing them with ω_{min}.

Conclusions and Perspectives

In this paper we analyze the possibility of representing a laboratory of interdisciplinary an trans-disciplinary research devoted to the science of sustainability with a complex network of the *small world* type. The structure of the network is designed in such a way that only three steps are at most necessary for an agent to reach any other one. The network may have any number of thematic clusters, and each of them may be composed by any number of agents, or black nodes of the graph, except for a special one, which is white and represents the coordinator of the cluster. The coordinator is linked to all the black dots of the cluster and has two neighbouring black dots, which represent its deputy coordinators. The coordinators of the various clusters constitute the scientific council of the laboratory and, therefore, are fully connected within each other. Any two agents of a cluster can reach each other in at most two step and any agent of a cluster can reach another of another cluster in three steps. The network is moderately sparse, with the number of links being only few per cent, or less, of the maximum possible number. We considered the possibility of introducing randomness in the graph keeping the number of links fixed and study the behaviour of the characteristic path length L and of the clustering coefficient C as a function of the randomness index ρ. A quantitative analysis has been done for unweighted networks deriving general formulas of L and C as a function of the number of cluster and of the cluster nodes. The results obtained confirm the feature that randomness increases the characteristic path length and reduces the clustering coefficient, even in presence of special nodes, the coordinator nodes, which have a different degree from all the other nodes.

A second part of the paper has been devoted to give weights to the nodes and to the links in the particular case of net of researchers doing interdisciplinary studies devoted to the science of sustainability.

The seventeen SDGs of the UN 2030 project have been confronted with 26 disciplinary macro-sectors extracted from the 369 disciplinary sectors introduced by the Italian academical legislation for Life and Hard Science and for Social sciences and Humanities plus other 35 coming from industrial sectors. Six indicators have been suggested for evaluating the research quality of the agents for their disciplinary activity of and other four have been identified to evaluate the interdisciplinary work. These indicators are supposed to be used to produce for every agent of the laboratory an histogram of 61 bins, one for each disciplinary macro-sectors. Each bin is characterized by the height h, corresponding to the evaluation of the disciplinary research produced by the agent and a width w giving a measure of his interdisciplinary activity. They have to be considered as two component vectors whose modules give the weights for each bin. The procedure to calculate the weight of a generic link and that to evaluate the minimum path between any two nodes are also explained in detail. The necessary elements to compute the characteristic path length, the clustering coefficient and the global efficiency of the SCN at any running time are also described.

In the initial evaluation of the network the data to be used come from the last ten years research production of its agents, as resulting from their curricula. The successive monitoring, should include the interdisciplinary research activity performed to face up the tasks assigned to the various clusters.

Some of the methods developed in this paper for the SCN can be adopted in other research or educational activities. For instance, a school complex could be facing with given tasks, for which the students should show the ability of problem solving together with that of soft skills and team working capability. Similarly, an innovation center may find useful to adopt the type of evaluation suggested in this paper for the laboratory devoted to quantitative sustainability scientific research.

Possible extensions of the network are under current study. One of these regards the inclusion of various levels of randomness in a systemic way. Another dynamical behaviour of the SCN is the proliferation of new activities, in the form of the black dots becoming new coordinators of new tasks and therefore new white dots.

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Sustainable Development Goals and Disciplinary Sectors

First of all let us give a schematic description of the historical path that the recognition of sustainability as a fundamental issue for the life of the Planet has followed. The first action against the risk generated by the human activity has been taken by a group of about 30 between scientists, educators, economists, humanists, industrial managers and policy makers during an informal encounter in April 1968 at the Accademia dei Lincei in Rome. This group became later on a virtual Institute, known as the *Rome's Club* which has been working on the limits of the growth [10]. About twenty years later, in 1987, the Brundtland Commission, in their report [11], gave the modern definition of *sustainable development*:

> *Sustainable development is development that meets the needs of the present without compromising the ability of the future generation to meet their own needs*

It is only in 2000 that the United Nations during the Millennium Summit proclaimed the Sustainable development Goals, the 17 *SDGs* of the UN 2030 project given in Fig. 1.5.

1. *Poverty eradication.*
2. *Zero hunger.*
3. *Good health and well being.*
4. *Quality education.*
5. *Gender equality.*
6. *Clean water and sanitation.*
7. *Affordable and clean energy.*
8. *Decent work and economic growth.*
9. *Industry, innovation, infrastructure.*
10. *Reduced inequalities.*
11. *Sustainable cities and communities.*
12. *Responsible consumption and production.*
13. *Climate actions.*
14. *Life below water.*
15. *Life and land.*
16. *Peace and justice strong institutions*
17. *Partnership to achieve the goals*

In the following we discuss them in the perspective of developing an interdisciplinary scientific approach to understand how far we are from the achievements of the SDGs and in which manner the risk of *compromising the ability of the future generation to meet their own needs* can be scientifically quantified.

Fig. 1.5 The seventeen Sustainable Development Goals of the UN 2030 project

First of all we need to confront the SDGs with the Disciplinary Sectors on which the evaluation of scientists, humanists, industrial researchers, financial experts, cultural operators, science journalists, politicians and the various actors of the social and environmental development are usually evaluated.

We propose to use the same evaluation categories for the agents of the SCN. Such evaluation is the key to give a weight to the links of the network [1]. According to the Italian academical system, Life and Hard Sciences (LHS) and Social Sciences and Humanities (SSH) are divided all together into 15 disciplinary Areas, each of them is subdivided into several disciplinary sectors, for a grand total of about 370 disciplinary sectors [1]. The these sectors we have to add the industrial sectors, namely those coming from the primary goods production (primary sector), from the material goods production (secondary sector) and from the service industry Tertiary&advanced tertiary sector). We define in the following the N_S macro-sectors t_m of the set S that will be used to give a weight to the nodes and to the links of the SCN. The acronyms that are used for LHS and SSH coincide with those used in the Italian legislation. Let us first consider the **LHS Disciplinary Sectors**

1. Mathematics: MAT/(01–09)
2. Informatics: INF/01
3. Physics: FIS/(01–08)
4. Chemistry: CHIM/(01–11)
5. Earth sciences: GEO/(01–12)
6. Biology: BIO/(01–19)
7. Medicine: MED/(01–50)
8. Agricultural sciences: AGR/(01–20)
9. Veterinary sciences: VET/(01–10)
10. Civil engineering and architecture: ICAR/(01–22)
11. Industrial engineering: ING-IND/(01–35)
12. Information engineering: ING-INF/(01–07)

Let us now proceed with the **SSH Disciplinary Sectors**

1. Antiquities studies: L-ANT/(01–09)
2. Linguistic studies: L-LIN/(01–21)
3. Philology studies: L-FIL-LET/(01–15)ART
4. Art history: L-ART/(01–08)
5. Oriental studies: L-OR/(01–23)
6. History: M-STO/(01–09)
7. Philosophy: M-FIL/(01–08)
8. Pedagogy: M-PED/(01–04)
9. Psychology: M-PSI/(01–08)
10. Physical Education: M-EDF/(01–02)
11. Law: IUS/(01–21)
12. Economics: SECS-P/(01–13)
13. Statistics:SECS-S/(01–06)
14. Political and social sciences: SPS/(01–14)

Let us now consider the three industrial areas. We list the disciplinary sectors belonging to each area. The acronyms associated with them are not referring to any previous labelling. They only follows the criteria that have been used for the LHS and SSH disciplinary sectors, just for the sake of uniformity.

Let us first consider the **primary goods production** area.

1. Agri-food industry: PR-AFI/(01–10)
2. Forestry economics: PR-FE/01
3. Fishing industry: PR-FI/01
4. Mining industry: PR-MI/(01–05)
5. Ceramics and Glass industries: PR-CG/(01–03)
6. Energy production industries: PR-EN/(01–05)

let us continue with the sector devoted to the **material goods production** area

1. Construction industry: SEC-EC/(01–03)
2. Chemical product industry: SEC-CH/(01–10):
3. Graphics industry: SEC-GRA/(01–03)
4. Paper converting industry: SEC-PC/01
5. Wood industry: SEC-WOO/01
6. Furniture industry: SEC-FUR/01–05)
7. Textile industry: SEC-TEXT/(01–03)
8. Engineering industry: SEC-ENG/(01–05)
9. Electronic industry: SEC-ELEC/(01–05)
10. Steel industry: SEC-STE/01
11. Shipbuilding industry: SEC-SHIP/(01–03)
12. Aeronautical industry: SEC-AER/(01–03)
13. Biochemical and Pharmaceutical industry: SEC-BIO-PH/(01–010)
14. Biomedical industry: SEC-BIOM/(01–05)

Let us finally consider the tertiary&advanced tertiary sectors, devoted to **services**.

1. Transport industry: TER-TRA/(01–10)
2. Logistic engineering: TER-LOG/(01–05)
3. Educational industry: TER-EDU/(01–10)
4. Culture industry: TER-CULT/(01–05)
5. Health industry: TER-HE/(01–10)
6. Commerce: TER-COM/(01–10)
7. Banks and Insurances services: TER-BIN/(01–05)
8. Environmental services: TER-ENV/(01–05)
9. Domotics: TER-DOM/01
10. Robotics: TER-ROB/01
11. Digital industry: TER-DIG/(01–05)
12. Telematic services: TER-TEL/01
13. Internet: TERT-INT/01
14. Journalism and Science journalism: TER-JOU/(01–05)
15. Science and innovation diplomacy: TER-S-DIP/(01–03)

We have defined a set of 61 Disciplinary sectors 26 of which coming from LHS and SSH and the remaining ones collecting up the industrial product chains. An example of product chains is provided by the North Adriatic industrial Union, which aggregates more than 1300 enterprises, grouped into 14 industrial product chains and include about sixty thousands employees in the industrial sector.

The SCN tasks necessarily refers to a number of SDGs and require the activity of researchers of few disciplinary sectors. The definition of the sustainable development goals and the disciplinary sectors for any given task is necessary in order to make evaluations of the behavior of the network and to measure its efficiency.

Let us make an example taken from the SCN Trieste Laboratory on quantitative sustainability (TLQS) [12]. This include seven clusters, one of which is *The Blue Planet and the sustainability of the sea economy*. Sees, oceans, coastal and internal waters are vital for our societies and the future of the Planet. They are sources of food, energy, biological resources, communication routs, work opportunities, leisure, cultural stimuli and they may also viewed as future new dimensions of human life.

In order to pursue a realistic strategy of the *blue prosperity* it is however fundamental to understand and make quantitative measurements and evaluations on the functioning of the oceans and the marine ecosystems as well as to learn their response to the antropic impact. Such a task requires the development and the deepening of several disciplinary aspects related to physical oceanography, marine biology, ecology, physical chemistry, environmental, economy, social sciences systems theory, engineering and others.

The SDGs related to this task are primarily number 6, 7, 9, 13 and 14. The macrosectors to be associated with the cluster are the following: LHS/01–06, LAS/11–12, SSH/11–14, PRI/04–06, PRI/06, SEC/08, SEC/11, TER/01–02, TER/06–08, TER/10–11 and TER/15.

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Part II
The Blue Planet and the Ocean Sustainable Economy

Seas, oceans, coastal and internal waters are vital for our living and it will continue to be like this also for future generations. Jack Kerouac wrote… *pick up a coup of water from the Ocean and you will find me.*

The oceans cover almost seventy per cent of our planet. They have a fundamental regulatory function for the climate, by absorbing large amounts of CO_2. They sustain the hydro-geologic cycle, and consequently, the availability of fresh water and in general of water resources. They host a broad spectrum of habitats and organisms—from the microscopic photosynthetic ones, that feed marine life and produce half of the terrestrial oxygen, up to the huge mammals and apex predators, ranging from sandy shores to oceanic grasslands or coral bottoms.

The Oceans produce food, energy, abiotic and biotic resources, routs of communications, but also job opportunities, leisure possibilities, cultural stimuli: in a word, they are an essential component of the planetary ecosystem. That is why the safeguarding of the ocean and marine life is so important that not only it is itself one of the UN objectives for the sustainable development (SDG 14), but it is also a prerequisite for most others to be fulfilled.

In spite of all this the oceans are increasingly threatened by several anthropic actions and by the recent development of the blue economy. How not to mention the marine heating and acidification, the pollution, the plastics, the over-exploitation, underwater noise, genetic contamination and more.

It is now time to significantly and strategically increase the observations and measurements of the marine phenomena, in order to really understand the response of the oceans and the marine ecosystems to the anthropic impact. We need to develop the instruments and the knowledge in order to constraint the blue economy to the sustainability principles and those of *the blue prosperity*.

This goal urgently asks for the development or the deepening of specific disciplinary themes belonging to physics oceanography, marine biology, ecology, chemical physics, environmental economy, social sciences, systems theory, engineering and more others. Such unique systemic contest, holistic and quantitative at the same time, needs of a new interdisciplinary way of doing research.

Our team will explore the possibility of developing this approach and of evaluating its application to a marine system, based upon the existing data and limited to the North Adriatic area.

In addition to that, we will stimulate the collaboration between scientific research, industries, public authorities, stakeholders on specific activities and public events to get new data and new innovative activities devoted to the diminishing of the anthropic impact and to the development of sustainable technologies and services.

In conclusion, the development of interdisciplinary and trans-disciplinary approaches to the sustainability of the oceans and the marine resources—fundamental key for the formalization of a *sustainability science*—will have a great impact on the European strategy on the research, education and science communication of marine technologies, as well as on the protection of the natural resources and on the employment of new job in the blue industry.

A time will come when the Ocean will break the chains of the Universe
and will become an immense Earth, and Teti will reveal new worlds
and no more will exist on the terrestrial globe a last Thule.
(Lucio Anneo Seneca)

This part includes Chap. 2, *Routes to Ocean Sustainability and Blue Prosperity in a changing world: guiding principles and open challenges*, by C. Solidoro, S. Libralato and D. Melaku Canu.

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Chapter 2
Routes to Ocean Sustainability and Blue Prosperity in a Changing World: Guiding Principles and Open Challenges

Cosimo Solidoro, Simone Libralato, and Donata Melaku Canu

Introduction

In December 2017, the United Nation decided to proclaim the United Nations Decade of Ocean Science for Sustainable Development for the 10-year period beginning on 1 January 2021 [1].

This important decision has a multifaceted meaning. From one side it reaffirms and stresses the importance of constraining human actions to the sustainability principles. Further, it emphasizes the central role of the Ocean as both a driver of future economic growth and an essential resource to be preserved. Finally, and quite relevantly, it states the need to base human activities on scientific knowledge.

In fact, the UN declared the Ocean Decade as a "once in a lifetime opportunity for nations to work together to generate the global ocean science needed to support the sustainable development of our shared ocean", with the specific underlying goals of: (i) to provide Ocean science, data and information to inform policy for a well-functioning ocean in support of all sustainable development goals of the Agenda 2030; and (ii) to generate scientific knowledge and underpinning infrastructure and partnerships.

The importance of ocean and seas for the planet ecosystem health and for human well-being is so large that cannot be overestimated. They cover over 70% of the planet, regulate its climate by absorbing a massive amount of heat and carbon dioxide

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from the atmosphere, sustain the hydrological cycle and its components (including rain over land and forest), host an amazing variety of habitats and marine organisms, ranging in size and ecosystem function from the microscopic photosynthetic organisms that fuel marine life and produce half of earth's oxygen and biomass to large marine mammals and top predators, from sandy coastal areas to deep sea hydrothermal vents, and more. They provide food, energy, transportation routes, genetic and mineral resources, job opportunities, recreational, cultural and social services [2]. Preserving ocean and ocean life is such a relevant task that it is—per se—one of the UN Sustainable Development Goals (SDG 14), but the ocean role is so relevant that many other SDGs cannot be achieved without preserving ocean health [3].

However, the ocean is challenged by a number of co-occurring pressures, and it is easy to foresee that the number and intensity of those co-occurring threats will increase in the near future, driven by the demands of the expanding blue economy sectors and the related society components.

It is therefore mandatory to monitor and understand how the ocean is responding to the cumulative impact of these multiple coexisting pressures [4], and to use this knowledge to identify safe operational thresholds—i.e. pressure levels not to be exceeded to guarantee the resilience of the marine ecosystems, ensuring their proper functioning and the persistence of good ecological state and proper functioning of marine systems—as well as effective ways to enforce the respect of those limits.

Blue economy can be instrumental in increasing the quality of life of billions of persons, and it is of crucial importance to promote its development. Of the same importance is to learn from the past and to avoid the errors made while promoting land base economy, which developed with too little or no awareness and attention to potential adverse consequences on the environment at the local or global scale. As we now know very well, overexploitation of the natural capital and/or excessive level of environmental impact cause ecosystem deteriorations with—sooner or later-cascading consequences also on the economic activities and the related social dimensions. To build the knowledge to find a proper and workable trade-off between minimization of environmental impact and maximization of socio-economic benefits, also accounting for the need and rights of other countries and future generations, remains a formidable challenge to be won. To enforce effective policies to reach that balance might be an even larger challenge.

Blue Economy

From an economic perspective, the ocean and seas represent a very relevant resource. Oceans have always been a valuable component of human societies. Coastal seas provided an accessible source of food and a convenient trade and communication routes: many important cities grew and developed along the sea coasts, and most civilizations of the past relied on their capability of sea travel and exploration. Industrial plants, too, often were located near the coast, because of the possibility of efficiently delivering raw materials and goods by ships. However, the sea was also perceived as a hostile environment, and the exploitation of marine resources has been limited by the difficulty of operating at seas and the fact that land operations were easier, and in many cases economically more rewarding.

The situation is different nowadays, since technological progress makes the use of sea resources possible and cost effective, also considering that land-based resources are becoming scarcer and more costly to exploit.

Today a significant share of oil and gas is drilled at sea, and not only is such a share increasing, but also the oil industry is moving to deeper and deeper water [5].

Similarly, there is an increasing interest in deep sea mining industries [6], which aim to exploit ores of valuable minerals (sulfide, iron), nodules (manganese), crusts (cobalts) [7].

About 10 billion tons of goods are transported by ships, and possibly 40% of the global population lives less than 100 km from the sea. Sea routes usually are toll free.

Beside fossil fuels, the ocean also provides an increasing amount of renewable energy, in the form of waves, currents, heat, and experts believe this might quickly account for almost 15% of the global electricity demand. Furthermore, offshore wind turbine fields are becoming more and more frequent.

Fisheries still sustain—directly or indirectly—almost 1 billion people worldwide [8] and represent a main source of food and protein in some parts of the world.

Aquaculture is growing exponentially and is projected to match and surpass fishery production in 10 years. By 2030 fish production will reach 200 million tons, a fish out of two will be farmed, and—even if the largest share of aquaculture refers to freshwater [8]—oceans will significantly contribute to feed humanity. In doing so it will also contribute jobs and prosperity.

In agreement with most recent figures [9] the EU blue economy 2019 established sectors (marine living resources; marine non-living resources; marine renewable energy; port activities; ship building and repair; maritime transport; coastal tourism) directly employed 4.45 million people, with an average salary of €24 739, and generated a turnover of €667,2 billions. They obtained a gross profit of €72.9 billion and a gross value added (GVA) of €183.9 billion. The net investment in tangible goods resulted to be €72.9 billion, with a net investment to GVA of 3.3%.

The fastest expanding sector being living resources (increased by about 30% in 10 years), shipbuilding (+40%), emerging and innovative sectors include the marine renewable energy sector (20%, focused on EU hydrogen strategy, and offshore renewable energy strategy goals), bioeconomy, desalination and blue technological innovation.

Ecosystem Services

The emerging need of taking into consideration environmental consequences of socio-economic activities called for new tools and methodologies to assess the environmental impact of human activities and possibly related costs, as well as the development of unifying integrated frameworks.

Ecosystem services assessment and valuation exercises are attempts to take into account the value of nature in policy making. Ecosystem services are benefits that nature contribute to people: they can be actual goods produced by ecosystems and exploited by humans, such as food, raw material and the like, or services, such as air and water purification, climate regulation, mitigation of adverse effects of extreme events, or other activities that results from a healthy ecosystem functioning and are useful to humans. Ecosystem services also include intangible benefits, such as inspiration for culture, religion or recreation and more generally the 'sense of place' that has an intrinsic individualistic value [10].

Ecosystem services can have a market, and in this case, it is relatively straightforward to assign a value to a service, even if the market price reflects the balance between offer and demand, rather than the actual intrinsic value of a good. In many cases, however, there is no market and no market value. Water purification, nutrient recycling, carbon sequestration, and wellness related to the beauty of nature are a few examples of extremely valuable services for which there is no market value. In these cases, some experts believe it still makes sense to devise methodologies to assign a potential value to them. Some of these methodologies analyze people choices in their real life (revealed preferences), other are based on surveys to assess the willingness to pay (*wtp*) for keeping a service running (would you be willing to donate a given amount of money to save whales from extinction?), or—on the contrary, the willingness to accept (*wta*) a payment as compensation for its loss (would you accept a given amount of money as a compensation for the extinction of the last whale?).

Without entering into the technicalities of valuation exercises, it should be noted that valuing is not pricing, meaning that not always money can be a substitution for nature, but a valuation exercise always is a way to make nature value less invisible and to highlight hidden values often taken for granted.

In 1997 a seminal paper [11] Costanza et al. attempted a fist assessment of the natural capital worldwide. The results highlighted that nature provides valuable services on the order of 33,000 billion US dollars per year. Notably, oceans and seas accounted for 70% (21,000 billion dollars) of that. Coral reefs resulted the most valuable ecosystem type, followed by salt marshes and mangroves.

The paper was followed by many discussions and critiques, had a tremendous impact (30,000 citations as of today) and had the great merit to put ecosystem services on the spot for the following decades.

Following the Costanza et al. paper, other major initiatives attempted to systematically estimate the value of nature, or to assess the capability of the global ecosystem to provide services.

In 2000, the UN secretary promoted the Millenium Ecosystem Assessment [12], to assess the consequences of ecosystem change for human well-being and to define the actions needed to improve the conservation and the sustainable use of those systems. The MA involved more than 1,000 experts worldwide and provided a state-of-the-art scientific appraisal of the condition and trends in the world's ecosystems and of their services, and the options to restore, conserve or enhance them. The MA concluded that human actions are depleting Earth's natural capital, but also indicated that it is possible to reverse the degradation of many ecosystem services over the next 50 years.

In 2015 UN launched the Intergovernmental Panel for Biodiversity and Ecosystem (IPBES) assessment, which—similarly to the Intergovernmental Panel for Climate Change IPCC—attempted to provide rigorous and systematic reviews of scientific literature on this important topic. They released their first assessment in 2019, both for the global and 5 macro-regions. One of the results was that biodiversity is decreasing everywhere. Another evidence arising from the study was the lack of quantitative information on the ocean, in respect to land [13].

Environmental costs has been assessed also by using other methodologies and indicators, such as the Ecological Footprint, that translates the input required to build up a good or to supply a service in terms of 'extension of equivalent area' [14], or the embedded energy, eMergy, that translates them in solar energy equivalent [15]. In all cases, however, the overexploitation clearly appears and highlights how we are using future generation resources. In 2023, the overshoot day, i.e. the day in which humanity's demand for ecological resources in a given year exceeds the Earth's production in a year, was the end of July, implying that for 5 out 12 months we were living on future resources. Put in another way, we would need 1.7 planets to sustain our consumption. These indicators can be applied also to value marine systems. However, since they have been developed for terrestrial systems, specific adjustments and adaptations are needed.

Ocean contributions to people do include services that do not have a market nor a direct economic value, and whose importance might be difficult to assess. Incidentally, methodologies such as *wtp* or *wta* are in these cases even more delicate, given that the value assigned to the ocean usually depends on where a person lives, and their education.

Just as an example, we can remember that ocean adsorbed about half of the CO_2 released in the atmosphere by anthropogenic activity in the last 2 centuries [16], i.e., without the ocean, the CO_2 atmospheric concentration would be now much larger than 500 ppm, and the climate change much more severe. Ocean also adsorbed a significant amount of heat (the surface ocean is adsorbing about 0.5 watts/m^2, equivalent to about 10^{23} J per decade) so kept the atmosphere cooler than it would be otherwise, and buffer changes during the day night or seasons cycles. Ocean and seas act as giant water reservoirs and fuel the hydrological cycle, providing the crucial supply for rains and rivers all over the planet. They provide a source of multiple inspiration to artists and are perceived as beautiful and emotional (sea-view houses always have an added value) up to the point of promoting positive feelings, useful in health care.

To attempt a quantitative estimate of the value of these services on a global scale is probably meaningless since in some cases they are literally priceless.

More sensible estimates might be provided at the local scale, possibly with the aim to inform on specific local plans. Also in this case, however, to perform an assessment poses a formidable challenge, considering that it requires a quantitative knowledge of the relationships between the state of the ecosystem and its capabilities to provide services, as well as of how these services (which are flows) change in response to changes in ecosystem state. Overall, this assessment requires a fully quantitative understanding of the relationships between ecosystem state, ecosystem functioning and the capability to provide services. In fact, the valuation also depends on the starting situation, since the value of (for instance) a square meter of a given habitat surely depends on how large the habitat is, and whether or not there are other similar habitats in the region. Similarly, the value of a fish is higher if it is one of the last specimens of an endangered species. So it is the 'marginal value' that has to be considered and computed. Scientific literature offers examples of these studies also for the marine realm. For instance Canu et al. [50] quantified the role of plankton activity as contributor of carbon sequestration in the Mediterranean Sea by using a combination of state of the art deterministic biogeochemical and economic models, and considering the effects of different level of plankton activity; Zunino et al. [54], (2021) used food web models to assess the loss of ecosystem services related to the impact of ocean acidification on habitat forming species, [18] used surveys to assess the recreative value of seagrass and coralligenous.

Several studies can be found also on lagoons [19–21]. But few are the cases in which the quantitative understanding of the system with the functional relationships between pressure, functioning and services are estimated and quantified, thus allowing a proper valuation. In all cases the uncertainty of an assessment increases while propagating among physical, biological and economic dynamics (see Fig. 2.1), also because a holistic valuation exercise always includes a judgment phase that involves arbitrary and personal choices [22] for capturing cultural, ethic and social aspects that cannot be captured by purely deterministic laws.

Integrating Blue Economy and Ecosystem

Our vision and policy should be based on an integrated view in which the economy is a subsystem of the finite and non-growing ecosphere [23]. There are three possible theoretical frameworks for such integration, all considering economy as a subsystem of the ecosphere, but differing in how they consider the boundaries, feedbacks and dependencies between the subsystems.

In the *Economic Imperialism* the economic subsystem can growth up to encompass the entire ecosphere, and everything is sees as whole macro-economic system in which external costs and benefits are internalized into prices, or 'shadow prices', i.e., the price they would have if traded in a competitive market, and the economic expansion is considered acceptable as long as all costs are internalized. While costs should

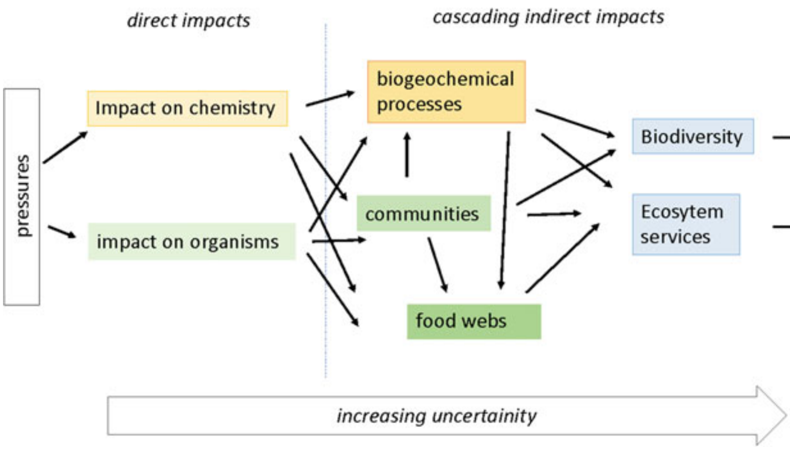

Fig. 2.1 Direct impacts of environmental threats on physical and chemical properties of the sea have cascading effects on marine organisms, communities, food webs and ecosystems, which in turn can affect biodiversity and marine ecosystem services, with effects on their social and economic values. Uncertainties propagate and usually amplifies along this chain, so that our understanding and capabilities to produce robust assessment of impact on socio-economic components is more uncertain than for biological or physical ones

surely be internalized, this approach has important conceptual limitations, since not always good and services having the same economic value can be regarded as equivalent, i.e. natural capital (ocean, forest, rivers, coast) is intrinsically different and not replaceable by antophogenic capital (machines, factories, industries). Moreover, not all processes and transformations (none in reality) are reversible. In principle, a perfect pricing mechanism might take into consideration and possibly compensate for some of these limitations, but in practice it is very difficult to implement them, since (once again) we would need a perfect knowledge of the complete implications of any action, including those on future ecosystem dynamic, and a continuous update of the prices. Furthermore, on a more pragmatic side, internalization has been very slow, partial, and much resisted, since firms have economic advantages to externalize costs.

In the *Ecological Reductionism* paradigm, the economic subsystem and its growth are considered as bounded by natural laws and constrained by ecosphere limits. Everything is seen as a whole macro-ecosystem and explained in terms of materialist deterministic actions. Also, this vision has important limitations. In fact, if it might be possible to reduce to deterministic laws the main properties of a simple natural system, it is difficult to assume that this is true also for complex systems, and even less for human activity. Granted that natural constraints exist, humans do have the possibility to freely determine their actions among the many possible courses, and are responsible for the implication of the policies they chose.

The above-mentioned paradigms are opposite monistic visions. The third remaining perspective is the *Steady state subsystem*, in which one treats economic and ecological systems as distinct subcomponents working on different scales and driven by different forcing, but tightly interrelated. Within these *Ecological-Socio-Economic systems* the ecosphere physically supplies material and energy to drive the economic subsystem, and the throughput has to be continuous to keep the subsystem working. Indeed, the economic system can be seen as a dissipative, far from equilibrium, ordered system. In this context many different steady states can exist, and the goal of sustainable economy is to minimize the throughput, and the entropy produced by the system, by adopting efficient technologies and increasing the recycling of by-products and waste [23, 24].

Economy for a Full World

The fact that human well-being depends upon the existence of a healthy ecosystem has been obvious for centuries, during which life was regulated by rhythms and constraints posed by nature, and humans simply had to accept that their very life depended upon their relationships with the planet. On the other hand, anthropogenic activities had the capability to modify the environment only to a limited extent, and mainly to a local scale, so that it was normal to perceive the environment as having a so large buffer capacity to be virtually infinite. We lived in an 'empty world' (see Fig. 2.2). The economic subsystem was physically small in comparison to the ecosphere, and the exchanges of matter and energy needed to sustain economic activities were small relative to the containing system. Renewable resources reproduced faster than our harvesting capabilities, mineral and natural resources were perceived as not scarce and not limiting economic growth, human footprint was limited, and ecosystems had the capability to recover from perturbations. At that time, it made sense to think that there was no conflict between economic growth and nature.

Since the industrial revolution, technological development gave humans the capability to modify the Earth to an extent that basically detached us from the rest of the planet and gave us the illusory perception of owning the planet and having the possibility to dispose of its resources.

Humans forgot to be animals living within ecosystems and bound by natural constraints, and started to impose anthropogenic rhythms to nature [52]. Anthropogenic driven technological transformations modified and accelerated natural cycling—e.g. by mobilizing reduced carbon from fossil fuels as oxidized carbon in atmospheric CO_2-and imposed changes at unprecedented rates. The underpinning shared belief was that, thanks to its ingenuity, mankind could grow and evolve with no limit, and technology could solve any problem [25].

Even if this attitude is still present in a part of the population and political debate, it is now increasingly recognized and widely accepted that some limits exist and have to be considered, since—in spite of any technological improvement—there cannot be an infinite growth on a finite planet, and since in our globalized era environment buffer capacity has been not only reached, but in some case also exceeded at the local, regional, and planetary levels [23, 26].

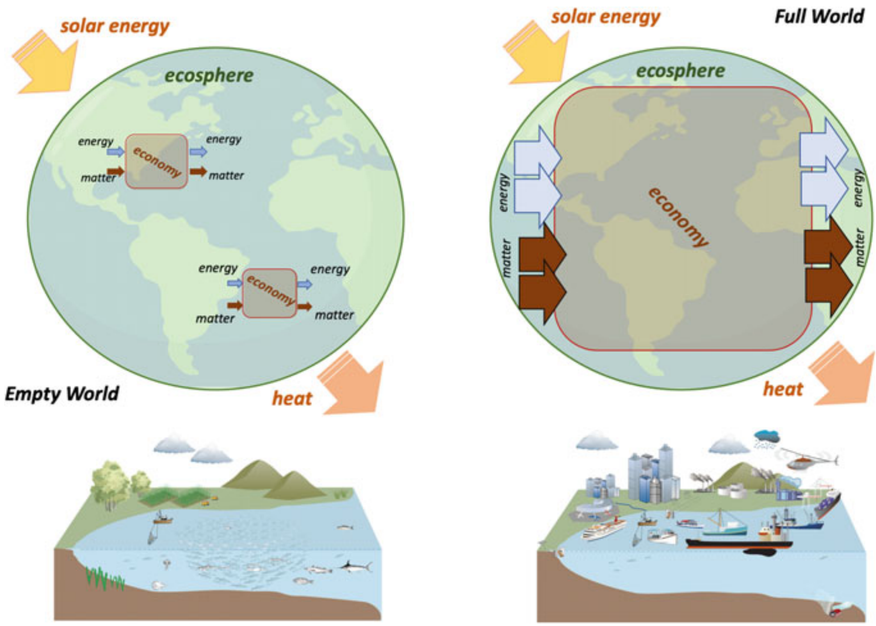

Fig. 2.2 Economy is an open subsystem of the larger ecosphere, which sustains economic activities through exchanges of matter and energy. The ecosphere is finite, close to mass exchanges, not growing and fueled by the negentropy flux related to the dissipation of the continuous solar energy throughput. Humanity moved from an 'Empty world' to a 'Full world' economy, which now requires enormous fluxes of matter and energy, diverted by their original use. The human footprint is now of planetary relevance

In the last two centuries the millennia balance with nature was somehow lost and the empty world quickly turned into a full world: the global population grew from 2 to 8 billions, the number of farmed animals grew even more rapidly, the mass of artificial things become larger than the living one and the maintenance of the economy subsystem requires now an enormous throughput of mass and free energy, a metabolic flow that begin with low entropy resources from the ecosphere and ends with the return of polluting high entropy output back to the ecosphere, a massive flow that impact the ecosphere at both ends and need to be considered (internalized) when assessing the net utility of an activity (see Fig. 2.3). This view also reminds us of the thermodynamic limits constraining the ecosphere and its open economy subsystem: while the first law imposes the quantitative balance of matter exchanges between the ecosphere and the economy, the second law prescribed the existence of upper limits to the efficiency of any transformation, the consequent impossibility of infinite growth, and the necessity to rely on solar and related renewable energy as the ultimate source of negentropy required to sustain the ecosphere and the economy [27].

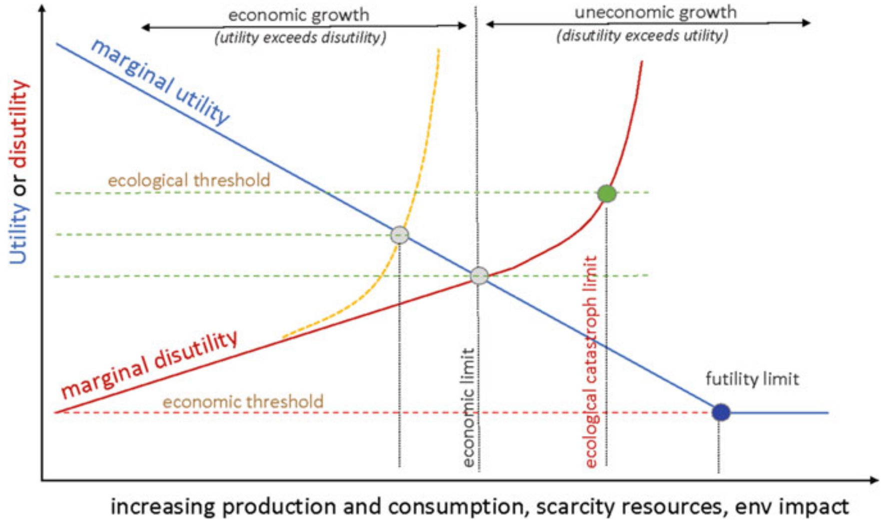

Fig. 2.3 If environmental and external costs are internalized, production and consumption levels stop at the economic limit, before the disutility exceeds the utility, and when there still is an economic growth. The equilibrium point between utility and environmental costs occurs at different production level, depending on the shape of the marginal disutility curve: if environmental costs are highly valued, the curve increases more steeply and at lower production level, and the economic limit equilibrium point and environmental costs decreased below the ecological limit. The opposite happens when environmental costs are valued too little, and production increases at levels in which ecological limits are exceeded. If no environmental costs are considered, production and consumption levels are driven by utility alone, up to reach-or exceed—the futility limits, above which there is no marginal utility left, the growth is largely uneconomic and the impact on the environment extremely high

The view also reminds us that capital and natural capital are not interchangeable, and technological improvements cannot substitute nature in all its processes and mechanisms, and humankind will always rely on natural products and services.

Sustainability

Sustainability pertains to integrated ecological-social-economic systems, and is related to time: it implies comparing rates of human activities against rates of natural cycles, or the entity of the energy/matter throughput needed to sustain the economic subsystem dynamic in respect to the remaining ecosphere.

The concept is often illustrated also with reference to the superposition of its social, economic, and ecological dimensions, to stress the fact that it is not something related to ecology or economy only, but to the combination of the two, with the important expansion over social justice [28]. The concept is qualitatively simple: an activity can be sustained (proceed indefinitely) in time if and only if there is an economic interest in maintaining it (otherwise the owner quits it), it has a limited impact on the environment in term of resource exploitation (otherwise it runs out of resources) and pollution (otherwise is not acceptable), it is socially acceptable (otherwise it gives rise to social tensions that make it infeasible in the long run). It is clear that in all cases these requirements refer to a balance to be made over a long enough time. Indeed, the sustainability debate is deeply rooted in the intergenerational debate: to what extent people today are responsible for the wealth of future generations.

It implies also to give full considerations to the fairness of distribution of resources and services, the efficiency in their use and the capability to maintain the wellbeing for nature and humans [29].

The concept of sustainability has been rediscovered many times. It is possible to trace it back to the 1716 in silviculture treaties by von Carlowitz, then in the Malthus dissertation [30] or the Marsh essay [31] up to the environmentalist movement of the seventies, protesting for smog, acid rain and environmental degradation in Europe and North America. In 1972 the Club of Rome published the seminal 'Limit to Growth' [25], which introduced the concept of sustainable *global* system, and warned the world against the consequence of overexploitation, and in the 1987 the UN world commission on environment and development presented the Brundtland report, which defined sustainable development as 'the development that meets the need of the present without compromising the ability of future generation to meet their own need' [32]. In 2000 the UN launched the Millenium Goals and a few years later redefined the concept by listing the UN Sustainable Development Goals. Even Pope Francis felt the issue so relevant to devote his encyclical "Laudato sii" to the importance of preserving biodiversity and ecosystem functions from the unsustainable exploitation of the planet.

Sustainability is today a central concept deeply rooted in any political debate and agenda. What we are still missing, however, are concrete directions for political interventions.

Unfortunately, while everyone agrees on the general principles, the wording of sustainability definition is open to different interpretations by different stakeholder groups, and even the Brundtland report contains no operational indications on how to move from principle to practices. Some theoreticians developed the 'three pillars' model, giving equal importance to the three dimensions of sustainability. Others stressed that social and economic SDGs cannot be reached without achieving the nature-related SDGs to begin with. But we still miss a shared idea on how to move forward, and possibly—as the UN Ocean decade declaration reminds us—the science and knowledge underpinning that.

Ocean Under Multiple Threats

The ocean and sea health is currently menaced by a number of co-occurring pressures, causing a cumulative impact that is increasing and bound to growth also in the near future, as a consequence of the expansion of the blue economy.

A non-exhaustive list of current anthropogenic driven environmental threats includes climate change, ocean warming and acidification, marine litter, a countless variety of marine pollution (e.g. oil spills, heavy metals, persistent organic pollution, antibiotics, drugs, and emerging pollutants), extractive activities and deep-sea mining, underwater noise, marine litter and marine plastic, genetic contamination, overfishing. Most of these threats were never assessed before their introduction into the ecosphere, and we became aware of their individual and combined impacts only after the fact. Even now, different countries and legislation have different approaches to pollution, with more or less restrictive and environmentally sensitive approaches. Some of those threats originated globally, others locally. Most of them interact, inducing synergistic and additive impacts, locally and globally.

Climate change has extremely relevant and pervasive impacts, which unfold through direct effect and cascading processes [33]. The warming of the atmosphere causes the warming of surface water, in turn affecting water density and therefore the seasonal alternance of mixing and stratification processes occurring along the water column which are driven by density gradients. The changes in density also affect the dense water formation triggering the thermohaline circulations, with potentially extremely relevant consequences on the global ocean circulation [34] and related space redistribution of dissolved substances, including oxygen [35]. In turn this might alter the onset, phenology and spatial distribution of plankton primary production, giving rise, in combination to differential warming of surface waters, to relevant changes in the properties of the sea regions and therefore in their suitability for marine organism's life, migration of mobile organism, possible extinction of low mobility organisms no longer fit for new conditions, invasion on new immigrant species, occurrence of new assemblages and emerging food webs. In particular, the foreseen deoxygenation of world oceans is expected to have overwhelming effects on species bioenergetics, on mortality of sessile species and eventually displacement of mobile species and their productivity [36, 37].

The other side of increasing atmospheric CO_2 is the dissolution of CO_2 into surface water, leading to formation of carbonic acid and an increase in ocean acidification, which has been already observed and estimated in about 0.3 pH units per century, i.e. doubling the concentration of acid in the ocean (the pH is a logarithmic measure of acidity concentration). Experts expect that ocean acidification will continue for at least several decades [51] with an extremely relevant impact on ocean life and related services.

Climate changes will appear not only in the monotonic increase of averages values, but also as an intensification of extreme events, with an increase in the frequency, severity and deep penetration of marine heat waves, [38, 39], cold spell, bottom hypoxia, hypercapnia [40], not to mention the impact of sea level rise.

Pollution is another dangerous, ubiquitous and pervasive impact of human activities. The seas continue to receive massive amounts of traditional contaminants, such as metals and permanent organic pollutants, that—being permanent—bioaccumulate in marine organisms, eventually biomagnificate, and move though the whole ocean. But they also are the receptacles of a variety of 'new' pollutants, like pharmaceutical compounds, whose impact on marine life is still to be understood, antibiotics that might trigger the selection of resistant microorganisms, and the group of so-called emerging contaminants and of contaminants of emerging concern, about which very little is known as yet. Nutrients, in particular nitrogen and phosphorus from agricultural sources and wastewater treatments, noise pollution from ships and off-shore industry, changes in light and water color as a result of artificial lightning along the coast and electromagnetic waves are other forms of pollution which are increasingly being recognized. Plastic and marine litter are becoming so abundant to make the cover page of main newspapers.

On the exploitation side, many nations overexploited the fish stocks in their coastal area and several fish stocks experienced severe declines [42]. According to FAO the share of collapsed or overfished stock is now around 30% [8], and since most stocks have been depleted in the northern hemisphere and in particular European Seas appear subjected to high fishing pressure [48], fishing vessels are now moving south, undermining stock and local population in other parts of the planet [49]. Climate change projection agrees in indicating a significant decline of total animal biomass in most part of the planet [41], (33; see Fig. 2.4).

Having stocks overexploited is an inherent inefficiency, since at the same level of effort, the fisheries extract less catches (i.e., food for humankind) because of the depleted population biomass [43]. However, several growing efforts to include regulations, management plans and rebuilding plans are providing important results

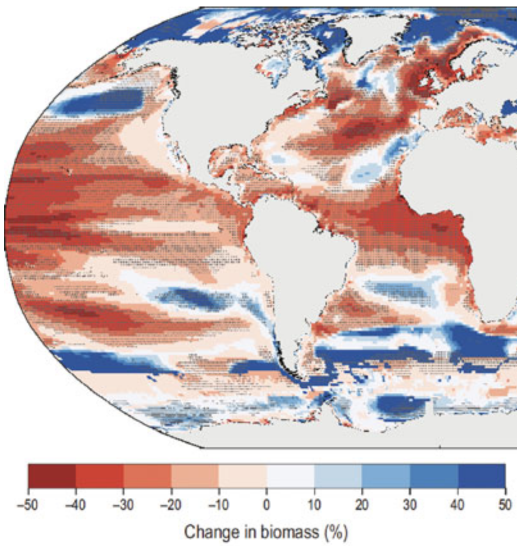

Fig. 2.4 Projected changes in total animal biomass (including fishes and invertebrates) based on outputs from 10 sets of projections from the Fisheries and Marine Ecosystems Impact Model Intercomparison Project (FISMIP). The figure illustrated the multi-model mean change (%) in unfished total marine animal biomass in 2085–2099 relative to 1986–2005 under RCP8.5, respectively. Dotted area represents 8 out of 10 sets of model projections agree in the direction of change (from IPCC report [41])

with stocks improving conditions and reduced overfishing issues [44]. Analyses also point out that only measure with great strength (like multiannual fisheries bans or moratorium) allows for a relatively fast rebuilding (approximately 10 years), while less severe measures improve fishing mortality, but do not assure rebuilding of the natural capital [45]. Once again, therefore, there is evidence that the speed of human impact is much faster than natural dynamics, and thus the effects of pressure release need quite a long time to promote recovery.

On this aspect it is appropriate to remind that given the nonlinearity in trophic relationship occurring in the marine food webs, tipping points and hysteretic effects can exist, and often the decline in fishery effort taking place after the collapse of a stock not always results in a recovery of the stock, as the cod collapse in north Atlantic exemplified.

The global increment of aquaculture also represents a threat, if pursued in its intensive form, because of the use of related input of fish food, medicine, and export of waste to the sea bottom [46]. Moreover, in many cases the farmed marine animals are not herbivorous-like in terrestrial systems, were farming regards herbivores or at maximum omnivores. Thus, most of the farmed marine species have to be fed with either fish meal, fish-oil or other farmed organisms thus impacting on wild resources indirectly. Although aquaculture is doing enormous efforts to use alternative sources (like insects), increasing efficiency of feed, or farming alternative low trophic level species, a lot has still to be done to decrease the unsustainable aspects of fish farming (see also EU 2020, Mission Starfish-Restore our oceans and waters).

Maritime transport, oil spill, bioinvasions (sometimes related to ships traffic and ballast water), loss of biodiversity, are other sources of alteration to ocean life.

Two additional factors are important to be stressed in this context: a) different stressors can co-occur and combine into cumulative impacts whose dynamics is still little known and very far from being quantitatively understood; b) the ocean has an enormous mass, which dilutes and buffers any impact, but also accumulate them, so that changes takes time, and it is difficult to assess the impact of any action by monitoring over the short term.

Managing the Last Commons

The ocean is one, has no borders, and it belongs to everyone, since everyone benefits from its contribution and everyone has the capability to negatively impact it, together with the responsibility of not doing so. Indeed, marine pollution and environmental degradation are paradigmatic examples of threats that propagate in space and time also across political boundaries, and need to be addressed by transitional coordinated actions based on evidence-rooted common understanding [2].

The ocean—as the atmosphere and the climate system—really is one of last common, i.e. a shared open system that can be impacted by everyone, and—as it is well known—in these cases the combined action of individual users acting independently according to their own self-interest does not result in an optima equilibrium point (since players do not pay costs proportional to their benefit), but rather cause the depletion of the resource [47]. The tragedy of unmanaged commons can be avoided by sustainably-oriented management and regulating access, and examples exist where members of a community co-operate to exploit shared resources prudently, and without collapse [28]. Often, however, these examples are local and context-specific, while an implementation of efficient regulating systems at a larger scale, or planetary one, is much challenging, as can be easily seen also in the discussion on climate change regulation.

A central problem in this case is who has the power to define, enforce, revise, the regulation system, and possibly monitor its efficacy. In fact, often purely top-down regulations fail, because not all players comply with the prescriptions, the control system is not efficient enough, or there is not enough faith in the proposed solutions to ensure compliance. Furthermore, there is the perception of large uncertainties that hamper easy direct decisions, thus avoidance of taking responsibility prevails. Sometimes co-management based on a shared knowledge pool, to which every player is called to contribute, is more effective. Indeed, earlier engagement of all stakeholders and their empowerment is often advocated as an essential ingredient for efficient environmental management. Also, this approach, however, is difficult to implement when dealing with global scale resources, where there is a very large number of very diverse stakeholders, often with different power and authorities and interlaced interests. Standard representative systems might be useful, but often globalization weakens the feedback loop connecting people's response to a local impact to the global governance system, making the adaptation weak, slow and less effective.

The picture becomes even more complex in transnational areas, where the fragmentation of the governance framework implies that different authorities might have different priorities and agenda, and—paradoxically—in coastal areas, where the number of overlapping managing authorities increases significantly.

It is not surprising, therefore, that the UN stressed the urgency and the importance of knowledge, as a common shared base to define and support adaptation strategies and science-informed policy responses to global environmental crises.

These aspects highlight as the sustainability problem really requires a multi and inter—disciplinary approach, combining physical, natural, and social sciences. The integration of these approaches, long advocated, has been so far slow and difficult, and not only because of differences in languages. Other hampering factors were the existence of unrealistic expectations from other disciplines, problems related to lack of openness of data and information, the attempt of a single discipline to dominate over others, diversity in spatial scales implicitly addressed by the different disciplines, differences in the valuing system [3]. Geopolitical, historical and wealth differences, moreover, further complicate the picture. These aspects also highlight the need of using simplicity, transparency and integrity as major principle orienting and guiding future cooperative efforts [3].

Concluding Remarks

Sustainability is a key concept in today's political agenda and an essential tool for preserving the wealth of future generations, and their rights to meet their demands. Quantitative approaches to sustainability are much needed and can help in overcoming the remaining lack of clarity in the interpretation of concepts, if any, and in providing directions for effective and sensible operationalization of the sustainability principles. Quantitative tools require an exact definition of the system to be considered, the boundaries and the relationships among its subcomponents, the space and time scale analyzed, the physical laws considered or neglected, the value choices arbitrarily adopted, and all other details. These requirements favor a transparent and rigorous dialogue among disciplines concurring to managing the problems, and also provide an ideal framework for identifying potential alternative management scenarios, to assess the expected impact of their implementation, and to offer support to decision makers.

The application of quantitative sustainability approaches is particularly relevant in the ocean, because its intrinsic global, trans and over-national dimension makes essential to have the capability to reach a shared understanding and a clear consensus on present ocean state and trends, as well as on plausible expected future dynamics under alternative policy scenarios, and eventually pathways towards desiderable states.

Blue economy has the potential to contribute to increasing the quality of life of billions of persons, but it has to be a sustainable economy, i.e., truly constrained by sustainability principles. This is still possible, since the blue economy is developing now, and there still is the time to direct its growth toward true and real prosperity.

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Part III
Food Security and the Health of the Planet and Its Inhabitants

The food system is responsible, according to recent estimates, for 34% of total climate-altering gas emissions. Of this 34%, 71% is due to primary production alone, that is to agricultural activities. To this must be added, among others, the effects on biodiversity loss mainly due to the cultivation of surfaces that are removed from their role as hosts of natural ecosystems that are always much richer in biodiversity than an agricultural system and the effects on soil fertility which tends to decrease as a result of many current agricultural practices. It is therefore evident that food is a sector in which the issue of sustainability is central and should be combined with the global need to produce in sufficient quantities, at reasonable prices and with ever-increasing quality, also to better protect human health.

It is also a sector in which there is a great need for accurate quantitative analyses to avoid the excessive simplifications that often characterize it and to better identify effective and lasting solutions. Identifying where and at what level the environmental impacts are generated within each production chain is essential to be able to mitigate these impacts with the joint action of farmers, agri-food industries and consumers. Obviously, we must start from an estimate of food needs in local and global terms, and in a perspective of future evolution of food needs in relation to the demographic, economic and social dynamics of the world population.

Having determined the needs, it is necessary to determine the mosaic of solutions that can make it possible to meet these needs by minimizing the impact on the environment and keeping the dynamics of prices within reasonable limits that do not cause social tensions. It is difficult to think that there could be a single solution for all types of productions and for all production environments but it is certainly necessary that for each process and production chain, it is possible to determine in an analytical and accurate way the environmental impacts of various types. In this regard, our group, which also includes researchers from the Universities of Udine and Trieste, the Italian Liver Foundation (FIF) and Illy Caffe Spa, aims to investigate innovative life cycle assessment (LCA) and data integration tools that can act as input to the LCA.

But in addition to photographing the existing, it is necessary to look ahead and identify innovative solutions to reduce the environmental footprint of agri-food production. Today in agriculture, and in particular in the Italian one but not only, innovation finds it difficult to reach the market both for regulatory constraints and above all for a lack of acceptance by the consumer who has been induced to make his choices based on to two simple equations both based on incorrect assumptions: the first is *old equals good, new equals bad*, the second is *natural equals good, artificial equals bad*. And these erroneous assumptions derive from a distorted vision of what is natural and not, which derives precisely from the development of agriculture. With this development, in fact, Western man has increasingly made a very artificial system and landscape, such as agricultural ones, entirely shaped by man, the result of his constant work of domestication, modification, creation, with the natural one, which is the result of natural evolution.

The paradox of Western man in this context is that he seems very often more willing and sensitive to protect the pseudonymity he created than the true nature that we should seriously take care of. In the case of the future of agriculture and its sustainability, the dilemma we face today is precisely that of deciding whether to continue as we have done until now, without changing anything or even returning to the past, as someone seems to want, and jeopardizing what remains of true nature, or if we want to rely on scientific progress to be able to reduce the environmental impact of agriculture without having to cultivate other soils, and therefore, without endangering those natural ecosystems that are already so threatened today and so rare.

It will therefore be necessary to examine a series of innovative technologies with the potential to improve agricultural sustainability (agronomic practices, genetic improvement, etc.) and evaluate their impact with the same LCA methods described above not only in terms of environmental, but also economic and social sustainability. Great attention in a quantitative sense will also be placed on the issue of reducing losses in the food production and distribution chain, paying particular attention to distinguish between food waste and food losses and to the possible benefits that could derive from a change in the food habits of the population for directing their choices towards truly more sustainable solutions from an environmental point of view and bringing greater benefits to human health.

This part includes two Chapters, the first one, Chap. 3, *Sustainability, Agricultural production, Science and Technology* by Michele Morgante, and the second one, Chap. 4, *Liver and Nutrition* by N. Rosso and C. Tiribelli.

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Chapter 3
Sustainability, Agricultural Production, Science and Technology

Michele Morgante

An editorial published in August 2021 in Nature Ecology and Evolution [1] entitled "Agriculture isn't all rocket science" stated that agriculture and food security do not need high-tech solutions and that low-tech solutions may be just as important as they have been for the COVID-19 pandemic. Perhaps the authors have forgotten that if the effects of the pandemic are no longer as devastating as they were in the beginning, the main merit is of a high-tech solution, i.e. mRNA vaccines. And even when it comes to agricultural production we have to be fully aware of the importance of the introduction of combinations of novel scientific solutions and technological innovations if we want to be able to combine productivity with environmental and economic sustainability [2]. It is a dangerous illusion to try to recover from the past alleged golden ages and ancient glories, which puts at risk the projection towards the future by trying to turn our gaze towards the past. This illusion is always very present and pervasive when the discussion revolves around food and agriculture.

The objective of this chapter is to frame the problem of the impact of food production on the environment, identify what the possible solutions could be with particular attention to the use of new technologies and finally discuss what the main obstacles are which today hinder the adoption of these solutions.

Let's start from a simple observation: today we are exploiting the capital of our planet's natural resources in an unsustainable way, i.e. we are consuming more natural resources than they regenerate spontaneously. The global impact equation [3], that compares the ecological footprint of human activities (equal to Ny/α, where N is the human population, y is the human economic activity per capita and α is the efficiency with which we utilise the biosphere goods to transform them into GDP) with the regenerative capacity of the biosphere, makes us understand this in a formal way. Today the footprint is approximately equal to 1.6 times the regenerative capacity of the biosphere [4]. This means that we are deeply eroding our capital of natural

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resources and the more we erode it the more the inequality increases. There are not many possible ways to at least bring the equation back to parity. Since it is impossible to reduce the population (N) and reduce economic activity (y) would be very unpopular, we just have to play on the alpha factor, which corresponds to the efficiency with which we exploit our natural resources to produce goods and services, in other words wealth. And efficiency corresponds to political choices and above all to technological innovation.

A significant proportion of the impact of human activities on the environment is linked to food production, although we commonly tend to think of other economic activities as the main causes of environmental degradation. Food production systems are responsible for 34% of global greenhouse gas emissions and the vast majority (71%) of these emissions are due to primary production (agricultural activities) and the related land use change, i.e. the fact that we dedicate land to agricultural production going to destroy natural ecosystems [5]. Only 29% of the emissions comes from all supply chain activities together.

Not only does food production have a great impact on the environment, but sensitivity analyses [6] show that by acting on food production, the type of diet and land use policies, it is possible to profoundly affect this impact, much more than we can do by acting on other economic sectors that we tend to think about much more often when we talk about these problems (fossil fuels, manufacturing processes, buildings, etc.).

The land use changes that have occurred over the last 300 years mainly to respond to increased food production needs have been dramatic [7]. Forests, savannas, grasslands have decreased and cultivated land and pastures have increased. Suffice it to say that in 20 years, between 1980 and 2000 in tropical areas, those richest in biodiversity, land used for agricultural use increased by more than 100 million hectares [8], an area equal to more than 3 times that of Italy. Or that the production of pet food alone occupies about 1% of the world's agricultural area (equal to approximately twice that of the UK) [9] and that animal farms alone use 77% of the world's agricultural area [10].

Taking a simple and concrete example, if we use an advanced life cycle assessment (LCA) tool to consider the environmental impact of the production of a loaf of bread starting from the sowing of wheat in the field until it reaches our tables, whatever the impact indicator, about two thirds of the impact are due to primary production alone (and one third only to everything that comes after, transformation, distribution chain, etc., with transport that weighs extremely little) and two thirds of these two thirds, i.e. about 45%, are due to the sole use of nitrogenous fertilizers [11]. It is clear that if we want to reduce the environmental impact of food production it is important to know what weighs more and what weighs less on the impact.

The current already serious situation is going to become more worrisome with time: as a consequence of an increase in both population size and in dietary needs the global food demand will be increased by 50% in 2050 [12]. Without changes in technology between now and then, the agricultural yield levels will not be able to meet the global demand for food (with a 5–25% deficit of food production, depending on the climate change scenario assumed) and we will face an increase in global food prices ranging from 30 to 50% above current ones. There is a common belief according to which we may solve this problem simply by wasting less food and consuming less meat in the developed countries. While these actions are certainly needed and useful, there is also an increasing awareness of the fact that they will not be sufficient and that there is a need for the agricultural system to increase yields on a per surface unit basis while decreasing the environmental impact of agriculture [13], i.e. to achieve a sustainable intensification of the agricultural systems. To put it in very simple terms we need to increase output, i.e. yields, while decreasing inputs, i.e. water, fertilizers and crop protection products.

To make things worse, climate change is going to affect agricultural productivity very differently in different areas of the planet, and will decrease productivity where it is already lower, where the shortage of food is greater and where the environmental efficiency in producing it is lower [14].

How can we help make food production more efficient, i.e. improve the alpha factor that appears in the global impact equation? We have to intervene on the processes of primary production and wanting to be very schematic there are three ways to do it: modify the genetic makeup of the plants and animals we use to feed ourselves, as we began to do 10,000 years ago and continued until today with increasingly more fast and precise methods, through the use of chemistry (fertilizers, crop protection products, herbicides) and finally with agronomic techniques. Looking at historical data, it can be seen that the greatest contribution to the increase in agricultural productivity and sustainability has come from genetics through plant breeding activities.

Perhaps the best-known example of the impact of genetic improvement is given by the adoption of corn hybrids starting around 1930, which allowed corn yields to at least quintuple within 70 years.

Nowadays we have much more refined tools available than in the past to be able to genetically improve the plants and animals that we use for our food. On the one hand, the tumultuous development of genomics, in addition to allowing us to sequence our genome, has allowed us to sequence the genomes of many species of interest for agriculture, helping us to identify the entire set of genes that characterize them and subsequently to identify the genes responsible for the characteristics we are interested in improving. On the other hand, the development of technologies such as cisgenesis and genome editing via CRISPR/Cas, which in the European Union are now called new genomic techniques, allows us to modify single genes or even single DNA bases within genes in a targeted manner obtaining results that are indistinguishable from those that we could obtain by crossing or by spontaneous mutation but much faster and in a more precise way, i.e. without unwanted side effects. And we can use these technologies to make plants more resistant to pathogens, to make them more tolerant to drought, a very topical issue, to make them better able to exploit nitrogenous fertilizers [15] and also to make them better able to exploit solar energy through the photosynthesis process [16, 17]. All modifications that can allow us to improve the sustainability of agricultural production and reduce the environmental impact of agriculture.

Genetics is by no mean not the only way to improve the ecological footprint of food production, the other great revolution that awaits us in agriculture is that of digital or precision agriculture, which through a series of innovations in the agronomic field can allow for better exploitation of production factors, i.e. water, fertilizers and crop protection chemicals.

What are the obstacles that hinder the adoption of these new technologies today? They are not scientific and are not even related to the technology transfer process but are social in nature. Man, as we have seen several times throughout history, is traditionally averse to innovations.

And this seems even more true in the food sector where consumers seem more willing to go back than to go forward. The values that win today in food marketing are those of the traditional, the natural, the small is beautiful and many seem to have great nostalgia for a past that was actually much less rosy than we tend to remember. In the not too distant past, eating adequately was a luxury for a few and some seem tempted to go back in time by decreasing productivity per hectare, decreasing the environmental impact per unit of surface but increasing the environmental impact per unit of product and ending up with making others produce what at this point we could no longer produce ourselves.

This, for example, would be the result of a complete conversion of agriculture to an organic farming model, which, having lower production per hectare, would oblige us to cultivate 40 to 75% more land globally [18], a fact that we cannot allow to happen unless we want to permanently compromise the biodiversity present in nature.

This type of choices, to go in the direction of decreasing agricultural production to reduce its environmental impact, even when made at a local level as could be the case for the European Union, can translate into profound social and economic injustices which further increase those great inequalities that exist on our planet and which represent as serious a problem as climate change and the loss of biodiversity. Deciding to produce less even if in a more sustainable way, if it corresponds to making others produce what we no longer produce, does nothing but shift the problem and make the situation worse if those who produce for us do it less efficiently than we can do. And it adds a further injustice because the rich countries, in which consumption is concentrated, in doing so impoverish the capital of natural resources of the poorer countries in which biodiversity is concentrated, without this loss of capital to be in any way compensated. With our consumption and with our agricultural policy choices, we are going to affect the natural heritage of the countries where this heritage is concentrated.

If process innovation is essential to reduce the environmental impact of agricultural production, how can we try to make it more acceptable to consumers? We must make people understand that science can allow us to reconcile productivity and sustainability, to reconcile innovation and tradition, to maintain agricultural and food diversification and to reduce the dramatic economic and social inequalities between different parts of the planet. We need a flexible and non-dogmatic approach, we need to establish a new pact based on trust between scientists, farmers and consumers.

Going back to the initial comparison to rocket science, it should be very apparent by now that agriculture is far more complex than rocket science. It is a complex problem that requires a very complex solution and in this solution we must be use quantitative analyses, rationality and science and not emotion and ideology.

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Chapter 4
Liver and Nutrition

Natalia Rosso and Claudio Tiribelli

Situated beneath the diaphragm in the upper right part of the abdomen, the liver is the largest organ in the body (weighing 1–1.5 kg in adults). All of the blood that leaves the stomach and intestines must pass through the liver before reaching the rest of the body. The liver processes nutrients and drugs absorbed from the digestive tract into forms that are easier for the rest of the body to use. In essence, the liver is the body's refinery. Furthermore, this organ plays a principal role in removing toxins from the blood whether they were ingested or internally produced. The liver converts them to substances that can be easily eliminated from the body. And, in addition, it modifies many drugs governing their activity in the body. The liver also makes bile, a green-yellow fluid, which contains detergent-like substances essential for digestion. Bile is stored in the gall bladder, which contracts after eating and discharges bile into the intestine.

Nutrition and the liver are interrelated in many ways. Some ways are well understood; others are not. The liver plays a key role in converting food into the chemicals essential for life, and it serves several important metabolic tasks in handling nutrients (Table 4.1). Carbohydrates (sugars), absorbed through the lining of the intestine, are transported through blood vessels to the liver and then converted into glycogen and stored. The liver breaks down this stored glycogen between meals releasing sugar into the blood for quick energy to prevent low blood sugar levels (hypoglycemia). This enables us to keep an even level of energy throughout the day. Without this balance, we would need to eat constantly to keep up our energy.

The liver is vital in maintaining the body's protein and nitrogen metabolism. Proteins in foods can be broken down into amino acids in the intestine and delivered to the liver for use in making body proteins. Excess amino acids are either released

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Table 4.1 Liver metabolic functions according to the type of nutrient/compounds

Liver metabolic functions			
Carbohydrates	Lipids	Proteins	Others
Converts carbohydrates to glucose	Builds and breaks down triglycerides, phospholipids, and cholesterol as needed	Makes nonessential amino acids that are in short supply	Detoxifies alcohol, other drugs, wastes, and poisons
Makes and stores glycogen	Breaks down fatty acids for energy when needed	Removes from circulation amino acids that are in excess and converts them to other amino acids	Helps dismantle old red blood cells and captures iron for recycling
Breaks down glycogen and releases glucose	Packages extra lipids and transports them to other body organs	Removes ammonia from the blood and converts it to urea to be sent to the kidneys for excretion	Stores some vitamins and minerals
Breaks down glucose for energy when needed	Makes bile to send to the gallbladder for use in fat digestion	Makes other nitrogen-containing compounds the body needs (e.g. DNA & RNA)	Forms lymph
Makes glucose from amino acids and glycerol when needed	When needed, makes ketone bodies when necessary	Makes plasma proteins such as clotting factors	

by the liver and sent to the muscles for use or are converted to urea for excretion in the urine. Certain proteins are converted into ammonia, a toxic metabolic product, by bacteria in the intestine or during the breakdown of body protein. The ammonia must be detoxified by the liver and made into urea, which is then excreted by the kidneys. Through the production of bile, the liver makes it possible for dietary fat to be absorbed. In addition, vitamins A, D, E, and K, which are fat soluble, are dependent on bile from the liver for absorption.

Many chronic liver diseases are associated with malnutrition. For instance, Metabolic Associated Fatty Liver Disease (MAFLD), a condition characterized by a build-up of fat in the liver that affects over one billion people, is tightly associated with obesity, type 2 diabetes (T2D), and Metabolic syndrome (MetS). MAFLD entails a broad spectrum of conditions, spanning from simple and uncomplicated steatosis to nonalcoholic steatohepatitis (NASH), which is characterized by hepatocyte ballooning, lobular inflammation, and fibrosis that could worsen into cirrhosis and hepatocellular carcinoma (HCC) [1, 2]. MAFLD pathogenesis is closely entangled with increased adiposity, insulin resistance (IR), and dyslipidemia [3]. Indeed, dietary habits such as excessive caloric intake, high fructose consumption, and poor physical activity represent paramount risk factors for this condition [4]. In the last decades, the prevalence of metabolic disorders (e.g., MAFLD, obesity, and T2D) has exponentially increased in Western countries. This escalation is strictly correlated with changes in dietary habits. Indeed, the Western diet is evolutionally modified, replacing fruits, vegetables, proteins, and omega-3 fatty acids with saturated and trans-fat, omega-6 fatty acids, carbohydrates, and high-energy nutrients [5]. It has been demonstrated that nutritional and lifestyle interventions exert beneficial effects on MAFLD outcomes and its comorbidities.

The human gastrointestinal lumen is the largest reservoir of microorganisms in the body, representing the physiological habitat for more than 100 trillion microorganisms (bacteria, archaea, fungi, yeast, and viruses) [6]. Among them, 85% of total bacteria are commensal microbes that live in synergy with the host, providing biological and metabolic functions. All abnormalities in intestinal flora taxonomic composition and/or function are usually referred to as 'dysbiosis,' a condition that has been largely explored in rodents and MAFLD patients [7, 8]. The dietary habits along with the caloric intake may strikingly contribute to the inter-individual variability of the intestinal bacterial strains. Indeed, a diet composition unbalanced in animal fat and sugars may more strongly increase the personal susceptibility to pathogenic bacteria over-growth, exerting a detrimental effect on the immunological tolerance of mucosal cells, as shown in a large number of preclinical [9, 10] and clinical studies [11, 12] Western diet and High Fat Diet (HFD) have been related to the increased amount of pro-inflammatory bacterial species, altering gut barrier integrity, intestinal pH and lipopolysaccharide (LPS) transition into the blood flow (endotoxemia) [13]. Indeed, the intestinal barrier is constituted by tight and adherent junctions and desmosomes, which hold together the epithelial cells and regulate the bidirectional flux between the gut and the liver. Specifically, the intestinal barrier protects the host from pathogen invasions and impedes microbial systemic translocation [7]. Dietary modifications can rapidly normalize intestinal microbiota, thus representing a simple and effective approach to restoring eubiosis. Indeed, the diet is enabled to profoundly reshape the microbiota composition within a few hours. People consuming a Western diet and subjects with high-fiber dietary habits display a tremendous difference in microflora taxonomic composition, as shown in an elegant study in which American volunteers were randomized to receive an animal-based diet (meats, eggs, and cheese) or a plant-based diet (cereals, legumes, fruits and vegetables). Natural extracts, such as polyphenols provided by coffee, green tea, and chocolate, have been demonstrated to induce beneficial effects by directly interacting with gut microbial communities. In C57Bl/6 mice fed HFD, grape polyphenols administration improved insulin sensitivity, attenuated inflammation, and ameliorated intestinal barrier integrity. Overall, diets enriched in phenols have been associated with improved MetS features and immune tolerance, and with the restoration of intestinal barrier function, by promoting eubiosis.

Nutritional genomics studies the impact of nutrients on gene expression, genome evolution and selection, genome mutation rate, and genome reprogramming [14]. It entails even the detrimental effect exerted by specific macro and micronutrients on DNA metabolism, addressing mainly their role in DNA synthesis, degradation, repair, and alteration. In turn, genomic evolution and selection may contribute to the genetic variations observed within genetically different ethnicities. An important aspect *of nutrigenomics* is the effectiveness of nutrients (especially micronutrients) on DNA metabolism, even though it is not deeply investigated. Some evidence supports the notion that several micronutrients are required to maintain DNA homeostasis, as they are cofactors of a variety of enzymes involved in DNA synthesis and repair [15]. Thus, nutritional deficiency of these essential micronutrients could induce a strong DNA modification comparable to that observed after DNA exposure to mutagenic substances or radiations [16]. Another area of interest of nutrigenomics is represented by *nutrigenetics*. The latter entails the study of the effect of a genotype (e.g., the presence of SNPs or other genetic variations) towards specific dietary patterns. Indeed, each subject could respond differently to nutritive substances, and genetic variations within different human populations are a consequence of the adaptive evolution to specific dietary habits. Common SNPs in DNA sequence constitute the primary example of genetic variation. They arise from a process of DNA mutation and subsequent selection in the populations. Nutritional environment intervenes in this evolutionary process, precipitating the expansion of DNA mutations within the subjects.

Epigenetics is a hereditable but reversible phenomenon that affects chromatin ultrastructure and transcription without modifying DNA sequence in response to environmental cues including DNA methylation, histone modifications, and miRNAs targeting mRNA [4, 17]. The emerging knowledge of '*nutriepigenomics*,' referred to as the interaction between nutrients and genome through epigenetic mechanisms, is increasingly grabbing attention in the field of human complex diseases such as MetS, neurological disorders, and cancer [18]. The hypothesis of the Developmental Origins of Adult Health and Disease underlined that exposure in utero to environmental stressors, such as diet, had intergenerational effects, compromising adult phenotype [19]. Hence, food intake could affect epigenome remodeling throughout life and, interestingly, several dietary habits could be critical during gestational and post-natal periods, leading to stable epigenetic changes, which, in turn, could impact metabolic disease susceptibility [4, 18]. Likewise, it has been reported in both animals and humans that risk factors, such as maternal obesity, could predispose descendants to metabolic disorders due to an imprinted metabolic signature induced on microbiota during pregnancy [18].

If on the one hand junk food and a sedentary lifestyle cause metabolic dysfunction, on the other hand, the study of nutrigenetics/epigenetics enables us to identify either different genetic polymorphisms, which may modulate the effectiveness of nutrients, and epigenetic markers that may be potential therapeutic targets of specific dietary interventions. Bioactive substances, such as polyphenols, flavonoids, fish-derived oils, and, in general, compounds enriched in the MedDiet, predominantly consisting of fruits and vegetables, have shown systemic benefits as preventive and curative molecules for metabolic diseases, cardiovascular risk, and cancer [20, 21]. Apple polyphenols and red wine extract as resveratrol and derivates have been shown to epigenetically prevent diet-induced obesity and ameliorate liver injury and cardiac dysfunction [22–25]. For instance, curcumin acts as a free radical scavenger and hampers lipid peroxidation and oxidative DNA damage. In a randomized double-blind placebo-controlled trial, the short-term curcumin administration in MAFLD patients improved hepatic fat content and metabolic profile (trial registration IRCT20100524004010N24) [26]. In addition, it has been demonstrated that curcumin exerts hepatoprotective effects on fibrogenic processes [25]. Green tea, rich in polyphenols and catechins, is a natural hypolipidemic, antioxidant, and thermogenic agent whose beneficial effects on hepatic steatosis and liver damage have been widely studied in both genetically and dietary-induced experimental models of MAFLD/NASH [27–31].

The Western human diet has evolutionally changed, and nowadays, it is markedly enriched in saturated and trans-fat, omega-6 fatty acids, carbohydrates, and high-energy nutrients against fruits, vegetables, proteins, and omega-3 fatty acids [5]. Nutritional genomics addresses the gene-environment interactions and the detrimental effect of the changes in our dietary landscape. It may represent a promising tool to revolutionize both clinical and public health nutrition practice and may favor the establishment of genome-informed nutrient and food-based dietary guidelines for disease prevention and a healthy lifestyle, individualized medical nutrition therapy for MAFLD management, and better-targeted health nutrition interventions, including micronutrient supplementation, maximizing the benefits and in turn minimizing the adverse outcomes within genetically diverse human populations [14]. In this context, the study of nutriepigenetics is becoming increasingly attractive, as it would allow the identification of novel appealing bioactive compounds, which may contribute to modulate the hepatic epigenetic signature from the maternal and lactation period onward.

To date, no therapeutic strategy is approved for the treatment of MAFLD, and lifestyle modifications, physical exercise, and weight loss remain the cornerstone of approaches to patients with MAFLD. Indeed, personalized nutritional recommendations for MAFLD patients remain largely unexplored and a deep understanding of the mechanisms behind gene-environment interactions should be a priority for future research. Considering nutrigenomics as an option will guarantee us the clef to compose the harmonic combination of nutrients suitable for our genome, orchestrating the perfect symphony of health. A better knowledge of diet-genome interactions will allow applying new approaches to the prevention and treatment of chronic disorders by using precision nutrition, which might be included in the personalized medicine therapy. However, the amount of studies is scarce and nutrigenomic research remains largely inconclusive. Therefore, there is an urgent need to increase the number of experimental data to unravel these mechanisms and to discover novel appealing candidate biomarkers for diagnosis as well as to introduce nutraceutical products as a preventive or therapeutic strategy [5].

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Part IV
Climate and Environmental Changes

The issue of climate change is central to the sustainability debate and requires a highly interdisciplinary approach, given that the physical and socio-economic components of the Earth system are highly interconnected.

Up to now, however, from the modeling point of view, these components have been treated separately. For example, socio-economic impact models use climate data as external input, while climate models use greenhouse gas concentrations or land use from human activities as external forcing.

The new frontier of climate modeling is therefore that of explicitly describing the interactions and the feedback processes between these two components within complex climatic models, both global and regional.

It is therefore essential to start this coupled modeling of physical and socio-economic components with regional cases of disruption, such as for example that of the North Adriatic area or a larger one as the Mediterranean area, using as a basic platform the regional model developed in the section Earth System Physics (ESP) of ICTP [1, 2].

We also want to give particular emphasis to the modeling of the idrogeological and economic risk associated with the increase in extreme meteorological events, both flood and drought, infused by global warming. This type of modeling requires not only the use of advanced modeling software, but also the analysis of big data both of an observational nature and those produced by climatic simulations available in public sites.

Alongside these modeling activities, the main ethical and philosophical issues related to climate changes and sustainable development in general, such as equity, economy, inter-generational pact and cognitive challenges, will be studied and discussed and brought to the attention of a not expert public.

In conclusion, let us report the famous sentence by Ursula von der Leyen "*I wish that Europe become the first neutral Continent from the climate point of view within 2050*". 2050 will not be too late?

This part includes Chap. 5, *Climate and Environmental changes* by Filippo Giorgi.

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Chapter 5
Climate Modeling of the Anthropocene

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Introduction

Since the beginning of the industrial revolution, and maybe even earlier, the Earth has entered the so-called "Anthropocene" [1], an era in which human activities have started to affect profoundly the characteristics of the climate system. For example, the atmosphere's composition has been modified by massive emissions of greenhouse gases (GHGs) of anthropogenic origin, such as carbon dioxide (CO_2) and methane (CH_4), which have caused global warming and consequent changes in a range of climate features (e.g. [2]). As another example, emissions of a wide variety of gaseous and particulate pollutants are affecting air quality, and similarly to the atmosphere, the ocean's chemical composition is being altered by water pollutants along with liquid and solid waste, such as plastics (e.g. [3]). The surface of the Earth is extensively modified by agriculture, rapid urbanization and deforestation, which can modify regional climates. Finally, the land and ocean biosphere is modified by activities such as soil overuse, excessive fishing and hunting, forest management etc. [4].

Not only human activities are affecting the Earth system, but human societies are in turn strongly influenced by environmental stresses, and respond to them, possibly generating feedback mechanisms. An illustrative example is given by mitigation policies aimed at curbing GHG emissions (e.g. [4, 5]), which can be considered as a response to global warming, in this case providing a negative feedback mechanism: greater warming would (presumably) lead to the implementation of more effective mitigation policies, which would in turn reduce the warming itself. As a second example, climate and environmental stresses in specific vulnerable regions may induce massive migrations (e.g. [5]), and this would lead to changes in land use, GHG and pollution emissions, with consequent regional effects on climate. Clearly, in order to fully understand the evolution of twenty-first century climate

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under the influence of human activities, the human dimension has to be considered as an integral and interactive component of the climate system.

Despite this realization, although today's climate system models (CSMs) have reached a high level of complexity, with the inclusion of interactive atmosphere, ocean, cryosphere, biosphere and chemosphere components, simulations of twenty-first century climate still consider the human component as an "external forcing". In other words, the forcing due to human activities, e.g. the increase in GHG concentrations due to the use of fossil fuels or land use management and change, is prescribed as input to the climate models. In addition, the impacts of climate change to different socioeconomic sectors are calculated off line using impact models driven by the output of climate simulations. This approach obviously cannot account for possible feedbacks between the physical climate system and human responses. An exception is represented by the category of so-call "Integrated Assessment Models (or IAMS)" [6], in which some aspects of climate response to impacts are described interactively. In these models, however, the climate component is extremely simplified, and is represented using bulk variables, such as global temperature, and therefore their use for informing policy decision is relatively limited.

It is thus evident that a major need in climate modeling towards improving our understanding of the possible climate evolutions throughout the twenty-first century is the inclusion of an interactive human component in CSMs. This is indeed a formidable task which calls for an interdisciplinary approach going well beyond the state-of-the-art of today's climate modeling, and will likely require a decadal modeling perspective. A few international programs have started to address this scientific challenge through the concept of "Digital Twins" of the Earth System [7], but they are still in their infancy.

Based on these considerations, the aim of this chapter is to present some considerations on this new frontier facing the climate modeling community. The chapter starts with a brief summary of the structure of today's CSMs and their application to twenty-first century climate change simulations. This information will serve as background for introducing the concept of the inclusion of interactive humans in climate models towards the development of "Populated Climate System Models" or "Pop-CSMs".

The Basic Structure of Today's CSMs

During the last 4 decades, CSMs have evolved from what were essentially atmospheric models to extremely complex systems including different components that fully interact with each other: atmosphere, oceans, cryosphere, land and marine biosphere, chemosphere. These models are three dimensional numerical representations of the basic equations that regulate the behaviour of their components and the physical processes at their interfaces. The models are numerically integrated in time to provide the evolution of the climate system using some of the most powerful supercomputers today available. As input, they require information such as topography, land-use distribution, atmosphere and ocean background composition, incoming solar radiation. The model resolution is determined essentially by the availability of computational resources, and the spatial resolution of most global models used for the latest generation simulations of historical and twenty-first century climate varies in the range of 50–100 km [8]. Physical processes that occur at scales smaller than the model resolution, for example cumulus convection, cloud microphysics, boundary layer turbulence and some radiative transfer processes, are typically "parameterized" in terms of resolved variables using modules based on the process physics understanding and on calibration against field observations.

Many impact applications, for example in hydrology or energy production, require climate information at regional to local scales that are not captured sufficiently well at the spatial and temporal resolutions of global CSMs. For this reason a number of "downscaling" techniques have been developed which use as input the coarse scale meteorological fields from global CSM simulations to produce fine scale climate information. These vary from the use of high resolution limited area regional climate models (RCMs, [9], to variable resolution global models [10] and a wide range of empirical-statistical downscaling techniques [11]. Current generation RCMs can reach spatial resolution of a few km (the so-called "convection-permitting" resolution), at which some processes parameterized in CSMs, such as cumulus convection, can be explicitly represented [12]. The various downscaling approaches have different advantages and limitations and their use depends on specific applications.

The performance of global CSMs in simulating the behaviour of the atmosphere has considerably improved over the years, with the increase in model comprehensiveness and resolution, to the point that present day models can reproduce reasonably well the basic features of the global atmosphere and ocean circulation, both in its climatological mean and basic modes of variability (e.g. [13]). The performance of RCMs and other downscaling techniques has similarly improved [14], so that the effect of local forcing, such as due to complex topography, coastline and land-use features, can also be well described. Despite these improvements, some key deficiencies are still there, particularly in the description of clouds, convection and precipitation, which are among the most difficult processes to simulate and are the main contributors to the different behaviours of the models [13]. More information on three dimensional climate models can be found in [15].

The Process of Producing Twenty-First Century Climate Change Projections and the Assessment of Related Uncertainties

The problem of climate "prediction" is very different from that of weather forecast. In the latter, the aim is to predict how the system will evolve given knowledge of its initial conditions. This is a deterministic, initial condition problem (also referred to as “prediction of the first kind”, [16], and due to the chaotic nature of the atmosphere there is a predictability limit of ~10–15 days, depending on specific weather patterns. Climate prediction, (or “prediction of the second kind” [16] is a boundary value problem, whose aim is to investigate how the climate system responds in a statistical sense and over long periods of time to changing external (boundary) forcings, e.g. solar radiation or GHG concentrations. In other words, climate change simulations can be considered not as predictions but as sensitivity experiments to changing forcings [17], and therefore the term “projection” (or “scenario”) is most often used instead of “prediction”.

An aspect that makes climate change simulation even more difficult is the unpredictability of the forcings themselves, since for example it is virtually impossible to predict socio-economic developments leading to given trajectories in GHG emissions. What can be done is to generate plausible hypotheses, or scenarios, of socio-economic development, and thus GHG emissions, input these scenarios into the climate models and assess how the system responds over long periods of time, typically order of a century (end of the twenty-first century). In other words, the question posed in climate projection is not to predict the actual future climate, but to characterize the full distribution of possible future climates under different forcing scenarios and their probability to occur. Thus climate prediction (or better “projection”) is not deterministic, but has a probabilistic nature.

The process of completing climate change projections for the twenty-first century and related impacts essentially follows a number of sequential steps: (1) develop a range of possible socio-economic scenarios –> (2) derive a range of GHG and aerosol emission scenarios (and in some cases land-use change scenarios) –> (3) derive GHG and aerosol concentrations –> (4) Input this information in climate models to simulate the global climate response (although some models have interactive aerosols or interactive carbon cycle) –> (5) downscale the global climate information to regional and local scales –> (6) use this information for assessments of impacts in support of the development of policy response options. For each step, typically an ensemble of models is used to estimate the full range of possibilities, since there is no single “perfect” model available and different processes in the models are represented in a number of ways. Climate models used for twenty-first century projections have been developed by a multitude of research groups worldwide, and this leads to possibly hundreds of projections available for users.

Each step of the projection procedure just described is affected by its own sources of uncertainty, which compound sequentially in a cascade process leading to an overall uncertainty range in possible future climate outcomes [17]. This uncertainty needs then to be fully characterized in order to provide robust information to relevant stakeholders. In this context, it is important to conceptually separate the full uncertainty range into a portion related to the intrinsic variability of the climate system and the external forcings, and one related to incomplete knowledge of processes and deficiencies in models and observations. The former needs to be fully characterized in a quantitative way, because, most often, extreme outcomes, although low probability ones, are most relevant for impacts. Within this context, different realizations with the same model using different initial conditions of the slow components of the climate system (e.g. the oceans) is necessary to sample the internal variability of the climate system. The latter portion of the uncertainty range is for example related to the existing wide spread in model responses to the same forcings, which is due to different and imperfect physics and dynamics representations in the models. This needs to be reduced through the improvement of models, observations and physics understanding.

The provision of climate change information, including assessment of uncertainties, is thus based on large multi-model ensembles carried out by several tens of laboratories worldwide under the auspices of large international programs such as the Climate Model Intercomparison Project (CMIP, [8] or the Coordinated Regional Downscaling Experiment (CORDEX), [18]. Therefore, the finite amount of available computing resources needs to be shared among three model needs: increase in resolution, increase in ensemble size (to better characterize uncertainties) and increase in model complexity. A continuous discussion across the modeling community has been ongoing on what is the priority among these three directions for a most effective improvement in climate projections. In the next section it will be argued that the latter one is clearly an important, albeit extremely challenging, direction which should have a high priority.

The Need and Challenge of Including an Interactive Human Component in Climate Models

It is by now recognized as unequivocal that human activities are modifying the climate system both globally and regionally [2] and that in turn, the resulting changes in climate characteristics are affecting a range of socioeconomic [4]. Under most plausible GHG emission scenarios, these interactions are due to strengthen in the next decades [2]. Therefore, building a digital twin of the climate system cannot neglect the representation of the mutual interactions across the natural and human systems.

We have already seen the example of mitigation as a negative feedback mechanism across these two systems and migration as a mechanism by which they interact at regional scales. Additional examples may be useful. Most current CSMs include dynamical vegetation modules mostly considering vegetation as "natural", i.e. unmanaged. Yet, it can be argued that the fraction of total continental land that is truly unmanaged by humans is relatively small and mostly limited to remote areas. The assumption underlying present modeling of vegetation in climate models is thus, to say the least, of limited value. The implementation of pollution control measures is another example of a possible negative feedback across the natural and human systems. As we enter more ubiquitously into the Anthropocene, the two systems are destined to become increasingly intertwined, and therefore it is paramount that their interactions are represented in the next generation CSMs.

Today there is a range of population dynamics and socioeconomic models [5], so that the basic modeling frameworks for carrying out their coupling with CSMs is already available. Once the population response to environmental stresses is described, its feedback on the climate system occurs primarily through emissions of GHG, aerosols and other pollutants along with modifications of the earth's surface. This interaction should be represented in a distributed way on a common spatial grid across all model components. The key bottleneck in this approach is to disentangle the human response (or lack of) to environmental stresses from the response to other socio-economic factors. For example, population migration can have a multitude of causes, often deeply interconnected, which depend on specific socio-economic conditions. While conceptual models can certainly be constructed to address this issue, large field campaigns are necessary to provide sufficient data to build response models.

Given the dependence of this coupling exercise on specific environmental and socioeconomic settings, it may be useful to first carry out pilot studies over limited areas using RCMs as basic modeling systems [19]. One region that may be especially suitable as a pilot case is for example the Sahel, since agriculture and population dynamics are strongly dependent on climate variability [20] and in turn the region's climate features, e.g. the monsoon dynamics, are significantly affected by human forcings such as biomass burning, urbanization and deforestation [21, 22]. This is also a region were both accurate climate and population dynamics data may be scarce, so that innovative data production approaches are necessary. The extension of results to different climate and socioeconomic settings is not trivial, but at least from the methodological viewpoint such a pilot study may represent an extremely useful testbed, which would pave the way for other similar activities.

It can be argued that, of the three directions identified to improve the actionable value of climate change information, i.e. increased model resolution, increased ensemble size of model projections and increased model complexity, the first two are substantially, albeit certainly not exclusively, of technological nature. The third one, in particular concerning the natural-human system coupling, is an outstanding scientific challenge which will require truly interdisciplinary efforts and innovative modeling and field campaign approaches. Although the climate and socioeconomic modeling communities have increased their interactions within the realm of the climate change debate, they are still far from speaking a common scientific and methodological language. Training of a new generation of scientists lying at the interface between these two modeling communities is thus necessary.

As mentioned above, such coupling efforts will entail the production and analysis of very large datasets, and within this context mobile and internet technologies, along with machine learning techniques will play a central role, tying in with other research communities. In addition, the occurrence of natural geophysical disasters, such as earthquakes, tsunamis and volcanic eruptions, is another important element interacting with the climate system with strong socio-economic implications, and there are suggestions that global warming, through the induced changes in glacier mass, may actually affect the statistics of earthquake occurrence (e.g. [23]). Inclusion of this geophysical component in twenty-first century projections is therefore another promising and highly innovative area of further research.

In conclusion, the development of what we have called Pop-CSMs represents one of the main frontiers in climate, and more generally, Earth system modeling. It is also one of the research pillars of the development of Digital Twins of the Earth System, a major upcoming enterprise in climate system modeling which cannot prescind from modeling in an interactive way the role of humans in the climate system. These efforts will offer very challenging and exciting opportunities for innovative research, especially for a new breed of truly interdisciplinary scientists, and it will constitute a qualitative step forward towards a better understanding of the Anthropocene.

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Part V
The New Data Science for Sustainability and Human Ecology

The world population has exceeded 7 billion and is projected to grow by 9 billion or more in 2043. This poses several sustainability challenges, including growing pressure on ecosystems, growing economic inequalities, migration, aging populations, unsustainable urbanization rates. Being the dominant species on the planet, man has today become the target par excellence of new pathogens, or old ones with increased resistance to our defense systems.

These challenges are of a new nature and require the development of new approaches that integrate disciplines such as demography, economics and social sciences, biology and epidemiology with modeling methods typical of quantitative sciences, such as applied mathematics, physics of complex systems and Data Science. This integration is now possible thanks to the increasing access to quantitative data on human, social and economic phenomena. This has allowed the development of Computational Social Science and allows us to address global issues with the same methods.

The recent Covid-19 pandemic has made it clear how much human beings have become a fundamental variable in addressing global issues. Mitigation of humanity's future challenges crucially depends on how and if we will be able to integrate demographic projections with the mechanisms of our economies, of human mobility, to predict the impact these may have on our environment.

Our goal points to contribute to the birth and development of this new science, which we call *Human Ecology*, with the creation of an interdisciplinary Research Group, in synergy with the other research lines of the project.

This part includes two different chapters, the first one, Chap. 6, *Quantitative human ecology*: *data, models and challenges for sustainability* by E. Omodei, J. Grilli, M. Marsili and G. Sanguinetti, and the second one, Chap. 7, *Computations for sustainability}* by S. Salavatidezfouli, A. Nikishova, D. Torlo, M. Teruzzi and G. Rozza.

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Chapter 6
Quantitative Human Ecology: Data, Models and Challenges for Sustainability

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Introduction

In July 2022 we entered the international year of basic science for sustainable development (IYBSSD). There are two ways in which basic sciences can play a crucial role in attaining a more sustainable planet. The first has to do with applying the wealth of knowledge we have accumulated in basic sciences so far, to issues relevant to sustainability. The second focuses on addressing what we still do not understand about sustainability. The first is the most direct use of basic sciences for sustainability and it is currently carried out within well defined disciplinary boundaries (e.g., physics and climate change, material science for energy efficiency, etc.).

As argued long ago [1], the sustainability crisis arises from the incompatibility of the expansion of human activity with a finite planet. Increasing the efficiency of key processes of human societies, such as e.g., more efficient ways of producing energy, can help mitigate the forthcoming crisis. This pushes further the limits under which human activity can continue expanding without impairing global stability but it may not remove the fundamental problem. It is likely that ultimately sustainability will entail a change in our patterns of behavior, based on the understanding of the limits we and our planet face. Such an understanding needs to acknowledge the interdependencies between the different systems that our planet harbors: the atmosphere and the oceans, ecosystems, economies, societies and cultures, technological infrastructures, the financial system, etc. Hence, a comprehensive approach to sustainability requires the integration of hard with soft sciences, and in particular interdisciplinary

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dialogue across many disciplines. In brief, sustainability issues often entail highly interdependent systems, each of which is often addressed only within strict disciplinary boundaries. For example, climate change affects soil microbiomes, water resources, marine and terrestrial ecosystems, which in turn affect our consumption patterns, our economies, our health and lead to demographic changes, such as forced migrations if not wars. Such changes in the human dimension, in turn, are going to affect ecosystems and the resource-base on which the subsistence of human societies rely, and ultimately climate itself. Any prediction, not only of what will happen, but also of the systemic stability of the biosphere, requires the integration of knowledge which is currently fragmented into many disciplines.

We believe that two aspects are key in addressing these issues: first the inclusion of the human dimension with the dynamics of physical (e.g., climate) and natural (e.g., ecosystems) systems. Second, an approach based on empirical data and rooted in the basic sciences. We believe indeed that mathematics and quantitative analysis can become the shared language that may foster interdisciplinary dialogue and promote a consensus on potentially divisive issues.

In what follows we shall explore three different modeling approaches that we believe will be important in a scientific approach to what we refer to as Quantitative Human Ecology, i.e., a complex planet system where the human dimension is key. We shall start from conceptual models, aimed at capturing the qualitative behavior of emergent phenomena, then we shall discuss more detailed data-driven computational approaches and finally machine learning approaches. We shall conclude with some final remarks.

Conceptual Models

It has been reported [2] that the production of bio-fuels, promoted with the best intentions in order to mitigate climate change, "have forced global food prices up by 75%" [2], causing the 2008 food crisis. The unfettered expansion of credit derivatives, introduced in order to provide more instruments for risk management, has likely made the world riskier [3], leading to the 2007-08 financial crisis and to the following decade of economic recession.

Unintended consequences such as this arise from the neglect of systemic effects of man-made policies. Developing models that can relate "micro-motives to macro-behavior" can provide key insights in this direction. In 1969 Robert Shelling showed by a very simple model that even mild preferences for homophily can lead to large scale segregation in residential districts [4]. This example shows how extremely simplified models can capture, though in an admittedly stylized way, the interactions and non-linearities which are responsible for the rich phenomenology observed at the collective level. This modeling strategy relies on the fact that collective behavior is ultimately governed by statistical laws, which are rather insensitive to microscopic details [5]. The theories developed in the last decades in statistical physics and complex systems science provides a toolkit of methods that can be deployed to address challenges related to sustainability issues. There are already countless examples along this line of research. An exhaustive review is beyond the scope of this contribution. Yet it might be worth mentioning few examples, from our experience, in order to highlight few aspects.

Jerico et al. [6] addressed the relation between inequality and economic growth in a very stylised model of an exchange economy. They assumed a given wealth distribution and observed that larger levels of inequality result in slower economic activity, as observed in data from the US economy. Even though highly stylised, these result show a clear causal link between inequality and growth that arises for purely entropic reasons. This does not exclude causal links in the opposite direction, but it suggests that the direct link is sufficient to reproduce the empirically observed behavior. Furthermore, this approach also clarifies when inequality becomes untolerable, which is when the economy freezes. Bardoscia et al. [7] investigate the relation between inequality and social mobility, within a simple network model of a society. They show that when individuals intensely seek centrality in a social network, the society develops a strong hierarchical structure, characterised by dramatically reduced social mobility. The model may shed some light also on the observed relation between income inequality and status anxiety [8].

Stylised models have been particularly successful in shedding light on mechanisms at the origin of complex phenomena and global stability in finance. The Minority Game, for example, suggests that anomalous fluctuations in financial markets arise precisely when markets become informationally efficient [9]. Scaling up the insights of global games [10] to the systems level, Anand et al. [11] show that the phenomenology of the 2008 financial crisis can be captured in a simple model, shedding light on determinants and possible policy measures.

Toy models are the first step in a scientific approach to complex phenomena. They can expose non-trivial mechanisms at the origin of complex phenomena and inform further empirical research or more computationally demanding modelling approaches. Because of their simplicity and transparency on micro-foundations, they can help inform and discipline policy debate.

Another advantage of conceptual models is that they allow to explore scenarios in context where data are scarce or not existing at all.

Despite their intrinsic simplicity, toy models can reveal the existence of abrupt transitions and catastrophic shifts that are impossible to predict simply by data extrapolation. One paradigmatic examples is given by regime shifts in ecology. Relatively simple (non-linear) models describing the abundance of a biological population predict the existence of saddle-node bifurcations and alternative stable states, leading to catastrophic shifts [12]. By analogy, such behavior can potentially occur at the level of the biosphere [13], implying that a planetary scale tipping point, which a catastrophic loss of biodiversity and ecosystems services, could occur even in presence of a moderately paced deterioration of the environment.

The central goal of conceptual models is therefore not to provide accurate forecasts, but rather to define a “phase diagram”: reduce the uncountable infinity of possible worlds into a finite discrete set of qualitative scenarios. In the context of sustainability, the goal of conceptual models is not to predict accurately the loss of ecosystem services and human demography under certain global warming scenario. The main goal is to define under what conditions the planet and its human population can survive in a way analogous to the present one.

Clearly this kind of questions require the integration in the same model of multiple factors, many of which are very distant from having being described with any for of data. For instance, in [14] the authors integrate in the same conceptual model human population growth, ecosystem services and technological innovation. The relatively simple model show very different outcomes of population growth and level of technological innovation, depending on two critical parameters which define the rate of technological innovation and the feedback of technology on the environment. While this approach does not predict (or even try to) what is going to happen in the next 100 years, it identifies what could be the relevant observable we should pay attention to and the data we should aim at collecting. In this context, one relevant bottleneck for sustainability science, appears to be our understanding of the dynamics of technological innovation and its feedback on the biosphere.

Data-Driven Computational Models: Network Science

Network science is an interdisciplinary field studying complex systems through their representation as a set of distinct elements–usually a large number–and a set of connections between them [15]. In the last decades, the availability of large datasets has paved the way for data-driven computational approaches that allowed network models to gain realism and explain the patterns found in empirical networks [16]. Given its focus on interdependencies and emergent phenomena arising from them, network science is well suited to study sustainability as a complex problem entangling environmental and socioeconomic aspects.

The study of social and economic phenomena through the lenses of network analysis has a long tradition dating back to the 1930s [17]. Network approaches to study the natural and physical world are somewhat more recent, spanning from ecology [18, 19] to climate [20, 21]. The two aspects have been considered separately for a long time, but the increasing interest in the complex interplay between humans and the environment has eventually lead to the investigation of social-ecological networks [22] as well as of "networks of climate change" describing the interplay between natural and anthropogenic processes [23].

Different aspects of sustainable development have been addressed using the tools of network science. Examples include network-based interventions to optimize the diffusion of information about poverty-reducing programs and their uptake [24], the impact of globalization on the resilience of the food supply chain [25], the global spatio-temporal patterns of human migration [26, 27] and of immigrant community integration in world cities [28], and the impact of socioeconomic inequalities and environmental factors such as climate change on the emergence and spread of infectious diseases [29–31].

Cities have been a natural focus of network-based sustainability studies, since they are an exemplary model of networked complex systems in which humans interact with the physical space [32]. In this context, the ultimate goal is to design environmentally sustainable and socially equitable human settlements [33]. Thanks to the current availability of new data such as high resolution satellite imagery, cell phones metadata and GPS traces, this goal can be achieved with the help of mathematical analysis of street and building networks and the development of service optimization algorithms, specifically to solve the problem of informal urban settlements (e.g., slums), lacking services and facing poverty, health and environmental degradation challenges [33]. Examples of network-based approaches for urban sustainability include optimization of car sharing to reduce costs and emissions [34], of bicycle [35] and sidewalk [36] networks to improve the cycling and pedestrian infrastructure, and of facility distribution over the road network to reduce travel costs [37].

Finally, game theory research studying social cooperation to manage common-pool resources and achieve environmental goals should be mentioned. Specifically, a few studies have focused on the influence of the network structure on the cooperation dynamics, studying the role of social norms and showing that the emergence of cooperation is only possible in specific settings [38–40].

Machine Learning

The last two decades have seen an exponential increase in the importance of data-driven technologies in every field of human endeavour, with a transformative impact in areas as diverse as business and astrophysics. Conceptually, the reasons at the roots of this phenomenon are simple: data science technologies can derive easy-to use approximations of complex systems by simply interpolating across very large instances in a data set. In this sense, algorithms can provide useful shortcuts in cases where the complexity of a system prevents the discovery of causal mechanisms, substituting prediction for understanding (which may be practically acceptable in some cases). A similar approach can in principle also be adopted for addressing questions of sustainability; however, at present the role and potential of data science as a force for good in the efforts for an equitable development is controversial, particularly concerning the subfields of machine learning and artificial intelligence (AI).

A recent study focused on the potential of AI to help the attainment of the sustainable development goals through a series of interviews with AI practitioners [41]. The overall picture described a significant potential towards a positive impact; however, as the authors themselves acknowledge, the chosen focus group (AI practitioners) might have led to an over-positive perception. Additionally, and perhaps more importantly, the focus of the study was the *potential* for positive impact, which may well be distinct from the actual impact of the current usage patterns of the technology.

When discussing the impact of AI and Data Science more in general on sustainable development, a few home truths cannot be avoided. First of all, as forcefully argued in [42], the environmental costs of AI systems are punishing, from the high energetic requirements of data centres and supercomputers, to the mining of the rare materials needed for processors. Secondly, current AI systems are strongly susceptible to embedding human biases in black-box decision-support tools, with the potential to seriously hamper efforts towards a more equal society, for example in the context of gender and minority rights [43]. Finally, and perhaps most importantly, the vast accumulation of data, and the related development of advanced analytics, by a handful of state and non-state actors has amplified already large economic and power imbalances, contributing to an exacerbation of inequality and the potential for significant distortion of the political discourse [44, 45]. All of these are well documented facts, pointing to the serious societal and environmental consequences of an unregulated harvesting of data and deployment of AI.

On the other hand, multiple examples exist of applications of machine learning and AI technologies that concretely point towards its potential for achieving the SDG goals. Familiar examples include the use of machine learning techniques in health: while ethical concerns need to be addressed [46, 47], concrete results in fields such as early detection of retinopathy [48] already demonstrate the usefulness of the technology, although the vision of precision medicine might be oversold and certainly remains distant [49]. Another prominent example in a completely different field is the deployment of adaptive traffic signalling in the city of Pittsburgh: based on an application of planning and multi-agents systems [50], the deployment of the Surtrac system has already led to a 21% reduction in traffic carbon emissions in the city, and a 26% reduction in journey times.

Alongside these direct applications of AI technology, a major indirect role is emerging as a tool to extract difficult to access information from indirect measurements. A prominent example is the use of night-light measurements, readily available from satellite imaging, to estimate levels of poverty in rural communities [51], a type of data that is otherwise expensive and difficult to obtain. In general, automated processing of satellite images is rapidly emerging as a key tool to obtain reliable and inexpensive estimates of parameters such as land and resource usage and air quality, for the purposes of informing policy and monitoring compliance with environmental regulations [52–55].

Challenges

The challenge of integrating the feedback between human actions, biosphere, and climate in a unique predictive framework is daunting and will likely keep us busy for decades. At present, we lack an established quantitative, data-controlled framework for many factors. For instance, we cannot quantitatively predict how ecosystem services function (e.g., how much nitrous oxide is emitted by microbes performing nitrogen fixation) depends on abiotic factors (e.g., temperature or precipitation) since we lack an understanding of how community composition impact ecosystem services (e.g., how the change in soil microbial communities due to temperature affects the emissions of nitrous oxide). Similarly, it is extremely hard to predict human collective decisions (e.g., migration patterns or demographic changes) over decades, which will have a strong impact on human societies and the biosphere.

While this level of knowledge is still lacking, much progress has been made. Further investment in these problems can produce a significant increase in our predictive power and conceptual understanding, because they may allow us to test models that attempt to capture the inter-dependencies between different factors thanks to the availability of large data-sets. Basic sciences will play a key role in this.

Such efforts should proceed across a wide range of quantitative approaches, ranging from the highly stylized conceptual models to fully data-driven forecasting tools. This range of approaches can be characterized along many axes: simple versus complex, parameter-poor versus parameter rich, low- versus high- dimensional, conceptual versus predictive, etc. Both of the approaches (and all the ones in between) are obviously characterized by their own challenges. Identifying synergistic approaches, to combine data-driven tools with low-dimensional stylized descriptions, is a challenge in its own, which could present great opportunities for addressing the issues related to sustainability.

The expertise in connecting the dynamics at the micro-scale to that of the meso- and macro-scale, which has been developed in theoretical physics and complex systems science, is an indispensable asset in this endeavor. This can also shed light on the scale (e.g., communities, cities, regions, states or the world) at which policies can be more effective in particular system. Identifying robust stylised facts and developing models that can reproduce them in the simplest possible way, requires however to have the right "intuition" about which factors and processes can be neglected in the description. Such a-priori choices are hard to formalize and can only proceed by trial and error.

On the other hand, data-driven methods can aid the development of such models in at least two complementary ways. First of all, data driven methods can be used as a "shortcut" to approximate complex functions directly from data: at a very low level, this is what is already happening when satellite images are transformed from a collection of pixels to annotations about land use through a classifier such as a neural network. Conceivably, such methods could be used in many other situations where data needs to be summarised efficiently and no a priori model is available. A second major potential use of data science techniques is in the development of rigorous statistical methods to test the validity of models, for example through the use of Bayesian model selection or model criticism techniques [56]. Such approaches can provide firm statistical foundations to the "intuition" used in stylised models.

An alternative, potentially fruitful synergistic way of combining the two approaches would be to use stylized facts and models as constraints for data-driven tools. For instance, simple and regular laws emerge in the patterns of human mobility and migration. While these patterns do not capture the heterogeneity of how individuals take decisions, they encapsulate statistical constraints which appears at the collective level. Such collective patterns could be put as statistical constraints of ML algorithms.

In brief, the Sustainable Development Goals demand not only the application of our current know-how to address specific challenges, but also the expansion of our scientific base and its integration. We strongly believe that the growth and consolidation of "Sustainability Science" will be one of the main trends in the next decades. Besides initiating research in-house along these lines, we also believe that it will be important to promote interdisciplinary dialogue by international workshops on key aspects of sustainability, that can be addressed by different angles.

There is a growing trend of interdisciplinary research along these lines. Yet the community is rather fragmented, and we believe more efforts has to be put in reaching a critical mass. For example, departments that can host researchers that venture in these domains are rare, as well as cross-disciplinary funding opportunities. This renders a career path in these areas much less well defined than the one of a researcher that invests within traditional disciplinary boundaries.

We are at the beginning of a long journey. Ultimately, we believe, the real challenge will be to develop programmes to train a new generation of scientists, endowing them with a background in basic sciences that fosters interdisciplinary dialogue and a curiosity driven approach to sustainability science.

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Chapter 7
Computations for Sustainability

Sajad Salavatidezfouli, Anna Nikishova, Davide Torlo, Martina Teruzzi, and Gianluigi Rozza

Introduction

Parallel to the need for new technologies and renewable energy resources to address sustainability, the emerging field of *Artificial Intelligence* (AI) has experienced continuous high-speed growth in the application of its capabilities of modelling, managing, processing, and making sense of data in the entire areas related to the production and management of energy. Moreover, the current trend indicates that the energy supply and management process will eventually be controlled by autonomous smart systems that optimize energy distribution operations based on integrative data-driven *Machine Learning* (ML) techniques or other types of computational methods.

Computational techniques can be applied in a broad range of applications related to sustainable implications including life and health sciences, environment and ecosystem, and product and process optimization by taking data and analyzing them to provide recommendations for improving sustainability parameters. Thus, the integration of computational methods can be a solution to sustainability challenges. Any product can be designed to be more efficient and optimized if it is modelled, analyzed, and tested in advance before it is built. The *Digital Twin* (DT) is a novel coupled approach for any form of modelling and analysis based on big data and AI/ML techniques.

Digital twin in general refers to the creation of computational models or platforms by monitoring, modelling, optimizing and predicting a complex interdisciplinary system based on real-time big data sets. In terms of the digital twin, any forms of computational techniques including the *Internet of Things* (IoT), AI, ML, and analytics may be integrated to create live digital models able to update and change information as needed. Digital twin models are self-learning systems in the sense of

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Fig. 7.1 The classic design process

Fig. 7.2 The sustainable computational design process

continuous learning and updating from multiple sources to reach real-time status and are regarded to serve as a panoptic reflection of a physical body in the digital world.

The physics-based computational digital twin is a unique technology that focuses on bilateral interdependency between virtual and physical representations, and as a consequence, benefits the product in the sense that it can adapt to modify its real-time behaviour simultaneously to the feedback generated by the digital twin. Conversely, the bridging allows the simulation to be able to precisely mirror the real-world condition of the physical body (see Fig. 7.1).

An exciting aspect of the digital twin is the potential to break the classical *Product Lifecycle Management* (PLM) paradigm with fixed static steps in which *Need* defines *Concept* of the meant system and then turns it into *Digital Design* to facilitate *Manufacturing* step.

On the other hand, in the state-of-the-art design process, beyond all the initial and continuous sustainable resourcing and maintenance, an active step emerges to refine the product, i.e., **Computations Aim at Sustainability**. Moreover, the well-structured PLM platform integrated with AI/ML techniques is capable of offering a sustainable solution (see Fig.7.2).

Nowadays, computations in terms of numerical models and simulations play a significant role in reaching the optimal sustainable solution. Meanwhile, the exponential growth of computational resources makes it available to utilize numerical methods in various scientific fields. To illustrate, a computational framework for the twin's architecture in the form of data assimilation similar to that of weather prediction has shown a progressive accuracy concurrent with the development of computing technologies, especially in the last decade.

Mathematics for Sustainability

Real-Life Applications

Environment

Modelling of the Ocean Flows

Anthropogenic climate change is the greatest threat the world has ever faced. Sophisticated computational models simulating the physical dynamics of the atmosphere and oceans are essential to obtain a projection of future changes with respect to different scenarios designed by policy makers. Therefore, the availability of models that give accurate results in a feasible computational time is a substantial factor in decision-making to assess and prevent climate change's catastrophic threats.

Numerical modeling of geophysical currents is crucial for predicting the state of the ocean and weather. It provides knowledge and understanding of the mechanisms that drive climate change, however, in order to evaluate all the significant flow structures, a resolution of the order of 0.1 mm is required. Such refined mesh is beyond reach even with modern supercomputers. Moreover, memory demand due to the large amount of degrees of freedom in consideration for a proper description of the flow system can be prohibitive. Hence, it is a challenge to perform the simulations for a sufficiently long period to observe the variations in the quantities of interest. For this, advanced techniques from reduced order modelling are applied in order to make such simulations feasible. The reduced modeling will be discussed in the following section. One of the results of the modeling of instantaneous vorticity distribution in the North Atlantic Ocean is shown in Fig. 7.3.

Large-scale Modelling of Urban Air Pollution

Urban air pollution leads to poor public health, global warming, and destruction of ecosystems. This dramatically increases deaths in the population, health care costs as well as magnifies even further the hazards of climate change. Therefore, mathematical modeling of the evolution of urban air pollutants is a very important tool to extract the knowledge from the observed data on air quality and make the prediction about the pollutants propagation in time and space. For instance, one of such models is the transport-diffusion equation, where the convective field is given by the solution of the Navier-Stokes equation, and the source term is an empirical time series. An example on an output of the model is shown in Fig. 7.4.

Optimization of Hybrid Energy System

Hybrid Energy System (HES) are such energy systems that can satisfy the power demand with both non-renewable and renewable energy sources. They play one of the central roles in solving the challenge of reducing our dependence on non-renewable

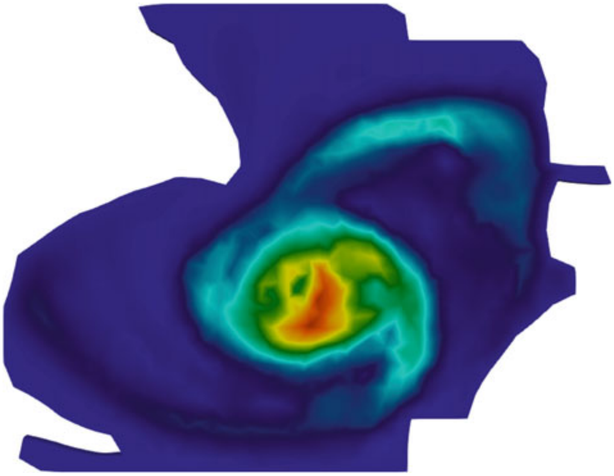


Fig. 7.3 Instantaneous vorticity distribution in the North Atlantic Ocean computed using methods of reduce order modelling

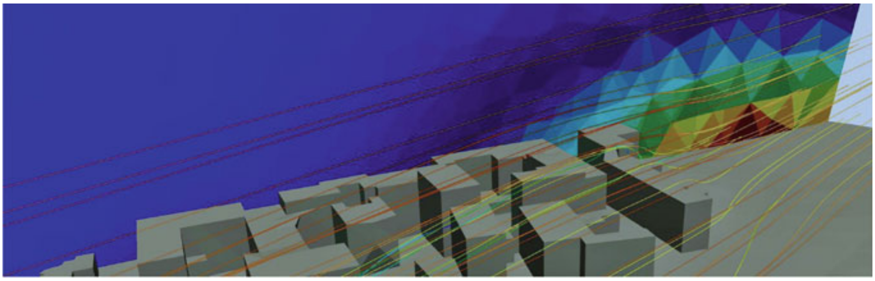


Fig. 7.4 Streamlines of the velocity and a cross section of the concentration field

energy sources when an immediate transition to renewables is not feasible. At the same, a clever way of managing the energy system is central in order to obtaining a substantial reduction in emissions.

Mathematical optimization is a great tool for obtaining such values of the control variables that reduces the overall emissions while maintaining the satisfying power demand. For instance, in the work on minimizing the emissions associated with the fuel consumption during the navigation of a vessel, a significant reduction of the values of the key performance indicators has been obtained by applying such statistical optimization technique as Simulated Annealing. The results presented in Fig. 7.5 show the reduction up to 31% even though in the work highly heterogeneous examples of the missions were presented. Hence, one may conclude that similar approaches can be applied to real-world scenario when variability and uncertainty are present.

Fig. 7.5 Comparison of the key performance indicators in standard energy management system (EMS) and SHEMS (Smart Hybrid EMS)

Life Science

Coronary artery diseases are one of the main causes of sudden death worldwide. Patient-specific nature of the arterial system makes it almost impossible to predict the appropriate time for the therapeutic intervention, empirically. Moreover, it is well-accepted to use animals, as the closest biological system to that of humans, for conducting research in this field [4, 18]. However, breeding laboratory animals demand high financial and human resources. Computational methods can be used to predict biological systems and reduce the necessity of laboratory experiments on animals. Blood flow hemodynamics has a direct influence on the biology of the arterial wall, and is closely linked with coronary artery disease development. Computational fluid dynamics (CFD) solvers can be employed to analyze the hemodynamic metrics, such as blood flow-induced shear stresses at the inner vessel lumen, to assess an individual's coronary disease risk. Still, calculating hemodynamic indices using traditional CFD methods is relatively slow and relies on high computational resources. Consequently, CFD-based hemodynamic computation is not reasonable for integrated and large-scale use in clinical settings. Novel model reduction techniques such as neural networks integrated with CFD make it possible to lower the computational cost of the numerical simulations and at the same time to provide accurate predictions of the blood flow hemodynamics. In traditional pure CFD methodology, a patient-specific geometry is derived by the image processing and 3-D model reconstruction of the CT-scan images, and then, is modelled by CFD solvers to evaluate hemodynamic indices. In general, several simulations on different geometries are needed to derive a general relationship. Hence, it demands a high level of computational time and resources. On the other hand, modern model reduction techniques can reduce the computational time from days to seconds. The technique utilizes advanced mathematical methods to parameterize a system of equations and is trained by the set of simulations, a stage known as the offline stage. Then, this trained model can be utilized to predict every other geometrical and flow case in terms of seconds. The procedure is shown in Fig. 7.6.

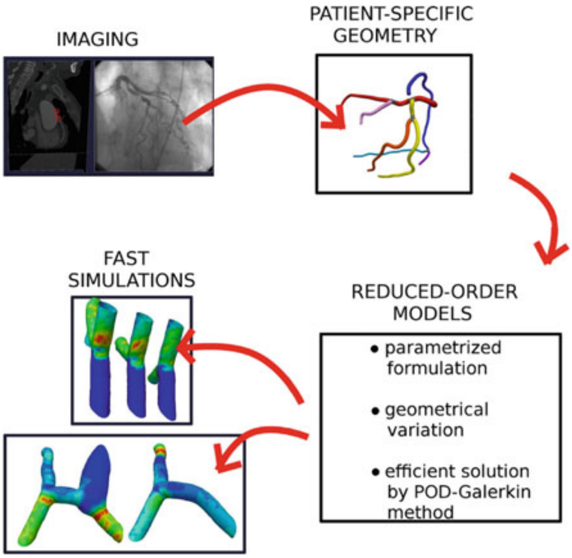


Fig. 7.6 A sketch of reduced order framework for biomechanical models [6]

Ballarin et al. applied the mentioned methodology to conduct research on the blood hemodynamics study on patient-specific coronary artery bypass grafts [6]. Oscillatory Shear Index (OSI) is of great importance in recognition of the blood hemodynamics and vessel lifetime upon the rupture [5, 22]. Figure 7.7 shows the evaluation of OSI for different geometrical and flow conditions near the coronary arteries and bypass grafts near the anastomosis.

In related studies, Siena et al. [45] and Balzotti et al. [8] utilized ROM-CFD based on the Feed-forward Neural Network (FNN) for the evaluation of the hemodynamic indices adjacent to the walls including wall shear stress. The predicted results based on the machine learning method showed a fantastic agreement with that of the Full Order Method (FOM), i.e., CFD simulation. To compare, the former took computational time of order of hours, whilst the latter is accomplished in just a few seconds (see Fig. 7.8).

Process and Product Optimisation

Freight and passenger transport (land, air, sea and water) provide assistance to economic growth by making access to resources and markets. Eventually, it improves the quality of life linking persons to employment, health, education and other amenities. Thus, transportation takes an important role in economic and social development. Nevertheless, it comes with spillover negative effects such as congestion, pollution, depletion and resource-intensive consumption. Sustainable transportation is associated with the concept of clean transportation with the least impact on the environment.

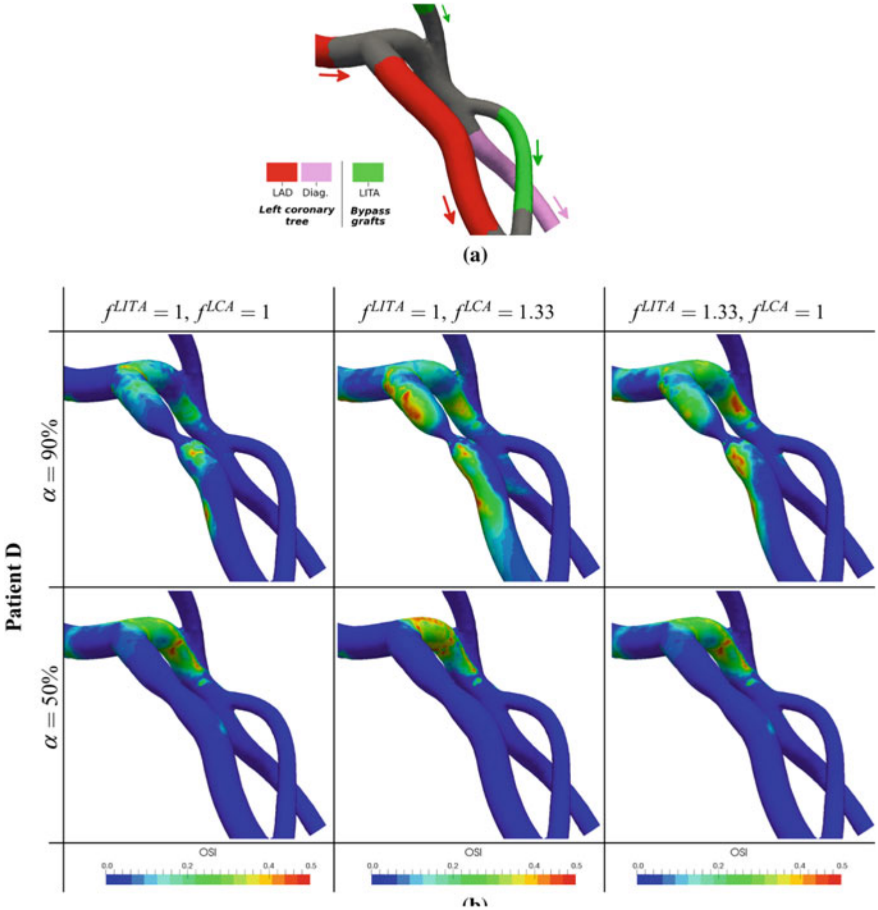


Fig. 7.7 Left internal thoracic artery (LITA) to diagonal branch of the left anterior descending artery (DIAG) anastomosis for different stenosis (rows 1 and 2) and inflow conditions (columns 1 to 3). Coloured arrows denote blood flow direction [6]

Above all, sea transport is one of the main components of the world's economy, as the largest carrier of freight around the globe. Motorised transport is over 95% dependent on oil and accounts for almost half of the world's use of oil [54]. As a consequence, it attained a lot of concentration in the past few years in order to reduce the carbon footprint of sea transport by adopting sustainable practices.

Accordingly, the shipbuilding industry is making a radical change toward solutions with a smaller environmental impact by employing low emissions engines, optimized shape designs with lower wave resistance and noise generation, and by reducing the metal raw materials used during manufacturing. In a brand-new research study, Tezzele1 et al. carried out a structural optimization pipeline for modern passenger ship hulls which exploits advanced model order reduction techniques to reduce the

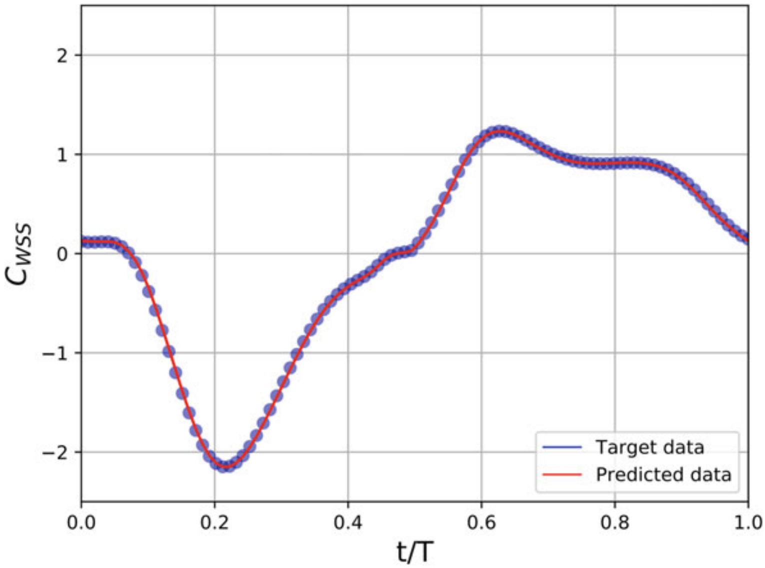


Fig. 7.8 Time evolution of wall shear stress prediction provided by FNN (red line) and the FOM simulation (blue points) [6]

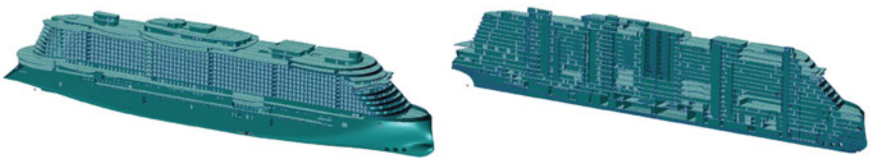


Fig. 7.9 A complete view of the hull on the left, and a longitudinal section on the right [48]

dimensionality of both input parameters and outputs of interest [48]. Figure 7.9 demonstrates the geometry of the passenger ship in their research study.

Figure 7.10 below depicts the successive runs performed using a novel model reduction technique called POD-NARGPAS, to predict the reduced mass.

More than 7% of total carbon dioxide emission in the US is related to the healthcare industry, contributing to an estimated 479 million tons of CO_2 each year [36, 49]. When assessed by sector, hospitals and clinics, medical structures, and pharmaceutics are the top emitters. Among these, pharmaceutical industries and drug development activities are believed to be among the top contributors [41]. Nowadays, drug development has become the exclusive activity of any pharmaceutical company. But interestingly, the output of new drugs has been decreasing for the past decade and the prices of new drugs have risen steadily, leading to access problems for many patients [31]. This may contribute to the fact that the drug development process involves a range of operations such as blending, granulation, milling, coating, tablet pressing and filling, and therefore, regarded as an interdisciplinary science of

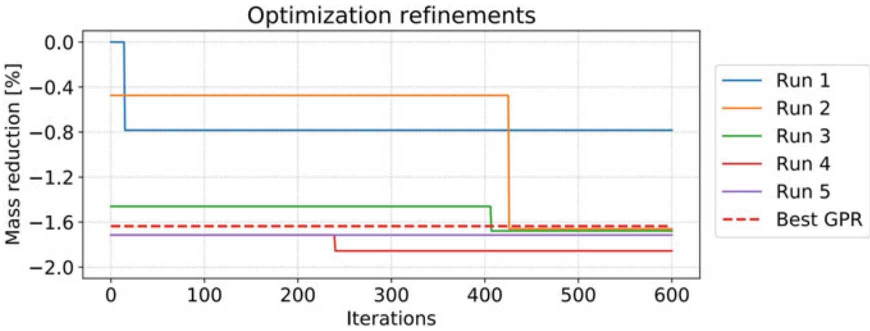


Fig. 7.10 Results of relative mass reduction for different optimizations runs of the parametrized hull [48]

chemistry, mechanics and medicine [25]. Granulation, the process of particle enlargement by agglomeration technique, is one of the most significant unit operations in the production of pharmaceutical dosage forms, mostly tablets and capsules [44]. The complex physics of the granulation process can be predicted by mixing several numerical methods. Dompé Farmaceutici S.p.A. is one of the greatest biopharmaceutical companies and is engaged in innovative drug processes and biotechnologies. In this regard, in a novel research study, in collaboration with SISSA, they have developed a hybrid CFD-DEM model to describe the granulation process by taking into account both a thermal and dynamic balance between particles and flow. Discrete Element Method (DEM) is based on the Lagrangian frame of reference and is able to simulate particles with any shape and inter-bonds. Figure 7.11 shows the CFD-DEM simulation steps for granulation process modelling in the drug production system.

Interestingly, to exploit maximum computational capacity, the machine learning technique based on offline/online phases for training/evaluation of the data was employed on the model. Figure 7.12 compares the FOM results with that of ROM. In this model, due to a high number of particles ($10^6 \sim 10^9$), the computational time of FOM is of the order of days, while the ROM model took only a few seconds/minutes.

The invention of the first electrical appliances goes back to the first decades of the 19th century, meaning that home appliances have been making our lives easier for more than two centuries. Addressing appliance energy consumption is important both because of its present consumption and emissions, and also for its exponential growth. Household energy consumption represents a great portion of energy consumption in developed countries and in some cases even higher than that of the industry [24]. Although there have been many innovations over the past years, we still need to take a long way to reach a sustainability standpoint. Sustainable modern home appliances can reduce energy consumption by up to 50% [2]. Moreover, another aspect of sustainability is water consumption, especially in water-using appliances such as dishwashers and washing machines. Electrolux is a Swedish multinational home appliance manufacturer, headquartered in Stockholm. It is consistently ranked one of the top world's largest appliance makers by units sold. Electrolux brand appli-

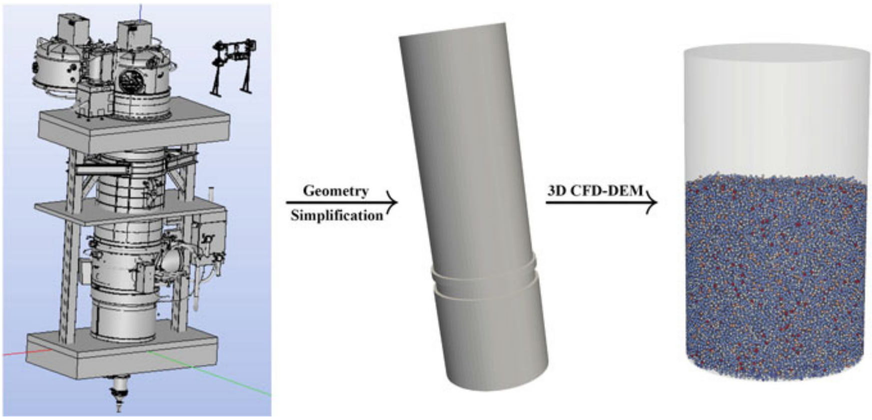


Fig. 7.11 Steps for the CFD-DEM simulation of particle granulation process

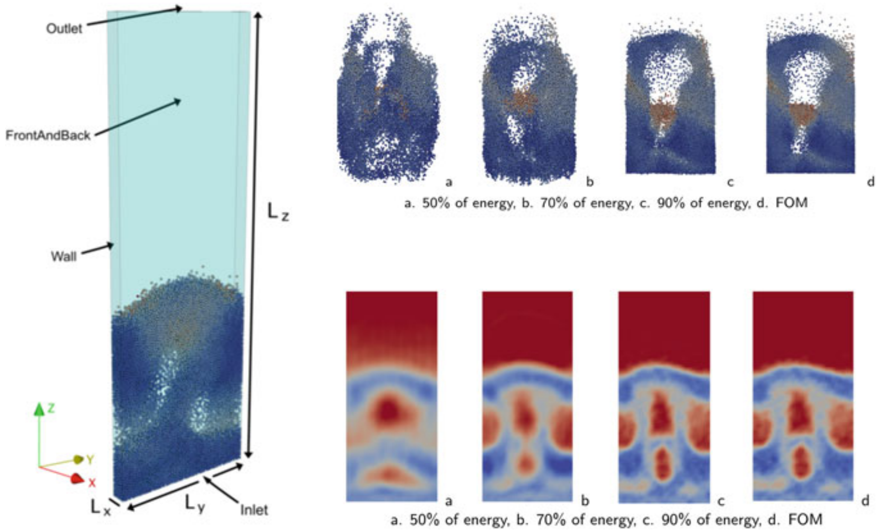


Fig. 7.12 CFD-DEM simulation of the granulation process. Left: the computational model. Right: comparison of ROM results **a**, **b** and **c** and ROM result **d**

ances have been making housework easier for more than a century. The Company's products include refrigerators, dishwashers, washing machines, cookers, vacuum cleaners, air conditioners and small domestic appliances. Electrolux, as one of the leading providers of technological and modern home appliances, has been developing Research and Development (R&D) projects, particularly to pursue sustainable less energy- and resource-intensive products. In a recent collaboration with SISSA, they aim to reduce the water and electricity consumption of a professional dishwasher. A dishwasher is regarded as an energy-intensive home appliance. To illustrate, one cycle

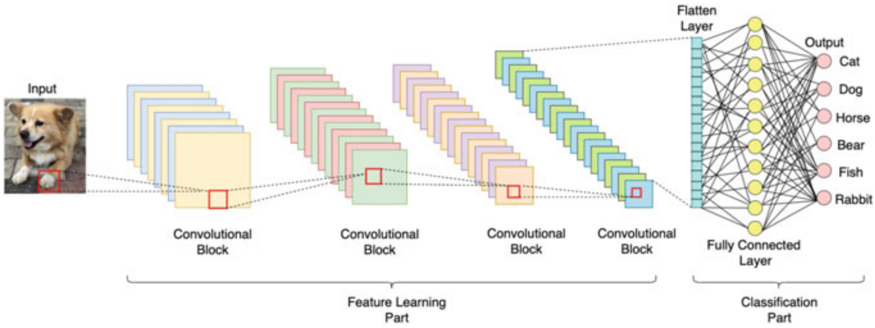


Fig. 7.13 Architecture of a typical CNN which includes Feature Learning and Classification parts [29]

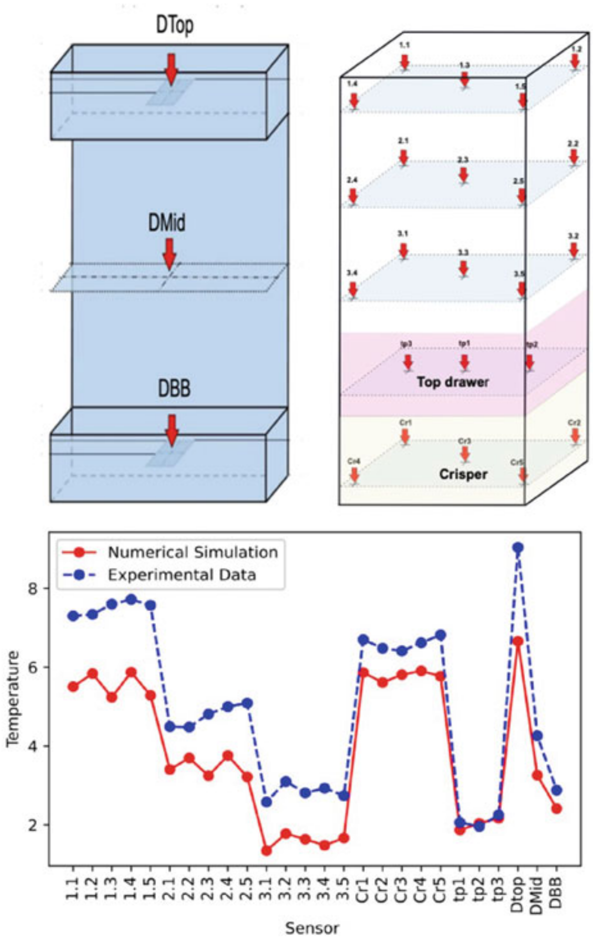
of dishwashing is equivalent to 20 hours of continuous TV running. The current technology uses an identical washing program for all the items in the washing machine. Whereas, rinsing for plates should be different from that of glasses, for instance. The idea was to implement an optimized image recognition device in the dishwasher to obtain a correct and suitable washing cycle. Meneghetti et al. developed an image processing technique for the image recognition device in the dishwasher based on the Convolutional Neural Network (CNN) algorithm to differentiate objects in the machine [29]. In Fig. 7.13 is the workflow of the CNN method used in the research. Such a system results in optimized water consumption in the washing cycle.

The next step of the project was to reduce the memory consumption of the image recognition device. To do so, they proposed a novel reduced approach for CNN and successfully developed a less energy-intensive device. More details of the project can be found in [30].

Another energy-intensive home appliance is the fridge. In general, experimental and numerical methods are used to predict and improve refrigeration efficiency in terms of energy saving and temperature maintenance. The cabinet and door gaskets play an important role in the heat transfer phenomena in the fridge. This complex system involves several physical phenomena including natural/forced convection, conjugate heat transfer (CHT), recirculation made by a fan and radiative heat transfer. Electrolux company, in another collaboration with SISSA, modelled air flow and heat transfer in the fridge and successfully validated numerical results (see Fig. 7.14). The model was based on the mass, momentum and energy conservation principles and the set of equations was solved with the well-known open-source flow dynamics solver, OpenFOAM.

Interestingly, CFD could provide us with every detail of the flow in the cabinet in terms of velocity and temperature for every working condition. For instance, the effect of fan on the ventilation in the cabinet is shown in Fig. 7.15.

The next part of the project deals with creating high fidelity database based on the validated CFD model for the real fridge geometry. To do so, an offline phase consisting of approximately one hundred simulations for different geometrical parameters



	Numerical Simulation	Experimental Data	accuracy level
Average T FF 1st floor	5.7	7.4	1.7
Average T FF 2nd floor	3.46	4.77	1.31
Average T FF 3rd floor	1.9	2.83	0.93
Average T Crisper	2.08	2.09	0.01
Average T Top drawer	5.99	6.61	0.62

Fig. 7.14 Sensor position in the fridge and validation of the temperature against experimental data

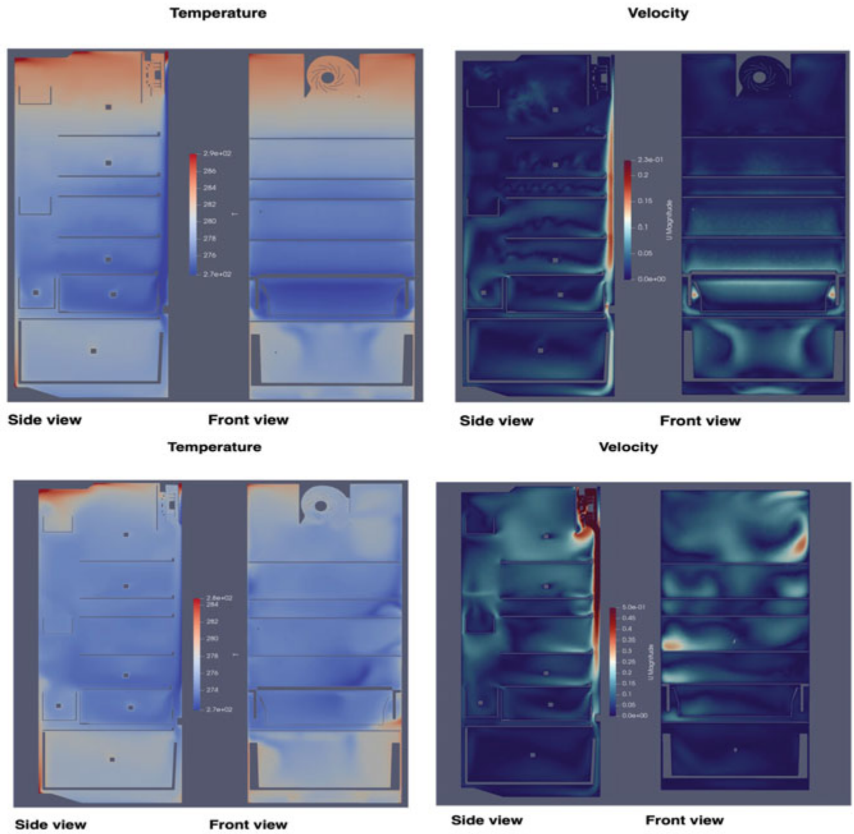


Fig. 7.15 Temperature distribution and velocity contour in the ventilated fridge, in the presence of: up) fan is off down) fan is on

was carried out. After implementing a suitable model reduction technique, the concluded library could estimate temperature distribution at any point of the fridge within a few seconds. Figure 7.16 compares the temperature distribution of FOM (CFD) and that of ROM. The ROM could predict temperature distribution with an error less than 0.6 °C.

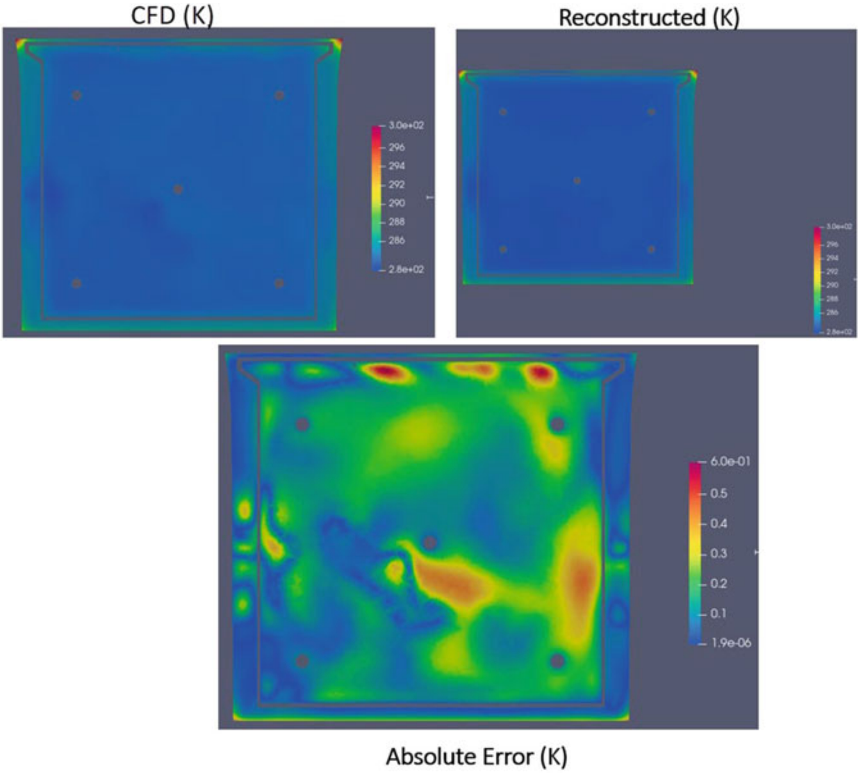


Fig. 7.16 Comparison of temperature distribution between FOM and CFD and error

Enhancement of Computational Performance

While the examples above themselves demonstrated the indispensable role of the computational modelling for sustainability, these simulations can demand high power and frequently high performance computing is required in order to make them accessible. Hence, in this section, we discuss how the simulations themselves can be more sustainable and use less energy to obtain nevertheless reliable results. Thus, one of the class of methods that provides an "energy-efficient" version of the original model is the Reduced Order Modelling (ROM) [10–12, 43].

Reduced Order Models

Many techniques have been developed in order to decrease the computational costs and the energy consumption of computational simulations. In the context of time-dependent or parameter-dependent problems, Reduced Order Models (ROMs) aim at building a surrogate model that can accurately represent the solution of the full order model (FOM) simulation within smaller computational costs. In some of these techniques, there are two phases: an "offline" phase, where a reduced space is computed and the ROM is learned and that still requires the costly computation of few solutions of FOMs, and an "online" phase, where the ROM is used for a fast and energy-saving evaluation of many ROM solutions [20].

One of the first developed model order reduction (MOR) techniques to compute reduced spaces is the proper orthogonal decomposition (POD) method [23, 26]. It uses some FOM solutions to extract the most representative reduced space that will be the basis for the ROM. Then, in the online phase, the much smaller ROMs can be used to run many simulations for different parameters/times using an infinitesimal amount of the energy used by the FOMs. Examples of the application of the POD can be found in [47] for optimal control flow in water simulations, in [52] within a weighted method for stochastic problems or in [51] for dispersive wave equations. The greedy algorithm is a technique that aims at reducing the energy consumption also in the "offline" phase [38, 39]. Indeed, it does not require the FOM solutions of the whole training set from which we want to learn the reduced space. Instead, it iteratively selects a new parameter, thanks to an error estimator, and it computes the FOM only of very few parameters and uses them directly to constitute the reduced space. The resulting method reduces the energy consumption also in the offline phase, though slightly worsening the accuracy of the found reduced space. As an example, in [50] there is an application of the Greedy algorithm in uncertainty quantification problems, in [1] for Navier–Stokes problems or in [13] for Euler equations.

For more complicated problems, where these techniques do not achieve enough accurate results, recent nonlinear tools can be used to still catch the underlying reduced latent space. One of the many techniques that can be used to this end is the autoencoder neural network [17, 28, 42]. These networks are able to obtain very small reduced spaces even when the solutions cannot be well represented by a linear combination of basis functions. Once the reduced space has been found, the reduced order model can be obtained with different techniques.

In case of linear problems with affine dependence on the parameters, a simple Galerkin projection onto the reduced space can guarantee very accurate results consuming much less energy [7, 20, 46, 51]. When there is the presence of nonlinearities, further reduction techniques (hyperreduction) can be used to recast the problem into a linear one. Among these techniques, it is worth mentioning the empirical interpolation method [9, 20, 40, 51], the empirical quadrature method [33, 55] and Gappy POD [34, 53]. These techniques aim at reducing the computations of nonlinear terms, through the evaluation of only a few points in the domain, saving, again, energy consumption. More recent techniques have been developed to solve these nonlinear problems in less intrusive ways. A broad class of neural networks has been tailored to solve such problems [17, 21, 27, 35, 42, 56] as well as the dynamic mode decomposition (DMD) [3, 14, 16, 19, 37]. The common denominator of all these techniques is the ability to strongly reduce the computational cost and the energy consumption in the online phase after a learning procedure in the offline one.

Dimensionality Reduction

When one examines the main sources of the computational cost of a simulation, the dimensionality of the model parameters should not be omitted. In fact, the cost of some computations may grow exponentially with the increase in the number of parameters in the system. Therefore, the methods that obtain the estimates on how important[1] the parameter of the model may drastically reduce the computational burden of the experiments.

One such method reduces the parameter space by unveiling the directions in the parameter space along which the model function has the greatest fluctuations. This is achieved by normalizing the inputs in a reference domain centered in the origin and then by rotating the parameter space until a lower-dimensional structure is identified [15].

Sensitivity Analysis (SA) can be used as well for identifying the most important parameters for the model results. However, SA methods can be highly computationally intensive by themselves. Alternatively, for the computational models that have some types of coupling stricture, some advanced techniques that adopt SA can be applied. Thus, in [32], the coupled structure of some multiscale models is exploited to perform SA on the less computational-intensive pieces such that the results are applicable for the dimension reduction of the overall model.

Reduction of Memory Storage

We go even further and suggest an additional reduction of the computational load of the reduced simulation by improving the storage system of the reduced model. In fact, the reduced order models have a significantly better performance in time, however, they can occupy large memory space and, thus, its sustainability decreases. There exist several approaches to address this issue, like the one presented in [29] where the memory storage of a Convolutional Neural Network was reduced by 90%. This reduction was obtained by replacing a finite set of the network layers with a response surface, involving dimensionality reduction techniques to operate on a low-dimensional space. The main idea of the approach is presented in Fig. 7.17.

Conclusions

This chapter mainly focused on the computational methods in achieving sustainable products. The surging growth of computational resources in the last two decades make it possible to simulate any actual system in the context of the digital twin.

[1] Here, the term "important" means that the change in the value of an important parameter has a great effect on the value of the quantity of interest. On the contrary, fluctuations in the value of an unimportant parameter do not affect significantly the value of the studied output.

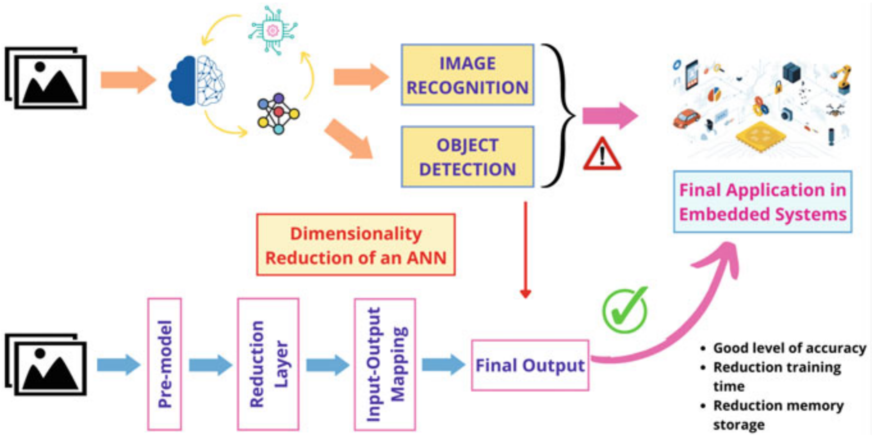


Fig. 7.17 A reduced order approach for artificial neural networks (ANNs) applied to object recognition

Digital twin in particular integrates data from various sources and process these data accordingly. Moreover, utilizing data smart asset solutions are a key to reduce operational costs.

This chapter, in such sense, divided into two sections; first a couple of industrial examples of utilization of computational methods in modelling a process or system was introduced. The section includes a vast number of examples in environment and pollution, life sciences and product life cycle optimization. Second part mainly focused on implementation of novel techniques of machine learning and artificial intelligence for model order reduction to predict the system solution.

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Part VI
Energy Transition and Industrial Product Chains

Energy and industrial processes, fuel and engine of human activities, are two of the main cornerstones of the transition towards sustainability.

On the one hand, an important topic will be the analysis of the production system and the energy system that powers it, in the light of the current radical revolution that is affecting both (smart industry) and that passes through digitization and automation, the integration with telecommunications, data science. The evolution and sustainability of the system depend on the complex interaction between these scientific-technological aspects, the obvious need for economic sustainability, but above all the unprecedented social and political-economic implications, which derive from the new role that the human being necessarily will acquire in these systems.

From this point of view, the role of industrial design, as a tool to adequately represent the presence of man in the process that goes from the conception, to the realization, to the use of a product, represents a methodology that must become an integral part of industrial production and of innovation processes.

In 2013, the European Commission released the programmatic document *Design for Growth and Prosperity—European Design Innovation Initiative*, in which the Commission envisaged and indicated in 2020 the design as an integral part of Europe's innovation systems and at the service of society. The design thus becomes a key element of territorial competitiveness, a synthesis of capacity, objective, vision and system.

Using its typical tools (interdisciplinary dialogue, attention to human needs or human centered design, comparison with the productive and economic fabric, etc.), design can represent a methodology not only for the industry, but a real basis of the various issues dealt with in this document, from an operational and structural point of view. With the new seven-year term of the Commission, s*ustainability* has become a central theme in the design debate. From the definition of the demand to the production of the idea and its subsequent realization, design works to mend the relationship between man and context/nature.

A second topic of importance and capital urgency today, regarding energy and industrial processes, is environmental sustainability. The emissions of GHG (the gases that lead to anomalies of the greenhouse effect, the main one being carbon dioxide, CO_2) are today due to more than two thirds of the use of energy in its various forms (including the use in industrial processes, which accounts for over 20%. If we also consider the emissions deriving from the by-product of the industrial processes themselves, the energy system and that of industrial production contribute to more than 75% of global GHG emissions. Therefore, acting on the energy and production system is by far the strategy of maximum impact to contain climate change—considering the established link between these and GHG emissions.

In turn, the greatest impact on the reduction of emissions due to uses in the energy sector is obtained primarily from a reduction in energy consumption and secondly through the transition to renewable sources, which bring with them a significant increase in the complexity of the system, also only considering the mere technological aspect (take for example the transition from the traditional electricity grid to the so-called smart grid). The work of our group will primarily focus on these most untactful strategies—once again considering the scientific-technological, economic and social implications in an integrated way.

A further topic of study, which still concerns the field of energy and which must necessarily be addressed with the tools typical of complex systems, is the relationship between the energy system, the system of mobility and transport and human settlements. Among the uses of energy, transport (15%) and residential and commercial uses (over 17%) are the other two main components in the contribution to GHG emissions. For this reason, the theme of the smart city, that is the rethinking of human activities, from recreational to working ones, and consequently of spaces and modes and transport networks, especially in the urban environment, assumes a cardinal importance in the path towards sustainability of the energy and production system.

An important role of the activity of our group will be to provide orientation keys for citizens, decision-makers, the scientific community itself, through the complex interconnection and transversal character between these issues (energy, production, smart city, mobility ...), also through the identification and definition of clear and robust sustainability indicators in these areas.

This part includes Chap. 8, *Sustainability in the Energy System and in the Industrial System* by M. Cobal and V. Lughi.

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Marina Cobal
Stefano Fantoni
Cosimo Solidoro

Chapter 8
Sustainability in the Energy System and in the Industrial System

Marina Cobal and Vanni Lughi

The Industrial System and the Energy System

"Fuel and Engine" of all Human Activities

With the term "industrial system", one refers to the set of processes, technologies, and infrastructure used to produce goods and services in a society. This includes the factories, machinery, and all the equipment used to manufacture products, as well as the transportation and distribution systems that deliver the products to customers.

The term "energy system" refers instead to the infrastructure, technologies, and resources used to generate, transmit, and distribute energy for various purposes. The energy used in industrial systems can come from a variety of sources, including fossil fuels such as coal, oil, and natural gas, as well as renewable energy sources such as solar, wind, and hydroelectric power. The energy system includes power plants, transmission lines, and distribution networks that deliver electricity to homes and businesses, as well as the systems and technologies used to produce and transport other forms of energy such as oil, natural gas, and renewable energy sources like solar and wind. The energy used in industrial systems can be used to power machinery and equipment, heat and cool buildings, and provide lighting. It is also used to produce raw materials and intermediate products that are used in the manufacturing process.

Industrial and energy systems are closely related since industrial processes require energy to function. Together, they form the backbone of modern society, enabling us to live, work, and thrive. They are the engine and fuel of all human activities since they provide the power and resources that allow us to produce goods and

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services, transport people and goods, and support modern living. Their relationship is complex and dynamic, since the demand for energy by industrial systems can drive the development of new energy sources and technologies, and, on the other hand, the availability of energy can affect the growth and competitiveness of industrial systems. At the same time, the efficiency of energy use in industrial systems can have a significant impact on the overall energy demand and on the environmental impact of energy production.

Since most human activities are in many ways part of the industrial system, and since all human activities are powered by the energy system, any discussion about true sustainability (i.e. simultaneous economic, environmental, and social sustainability) must involve the analysis of energy, industry, and their interrelation. This will be the scope of this chapter.

A Brief Historical View

The development of the energy system and that of the industrial system have been strongly coupled ever since the first industrial revolution, when mechanization of the industry started, going hand in hand with a number of important advances in energy production—mainly coal-fired steam engines. The increased energy availability enabled industrial development, which in turn drove further technological advances for the energy system (e.g. electricity, the internal combustion engine, etc.)—a loop that led to the exponential growth of both energy demand (Fig. 8.1) and the industrial system.

Fossil fuels (initially coal, then oil, and later gas) have been the main sources of energy for the entire twentieth century, accounting for up to 80% of the global energy demand; this peak was reached in the 70ies, when increased environmental concerns, the advent of nuclear power, and the shift from a massively industry-based economy towards a tertiary economy, led to a reduction of the energy demand growth rate from near-exponential to approximately linear, and to a plateaux in the use of fossil fuels. The share of fossil sources is nowadays showing a weak decrement and is currently at about 77% of the total energy demand (Fig. 8.2).

Starting from the beginning of the new millennium, countries of the so-called Western World (or more in general OECD[1] Countries) have shown a stabilization of the energy consumption, despite a continuous growth of the economy (incidentally, this shows that it is indeed possible, despite common belief, to decouple economic growth from an increased energy consumption). Almost simultaneously, however, a number of other countries have started emerging as new important global economies (mainly the so-called BRICS Countries: Brazil, Russia, India, China, South Africa). China in particular has undergone an impressively fast economic growth, accompanied by a massive increase of industrial production and of energy consumption [1].

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[1] OECD: Organisation for Economic Co-operation and Development.

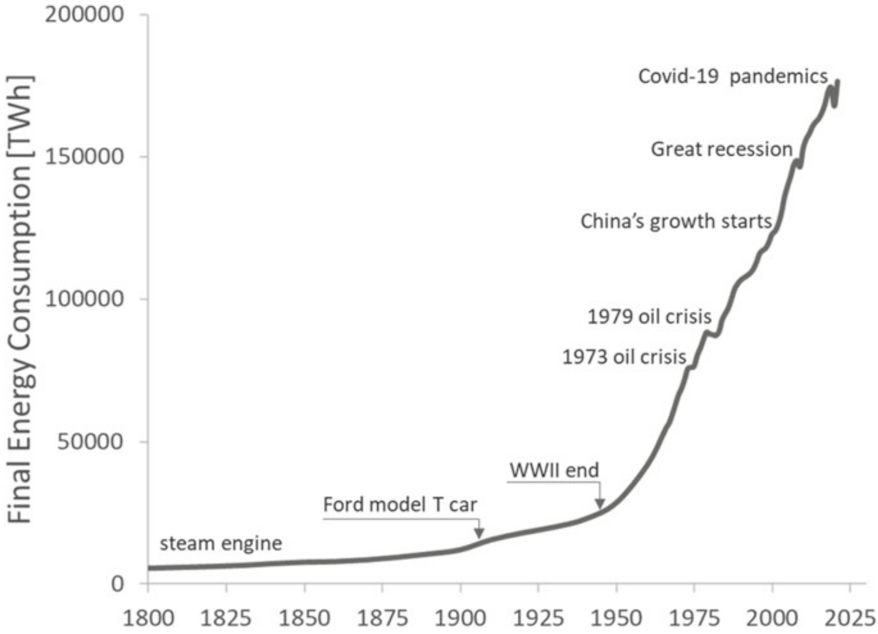

Fig. 8.1 Historical global energy consumption and major industrial and geopolitical landmarks that greatly influenced energy consumption (data retrieved from [1])

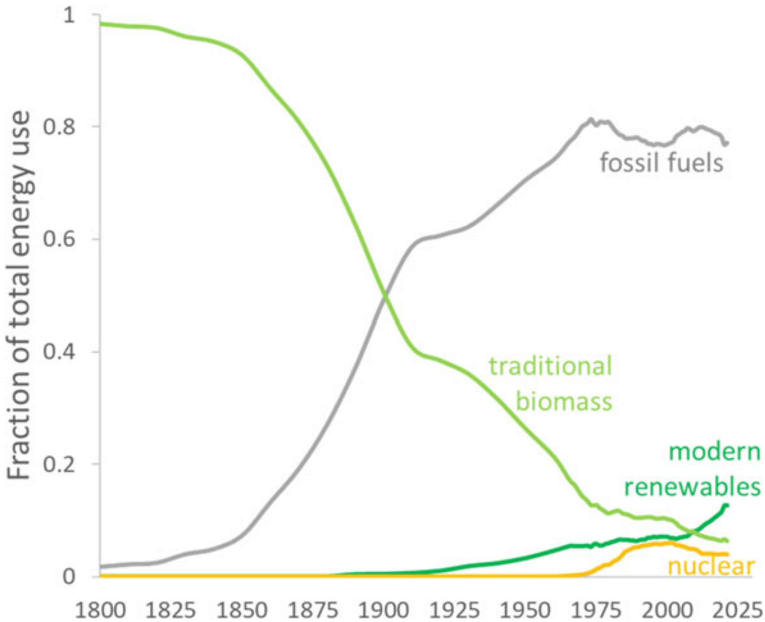

Fig. 8.2 Fraction of the total energy use, by energy source (data re-elaborated from [1])

These opposite trends can teach us a lot about the dynamics of the near future: on the one hand, there is a large pool of Countries with currently limited industrial production but large potential for growth (e.g. in Southeast Asia, Africa, South America), whereby a massive increase of the industrial production and of energy demand is expected. On the other hand, new technologies, industrial and energy policies (and partially new habits and awareness) are enabling a more efficient use of energy and resources, and potentially a reduction of the final energy consumption and of the use of raw materials.

Which of these opposite trends will prevail is hard to predict, but a drastic change in the way we produce and use energy and goods is now possibly the most important and urgent challenge of our times. As nearly 70% of the annual emissions of greenhouse gas are currently associated with energy transformation, distribution and use (including energy for the industry), and an additional 10% is associated to direct emissions due to the industrial processes [2], acting on the energy system and on the industry system are by far the primary strategies we have to mitigate climate change. Failure to do so will have a major impact on all planetary systems, with catastrophic consequences on humankind.

Recent (R)evolutions

A number of transversal disciplines have been playing an ever-increasing role in the industrial system over the past few decades. Automation and digitalization of the industrial processes have emerged in the last three decades of the past century, proceeding hand in hand with the main aim of increasing productivity, in what was dubbed as the third industrial revolution. The exponential improvement of telecommunication and digital networking technologies of the past two decades have then brought about the ability of remotely controlling the production processes, but most of all to instantly transmit, share, and elaborate the process parameter data, thus enabling the development of concepts such as augmented reality and digital twins in the industrial context. One initially unexpected side benefit of the widespread digitalization (and later sensorization) of processes has been the collection, storage, and sharing of impressively massive amounts of data, leading to the so-called "big data" and thereby the possibility to fully exploit machine learning techniques to improve the industrial processes beyond what was previously thought possible. The integration of all these tools is known as the fourth industrial revolution, or industry 4.0 [3], where manufacturing takes place in ever-evolving "smart factories".

An analogous series of revolutions has taken place in the energy industry, where automation, digitalization, telecommunication and networking capabilities have acquired a critical role along the entire energy supply chain especially over the past couple of decades [4]. The impact of these disciplines has rapidly grown at all levels of the energy supply chain, from resource extraction to production, distribution, and use.

The electric energy sector has been particularly affected by these technologies, but has also undergone a very peculiar revolution. The massive increase of producing electrical power from renewable sources [5] such as photovoltaics, wind, hydroelectric (which are inherently intermittent, thus posing previously unexpected challenges), along with the possibility for the end users, or consumers, to also become producers, which leads to bidirectional power fluxes in the grid, have stimulated an unprecedented development of the grid structure and capabilities. The new "smart grid" features a more network-like architecture, a capillary and instantaneous data monitoring, as well as the ability to remotely act on it to control the fluxes and the overall system's balance. Machine learning approaches are now commonplace in predicting the system's status and in defining the optimal control configurations.

As will be noted in more detail in section "Current Status of the Industrial System and the Energy System", the evolution of the electrical system is particularly important: while electric power currently accounts for only approximately 19% of the global energy balance [6], it is expected to acquire the largest share of the final energy consumption by mid-century.

The renewable energy revolution described here is in itself a key step toward sustainability. But another element that is gaining recognition as a fundamental piece of the sustainability puzzle, is the emerging centrality of the human being in both the energy system and the industrial system, as we shall see in the next paragraph.

Central Role of the Human Element in Sustainability

Sustainability has been, and still often is, identified with a rather undefined need to protect the environment, or with a concept mostly associated with the economics of a system. While these two widely accepted facets of sustainability are both essential, the "human element"—or in other words the "social dimension"—is also a crucial component of sustainability, although it is not as widely recognized as such. As a result, the centrality of the human factor in sustainability, especially in the industrial system and in the energy system, is still a somewhat poorly defined concept. While it certainly rests on the idea of including social justice, community participation, poverty, etc. in all decision-making processes related to environmental and economic development, the idea can and should be further developed.

In the industrial system, the shift from a purely environmental-economical sustainability to a sustainability that includes the social dimension is finding better definition and practical application through the so-called fifth industrial revolution ("Industry 5.0") [7]. This is a new paradigm with respect to Industry 4.0, where the focus has been and still is mainly on just improving the industry's efficiency, productivity, and adaptability by integrating robotics, IoT, AI, big data analytics and other digital and physical technologies into manufacturing processes. Governmental policies and funding are being deployed to support such a shift, leading to some practical guidelines such as the focus on welfare and continuing education for the workers, the livability of the workplace, and similar measures. While these actions are commendable, our impression is that more can be done and the degree of innovation in the practical aspects of these policies is still rather marginal.

The energy system, too, is undergoing an important shift, where the role of the individual is becoming more central. Because of the evolution of the energy system's structure—particularly in the case of electricity, as the power grid becomes an increasingly interconnected and smart network—citizens have the opportunity to become producers of energy, too, rather than just consumers. This new concept of "prosumer" [8] puts the human being back at the center of the energy system, both as an individual and as a community. A strictly related phenomenon is the rapid diffusion of the "energy communities", where groups of citizens self-organize to best deploy and exploit local energy resources. This is an efficient strategy for mitigating the rising phenomenon of "energy poverty" and represents, in a way, a democratization of the energy system, where communities are empowered and at the same time the individuals are made more accountable—for example in terms of energy consumption.

Current Status of the Industrial System and the Energy System

A Critical View on Current Data

The global energy system is mainly sustained by fossil fuels (coal, oil, gas, almost equally distributed), currently contributing to about 77% (Fig. 8.1) of the energy demand and causing the energy system to be the largest contributor to the greenhouse gas (GHG) emissions, with nearly 70% of the total [2]. Importantly, there is a growing share of renewable energy sources (RES), mainly solar photovoltaics, hydroelectric power, and wind power, now collectively contributing to approximately 13% of the global demand (Fig. 8.2). Most of the recent growth of the share of RES has been driven by photovoltaics and wind combined (Fig. 8.3). Globally, an average of about 28% of the electricity is generated by RES [6], and this fraction varies widely for different Countries [1], ranging about 40% in many European Countries, with peaks up to over 99% as in the case of Norway.

While these latter data might sound rather promising, as RES contribute to reducing GHG emissions, there are a number of challenges and open questions. While the introduction of RES in the electricity production is an acquired capability and can in principle be pushed to rather large levels (despite a number of challenges related to the management of the grid and the need to store the electricity), even bringing to zero the amount of greenhouse gas emitted per unit power produced ("electricity intensity") would only solve a small portion of the energy problem. In fact, only 19% of the energy consumption is used for generating electricity. About 31% of the final energy demand is used for transportation while 50% is used as

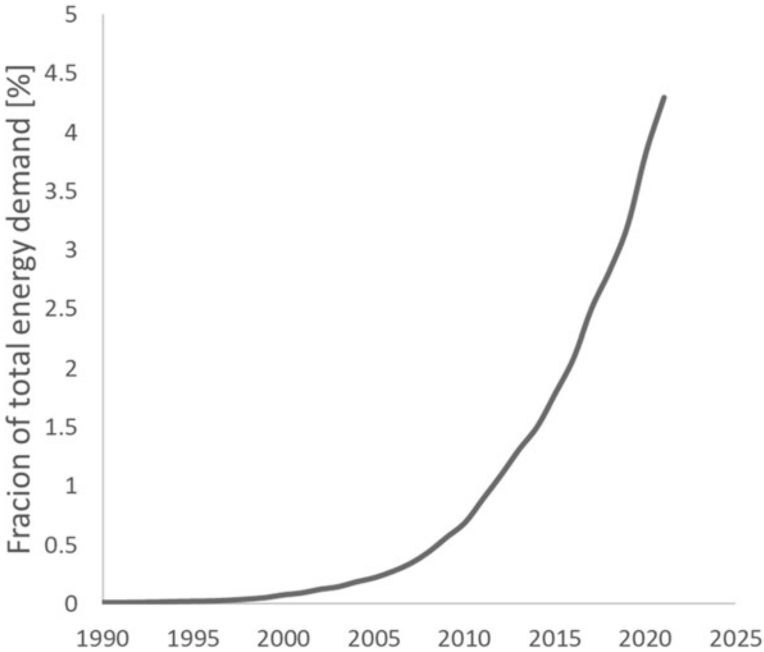

Fig. 8.3 Combined fraction of the total energy use for solar photovoltaics and wind power (data re-elaborated from [1])

thermal energy, mainly for heating buildings, and only approximately 4% of the transport uses and 10% of the thermal uses is obtained by RES [6].

Therefore, to favor the reduction of GHG emissions, a major growth of the electricity demand ("electrification") is desirable, and it is indeed expected in the near future (in some scenarios, RES are projected to provide up to 90% of the global electricity demand by 2050 [9]) for a number of reasons. First, there is a driver of geopolitical nature, as currently about 18% of the World population has little or no access to electricity. A second driver is the very rapid growth of electric mobility. Finally, there is a very strong push for the expansion of RES, which are intrinsically sources of electricity and find their natural implementation in the expansion of the electric power offer. This push is driven by governments, in order to meet the greenhouse gas reduction goals stated in the international agreements; it is also driven by investors and by the energy companies, as RES electricity is now typically cheaper than that produced by fossil fuels, and for the same reason it is also driven by the final consumers.

Despite these seemingly positive signs and trends, the ability of the energy system to change in order to drastically reduce the GHG emissions is and will be increasingly challenged as the global energy demand continues to increase, driven by population growth and economic growth of developing Countries.

The industry system is currently in the midst of the fourth industrial revolution [10], characterized by the integration of physical and digital technologies into industrial processes with the main goal of reducing costs and enabling innovative business models by increasing automation and improving efficiency, productivity and flexibility. While precisely assessing the actual state of this transition is rather difficult for the lack of standardized methodologies and because of the limited number of studies on this aspect, the available data show that the majority of the manufacturing companies have already adopted or are adopting one or more of the key enabling technologies of Industry 4.0. Big data, IoT, cloud computing and artificial intelligence are among the most widely adopted solutions.

However, the fourth revolution is still far from being mature and it is hindered by a number of barriers [10]. One such barrier is the lack of a "culture" of Industry 4.0 at various levels of the company, or more specifically the lack of knowledge about these technologies and their potential interaction. Also, the very large number and variety of new technological solutions in this field, their continuous upgrading, the lack of interoperability or of conformance to standards, etc. can, too, hinder the adoption of these technologies. Another barrier is the lack of a clear vision or of an appropriate business model to fully exploit the advantages and the synergies among these technologies. In addition, implementation of Industry 4.0 requires the integration of multiple technologies and a fundamental change in the way the different departments of a company cooperate. It is also observed that small companies and companies characterized by a low degree of digitalization are found to be less prone to implement the new paradigm. Finally, perhaps the single most limiting factor in adopting the Industry 4.0 revolution is the difficulty of finding personnel with the right combination of expertise.

The overarching goal of Industry 4.0 is primarily of economic nature. Recently, however, increasing attention has been given to the environmental sustainability of the manufacturing processes. This is of primary importance since 32% of the global GHG emissions are associated with the industrial system (of which one third are direct emissions, and the rest are emissions associated with the energy required to power the processes). In addition, raw materials consumption has steadily grown over time, leading to an increasing stress on the natural resources (mining, forestry, fresh water, etc.); therefore, the resource efficiency of the industrial system needs to be improved. Finally, industrial activities often have a heavy direct impact on the environment such as water, air, and land pollution or land use change.

Circular economy, a paradigm that aims at keeping resources in use for as long as possible, is the key strategy for reducing both raw materials and energy consumption, making the industrial system more sustainable. While rapidly emerging, however, the circular economy is still at an early stage of implementation, and only few industries have been able to adopt effective circular business models.

Electrification of the industrial processes, associated with the use of RES-derived electricity, is another important strategy that is expected to facilitate the transition to a more sustainable industrial system [9], and it goes hand in hand with the electrification of the energy system as described above.

As mentioned in the introductory paragraphs, the industry system is on the verge of the fifth industrial revolution or Industry 5.0, a new transition focused not only on the economic and environmental sustainability, but also on the centrality of the human being and therefore on the social sustainability [7].

In conclusion, while some positive effects and changes are now starting to become evident, much more needs to be done to achieve a full transition to a sustainable energy and industrial system, since circular economy, the introduction of RES, electrification, and Industry 5.0 are all still at an early stage of implementation.

The Urgent Need for a Transition

We have mentioned before the need for a drastic reduction of GHG emissions over the next few decades in order to mitigate climate change. In this paragraph, we shall provide a quantitative basis for those statements.

Climate models have been shown to reliably predict a number of climate change phenomena, and there is overwhelmingly vast agreement on the fact that, in order to limit the global average temperature increase with respect to pre-industrial levels to less than 2 °C, the very first step is the reduction of 25% of the annual GHG emissions by 2030 (Fig. 8.4).

This is in itself an extraordinarily challenging task, which can be accomplished only by a drastic and immediate action coordinated across the globe; unfortunately, the expected GHG emission reductions (as declared in the National Determined Contributions by the countries adhering to the Paris Agreement) are far from being sufficient (Fig. 8.4). Moreover, while already extremely challenging, this so-called 2 °C scenario would in any case be accompanied by drastic climate changes, and in turn to dramatic environmental, social, geopolitical and economic consequences. Limiting the global temperature increase to a more desirable 1.5 °C (which would likely lead to a slightly less dramatic scenario, but still to very impacting global consequences) would require about 40% reduction of the annual GHG emissions with respect to current levels—an even more challenging task. It is also important to note that the global temperature increase is related to the overall GHG concentration in the atmosphere; as a consequence, every delay in reducing the annual emissions means that in the following years the required emission reduction will be higher, and even harder to achieve.

Clearly, immediate action is required at all levels and on a global scale, especially on the energy system and on the industrial system—i.e. the first and second cause of GHG emissions, contributing together to more than 80% of the total.

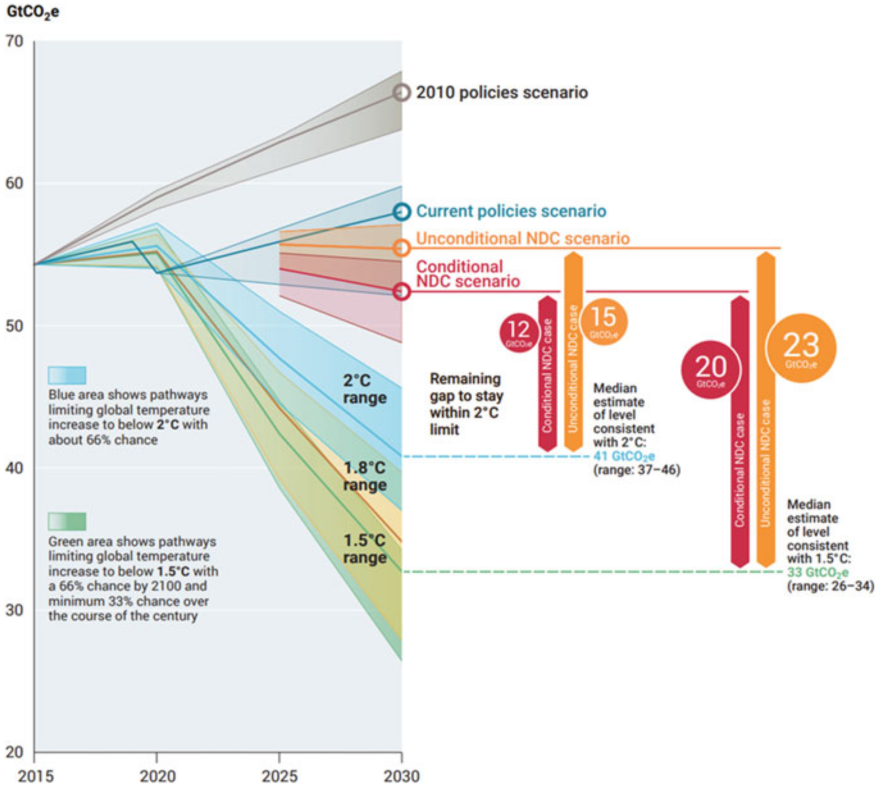

Fig. 8.4 Annual Greenhouse gas (GHG) emissions (Reproduced from [11] with permission). The green, yellow and blue ranges identify the annual GHG emission trends required to comply with different scenarios of temperature increase mitigation (under 1.5, 1.8, and 2 °C, respectively). The red and orange ranges identify the annual GHG emission trends, should the current Nationally Determined Contributions to GHG reductions be fully implemented. Conditional NDCs refer to contributions that the single Countries would implement if specific conditions are met

Implementing the Transition

The analysis in section "The Industrial System and the Energy System" demonstrates the need for immediate drastic measures to reduce GHG emissions. The transition of the energy system and of the industry system should therefore focus on this goal. This is, however, a multidisciplinary task that requires not only a technology-based approach, but also education and awareness, the understanding of the economics, social, political and juridical implications, and—especially—an interdisciplinary dialogue. Moreover, it requires a quantitative approach and therefore appropriate measurable indicators. In the following, we shall discuss the key available tools for undertaking these approaches.

Measurement: Quantitative Indicators

Several tools and indicators can be used, to help implement the transition of industrial and energy systems towards sustainability. A brief overview of some of them is given below:

1. **EROEI** (Energy Return on Energy Invested): measures the ratio of the amount of usable energy (*exergy*) that is obtained from a particular energy resource, to the amount of exergy that is required to extract, process, and distribute that usable energy. It is used to compare the efficiency and sustainability of different energy sources and technologies.

   When the EROI of a source of energy is less than or equal to one, that energy source becomes a net "energy sink", and can no longer be used as a source of energy. Of course, measuring the total energy output can be often easy, especially in the case of an electrical output, where appropriate power meters can be used. However, there is not always agreement on how to determine energy input accurately and therefore one can arrive at different numbers for the same source of energy. Another issue with EROI is that the energy returned can be under different forms, and these forms can have different utility. For example, electricity can be converted more efficiently than thermal energy into motion, due to electricity's lower entropy. In addition, the form of energy of the input can be completely different from the output. For example, energy in the form of coal could be used in the production of ethanol. This might have an EROI of less than one, but could still be desirable due to the benefits of liquid fuels (assuming the latters are not used in the processes of extraction and transformation).
2. **CO_2 Footprint**: measures the total amount of carbon dioxide (CO_2) emissions that are associated with a particular product, process, or activity. It includes direct emissions, such as those that result from fossil-fuel combustion in manufacturing, heating, and transportation, as well as emissions required to produce the electricity associated with goods and services consumed. In addition, the carbon footprint concept also often includes the emissions of other greenhouse gasses, such as methane, nitrous oxide, or chlorofluorocarbons (CFCs). Rather than the greenhouse gas emissions associated with production, carbon footprints focus on the greenhouse gas emissions associated with consumption. They include the emissions associated with goods that are imported into a country but are produced elsewhere and generally take into account emissions associated with international transport and shipping, which is not accounted for in standard national inventories. As a result, a country's carbon footprint can increase even as carbon emissions within its borders decrease. The footprint can be used to assess the environmental impact of different industrial and energy systems and to identify opportunities for reducing emission. A carbon footprint is usually expressed as a measure of weight, as in tons of CO_2 or CO_2 equivalent per year.

3. **LCOE (Levelized Cost of Energy)**: measures the total cost of producing energy from a particular source over its lifetime, including the costs of construction, operation, and decommissioning. It is used to compare the costs of different energy sources and technologies (e.g. wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return and capacities, and to identify then the most cost-effective options. It is a critical indicator to make an informed decision to proceed with development of a facility, community or commercial-scale project.
4. **Criticality**: measures the importance or criticality of a particular resource or material to an industrial system. It can be used to identify key resources that are essential for the operation of an industrial system and to assess the risks associated with potential shortages or disruptions in the supply of those resources.
5. **Social Sustainability Indicators**: There are eight of them, namely: location, supply chain, social innovations, labor practices, training and education, reporting, health and safety, and legal–social aspects. They measure the social impacts and implications of industrial and energy systems, including factors such as employment, health, education, and quality of life. These indicators can be used to assess the social and economic benefits and costs of different industrial and energy systems and to identify opportunities for improving social sustainability.

These are just a few examples of the tools and indicators that can be used: there are many others and the choice of which ones to use will depend on the specific goals and objectives of the transition and the needs and priorities of the stakeholders involved.

Education: Communicating the Industry-Energy Transition

Communicating the industry-energy transition to the public is an extremely important task.

One of the past problems was that more often than not, energy sector experts did not explain how certain changes just applied or to be applied, would impact a person's life on a daily basis, or explain well what abstract concepts really mean. In this way, a real understanding about the energy sector and the needed reforms would mostly stay restricted to the circle of experts, with the wider society just being influenced by emotional, simplified and short-term insights.

Stated its importance, this communication about the industry and energy transformation is however complex, given the fact that the public is not homogenous: values and beliefs depend on generation, social status, material wealth and other factors. What is most important is to ensure the interaction and collaboration among NGOs, the media, scientists, universities, companies and ministries in the production and distribution of information explaining and promoting the sustainable energy transformation.

This task can be done through a variety of channels, including:

1. Media, which include traditional media (e.g., television, radio, newspapers) as well as social media platforms, best suited for the younger generations.
2. Educational campaigns, involving the production of educational materials (e.g., brochures, posters, videos) that can explain the benefits of the energy transition and how it will affect the public.
3. Community outreach, involving the organization of public meetings or events where people can learn about the energy transition and ask questions.
4. Government outreach, since Governments can also play a role in communicating the energy transition to the public through press releases, public statements, and other official communications.
5. Industry associations, which can also help communicate the energy transition to the public through their own marketing and outreach efforts.

It is important to consider the audience you are trying to reach and tailor your messaging and communication channels accordingly. It may also be helpful to work with experts in the field to ensure that the information you are sharing is accurate and complete.

Key Enabling Technologies for the Transition

The energy transition should rely on a number of strategies to reduce the GHG emissions, which primarily consists in reducing the carbon intensity of the system. In the following, we outline some of the key enabling technologies and strategies to implement the energy transition. An important assumption is made here, i.e. that the transition will be accompanied by a large-scale electrification of industry, mobility, and a large portion of many other final energy uses currently powered by other forms of energy. While this is a rather big assumption, it does reflect a widely agreed-upon outlook on global energy [9]. The key strategies and technologies for the transition are:

- **Renewable** [11] **and alternative energy resources**
  - *Solar energy*. Photovoltaic (PV) cells have seen significant improvements in efficiency and cost, making photovoltaic electricity competitive and in most cases cheaper than fossil fuels. PV has seen a large-scale deployment over the past decade, now contributing globally to more than 4% of the electricity production, and is now considered one of the pillars of the energy transition, expected to become the largest source of electricity at a global level by 2030. Thermal solar panels, on the other hand, have not seen a true large-scale diffusion so far. However, this would be an excellent technology to support the low-carbon transition for the large portion (now over 50%) of the final energy consumption dedicated to thermal energy uses (e.g. building heating).
  - *Wind power* is the other workhorse of the renewable energy transition. Economies of scale and the development of larger and more efficient wind

turbines has made wind power cost-effective and in most cases cheaper than fossil fuels. Wind power has steadily grown over the past three decades, now contributing to 7% of the global power generation, and is expected to grow further and to pair with PV as one of the pillars of the transition to renewable energy.
  - *Other renewables*. Hydroelectric power has been for several decades the only sizable renewable source for power generation, contributing to more than 15% of the global power generation. Hydropower is however nearing its natural capacity and further growth is expected to be rather limited. Other renewables such as geothermal or tidal energy can provide important contributions at the local level, where available and economically viable, but are not expected to contribute sensibly to the overall power generation.
  - *Nuclear power* is a carbon-free technology classified as an alternative energy source as it is non-renewable. The overall production has remained approximately constant over the past couple of decades and is currently providing about 10% of the global electricity—down from a share of almost 20% in the 1990s. While nuclear power has some characteristics that would make it a potential sizable contributor to the energy transition, it is now a rather controversial technology because of a number of concerns associated with safety, waste management, and commissioning [12]; for the same reasons, the cost of nuclear electricity has increased. The outlook for nuclear power is, according to most analyses, to keep contributing to the overall power production, but a massive scale-up is rather unlikely.

- **Smart grids**. The electricity grid is undergoing a major transformation, from a tree-like structure with unidirectional flows of energy from the power production plant to the user, to a web-like structure where producers, consumers, and "prosumers" are interconnected. This architecture will occur at different scales ("nanogrids" and "micro-grids"). Widely distributed integration of sensors and actuation devices, and the integration of the power grid with an information grid enables real-time monitoring and control of the network configuration, and thus very high flexibility. Data analytics and AI techniques are used to optimize the energy fluxes, maximizing the network efficiency, reliability, and robustness, thus reducing cost and improving the services for the final user. This flexibility enables the integration of an increasingly high quota of intermittent sources such as PV and wind power, as well as new management and business models to tailor energy demand (e.g. demand response) and favor supply–demand matching, thus reducing the need for large energy storage capacity in the network.
- **Energy storage**. While the flexibility of the emerging smart grids will help a lot in managing the challenges associated with the introduction of intermittent energy sources, storing electrical energy will in any case be necessary. Battery storage technology has advanced significantly, leading to a major cost reduction. For stationary storage (e.g. large scale storage dedicated to the power grid, or storage for the end user), there are no particular requirements on the storage capacity per unit mass or volume, as space and weight are not an issue in this case; the cost per

unit of stored energy is the most meaningful figure of merit for this technology—currently ranging in 2–300 $/kWh, projected to fall by a factor of almost two by 2030. Batteries are also very important for the growth of electric mobility. In this case, the specific capacity per unit mass and volume is very important, and lithium batteries are the technology of choice for the unbeatable fundamental properties of this element (size and electrochemical potential). While the technology is rather mature and the economies of scale have so far enabled a drastic reduction of cost, the massive scale-up required to sustain the growth of the electric mobility market is expected to be a challenge in terms of the ability of supplying the required critical or potentially critical raw materials, such as Li, Co, Ni [13]. However, the latest analyses demonstrate that this transition is actually feasible and sustainable; moreover, a number of variants are currently being studied to diversify the portfolio of available technologies, releasing the pressure on critical raw materials supply or shifting the requirements to less critical materials.

- **Electric mobility**. The sales of electric vehicles (EVs) are growing at an almost exponential pace. This has a number of benefits. Currently, about 30% of the global energy consumption is for transportation [6], and it is almost entirely supplied by oil-derived products; therefore, the introduction of EVs gives a strong push in the direction of the much-needed electrification of the energy system. Moreover, the electric vehicles are extremely efficient (over 70% grid-to-wheel energy transfer), and if the electricity mix fed to the vehicle includes even a marginal quota of renewable energy sources, the overall GHG emissions of the EV will be lower than that of a conventional vehicle powered by an internal combustion engine. In any case, EVs do not emit any pollutants locally and produce much lower levels of noise—leading to a much more livable urban environment. As for the electric infrastructure, this will require some important but feasible adaptation—including the installation of an appropriate network of EV chargers and in some cases the adjustment of the local carrying capacity; however, EVs are expected to bring enormous flexibility to the electric grid, acting as temporary energy storage while attached to the chargers, mostly lifting the currently expected requirements of stationary storage capacity. This solution rests on the fast developing ability of intelligently controlling the bidirectional energy flux to and from the vehicle connected to the grid (V2G and G2V, or vehicle-to-grid and grid-to-vehicle technologies). Finally, while the factory gate material intensity for EVs is typically higher than that of conventional vehicles, the life-cycle raw material intensity and GHG emissions are drastically lower. As a final note, we observe how the smart grid and electric mobility are expected to increasingly become a unified, synergistic system.
- **Carbon capture, storage and utilization**. Carbon capture technologies aim to capture carbon dioxide emissions from power plants and industrial processes. In CCS (carbon capture and storage), the CO_2 can then be stored underground—for example in exhaust oil and gas reservoirs, coal beds, deep saline formations. While in some cases this technology has been demonstrated, some criticisms have been raised both in terms of the economics and in terms of the long term stability and sustainability of this solution. A better solution is the carbon capture and utilization

(CCU), where the CO_2 can be utilized in industrial processes, or transformed into fuels. In particular, exploiting solar energy by using photocatalysis would create fuels that are carbon–neutral and thus sustainable. As fuels are impossible to substitute for a number of applications where high energy density is required, this technology is also a potentially important component of the energy transition, and a massive research effort is currently underway.

The transition of the industrial system towards more sustainable processes, in synergy with the transition of the energy system, relies upon some other key technologies:

- **Industrial digitalization**. The application of digital technologies such as big data, IoT, and artificial intelligence (AI) approaches has a demonstrated potential, still mostly untapped, for the optimization of the industrial processes and the improvement of efficiency.
- **Circular economy**. Recycling, refurbishing, and reusing products—in order of increasing energy and materials efficiency—are the fundamental key strategies in the circular economy, and have an enormous potential impact on improving the overall materials efficiency and energy efficiency, while simultaneously reducing waste and pollution. However, in most cases, industrial processes and products must be redesigned and the value chain must be rethought, in order to favor such mechanisms. While some successful cases are being implemented, no systematic approach has been defined yet, and circular economy seems to still be at an infancy stage.
- **Electrification of industry**. As previously discussed, electrification of as much of the final energy uses as possible is desirable, as it enables a number of important strategies that favor sustainability—most notably, the massive introduction of renewable energy sources. In this effort, the shift to electricity-powered processes in the industrial system is an important step, as over 15% of the global GHG emissions are currently associated with the energy needs of industry.
- **Advanced materials and manufacturing**. The development of new materials, especially in combination with manufacturing technologies such as 3D printing, robotics, and automation, can improve energy and materials efficiency while reducing waste and pollution. For example, particularly relevant for the industry are new carbon-based materials, advanced polymers, ceramic materials, etc., which can be used, in substitution of metals, for highly resistant, stiff, or temperature-resistant components, yet much lighter or smaller. 3D printing in particular, being an additive technology, can produce components directly in its final shape, drastically reducing waste.

On a final note, **artificial intelligence** is a pervasive, transversal and rapidly growing technology, which has already been applied in a number of energy-related and industry-related applications, but has the potential for impacting on all of the technologies described above in ways that are currently hard to predict, and yet very promising.

Economics of the Transition

The economics of the industry transition and energy transition are complex and multifaceted, however cost is undoubtedly one of the key indicators. The cost of some key technologies for the energy transition, such as photovoltaics and wind power, has been decreasing rapidly (over 85% and 50% in the past 10 years, respectively) and is now on average lower than that of fossil fuels. Some other, less mature key technologies for the energy transition, such as for example batteries and electric vehicles, are still rather high though rapidly decreasing as scaleup proceeds. None of these technologies seem to be economic bottlenecks for the energy transition. The cost of the energy transition is estimated in 2 to 4 trillion USD per year through 2040, a sustainable amount considering that the global annual GDP ranges around 110 trillion USD, and in any case several times less than the direct cost of inaction (caused by increasing natural disasters, management of large-scale migrations, etc.) as well as the drastic and irreparable change of the global climate equilibria. In addition to the direct costs, there are also indirect costs associated with the energy transition, such as job losses in the fossil fuel industry; however, the creation of new jobs (over 11 million new jobs globally in 2019) and economic opportunities in the clean energy industry is projected to fully counterbalance these losses.

Analogously, the cost of key technologies for the industry transition, such as 3D printing, robotics, IoT, automation, digitalization and the implementation of AI in the industrial processes, have decreased remarkably. The cost of the transition towards a deep decarbonization of the industrial system is expected to range around 4 trillion EUR per year through 2050, again a challenging but feasible achievement as for the energy transition cost discussed above.

The cost of both the energy transition and the industry transition should, however, be considered as investments, as they lead not only to environmental and social benefit, but also to substantial economic returns both in the short and in the medium-long term through reduced energy bills, reduced waste, avoided costs associated to GHG emissions, etc. For example, the direct savings from the energy transition have been estimated at 12 trillion EUR. In fact, the global investments in the energy transition are quite high and in large part coming from the private sector. For example, the investments on renewable technologies alone were estimated at around 370 billion EUR in 2022 (+20% since 2017), in large part from the private sector.

Another important aspect about the economics of the energy-industry transition is the emergence of new economic opportunities and new possible business models [14], which are expected to accelerate the transition and amplify the economic sustainability of this transition. Some of the most notable business models are:

- **Community-owned renewable energy**. This model involves the community, typically through a co-operative or non-profit organization, owning and operating renewable energy projects, such as solar or wind farms. The community can then benefit from the income generated by the project or receive a discount on their energy bills.

- **Power purchase agreements (PPAs)**. Under a PPA, a company or organization agrees to purchase electricity from a renewable energy project, typically a solar or wind farm, at a fixed price over a certain period of time. This allows the project developer to secure long-term funding for the project, while the company or organization can reduce its carbon emissions and potentially save money on its energy bills.
- **Virtual power purchase agreements (VPPAs)**. A VPPA is similar to a PPA but instead of purchasing electricity from a specific project, the company or organization purchases renewable energy certificates (RECs) to match their energy consumption. This allows them to support the growth of renewable energy and reduce their carbon emissions without having to invest in or own a specific project.
- **Energy as a service (EaaS)**. This model involves companies offering energy-efficient products and services, such as energy-efficient lighting or heating, as a service, rather than selling the products themselves. This allows customers to reduce their energy consumption and costs without having to invest in the products upfront.
- **Distributed energy resources (DERs)** are small-scale energy generation and storage systems, such as solar panels or batteries, that are located near the point of consumption. This allows customers to generate and store their own energy, reducing their dependence on the traditional utility grid and potentially saving money on their energy bills.
- **Smart grid-enabled business models**. Smart grids can manage the flow of electricity in real-time, enabling business models such as demand-side management and peer-to-peer energy trading.

Overall, while the economics of the industry transition and energy transition are complex, there is increasing evidence that transitioning to a sustainable energy and industrial system is both necessary and economically viable in the long term.

Policy and Regulations

A number of industrial and energy policies aimed at mitigating climate change have been proposed, with a wide range of degree of success. At the global level, the most notable efforts to achieve binding cooperation among countries have been the Kyoto Protocol and the Paris Agreements.

The Kyoto Protocol, the first international treaty to set binding emissions reduction targets for developed countries, which was adopted in 1997 and went into effect in 2005. The protocol identified targets for 37 industrialized countries and the European Union to reduce GHG emissions by an average of 5% below 1990 levels between 2008 and 2012, but these targets were not achieved.

The Paris Agreement, adopted in 2015, is the most recent international treaty on climate change. It aims to limit global warming to well below 2 °C above pre-industrial levels and to pursue efforts to limit warming to 1.5 °C. Countries are required to submit and regularly update their national climate action plans (Nationally Determined Contributions, NDCs). While the Paris Agreement has been more successful in engaging more countries and to pursue more ambitious emission reduction targets, the NDCs submitted by countries are still largely insufficient—even to limit warming to 2 °C.

Industrial and energy policies need to be far more ambitious and include a wider range of measures, such as carbon pricing, regulations, and subsidies for clean energy, to achieve the necessary emissions reductions.

Conclusions

What has been discussed up to now, makes quite clear that there is an urgent need to reduce greenhouse gas emissions in order to mitigate the dramatic, potentially catastrophic changes of climate and, consequently, of many global equilibria affecting natural systems as well as human social systems. While it is already too late to stop these changes, we can nevertheless slow them down and reduce their impact: for this, it is mandatory to act now.

The "emission gap" between the current emission path and the one needed for significant climate change mitigation must be filled by acting first and foremost on the energy system and the industry—i.e. the first (by far) and second contributors to global emissions (collectively contributing to about 80% of the total).

The energy and industry systems must therefore undergo a transition towards carbon-free technologies, and a reduced and more efficient use of energy and material resources—in other words, towards a more sustainable path.

Actually, this transition is currently happening, and it is happening at unprecedented speed with respect to previous transitions in energy and industry. However, it is not happening fast enough since, while current key enabling technologies are in most cases mature enough and economically convenient, there are barriers to this transition which are mostly of political, social, and ultimately cultural nature. Since many different factors are involved, considering all of them can result in an interdisciplinary approach able to provide a more robust and nuanced understanding of the challenges and opportunities involved, and helpful in identifying the most effective strategies to accelerate and complete the transition.

Because of the complexity of the involved systems and the complex nature of sustainability, one key aspect in transitioning towards more sustainable systems is to measure the status and speed of this transition. Quantitative tools and indicators are required, have been developed and implemented, and are now mature.

One additional element of complexity is the definition of the boundaries of the system. Sustainability, by its own nature, must eventually refer to the global scale. However, actual implementation occurs necessarily at the local scale, and one key and difficult challenge is to appropriately coordinate all actions at the different scales. The requirements and the status of the transition in different geographical areas are, in fact, quite diversified.

A pragmatic approach can consist in identifying an appropriate area of interest, large enough to enable synergies between different and complementary subsystems, but small enough to present homogeneous cultural characteristics and to enable efficient communication.

For the purposes of the Trieste Laboratory for Quantitative Sustainability (TLQS), we propose to focus on the Alpe-Adria Region, a cross-border area characterized by the presence of four nationalities and a variety of environments, from the Adriatic Sea to the Alps. In order to monitor the transition of industry and of the energy system in this area, and to propose actions to improve their sustainability, one will need to identify and critically analyze currently available quantitative sustainability indicators. These indicators can be evaluated locally on selected industrial activities and on the energy sector (e.g. CO_2 emissions, water consumption, Energy Return on Energy Invested, material intensity, use of critical materials, etc.). On top of that, possibly new relevant indicators can be developed. Obtaining (from the available literature) or calculating, updating, and monitoring such indicators, will allow a quantitative measure and forecast of the change rate towards a more sustainable industry and a more sustainable energy system. The focus will be on specific case studies, selected for their relevance and/or for the lack of current data, including photovoltaics, solar thermal, gasifiers, hydrogen economy, energy harvesting. Where needed, the researcher will use established methodologies (Life Cycle Assessment, Total Cost of Ownership Analysis, Levelized Cost Analysis, Criticality Analysis, Technical Economical Analysis, etc.) to determine unknown parameters for the calculation of the indicators.

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Part VII
Sustainability Frames, Social Equity and the Right to Sustainability

This part looks at the issue of sustainability from two different perspectives. The first one is that of social sciences, and the second one is dealing with legal sciences.

Social Sciences Perspective

The focus of the social sciences analysis is the very notion of sustainability, the implications of its polysemy, the impact that its different meanings have or can have on socio-economic dynamics. The research activities of this Group, coordinated by the researchers of the University of Trieste, will then focus on two aspects that, in the perspective of the TLQS, appear relevant: environmental policies and social and territorial inequalities.

While there are no shared perceptions of sustainability that can derive from a univocal theory of sustainability, there are public policies that have sustainability as their objective. Observing these policies analytically can help to understand what are the ideas—more or less explicit—of sustainability underlying public action. Studying policies means evaluating their theoretical framework, objectives, tools and results achieved. Often, the evaluation action is limited to the consistency between the results achieved and the objectives, without looking at the secondary effects. In terms of the environment, however, the secondary effects are important, because they determine the social desirability or otherwise of the transition toward sustainability.

Very often, in fact, environmental policies have not taken into account the effects on social and territorial inequalities. For this reason, a sentiment hostile to the transition toward sustainability has spread to large sections of the population that have not benefited directly and immediately from environmental policies. The issue of socio-environmental justice is not only an ethical-political tension, but it is also a reasoning on how to make the transition to sustainability desirable. For these reasons, looking at environmental policies with the lens of SDG 10 (reducing inequalities within and between nations) should allow us to adopt a critical eye, capable of combining sustainability and reducing social and territorial gaps.

Assuming this posture, the research project can aim to suggest to institutions and companies how to translate sustainability into policy designs that increase social and territorial cohesion in looking at public policies, the research project aims to:

- reveal, through frame analysis, the implicit meanings and theories of sustainability that underlie public action; it will start from the comparative analysis of the different NRPs adopted by European countries and will monitor the policy measures that will be implemented by the various countries to achieve the objectives and achieve the expected results indicated;
- assess the distributive and re-distributive effects of the interventions, both from an economic-social point of view and from a territorial point of view; in this way, policies for sustainability will be assessed by investigating whether or not they are capable of reducing social and territorial inequalities;
- identify those cases that appear to be more effective in achieving sustainability objectives and at the same time reducing inequalities. Starting from the study of the most promising cases, policy proposals will be formulated through co-planning workshops with institutions, businesses and civil society.

The social sciences perspective is discussed in three different chapters: Chapter 9, *Framing sustainability,* by G. Carrosio, Chap. 10, *Natural parks and sustainable development: a theoretical study*, by F. Silvestri and Chap. 11, *The 'position' of social sciences in sustainability issue. The emblematic case of energy transition*, by Giorgio Osti.

Legal Sciences Perspective

SDG 16 is deemed to be the legal heart of the objectives. Indeed, the law always and everywhere shapes organizations, practices and destinies. Through the lenses of the law, it is possible to better grasp factors, directions and results of any process aiming at being sustainable, together with its interrelations with the diversity of cultures and legal traditions, both formal and informal, that inhabit the planet.

The same legal lenses allow one to understand:

(a) how debates, efforts and initiatives on the quantitative measurement of sustainability—starting with the SDGs—deeply shape the agendas, rhetoric and practices of a plurality of actors, ending up by directing and explicitly, or implicitly, regulating expectations, actions and claims regarding sustainability;
(b) that there is no *ideal model* of sustainable development, nor an *ideal model* of a just society.

There is no model of development and of society that can do without nourishing strong bonds of compatibility with the socio-economic, cultural and legal reality on which any model is exercised or wants to affect.

On these premises, the legal research within the TLQS should be carried out with the aim to evaluate:

- which rules are the most suitable for encouraging operationally virtuous behavior on the sustainability front, in matters, e.g., of food, drugs, trade and international finance;
- the optimal dimension of the specific rules on energy production/distribution/consumption, in light of their impact on the social fabric and on the production- and supply-chains, both domestic and global;
- the social costs of sustainable rules—who they favor, who penalize, where, in what time range;
- the design of liability rules for those who favor global warming as well as for the actors who, at the international level, disregard or do not keep up the promises they make.

But preliminary to all these researches, there is the problem of the legal dimension in which the same quantitative measurement of sustainability operates. As an initiative aimed at quantitatively determining sustainability objectives and results, the SDGs have had a powerful impact on the expectations and behaviors of a plurality of actors (from states to NGOs, from multinationals to citizens), determining the horizon and contents of the legal discourse about the rights and obligations in terms of sustainability. The SDGs are in and of themselves a factor in the production of rules. This is why there is the need to analyze and make clear who are the actors who claim to, or actually pursue the sustainability goals, what legal model do they presuppose (respectful of existing diversities, or purportedly universal and actually shaped along the Western lines, or even along the common law ones only). Precisely, because the SDGs are implicit rules-makers, it will be crucial to study which legal processes they trigger and which legal effects they determine, also in order to monitor how close or distant these processes and effects are with respect to the original ambitions.

Merging scientific and dissemination goals, the legal branch of the TLQS should also engage in the following activities:

- a series of Workshops centered on the legal-quantitative dimension, with the participation of relevant actors, at domestic and global level, in the construction of sustainability indicators and parameters;
- a Summer/Winter school involving jurists and other social scientists of international standing, and open to doctoral students, post-docs, researchers, staff of national and international agencies and NGOs—and encouraging the participation of non-Western teachers and attendees;
- the dissemination of the scientific results through (open access) publications and reports, and the organization of dissemination courses on sustainability for civil servants, media and business professionals.

The legal sciences perspective is discussed in Chap. 12, *The Law of Sustainability,* by Mauro Bussani.

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Chapter 9
Framing Sustainability

Giovanni Carrosio

Since the promulgation of the 2030 Agenda for Sustainable Development, adopted by the member states of the United Nations in 2015, the concept of sustainability has become pervasive in society. Most social organizations, businesses, institutions, political forces, associations, movements recognize themselves around the idea that sustainability is a goal to be hit. Businesses and public bodies are directing their social and environmental balance sheets, their development programs and plans on the basis of the indications that come from the thematic objectives set by the United Nations. No development strategy could therefore disregard sustainability objectives. Paradoxically, the major limitation of the concept of sustainability lies precisely here. As the French economist [1] claims "a key that opens all doors is a bad key", so a concept that satisfies everyone, that brings everyone to agreement, risks being a bad concept, a concept incapable of uniquely move to action. Star and Griesemer [2] would say that sustainability is a *boundary object*. Boundary objects, according to these authors, are projects, ideas, maps, texts, concepts "plastic enough to adapt to the needs and constraints of the various parties that use them, but robust enough to maintain a common identity between the different ways of usage. They are loosely structured in common usage and become strongly structured in the use of individual parts. They can be abstract or concrete. They have different meanings in different social worlds, but their structure is common enough to more than one world to make them recognizable, a means of translation" between different social worlds.

The different uses to which the concept of sustainability lends itself, allow us to deduce how large the semantic field of reference is, in which there is a common nucleus such as to ensure that each of us, when he hears sustainability evoked, understands what the boundaries of meaning are within which it is located, but at the same time plastic, malleable enough to ensure that each of us uses sustainability in a specific way, defines its own boundaries, translating it into actions, policies, projects

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that can also be radically different from those proposed by others [3]. There are therefore different social worlds, which assign changing attributes to sustainability.

Sustainability in Frames

The social sciences have tried to explain this plasticity through the theory of frames. Frame refers to the cognitive process of the social construction of meanings [4]. The frame is an interpretative scheme that simplifies and condenses external reality, attributing a particular meaning to objects, events, situations, experiences and actions. Through the frames, individuals codify reality and filter it, bringing it back to a recognized interpretative key. It is within these frames of meaning that everyone signifies the concept of sustainability, linking it to world visions, cultural assumptions, political wills, ideologies that attribute a coherent and specific meaning and move its boundaries within the vast semantic field.

The analytical posture of framing looks at how different subjects construct the concept of sustainability socially, as the process takes place through which single individuals, groups of people and organizations create its shared meaning. In this way, they can describe reality and organize its experience within a frame of meaning that guides individual and collective action. This frame of meaning allows us to arrive at particular definitions on the causes of a problem, on the possible solutions and strategies to be pursued to solve a problem or to reach a desired state. Frames can also be used instrumentally, to unite more people around ways of understanding a concept—in our case sustainability—that benefit specific meanings, values, beliefs, interests rather than others. The alignment around a frame—in the literature it is called the "frame alignment process"—can be a more or less explicit and intentional negotiation process, in which different subjects come to share the meaning to be attributed to sustainability. This process of alignment builds increasingly close relationships between different individual and collective orientations, interests, values and beliefs. It is therefore an active, dynamic, even conflictual process which implies an agency on the part of different subjects, but which leads over time to converge on a single interpretation scheme which facilitates unitary collective action.

We can identify two very general frames within which the boundary object sustainability is filled with meanings. These are two very broad worldviews, within which there may be various specifications, and performatives, capable of influencing the ways in which people think and act on the relationship between man and nature, between society and the environment. These two visions are: anthropocentrism and ecocentrism [5]. Anthropocentrism is the founding vision of Western thought. It is based on the idea that rationality constitutes the basis of morality and that only rational beings, men and women, can be granted a moral status. This vision places man above and outside nature and conceives an interest in protecting the environment only when the relationship between environmental degradation and a reduction in people's quality of life is evident. In sociological theory, we can include within this way of looking at the society-environment relationship the paradigm of human exemptionalism (HEP), which according to [6] accompanied the development of sociology. It considered the human being as endowed with exceptional characteristics that could make him exempt from the laws that regulate the life of living beings on the planet. At the center is man, the ability to manipulate the environment and to progress in the development of techno-science in order to determine one's limits. The ecocentric vision, on the other hand, starts from the idea of interdependence and holism between man and nature and for this reason calls for a radical rethinking of the ethical assumptions of the man-environment relationship. There is no separation between man and nature and there is no moral superiority of the human species over the others. For ecocentrism, the environmental crisis originates precisely from a vision of man's superiority over nature, which has morally legitimized a manipulative and destructive attitude on the part of man. The conjunction between ecocentric visions and sociological analysis is found in ontological-realist approaches, where the existence of fundamental, sociophysical and ecological phenomena is postulated, which cannot be measured or experienced directly, but which represent the biophysical basis of the structure of society [7]. At the center is the relationship between man and the material substrate, where the latter determines the limits of action and must be preserved in order to allow society to progress in harmony with nature. These two visions of the world, within which there are different nuances, imply different interpretations of the environmental crisis and therefore different attributions of meaning to the concept of sustainability. We are therefore dealing with two frames, or rather two masterframes, two very broad and inclusive frames from which other frames descend with more specific boundaries of meaning (Table 9.1).

Starting from these two masterframes, different positionings can be identified along the anthropocentrism-ecocentrism continuum. Each of these, through the alignment processes, builds an internally coherent idea of sustainability, with clear boundaries with respect to other ideas of sustainability [8] has distinguished, for example, weak and strong models of sustainability.

Table 9.1 Masterframes of sustainability

Anthropocentrism (human exemptionalism)	Ecocentrism (materialism)
Humans are the managers of the biotic community	Humans are part of the biotic community
The interests of humans define ethical principles	The good of the biotic community defines ethical principles
Humans have priority, but there is a limit beyond which environmental damage cannot be justified	Humans do not have the prerogative of using the environment in ways that counteract the welfare of other species
Environmental problems are viewed in separate ways	Environmental problems are tackled in a systemic logic
The limits are a function of the capacity for technological innovation	The limits are a function of the quantity and quality of the material resources available
Focus on man's ability to manipulate the environment	Focus on the preservation of the material-ecological substructure

Sustainability Frames: Very Weak, Weak, Strong, Very Strong

Based on Turner, we propose a schematization of the sustainability frames capable of recognizing the main families of ideas that animate the debate today (Table 9.2).

There are underlying characters that distinguish these frames. The element on which there are very different evaluations is the substitutability of natural capital. The idea of substitutability was born with [8], who tried to innovate the definitions of sustainability: he argued that it was important to leave future generations the opportunity to live in a situation of well-being. That is, leaving them a constant quantity of resources (natural capital + artificial capital). But how much physical capital and how much and which natural capital? In what proportions? The availability of natural resources is a central but debated issue. Depending on how we answer the question, we place ourselves in a sustainability frame. Here too we have a continuum of positions, ranging from those who believe that natural capital is perfectly replaceable with artificial capital, to those who believe that no portion of nature can be replaced,

Table 9.2 Frames of sustainability

	Anthropocentrism		Ecocentrism	
	Very weak	Weak	Strong	Very strong
Substituability	Perfect	Managing of the resources according to their sustituability	Safeguarding resources that are predominantly non-replaceable	Absolute irreplaceability
Causes of unsustainability	The freedom of enterprise is hampered by constraints and rules	Modernization deficit	Capitalistic accumulation	Instrumental rationality
Ethic	Rights and interests of living beings	Intergenerational equity	Collective interests coincide with the preservation of the ecosystem balance	Nature has intrinsic value
How to achieve sustainability	Maximization of GDP and technological innovation	Decoupling growth and use of non-replaceable resources	Redistribution of wealth and collective management of common goods	Reduction of scale and simplification of society
Reference indicator	GDP	Genuine Progress Index	Inclusive development index	Ecological footprint
Ideology	Postnaturalist transhumanism	Sustainable development	Ecosocialism	Degrowth or Deep ecology

those who argue that the next generations should inherit the entire stock of environmental resources present, and those who argue that the important thing is that the next generations are left with an aggregate stock (natural capital + artificial capital) equivalent to today's.

For the latter it is possible to compensate for a lower amount of environment with the increase of roads, machinery, money. Or again, it is possible to replace natural ecosystem functions with artificial ecosystem services, the result of technological innovation. If we think we have to bequeath the totality of natural capital we must preserve for future generations the same stock of pollinating insects that exist now; if, on the other hand, we opt for total replaceability, the decrease in insects due to the massive use of pesticides and global warming is not important, because we are confident that man will be able to design and build technological innovations capable of replacing ecosystem functions of insects (Table 9.3).

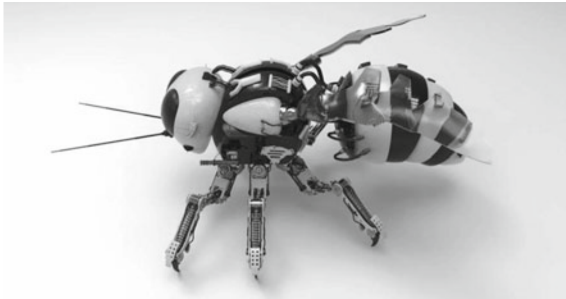
Very weak sustainability is based on perfect substitutability between different forms of capital. Very strong sustainability, on the contrary, postulates the impossibility of replacing different forms of capital. The middle positions, on the other hand, argue that there is no such thing as perfect substitutability, that certain stocks of natural capital cannot be replaced by man-made capital, and that some ecosystem functions and services are essential for human survival as services of life support. Substitutability is assessed according to a rational cost–benefit criterion. From this perspective, for example, the cementing of agricultural land can be accepted, if one is able to develop forms of hydroponic agriculture (a method of cultivation outside the soil. The plant is irrigated with a nutrient solution made up of water and compounds chemicals necessary to provide all the essential elements for normal mineral nutrition).

From the positioning with respect to the substitutability of natural capital, a series of ideas on sustainability derive, inherent to the causes of the environmental crisis, to possible solutions, to the relationship between man and nature, to the indicators that can measure sustainability. These are internally coherent systems of thought, which tend to manifest themselves as *ideologies of sustainability*.

The Very Weak Sustainability

The very weak idea of sustainability foresees the perfect and infinite substitutability between natural capital and artificial capital. His techno-centric tension leads to prefer technological objects to nature. They are in fact programmable and controllable, while the laws of nature and the functioning of ecosystems make man live in uncertainty and force him within limits. Hoping for the progressive replacement of nature with artifacts, the issue of sustainability is declined as the construction of policy and market conditions to ensure that the process of technological innovation is fast enough to deal with any environmental problems that may arise as unintended consequences development wishes. For this to be possible, it is necessary to push on the growth of the Gross Domestic Product (GDP) and on the concentration of wealth

Table 9.3 Natural capital (bees) and artificial capital (pollinator drones)

Natural capital	Artificial capital
	

in the large urban agglomerations, where research centers and technological companies are concentrated. Thanks to the spatial concentration of investments and the accumulation of knowledge, continuous solutions can be developed. In this frame, urbanization and concentration are tools for the artificialization of society, which generate an environment in the image and likeness of man and therefore recognizable and controllable. It is also through the market and the freedom of enterprise that it is possible to create systems favorable to innovation. At the heart of very weak sustainability is therefore the idea that nature, non-sentient beings, have no rights and have no value in themselves. Nature has an exclusively instrumental value with respect to satisfying human needs. This also applies to future generations: the rights and interests of contemporaries prevail. This frame is structured on a faith-based attitude towards technology and man's ability to continually find solutions to the problems he faces. It is so permeated by an attitude of faith that he hopes that one day humanity will be able to completely free itself from nature and manage every aspect of life on earth in a controlled way. We can include in this frame those who believe that in the future the climate can be controlled and managed through technological systems based on geoengineering [9]. In its most extreme version, there are those who believe that the resources available to man are infinite, because the universe is infinite: if one day the earth is inhospitable to man, we will still have found a way to migrate to other livable planets [10]. The ideology that supports this frame is postnaturalist transhumanism, a movement that supports the use of scientific and technological discoveries to increase man's physical and cognitive abilities, in view of a posthuman and postnatural transformation, where artificial intelligence and genetic and robotic technologies will be able to manage socio-technical systems and the progressive transformation of the natural environment into a technological one [11].

The Weak Sustainability

Weak sustainability postulates a partial substitutability between natural and artificial capital. There are ecosystem functions that must be protected, because today we do not have the technological capacity to deal with their possible impoverishment. Sustainability is built starting from a careful management of natural resources, evaluating the costs and benefits of actions and projects that can cause environmental damage. In general, the negative externalities of growth are recognized, which produce a decline in the quality of life and feedback on the efficiency of economic and production processes. We must therefore be careful not to deplete resources that we are unable to replace, also to guarantee option rights for future generations and continuity of levels of well-being. It is a vision still entirely within the market economy, convinced of the possibility of making capitalism ecological, by decoupling growth and resource consumption, thanks to technological innovation and the circularity of production processes. The problem is therefore not growth, but the quality of growth. It is not the existence of a limit to development, but the ability to continuously shift it over time thanks to technological innovation: produce and consume more, reducing the energy intensity of production and its secondary effects. For this reason, the reference indicator of this sustainability model is the Genuine Progress Indicator (GPI), which measures economic growth by subtracting all its secondary effects from the accounts. It is through the tools of the market economy that it is believed that the ecological transition can be accelerated to achieve a sustainable structure: incentives, regulatory systems, investment in technological innovation, supply and demand mechanisms based on the economy of agreements, together with bans and forms of environmental protection for endangered species and ecosystems. By the economy of agreements we mean the systems of exchange of goods that enhance the reputation of products and of those who produce, for example through environmental certifications. According to this approach, certification should generate preferences that lead to competition between companies to position themselves on green markets. The mechanism should make companies transition towards more sustainable production models. In the frame of weak sustainability, in assessing the value of the environment, one looks not only at the material instrumental dimension, but also at the immaterial instrumental dimension, linked to people's perceptions regarding the environment, healthiness, the beauty of nature, to walk in an environment rich in natural resources. However, the instrumentality and centrality of the human condition remains in the face of the need or otherwise to protect the environment. The most important European environmental policies are based on these principles, which respond to the dictates of ecological modernization: a mix of regulations and incentives to change the behavior of businesses and households, so that they increasingly adopt sustainable technologies and virtuous lifestyles. The idea of sustainable development promulgated by the main international organizations, starting with the Sustainable Development Goals, has many overlaps with this sustainability frame.

The Strong Sustainability

Looking at sustainability from a strong perspective means assuming the limit of natural resources and their reproducibility as a perspective within which to build social well-being. The perspective shifts from anthropocentrism to weak ecocentrism, not so much because it is believed that there is no ontological distinction between man and nature, but because the materiality of the environmental crisis is placed at the centre, as the result of the overcoming by the capitalist system of the limits of production and reproduction of natural resources. These positions on sustainability are therefore critical not only of the development model, but of the underlying principles that guide capitalist economies: in particular, the principle of capitalist accumulation, which leads to a continuous growth of the process of transformation of nature into commodities and the its pervasive expansion in space.

Natural resources are mainly non-replaceable: to use them sustainably it is necessary to change production relationships and de-commodify nature, which must be managed as a common good.

Among these ideas of sustainability there is space for eco-Marxist theories linked to political ecology. Unlike traditional Marxism, they innovate on the point of trust in progress and technology: historical Marxism is imbued with positivism and anthropocentrism, while eco-Marxism recognizes the limits of the laws of ecosystems, within which human experience it can progress, moving from a quantitative view to a qualitative view of development [12]. This vision of sustainability is attentive to the distributive aspects of wealth and critical of the new forms of green economy induced by environmental policies, which it considers as functional and instrumental in generating a new cycle of capitalist accumulation based on sustainability, as a discourse of legitimation of the dominant system. In its qualitative meaning of development, the inclusive development index finds space as an indicator of sustainability. In its formulation, in addition to GDP, it takes into consideration inclusion, intergenerational equity, sustainable management of natural resources and the expectation of a healthy life. This index includes criteria of social and environmental justice, even if the measurement of economic growth is not completely abandoned. Among the varied positions that refer to strong sustainability, we find the strand of environmental justice [13], which focuses on the social and territorial distribution of environmental bads and goods as an outcome of projects and policies for sustainability. In this case, there is a strong focus on social sustainability and on the possibility that environmental policies can be a vehicle for promoting social justice.

The Very Strong Sustainability

The very strong conception of sustainability focuses on the concept of limit and postulates the incompatibility between the paradigm of growth and the finiteness of environmental resources. There can be no sustainability within an economic system oriented towards the growing consumption of resources. The assumption of the limit to growth, which today appears radical among the ideas on sustainability, was for several years a concept at the center of mainstream thought on the environmental crisis, which gave shape to the famous 1972 report on the limits to growth drawn up by MIT for the Club of Rome. There was the idea that states should regulate capitalist economies by planning the balance between the economy, demography and finiteness of environmental resources and it was proposed to overcome the growth paradigm towards the achievement of a stationary state (Daly, 1974). In more recent years, the criticism of growth comes from approaches that take positions antagonistic towards the dominant economic and political system. To name a few: the political ecology of Andrè [14], the deep ecology of Arne [15], the degrowth of Serge [1].

These thinkers are not united only by the critique of capitalism and growth, but by the questioning of instrumental rationality, as a myth resulting from the Enlightenment "thought in continuous progress" [16]. EIt is in man's desire to dominate nature and to free himself from its constraints that the environmental crisis originates. Sustainability, then, must be pursued by re-incorporating human communities into the functioning logic of ecosystems, through appropriate technological development, which does not produce artificialisation, but sets the co-evolution link between society and the environment back in motion. To do this it is necessary to reduce the scale of technologies and reduce social complexity, and at the same time to recognize the entitlement of nature to rights. The comparatist legal school, which investigates the affirmation of environmental protection in national constitutions, has produced an interest in the subjective rights of nature, in an attempt to subjectivize natural elements from a juridical point of view, in order to make them interacting allies to empower human actors in the struggle for sustainability. In this regard, [17] speaks of ontological struggles, as they are based on a denaturalization of Western dualisms in favor of indigenous perspectives according to which all living beings always exist in relation and never as objects or individuals.

To measure sustainability, one must take into account the encumbrance of human activities on the planet. The reference indicator is therefore the ecological footprint, which is used to monitor the use of the ecological resources available on our planet by individuals, cities and nations up to all of humanity, depending on the level of aggregation at which it is calculated.

Humanity, therefore, must drastically reduce the consumption of resources, seeking forms of wish fulfillment that go in the direction of conviviality, frugality, gift economies.

In Summary: The Distinctive Elements of the Sustainability Frames

To summarize, we can identify the following distinctive elements of the different sustainability frames, organized in continuum within which the different positions find space:

– exemptionalism and human rights—ecosystem relationships and the intrinsic value of nature;
– science and technology as a solution—science and technology as a problem;
– artificialisation of ecosystem services—conservation of ecosystem services;
– unlimited development—the limits of development;
– capitalism and the market as a solution—capitalism and the market as a problem;
– centrality of the present generation—centrality of future generations;
– presence of many solvable environmental problems—presence of a systemic environmental crisis.

The four visions that we have schematized, and many nuances that we have left out, sometimes collide and other times coexist side by side in our society. They often hybridize and mix up. The policies, with respect to the quadripartition and the synthesis continuums, are contradictory. If we analyze the individual environmental and sustainability policies, we can place each one in different frames. From geoengineering policies on carbon dioxide capture in the subsoil, through the creation of biodiversity conservation areas, to the promotion of lifestyles aimed at reducing consumption. However, this variety must not mislead: most of them, invoking sustainable development, certainly fall within the context of weak sustainability [18].

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Chapter 10
Natural Parks and Sustainable Development: A Theoretical Study

Francesco Silvestri

Abstract We analyse the role of Natural parks in Europe and Italy in mediating among diverging interests about the use of natural resources. Using standard economic concepts, we highlight that natural parks provide different types of goods and act as place-based institutions for sustainable development.

Introduction

Established mainly with aesthetic and recreational purposes between the end of the XIX and the beginning of the XX century, during the 1950s the so called scientific and conservationist approach highlighted their nature preservation role, a kind of open-air science museums.

Nonetheless, during the 1960s parks are progressively alleged to become an instrument to increase wellbeing of local communities through natural capital interpretation. Due to the work of scholars and practitioners such as Valerio Giacomini and Robert Poujade, a new "systemic approach" guided the studies on natural parks, oriented to consider a park as a complex territorial system carved by man's activity through the centuries, and aimed to pursue sustainable development. This is the framework for the establishment in 1967 of early Regional Parks in France [13].

From this perspective, the park is a tool to recompose the latent conflict between the specific objectives of the economy (growth of average incomes and employment at the local level), the society as a whole (equity, respect for cultural and gender differences, production of social capital and mutual trust) and ecology (protection of biodiversity and—in recent years—fight against climate change).

Our contribution proposes an interpretation of the activity of protected areas in Europe and Italy to achieve the objectives of sustainable development, referring to theoretical elements of environmental microeconomics. In section "Introduction" we recall the notion of Sustainable development and associate it to the activity of

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natural parks; in section "Natural Parks and Sustainable Development", we provide a taxonomy of the type of goods and services provided by natural parks; in section "Park Supplying Goods: Searching for a Taxonomy" we focus on the role of natural parks as a place-based institution. A final section recaps the main issues and concludes.

Natural Parks and Sustainable Development

The notion of sustainable development is ambiguous. In the famous *Blueprint*, David Pearce counted as many as 25 formulations of sustainable development [12], a number in the meantime grew exponentially and which today finds its most extensive treatise in the publication of the 17 Sustainable Development Goals (SDGs) by the United Nations.

This plethora of definitions is suggestive not only of the complexity of the subject, but also of its intrinsic contradiction, generated by the need to include heterogeneous elements in the same concept: development, which connotes change, modification of the *status quo*, dynamics; and sustainability, which refers to conservation and maintenance of integrity [6].

One of the best-known and most quoted expressions of sustainable development is the one proposed by the Brundtland Report and adopted by official documents in 1992 Earth Summit in Rio de Janeiro, according to which sustainable development is "(…) development capable of satisfying the needs of the current generation without compromising the meeting the needs of future generations" [16]. The Report highlights the existence of three components in sustainability,: the economic one given by the ability to generate income and employment in a long-lasting and satisfactory way; the ecological, consisting in the need to keep ecosystem's ability to provide usable resources and services; the social one, concerning equal opportunities between generations, guarantees of safety, health and education conditions for citizens, respect and equal dignity for each culture.

The coexistence of the three dimensions, each with a system of values and an objective function in mutual potential conflict, generates an intrinsic tension, which also explains the difficulty in pursuing sustainable development. The profit maximization goal, typical of the economic system, can have negative impacts on the ecosystem, through the excessive withdrawal of resources and the generation of waste, and it can be in contrast even with the objectives of social equity (think to the existing contrast between technological efficiency and basic employment, generating the progressive marginalization of large segments of manpower). The objective of protecting the environment and biodiversity, on the other hand, can conflict with established social rules or traditions [14].

Sustainable development is the attempt to reconcile the conflict between previous sectoral objectives, allocative efficiency, distributive justice, and sustainable dimensional scale [3], in the will to find a balance between the three dimensions, overcoming the latent tensions. The "triangle of [8] allows the visualization of the issue:

Each vertex of the triangle corresponds to a maximum fulfilment of the component (100%) and of the corresponding objective, while each shift from the pure positions along the axes implies a trade-off between one objective and another. The concept of sustainable development consists precisely in the renunciation of the full maximization of each dimension, in favour of a compromise equilibrium, represented in the graph by the area enclosing the incenter of the triangle.

Once transposed to protected areas, Munasinghe's triangle allows to understand that a park is a complex reality in which divergent interests seek a composition under the concept of sustainability: the trade-off between ecological and economic objectives takes shape whenever limitations on production activities with a high environmental impact are enforced (for instance, the ban on turbo-blower rakes for collecting clams in the lagoons of the Po River Delta Park), but also—in the opposite direction—when visit to environmentally sensitive areas within a natural park are allowed. The trade-off between economic and social objectives occurs whenever we assist to the employment of social workers in the maintenance of the park (such as Aspromont National Park at the end of the 1990s) or to the current support given by many protected areas to the establishment of "community cooperative", a third sector firm with social purposes, including the maintenance of essential citizenship services for local communities subject to market failure. Finally, the trade-off between environmental and social objectives is highlighted in the management of hunting activity, allowed limitedly to residents in the "contiguous areas" of many parks as required by the Italian Framework Law on Protected Areas (Law 394/1991).

Figure 10.1 indicates the area closest to the lower left vertex as a representation of an under-utilization of natural resources, which implies the possibility of expanding the withdrawal with no risks in terms of non-sustainability; on the contrary, the upper vertex represents situations of over-use of natural capital, so that for the purposes of sustainability environmental protection interventions, limiting the purely economic objectives, are required.

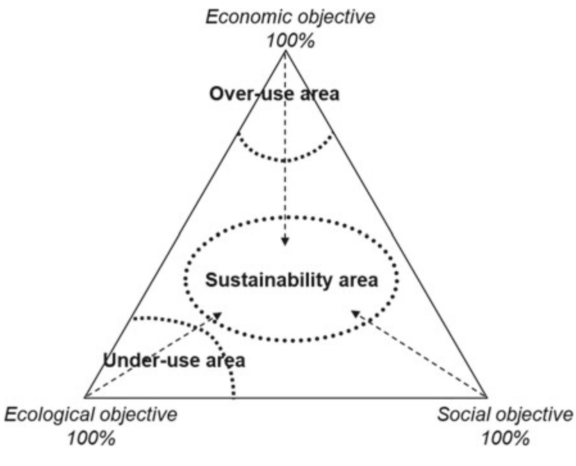

Fig. 10.1 Sustainable development and the Munasinghe triangle

To be achieved, sustainable development requires cooperation between subjects searching through confrontation the way to overcome conflicting interests, in the spirit of maximizing overall social welfare. This aspect recalls and substantiates another well-known theoretical model to solve contractually the issue of externalities and proposed originally by Ronald [2]. The Coase theorem, currently a cornerstone of environmental economics, claims that it is sufficient an ex-ante (even random) assignation of the property rights, to achieve the social optimum level for the use of a resource. As a matter of fact, the negotiation between the subjects interested in a rival use of the asset (and the consequent transfer of rights from the legitimate holder to the counterpart)—to define the equilibrium of the system, i.e. the desired level of environmental externality, in this case the exploitation of the natural resource and the related costs and benefits.

A Park, in this sense, can be viewed as a place where to negotiate and mediate among diverging interests, where the local community and the scientific one find the desired balance between the two model extremes represented by the 100% conservation of the natural capital and the unconstrained localization of any anthropic-productive activity. If so, it is not surprising that integral protection is absent or restricted only to small areas, particularly sensitive from the point of view of biodiversity, in most of Natural Parks in Europe.

This equilibrium includes levels of tangible and intangible compensation among stakeholders. When the property right *à la* Coase is assigned to nature protection supporters, negotiation can open to the implementation of activities with non-null environmental impact, such as tourism both sustainable (tour-guide for hikers, bird-watching) and conventional (the numerous ski-lifts present in almost all mountain parks), or extracting and polluting activities: this is what happens with royalties paid by Italian National Oil Company for oil drilling in National Park of Val d'Agri or, until few years ago, with compensations for emissions paid to municipalities of both regional Po River Delta Park (in Veneto and in Emilia-Romagna) by the coal-fired power plant in Polesine Camerini.

In a highly anthropized environment such as the European territory, a protected area can easily be established in places with a high use of resources, for example for agricultural purposes; in similar cases, one can imagine a property right assigned to the farm, who can evaluate compensations for adhering to agri-environmental agreements and reduce the impact of its activities.

Despite the negotiating opportunities highlighted by the Coase Theorem, the process is seldom put into practice, and the establishment of a natural park is mostly enforced by law. The reason is already present in the original work of Coase, who claims that the presence of transaction costs, often particularly high due to both the number of subjects to be involved in the negotiation and the high degree of internal conflict, generates the failure of the process. Nonetheless, specific practices are implemented in the field of environmental protection to reduce transaction costs: in France, the negotiation preceding the establishment of a protected area is followed by a facilitator (the *Animateur*), appointed by the government to increase the possibilities for dialogue between the parties and overcome the reasons for conflict; in Italy and other European countries, Local Agenda 21 initiatives are used for the same purpose.

Park Supplying Goods: Searching for a Taxonomy

Sustainable development relates to thicken relationships between agents, shifting the focus from products to goods. But what kind of goods? The economic taxonomy for goods is based on the dual criterion of rivalry (in consumption) and excludability (from benefits); the former triggers whenever the enjoyment of a good by the consumer generates a simultaneous reduction in the possibilities of consumption for other agents; the latter remarking that it is possible excluding consumers from the benefits once a good has been made available (Fig. 10.2).

According to economic theory, lowest levels of both rivalry and excludability define a (pure) public good, while the opposite (i.e., highest levels for both criteria) identifies private goods.

Differing from the previous categories, we find two types of collective goods: *commons*, characterized by high rivalry and low or null excludability, and club goods, described by high excludability and low rivalry. While *commons* distinguish free access resources, club goods are commodities generating utility and positive externalities only for particular categories of users, so that outsiders have no interest in taking advantage of the free access.

A fifth kind of goods is given by merit goods, equally possible for both private and public goods, whose relevant feature is being subject to systematic under-rating in the utility by consumers. Since they are not willing to pay the price requested by the market, to avoid the market failure the provision of this type of goods is ensured by public sector (paternalism).

Natural parks provide all previous kind of goods according to different conditions. If the supply of public goods such as natural landscape or biodiversity is straightforward, living apart the issue if proposed examples have more nature of public or

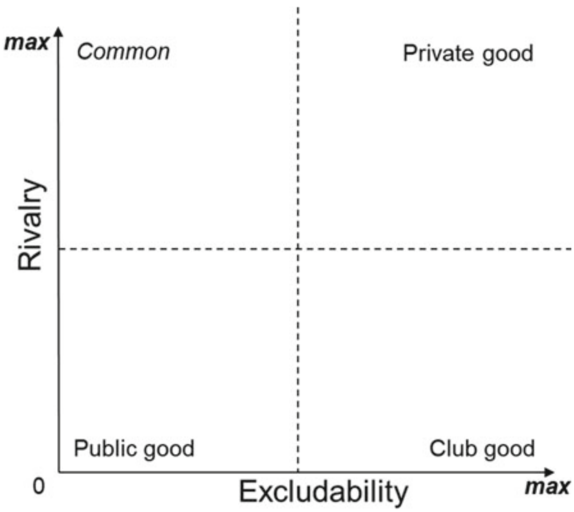

Fig. 10.2 The different kind of goods according to rivalry and excludability

merit good,[1] we can point out that many private goods, such as the management of an accommodation site (among the others, Peak National Park in England) or of an "adventure park", i.e. that particular kind of entertainment related to walking and climbing the trees (Regional Park of Colli Euganei in Italy) are sold in the market by park authorities. But the same happens for commons (the harvest of firewood from forest maintenance in many mountain parks) and even for club goods (for instance the management of nursery schools for local communities by Italian National Park of Cinque Terre in the first decade of 2000s).

Nonetheless, the ability of local agents to collaborate and produce collective goods is considered a distinctive element for development. Collective goods provision expresses a high level of self-organization by local communities, ability to recognize and fulfil own specific needs, being the natural playing field for place-based institutions.

Governing Collective Goods: The Natural Park as a Place-Based Institution

Until the 1990s, the theoretical models addressing collective goods basically belonged to two categories. The first one following and developing the intuition of Garrett Hardin, whose seminal article postulated the inevitable exhaustion of the environmental resource due to time inconsistency: each user gets a direct and immediate benefit and bears a shared and delayed cost from exploitation (whole benefit today, divided cost tomorrow), which favours over-use and exhaustion [7].

The second dates to [4], who achieved the same result as an application of the Prisoner's dilemma model to the collective goods issue, so that the appropriation of the good is represented as the dominant strategy of a non-cooperative game with complete information: the rational agent is obliged to anticipate the defection, and the non-cooperative equilibrium self-impose.

It takes almost two decades before Elinor Ostrom, first and until 2019 only woman Nobel laureate for Economics, proposes a new solution to the so-called "tragedy of the commons". Natali and Silvestri [11] starts from the empirical observation of local communities that self-designed long-lasting institutions to successfully govern the use of natural resources.

Ostrom remarks the high level of self-organization expressed by local communities in the production of collective goods: the ability to recognize own specific needs, and to exploit opportunities peculiar to the place, the need for coordination, the acceptance of information and implementation costs to bear [10].

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[1] It is known the opposition of [5] to the public funding of US Natural parks: "*Park's entrance (…) are few (…), so that it is easy setting up toll barriers and collect entry fees. If audience wanted this kind of holiday enough to bear the related burden, private firms would certainly have enough incentives to ensure the maintenance of such parks (…). I really do not see in these cases, effects (…) so relevant to justify government activity in this field*". One possible answer to Milton Friedman's astonishment could be that visiting National Park is a merit good.

The production of (local) collective goods is a primary task of place-based institutions (Barca, xxx). They take charge of the onerous work of involving public and private, individual and collective, local and external actors, for the most accurate identification of the need to be considered, and of the possible alternatives, the finding and organizing of assets required for the production of the goods. They take a guiding role in the production of collective goods, namely a fundamental management function to collect and coordinate a multiplicity of contributions.

This kind of activities are assuming growing importance with respect to economic dynamics increasingly attentive to relational aspects, linked to non-market factors and contextual conditions. Although their role was initially unveiled with reference to industrial districts [1, 9], they are not to be associated exclusively with that productive organization, nor only with manufacturing activities. In any type of territorial context, local development consists of the ability of local agents to collaborate both to produce collective goods, such as environmental heritage and resources, enriching external economies [15].

Apart from some advanced cases, it is hard for a park acting as an alternative to productive activities, a supplier of private goods in market failures contexts, nonetheless a park can act be an instrument of sustainable development, an agent of that system of coordination, production and exchange of collective goods which represents the future of a mature system.

Territorial public institutions develop policies and actions rooted in and aimed to places. In parks, this approach applies both to protection and to economic promotion: the protected resources are physical and linked to the equilibrium of the local ecosystem; human activities are the expression of social environments where relationships and cultural propensities have their own character.

Conclusions

A common feature of many European parks is that they are called daily to “re-negotiate” the mandate for nature conservation with the citizens. In parks operating in heavily anthropized territories this is due to pressures deriving from alternatives in the use of protected resources; in those with demographic crisis, such as mountain areas, to act as coordinator and bridging relationships for the production of collective goods.

The contribution of parks to sustainable development is possible from both the function of coordination and the supply of resources necessary for the production of (collective) goods. The mission of protected areas is the protection of natural resources. This is not an easy task, due to the conflict with local interests which have the economic exploitation of the natural resources as their possible expectation.

The intrinsic value of nature is not always perceived by citizens: protecting habitats means preserving them for future generations, a weak option, unpopular in times of crisis, and destined to lose against short-horizon choices with tangible and immediate economic outcomes.

One way to promote the protection of nature in the long term, is making natural resources the key for relationships capable of generating sustainable development. The production of collective goods, i.e. goods responding to situated and specific needs of local communities, is aimed to this purpose.

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Chapter 11
The 'Position' of Social Sciences in Sustainability Issue. The Emblematic Case of Energy Transition

Giorgio Osti

Abstract The paper aims to illustrate the different roles that social sciences can play in the study of the energy transition, intended as an emblematic case of human systems sustainability. To this end, a scheme is developed that frames the relative position of the social sciences with respect to other disciplines (metaframe). Secondly, socialization is identified as a charismatic category capable of providing an original, typically sociological contribution to the hesitant energy and environmental transition (masterframe).

Keywords Energy · Transition · Socialisation · Meta frame · Master frame

The paper aim is to justify and frame the contributions social sciences can provide to energy question, intended as an emblematic case of human systems sustainability. A general discourse on the social aspect of energy issues could start from different angles. A first angle could be a bibliographic review of the enormous scientific production of social sciences in the energy issue. The humanities and social studies have grown exponentially in this field. This type of analysis is facilitated by the digitization of papers and many times is based on content analysis. Some scholars are doing it very well (see [2, 9, 16]). A second angle could start with a plea for giving more space and weight to the social sciences in decision-making arenas or interdisciplinary research groups (see [34]). We often complain about the ancillary role of sociology in teams that have to plan large public works or smart cities. Finally, a third angle could be an effort to identify crucial concepts and theories that can shed light on the complex energy transition we are experiencing [32, 33]. We

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have a tremendous need for powerful theories that are useful to pierce reality, easily communicable outside social sciences and also that help people to make sense. This last term refers to sensations, significance, direction; they are basic ingredients of every social research. This last angle will be privileged in the paper.

We have as social researchers a compelling need for alluring concepts and theories useful for understanding and communicating to the public the complexities of energy issue. The purpose here is therefore two-fold. First, we must seek a sufficiently broad and insightful framework, a *meta-frame*, to simplify and include specific research paths. This task can be defined as 'analytical', that is, identifying meta-categories that can contain multiple perspectives for analysis. Second, we must inquire into a *master-frame* originating from within the social sciences, a frame capable of arousing the enthusiasm to expose or uncover unknown or original concepts or ideas never before studied. This second task is more heuristic, what we can call a 'search for a charismatic interpretative category' specific of social sciences.

Presented here is a play on words between the two types of frames. The former, the *meta-frame*, simply indicates a concept capable of containing others. The latter, the *master-frame*, is more ambitious and claims to be a discourse that motivates, guides and innovates. In the cognitive sociological literature, 'master frame' indicates a configuration of reality capable of profoundly modifying social structures [3]. Such was, for example, the idea in the 1980s that ecological thinking would modify the then-dominant labour-capital divide [10]. But before seeking out a master frame, it is important to illustrate the meta-frame as presented in Table 11.1, which represents the fulcrum of the analytical proposal.

Table 11.1 frames the *position* of the social sciences with respect to other forms of knowledge in the field of energy. It is a place search process useful also for other disciplines [29]. This scheme should apply to various environmental resources in addition to energy; that has been done for water [22] and buildings retrofit [23], as well for teaching.

Table 11.1 will seem very theoretical, but it arises from a practical need to relate to fellow scholars of the physical, engineering and medical sciences the many opportunities for collaborative work in universities, research centres and planning teams

Table 11.1 Social sciences position relative to energy engineering and management disciplines, according to key words and approaches*

Social sciences position (and analytical level)	Key words and (approaches)	
	Mechanisms	Reflexivity
ABOVE (macro)	Material Interests, power asymmetry (political ecology)	Cognitive Frames (social constructivism)
IN BETWEEN (meso)	Organisational Borders (neo-institutionalism)	Bridges among systems (network analysis)
BELOW (micro)	Behaviours (ABC model, nudge approach)	Games (strategic studies, theory of reasoned action)

Note 'Approaches' in the sense of 'paradigm' ([6], p. 532)

[21]. First, it is important to reinforce the idea that the relationship of the social sciences with the physical–mathematical-engineering sciences is mobile and variable, not unique. This reassures us that there is no fixed, constant ranking between disciplines, that there are not disciplines of first class and second class. The detestable prestigious academic rankings exist, but they are relative. Second, it is important to notice that there is a *meso*, an intermediate level between the macro and the micro [14, 26, 27]. This has been known for some time, for example since Merton [20] elaboration of medium range theories. But it is only during the *relational turn* of the last few decades that the meso level has embraced the social sciences [8]. Such a level is not *the solution* of agency-structure dilemma,[1] that indeed is reproduced in columns 2 and 3 of the table. Moreover, note that the first column not only collects the levels of analysis, but also the relative position of the social sciences with respect to the others. In other words, they are two criteria put together. For their part, columns 2 and 3 indicate two basically polar trends: mechanisms and reflexivity. The former indicates emerging impersonal qualities of a social aggregate, the latter indicates processes that pass through a certain awareness of the actors.

The position *above*, that is, when the social sciences are placed at an analytical level higher than that of other knowledges, is represented by two well-known models of analysis: political ecology and the frame approach. Following [7], these models claim the interpretation of technical-physical phenomena within a precise scheme. For its part, political ecology considers the unbalanced conflict between material interests and the resulting asymmetry of power: in their text Bridge et al. effectively summarize the matter thus 'We outline a political ecology perspective on EU energy policy that illuminates how the distribution of social power affects access to energy services, participation in energy decision-making and the allocation of energy's environmental and social costs'.

The framing approach is on the same analytical and positional level. Events, even of a very technical nature, must be inserted into 'finite provinces of meaning' [28], conceptual frameworks that allow understanding and making choices. Thus, some technological packages become attractive or rejected according to the cognitive frame that is adopted. For example, the evaluation of the wind farm changes depending on whether it is within the landscape frame or the 'renewable' label or whether it is within a top-down or bottom-up perspective in decision making. The frame per definition is always around the issue; in that sense, it is *above*, a level of knowledge able to contain another one.

To give a further example of the 'above' approach, we can use two controversial Dutch cases, one project concerning shale gas extraction and the second about the capture of CO_2 as studied by [25]. The authors identify three types of justice claims concerning both projects: distributive, procedural and based on recognition. The claim based on the struggle for recognition of local public resistance (that entails dignity, respect, identity, etc.) is the most neglected, but it is of high efficacy for both an understanding of the events and the capacity to mobilise people. In other words,

[1] In fact, referencing the work of [19], the two authors of [30], p.462] argue that 'meso level frameworks for the study of technological transitions tend to downplay the importance of agency'.

using the right frame allows one to understand the situation and prevent conflicts on the wrong target, waste of time and inefficient investments. Using the right frame is a very useful cognitive skill for all operators in the energy supply chain.

And we come to the meso approaches, those placed between very strong organisations such as multinational energy companies or the State, often owner of the same types of company. The meso approaches are based on the theory of organisational fields and on that of networks. The watchwords are *borders* in the first case and *bridges* in the second. According to organisational theories, there is a continuous work of building and maintaining borders; this process is called lock-in, self-referencing, autopoiesis, *to make* rather than *to buy*.

What happens with organisational fields that become too closed? There is a need to create bridges, connections, channels of dialogue and exchange with other clusters. Therefore, procedures, figures or organisations emerge that are responsible for establishing bridges. According to a famous expression of [13], they are *bridging or weak ties*, such as communications companies, brokerage offices or people on the margins. All of these have ease of establishing relationships with other organisations closed in their core business and internal languages.

The example does not seem risky, but Geels' multi-level perspective or transition model [11, 12] can be inserted in this approach. The problem consists in passing an innovation from one level to another in a situation in which niches, regimes and landscapes—every kind of bordered field—tend to be rigid and not communicating, even if shared by many people. In this case the social sciences, in particular the communicative sciences, play an intermediary role between systems. The examples are very concrete in the energy sector: they are scientific dissemination agencies, cooperatives that mediate between local populations and authorities, participatory platforms, public relations offices of large companies, and finally, the emergent "peer-to-peer and community-based markets" [31]. Thus, the position of social sciences is in this case in-between stronger knowledges and organisations.

Finally, there are the micro models, those referring to the behaviour and attitudes of single individuals in the face of the energy issue. Consumers are generally thought of, but these behavioural or actor-centred approaches are also applicable to business executives, administrators and technicians. The most famous model was called ABC: antecedents, behaviour, consequences [4]. More elaborate than the stimulus–response but substantially based on the same assumptions, subjects seek gratifications; if they receive them, they react positively and acquire a conditioned response.

The most sophisticated version of this model is the *nudge* approach, which envisages providing stimuli at a cognitive level such as information, recognition, the need for emulation or competition [15]. This approach has inspired intervention policies based on incentives and rewards. Strategic behaviour theories are also attributable to these micro approaches. They add to the stimuli the calculations and predictions that the subject makes of the behaviour of others. The best known case is the prisoner's dilemma. In absence of information on other's intentions, the best strategy is to defect.

Both nudge approaches and those that simulate strategic behaviour are positioned *low* in the table because they provide useful suggestions to other systems of knowledge and decisions on how to build policies. The followers of these approaches end up being consultants to governments or large companies, the only ones capable of adopting large-scale policies for consumers and employees.

This, therefore, would be the meta-frame, a scheme that is certainly not exhaustive (for example, social practices—a mix of routines and choices—are not contemplated), but which gives *serenity* to the researcher of the social sciences. The social researcher is not only a consultant at the service of others (microlevel), not even a facilitator or an *agit-prop* (meso level), not just a visionary who traces utopian world scenarios (macro level). Rather, the social researcher should play all three of these roles. Moreover, many actions depend on how other experts view and place social scientists. Just as social scientists are flexible and play multiple roles, so too should their interlocutors; sometimes, experts must be ready to accept a social frame in which their knowledge of environment is included or it can be at the same level of other ones. Nevertheless, mental flexibility and the ability to frame the phenomena broadly are not enough. We also need for sociology and other social sciences innovative skills, leadership, early prognosis. This cannot be commanded; it springs from the researcher’s intuitions, from intense readings, from immersion in daily social realities, in physical contact with other people and landscapes.

For this task, the proposal is to adopt the term ‘energy socialisation’, which has been applied to the water issues [22], with which energy has many similarities. It is always about flows. Socialisation refers to two aspects: the learning of ways of living in a society, the sharing of goods or services.[2] For the first aspect, there are socialisation agencies and practices [1], and for the second a variety of arrangements, such as car sharing and car-pooling, which connect to energy consumption. More structured examples of socialisation as sharing are energy cooperatives and energy communities, which comprise an immense literature themselves [24].

Socialisation would be a master frame simply because of the semi-invisible nature of energy. That makes it the prerogative of only expert knowledge and those who govern it, a sphere completely delegated to complex, auto-poietic, closed systems. This is what we notice precisely for the organisation of high-tech energy systems. Just to mention nuclear fusion energy. Ordinary people are completely de-socialised of the topic.

To overcome the invisibility of energy and the closure of human energy systems, much socialisation is needed to be developed at all the indicated levels, from the macro- to the meso- and up to the micro-level. Our expertise can fulfil this task by highlighting the educational needs of both technicians and consumers. When the investigation techniques themselves become educational tools, we can think, for example, of serious games, which we learn by playing.

[2] There is indeed a third aspect mentioned in literature: [17]. An interesting debate in social sciences is about differences between socialisation and education (see Mannheim & Stewart, 1962 [18]). The former process tends to reproduce society giving to younger generations the actual values and norms (adaptation), the latter is the achievement of creative attitudes (freedom). The issue, translated in the energy field, drives to learning methods respectful for human innovation capacity.

At the same time, the socialisation of the *means of energy production*, to put it in Marxist terminology, is another important task. In this case, energy sharing has the advantage of measurability and division between users, which makes it an easily marketable and then consumable good. But the market as a means of allocating resources fails when it is more convenient to produce and consume the goods together, such as certain forms of energy storage on a residential block [5] or the coordination among final users to avoid demand peaks or energy exchanges among rich and poor users. Let's imagine a condominium or a block in which the inhabitants exchange energy not only based on how much they produce individually, but based on the variable needs of each household. These are examples of energy socialisation as mutual and coordinated exchange.

The root of the word 'socialisation' is the same as social sciences and sociology. This is the modest gift of sociology to the cause of energy transition. But, for the gift is fruitful, the two meanings of socialisation must stay together. They work well when awareness—the cognitive dimension—goes hand in hand with the material sharing of energy production, distribution and consumption.

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Chapter 12
The Law of Sustainability

Mauro Bussani

Introduction

Inasmuch as keeping the world sustainable requires continuous commitments and substantial changes in human behavior, law is, and should be, a central concern for any sustainability-oriented initiative. Yet, in spite of the unavoidable centrality of law for any program seriously aiming to reorient and curb human activities, the legal architecture that is currently being built around the concept of sustainability is extremely thin and soft. As it happens with other Western-driven fights against global 'obvious evils' (such as poverty, human rights violations, and war), beneath broad and vague formulas about sustainability deep disagreements lie about what sustainability means, which obligations can be derived from it, who should be bound by these obligations, and for benefit of whom. To be sure, these disagreements account for the absence of clear rules and effective enforcement mechanisms for international sustainability commitments, as well as for the widespread reliance on pseudoquantitative assessments for 'measuring' sustainable behavior. But the point is that institutional and mainstream debates keep tapping into a functionally narrow view of the law that matters, and an even more limited awareness of the legal diversity of the world.

In the pages that follow, section "The Legal Framework on Sustainability" will sketch out the main features of current legal architectures and narrations on sustainability, delving in particular into the quest for development (section "Introduction"), the fight against climate change and efforts to advance corporate social responsibility (section "The Legal Framework on Sustainability"). Section Enforcing Sustainable Obligations from Below" will shed light on the potential opened up by some alternative paths. Section "Quantifying the Law? De-quantifying the SDGs?" will

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provide some illustrations of how quantitative approaches are deployed in the legal field. Section "The Dark Side of Numbers" will elaborate on the limitations and challenges of commensuration in the social world, while section "What Law?" will explore what quantitative techniques employed in the legal sector often miss. Section "What to Do?" will set up a tentative agenda for the activities of the Trieste Laboratory on Quantitative Sustainability (TLQS) inasmuch as the law is concerned.

The Legal Framework on Sustainability

There is no international treaty imposing legal obligations on state parties as far as sustainability is concerned. The closest document to a treaty is the Rio Declaration on Environment and Development adopted in 1992 by the General Assembly of the United Nations (UN), which however is a mere declaration[1]—in legal terms, it gives voice to an agreement upon standards but is not legally binding. As a consequence, notwithstanding that several international bodies—from the General Assembly itself to the United Nations Environment Programme (UNEP) to the United Nations Development Programme (UNDP)—cooperate and work with states and non-state actors on sustainability-related issues, there is no international agency entrusted with monitoring and enforcement powers.

Lacking an agreement on the creation of stronger legal regimes, contemporary legal debates and practices about sustainability have largely pursued other, less politically sensitive paths. These paths do not try to impose burdens on unwilling state and non-state actors, but rather attempt to engage these actors in quantitative initiatives, requiring them to keep track and monitor the effects of their sustainable-oriented activities. Measuring processes and outcomes have thus become the preferred mode of intervention in the field, insofar as they enable the mediatization of the sustainability discourse through a variety of actors, while leaving the latter substantial freedom as to what to do and how.

The UN Development Goals

The UN General Assembly embraced this approach in its 2001 'Millennium Declaration'[2] and the related 'Millennium Development Goals' indicators (MDGs).[3] The

[1] United Nations General Assembly, Report of the United Nations Conference on Environment and Development, on 12 August 1992, A/CONF.151/26 (Vol. I), at https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf.

[2] United Nations General Assembly, United Nations Millennium Declaration, A/RES/55/2, on 18 September 2000, at https://documents-dds-ny.un.org/doc/UNDOC/GEN/N00/559/51/PDF/N0055951.pdf?OpenElement.

[3] See the website https://mdgs.un.org/unsd/mdg/default.aspx.

same approach has later been confirmed by the Declaration on the ‘2030 Agenda for Sustainable Development’[4] and the related ‘Sustainable Development Goals’ indicators (SDGs).[5] The latter contain a few indicators that are clearly centered on legal matters, asking for statistics and data about the percentage of population enjoying this or that right, as well as the rate of progress in the implementation of selected sustainable-oriented rules and institutions.[6] But the legal potential of the SDGs goes, theoretically at least, well beyond the small number of indicators focusing on strictly legal features. In principle, the entire set of the SDGs actually aims to shape practices and promote legal change by inviting international agencies and states to collect data and by exposing states to the pressure of attaining benchmarks and competing with their peers.[7]

All this can be seen as a far-reaching nudging strategy, trying to drive ‘sustainable’ behaviors by the concerned actors and ‘sustainable’ decision-making by governments and public authorities.[8] But nudges may only work in legal environments where there are strong gate-keepers and law enforcement agencies suitable to ultimately make right undesirable actions and outcomes.[9] In the sustainability field, this not the case.

Climate and Corporations

The features just highlighted—the lack of hard rules and especially the absence of enforcement mechanisms, which are then filled by the more or less voluntary

[4] United Nations General Assembly, Resolution adopted by the General Assembly on 21 October 2015, A/RES/70/1, at https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

[5] United Nations General Assembly, Resolution adopted by the General Assembly on 6 July 2017, A/RES/71/313, at https://documents-dds-ny.un.org/doc/UNDOC/GEN/N17/207/63/PDF/N1720763.pdf?OpenElement.

[6] See for instance indicators 1.4.2, 5.1.1, 5.6.2, 5.a.1, 5.a.2, 12.6.1, 12.7.1, 14.6.1, 14.b.1, 14.c.1, 15.6.1, 15.8.1, 16.10.2; see also below, section “Quantifying the Law? De-quantifying the SDGs?”.

[7] See Ruth Buchanan, Kimberley Byers, Kristina Mansveld, “What gets measured gets done”: exploring the social construction of globalized knowledge for development, in Moshe Hirsch and Andrew Lang (eds.), Research Handbook on the Sociology of International Law, EE, 2018, 101–121; Sharmila Murthy, Translating Legal Norms into Quantitative Indicators: Lessons from the Global Water, Sanitation, and Hygiene Sector, 42 Wm. & Mary Envtl. L. & Pol’y Rev. 385–446 (2018); Sakiko Fukuda-Parr, Alicia Ely Yamin, Joshua Greenstein, The Power of Numbers: A Critical Review of the Millennium Development Goal Targets for Human Development and Human Rights, 15 Journal of Human Development and Capabilities 105–117 (2014); Kerry Rittich, Governing by Measuring, in Hélène Ruiz Fabri, Rudiger Wolfrum, Jana Gogolin (eds.), Selected Proceedings of the European Society of International Law, Hart, 2010, 463–487.

[8] Richard Thaler and Cass Sunstein, Nudge: Improving Decisions About Health, Wealth, and Happiness, Penguin Books, 2008; Cass Sunstein, Why Nudge?: The Politics of Libertarian Paternalism, Yale University Press, 2014; Cass Sunstein, The Ethics of Influence: Government in the Age of Behavioral Science, CUP, 2016.

[9] See e.g. Robert Lepenies and Magdalena Małecka, Magdalena, The Institutional Consequences of Nudging—Nudges, Politics, and the Law, 6 Review of Philosophy and Psychology 427–437 (2015); Alberto Alemanno and Alessandro Spina, Nudging legally: On the checks and balances of behavioral regulation, 12(2) International Journal of Constitutional Law 429–456 (2014).

imposition of some limited and quantifiable targets and of reporting obligations—are common to many other global initiatives for the 'good' of the planet.

This corresponds, for instance, to the dominant legal approach in the fight against climate change. As is well-known, the Kyoto Protocol to the United Nations Framework Convention on Climate Change of 1997, as amended in 2012, sets forth minimal quantified emission limitation and reduction commitments for states parties.[10] The Paris Agreement and subsequent international compacts require state parties to undertake and communicate to the international community their 'ambitious efforts' for limiting the increase of the global average temperature.[11] None of these texts provides for a mechanism to hold parties to their promises or to sanction their inactivity.[12]

Along similar lines, the instruments addressing the sustainability obligations of multinational companies basically focus on the so-called corporate social responsibility (CSR), to be meant as the voluntary adherence to systems of self- or external assessment of companies' compliance with legal, social and environmental standards.[13] In this regard, suffice it to mention: the Global Reporting Initiative (GRI), a program led by a non-governmental organization that rewards companies which submit reports about their sustainable activities[14]; the United Nations

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[10] See Kyoto Protocol to the United Nations Framework Convention on Climate Change, FCCC/CP/1997/L.7/Add.1, of 10 December 1997, at https://unfccc.int/sites/default/files/resource/docs/cop3/l07a01.pdf; Doha Amendment to the Kyoto Protocol, of 8 December 2012, at https://treaties.un.org/doc/Publication/CN/2012/CN.718.2012-Eng.pdf.

[11] Paris Agreement, of 12 December 2015, at https://unfccc.int/sites/default/files/english_paris_agreement.pdf; Conference of the Parties serving as the meeting of the Parties to the Paris Agreement, Glasgow Climate Pact, FCCC/PA/CMA/2021/10/Add.1, of 13 November 2021, https://unfccc.int/sites/default/files/resource/cma2021_10_add1_adv.pdf.

[12] Regional initiatives—such as the ones adopted by the EU, which set up in 2005 the world's first international emissions trading system, and now aims to become climate-neutral by 2050 (see Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality)—may have an impact on the concerned slice of the planet—and on those willing or forced to follow suit. But before global challenges, they remain size-limited achievements.

[13] Domestic and supranational legislation exist in this respect too, especially in Europe. EU Member States have for instance enacted legislation to comply with the Directive 2014/95/EU amending Directive 2013/34/EU as regards disclosure of non-financial and diversity information by certain large undertakings and groups (recently amended by the Directive (EU) 2022/2464 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting), according to which largest companies should publish annual reports assessing the adverse impacts of their activities. More recently, the Commission of the European Union has issued a proposal for a CSR directive that would require companies to perform due diligence as to identify, prevent and remedy to adverse human rights and environmental impacts (European Commission, Proposal for a Directive of the European Parliament and of the Council on Corporate Sustainability Due Diligence and amending Directive (EU) 2019/1937, 22 February 2022, COM/2022/71 final, at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0071). The Commission also announced a Sustainable Finance Strategy (COM(2021) 390 final) highlighting the need to include a better integration of environmental, social and governance (ESG) risks into the EU legal framework. The local/global mismatch of these initiatives is the same as pointed out in the previous footnote.

[14] See https://www.globalreporting.org.

Global Compact, that similarly relies on companies' declared respect for sustainability principles[15]; the standards developed by the International Organization for Standardisation (ISO), with the aim to certify the quality of companies and cities' environmental management and social responsibility.[16] Again, instruments of this kind do not impose obligations whose lack of performance exposes the obligor to liability; rather, they impose duties to assess, monitor, and document efforts towards sustainability.

These are simple illustrations of the mainstream legal approach to sustainability. They might be seen as the result of a conscious design choices that keep the (r)evolutionary potential of the notion of sustainability under control while promoting it with minimal challenges to the status quo. But they certainly are part and parcel of a more general shift towards the governance of the world through commensuration. It is a process that started five centuries ago[17] and has exponentially grown in the recent decades hand in hand with the ability to reap and treat large amounts of information. It is therefore of the utmost importance to understand the cultural and practical boundaries (and biases) of this pseudoquantitative legal approach to sustainability. We are going to delve into this issue in sections "Quantifying the Law? De-quantifying the SDGs? and The Dark Side of Numbers". Before doing this, however, a possible alternative path, and its limits, are worth highlighting.

Enforcing Sustainable Obligations from Below

Against the framework just sketched, it is no surprise that some of the most effective measures for promoting states' and companies' compliance with declarations, promises and voluntary commitments to sustainability have so far stemmed, rather than from the initiatives just recalled, from private-led actions brought before national courts.

For instance, with the very mediatized Urgenda decision of 2019,[18] the Hoge Raad (the Dutch Supreme Court) held that a Dutch environmental group, Urgenda Foundation, was entitled to sue the Dutch state for the latter's failure to adopt adequate measures to meet the objective of reducing the emission of greenhouse gases originating from Dutch soil, by the end of 2020, of at least 25% compared to 1990. According to the court, by failing to reduce greenhouse gas emissions by at least

[15] See https://www.unglobalcompact.org.

[16] See https://www.iso.org/developing-sustainably.html. For a list of similar initiatives and their effects, see Laura Valle and Maria Chiara Marullo, Contract as an Instrument Achieving Sustainability and Corporate Social Responsibility Goals, 24(1–2) International Community Law Review 100–123 (2022), doi: https://doi.org/10.1163/18719732-12341485.

[17] "[I]t may be recalled that since the sixteenth century the development of capitalism has called for the destruction of differences in laws, standards, currencies, weights and measures, taxes, customs duties at the level of nation state": B.S. Chimni, International Institutions Today: An Imperial Global State in the Making, 15 European Journal of International Law 1, 7 (2004).

[18] Hoge Raad, 20 December 2019, ECLI:NL:HR:2019:2006.

25% by the end of 2020, the Dutch government was acting in contravention of its duty of care under Articles 2 and 8 of the European Convention on Human Rights (ECHR). A similar decision was adopted in 2021 by the Conseil d'État, the French highest administrative court, which, upon request of the mayor of a town in Northern France, ordered the French state to reduce the curve of gas emissions on the French territory as foreseen by several international and national acts by March 2022.[19]

Promoting such actions before national courts requires plaintiffs to invest substantial energy, time and resources in the litigation. Litigating before national courts becomes even more burdensome when the action is led, rather than against states, against foreign companies, since this often requires victims of corporate activities to find an appropriate legal basis for their claims, and to raise adequate funding for their action in order to establish jurisdiction abroad, to engage in transnational evidence-gathering and in battles between scientific experts, and to pay teams of lawyers (and experts) for doing so. Yet, notwithstanding all these limitations, litigation against multinationals for their behavior abroad seems to be mounting.

Pioneers in this regard have been United States courts, which in the past have often used the jurisdictional basis provided by the 1789 Alien Tort Statute (ATS)[20] for hearing claims against foreign companies for illegal activities realized abroad. For instance, It was enough that a federal court accepted jurisdiction to hear the claims brought under US law against Royal Dutch Shell by the relatives of a few Ogoni leaders who had been killed by the Nigerian government, allegedly at the instigation of Royal Dutch Shell, in reprisal for their political opposition to the company's oil exploration activities in their territory,[21] for Royal Dutch Shell to rush to settle the case with the victims (for 15 millions USD, 4,5 millions of which went to a trust to benefit the Ogoni people).[22]

Other Western courts have been willing to step in. In 2017 the Oberlandesgericht Hamm held that, in principle, a Peruvian resident is entitled to sue the German electricity company, RWE AG, and that German law allows him to ask RWE, as the largest CO_2 emitter in Europe, to bear the cost of the protection measures necessary to prevent a melting glacier in the Peruvian Cordillera Blanca to flood his house[23]; it remains to be seen—evidence gathering in the legal proceedings is still ongoing—whether the plaintiff will be able to prove a sufficiently adequate causal link between RWE emissions and the melting of the glacier in Peru.[24] In 2019, the UK Supreme Court ruled that, under English law, a case for redress of environmental harm brought

[19] Conseil d'état, 1st July 2021, n° 427,301, ECLI:FR: CECHR:2021:427, 301.20210701.

[20] 28 U.S.C. § 1350: "The district courts shall have original jurisdiction of any civil action by an alien for a tort only, committed in violation of the law of nations or a treaty of the United States".

[21] Wiwa v. Royal Dutch Petroleum Co., 226 F.3d 88 (2d Cir. 2000).

[22] Seehttps://asil.org/insights/volume/13/issue/14/WiWa-v-shell-155-million-settlement. It has to be noted, however, that recent judicial developments restricting the scope of the ATS (Nestle USA, Inc. v. Doe, 141 S.Ct. 1931 (2021); Kiobel v. Royal Dutch Petroleum Co., 569 U.S. 108 (2013)) have curtailed the ability of American courts to hear claims brought by foreigners against foreign companies.

[23] Oberlandesgericht Hamm, 17 December 2017, I-5 U 15/17.

[24] See https://www.germanwatch.org/en/85108.

by almost 2,000 Zambian villagers against the local mining company and its parent UK-based company Vedanta could be heard by the English courts.[25] Two year later, the same court confirmed its position by holding that it was at least arguable that a London-headquartered parent company of a Nigerian oil company owed under English law a duty of care in negligence to claimants based in Nigeria with respect to the polluting activities of its local subsidiary.[26] In 2020, the Canadian Supreme Court affirmed Canadian jurisdiction to hear the case brought by three Eritrean refugees against a Canadian mining company which allegedly breached customary international law by being complicit with local mining companies in the use of forced labor at the Bisha mine in Eritrea.[27] In 2021, the Hague Court of Appeals, applying Nigerian law, held Royal Dutch Shell liable for several oil spillages produced by its Nigerian subsidiary company that polluted the arable land and water in the Niger delta.[28]

All the above shows that, in the absence of clear international obligations, activists, lawyers and judges can affirm and enforce sustainable obligations upon states and companies under existing national laws. Yet, one should also bear in mind that judicial interventions such as the ones just outlined are always lengthy and costly, have a legal impact geographically limited, and often are able only to provide a limited group of people with some form of compensation after a serious wrongdoing. In other words, they can complement, but they alone cannot sustain, a more general shift to sustainable practices.

Quantifying the Law? De-quantifying the SDGs?

We already underlined that, rather than affirming enforceable obligations and rights, the legal initiatives surveyed in section "The Legal Framework on Sustainability" prefer to rely on reporting duties and on pseudoquantification of processes and performances, as a less contestable (and less effective) way to promote legal change. The problem with this choice, however, is not only its ineffectiveness. As we are about to see, the very project of quantifying the law, and of nudging legal change through quantification, is inherently problematic.

Quantification of social phenomena, and especially quantification aiming at nudging human behavior, is different from measuring marine ecosystems, the environmental footprint of agri-food production, climate change and GHG emissions, demography or epidemiology. Measuring the law and, more generally, relying on quantification to change the law, are no exact science. Most often, this kind of quantitative initiatives cannot even qualify as measurements at all, for the very simple

[25] Vedanta Resources PLC and anor. v Lungowe and others, 10 April 2019, UKSC 20.

[26] Okpabi and others v Royal Dutch Shell and another [2021] UKSC 3.

[27] Nevsun Resources Ltd. v. Araya, 2020 SCC 5.

[28] Hague Court of Appeals, 29 January 2021, ECLI:NL:GHDHA:2021:132.

reason that, "when a measure becomes a target, it ceases to be a good measure".[29] In other words, when we are measuring something that reacts, or is expected to react, to the very act of measurement, we are not measuring anymore; we are rather co-producing (random numbers and real) change. The conclusion is undisputed in a number of disciplines, from anthropology[30] to sociology,[31] from psychology[32] to economics.[33] Actually, it is the very ability of social measurements to inspire change, coupled with the desire to avoid hard choices through soft politics, that explains the emphasis of current legal frameworks on sustainability on reporting and pseudoquantification.[34]

Yet one should additionally consider that, in the domain of social phenomena, there is often little (if any) agreement on what should be measured and how this should be done. The result is that one ends up measuring what can be more easily counted rather than what actually counts, thus leaving scores of important and yet hardly quantifiable or politically unacceptable features out of the spotlight.[35] This is very clearly demonstrated by the few SDGs indicators directly dealing with legal issues. Let us take, for instance, SDGs 1.4, 12.6 and 14.6:

– SDG 1.4 aims to ensure that, by 2030, "all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance". Two indicators measure the attainment of this goal. Indicator 1.4.1, whose custodian is UN-Habitat,[36] asks for the "proportion of population living in households with access to basic services". Indicator 1.4.2, under the supervision of UN-Habitat and the World Bank, requires to monitor the "proportion of total adult population with secure tenure rights to land, with legally

[29] Marilyn Strathern, From Improvement to Enhancement: An Anthropological Comment on the Audit Culture, 19 Cambridge Anthr. 1–21 (1996/7), at 5.

[30] See Strathern, supra fn. 29.

[31] Henry A. Landsberger, Hawthorne Revisited, Cornell U. P., 1958.

[32] Donald T. Campbell, Assessing the Impact of Planned Social Change, The Public Affairs Center, 1976, 49, at https://www.globalhivmeinfo.org/CapacityBuilding/Occasional%20Papers/08%20Assessing%20the%20Impact%20of%20Planned%20Social%20Change.pdf ("The more any quantitative social indicator (or even some qualitative indicator) is used for social decision-making, the more subject it will be to corruption pressures and the more apt it will be to distort and corrupt the social processes it is intended to monitor").

[33] Charles Goodhart, Problems of Monetary Management: The U.K. Experience, in Anthony S. Courakis (ed.), Inflation, Depression, and Economic Policy in the West, Rowman & Littlefield, 1981, 111, 116 ("Any observed statistical regularity will tend to collapse once pressure is placed upon it for control purposes").

[34] Marta Infantino, Numera et impera. Gli indicatori giuridici globali e il diritto comparato, FrancoAngeli, 2019, 72, 89–90, 215–230.

[35] Buchanan, Byers, Mansveld, supra fn. 7, 114–119; Murthy, supra fn. 7, 394, 418–429; Fukuda-Parr, Yamin, Greenstein, supra fn. 7, 106, 112–113; Rittich, supra fn. 7, 466–483.

[36] Every indicator has an agency which acts as a custodian for the data collection process: see https://unstats.un.org/sdgs/dataContacts/.

recognized documentation and who perceive their rights to land as secure, by sex and by type of tenure". What should be noted is, on the one hand, that the breadth of the goal is lost in the formulation of the two technical indicators, whose scope is incomparably narrower than the original goal itself. On the other hand, in spite of their narrow formulation, the legal content of these indicators remains intolerably vague. Suffice it to consider that, in light of the variety of entitlements of people and groups on land in different legal settings, neither the notion of 'secure tenure', nor that of 'rights to land' have a clear or uniform meaning[37];

- SDG 12.6 has more limited ambitions: it hopes to "encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle". Since it is clearly hard to measure 'encouragements', the only indicator for this goal, indicator 12.6.1, measures, under the supervision of the United Nations Environment Programme (UNEP) as custodian agency, the "number of companies publishing sustainability reports". The somewhat paradoxical result of this indicator is that, the higher the number of companies publishing these reports, the more SDG 12.6 will be considered accomplished—no matter what these reports say, and no matter how these actually behave in the real world –. The reason underlying indicator 12.6.1 is simple: it is easier to count the number of companies publishing sustainability reports than investigating about what these companies do. Additionally, the indicator also shows another drawback of relying on commensuration for legal change: commensuration favors gaming strategies of all kinds. In the field of social measurements, for the concerned parties it is often easier to engage in symbolic compliance and window dressing (or to manipulate the data or their treatment) rather than changing actual practices;
- the mismatch between goals and indicators is evident also in the case of the SDG 14.6. SDG 14.6 aims to "prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the World Trade Organization fisheries subsidies negotiation". Also in this case, only one indicator accounts for attaining such goal. According to indicator 14.6.1, whose custodian agency is the Food and Agriculture Organization (FAO) of the United Nations, the goal is attained whenever there is evidence of "progress by countries in the degree of implementation of international instruments aiming to combat illegal, unreported and unregulated fishing". Leaving aside the ambiguity of the idea of 'progress in the degree of implementation of international instruments on fishing', what should be stressed is that the second fragment of the goal—the one prohibiting the introduction of new subsidies for the benefit of developing and least developed countries—is simply silenced by the indicator.

[37] See e.g. Mauro Bussani, El derecho de Occidente. Geopolítica de las reglas globales, Marcial Pons: Madrid, 2018, 52–53, 229–230, 251–252.

Yet, and again, paradoxically, 'progress in the degree of implementation of international instruments on fishing' would allow countries also to comply with the goal prohibiting new subsidies.

The Dark Side of Numbers

Many illustrations could follow, considering that even SDGs indicators that do not explicitly focus on legal issues, still aim to produce behavioral and legal change. But the examples just mentioned suffice to demonstrate some of the very well-known side-effects of commensuration of social phenomena for policy purposes: the choice of what and how to measure is always, at least partly, discretionary, and more often than not it is determined by political and technical factors that (have little to do with what the measurement is for, and yet) make the measurement easier, cheaper, or more acceptable. By contrast, what is not measured—no matter how important this is—becomes irrelevant, deserving neither efforts nor attention.

This is not all. Even assuming that a complete and comprehensive measurement of what matters could be done, the history of quantification of social phenomena and of nudging through commensuration has repeatedly demonstrated one fact. Gaming strategies aside, the effects of pseudoquantitative governance techniques are often quite different from those expected, in ways that are very hard to predict.[38] It is therefore highly unclear whether measuring efforts, progress and results, multiplying reporting obligations, relying on certificates, labels and self-declarations would actually help reach the desired objective, or would rather nurture uneven and perverse consequences, at least for some of the actors involved.

This is why it is of the utmost importance for the Trieste Laboratory on Quantitative Sustainability to seriously analyze the quantitative dimension of sustainability to understand the legal models that such an approach conveys (are these models respectful of existing diversities, or do they promote as purportedly universal values that are actually Western?), and the legal effects that it triggers, also in order to monitor how appropriate these models and effects are with regard to the original goal.

What Law?

The above tasks should be performed by the TLQS by taking into account another limitation of currently dominant approaches to sustanaibility. The mainstream framework, in fact, is based on and nurtures the impression that the contribution of the legal

[38] E.g.: Sally Engle Merry, The Seductions of Quantification. Measuring Human Rights, Gender Violence, and Sex Trafficking, Chicago U.P., 2016; Kevin E. Davis, Angelina Fisher, Benedict Kingsbury, Sally Engle Merry (eds.), Governance by Indicators. Global Power through Quantification and Rankings, OUP, 2012.

architecture to sustainability is limited to specific fields and areas—such as pollution and environmental impact, human rights compliance, multinational behavior, and democratic processes. This is misleading because the relationship between law and sustainability runs much deeper. As language and culture, the law contributes to determine who we (think we) are, our relationship with fellow humans, other species and the environment, our use of resources, the boundaries of our actions and the horizons of our choices. Law always and everywhere shapes practices and destinies. It is at the level of the law (and its apparatuses) that it is possible to grasp the variety of factors affecting any operational process geared towards sustainability, together with its interrelations with the diversity of cultures and legal traditions (both official and unofficial ones) that inhabit the planet. In this perspective, law provides a magnifying glass for examining issues that, although usually neglected in the public discourse, deeply affect the sustainable and unsustainable way in which we look at the world we live in.

Underlying this view there are two fundamental assumptions that are often sidelined, if not thrown out, in mainstream debates.

First, the law that matters for sustainability goes beyond secure tenure land rights and treaties on illegal fishing, multinational companies' reporting, GHG emissions, and climate change responsibility. The law that matters is also the law that variably determines who can own and use what (entitlements, land, money, energy, status), for what purposes and with what limits; the law that shapes the relationship between people and the natural/supranatural/artificial environment they live in; the law that relentlessly cements and sometimes challenges the power structures at play within human societies.[39]

Second, different societies are ruled by different laws, with their own sources, vocabulary, management and dispute settlement tools. There is no 'ideal' model of sustainability, as there is no 'ideal' model of a just society. More precisely, there is no model of sustainability that can work without maintaining and nourishing a strong relationship of compatibility with the socio-economic, cultural and legal reality on which that model is expected to apply. It is therefore fundamental to keep in mind that the needs to be met and the tools to be used when devising any sustainability rule are factors which vary considerably, depending on the area of the law in question, and on the area of the world one targets. It is important to bear in mind that finance is not welfare, healthcare is not commerce and that what is necessary to make any reform work in the matter of energy or tax law is quite different if one considers the case of, for example, France as compared to Burundi.[40]

[39] H. Patrick Glenn, Legal Traditions of the World: Sustainable Diversity in Law, OUP, 2014, 5th edn.

[40] Mauro Bussani, Geopolitics of Legal Reforms and the Role of Comparative Law, in Mauro Bussani and Lukas Heckendorn Urscheler (eds.), Comparisons in Legal Development. The Impact of Foreign and International Law on National Legal Systems, Schulthess, 2016, 235–248.

What to Do?

On the basis of these assumptions, that are largely neglected by contemporary Western-driven approaches to sustainability in the law, it is therefore crucial to evaluate:

- which rules are the most suitable for encouraging operationally virtuous behavior on the sustainability front, in which areas and for what sectors of human activity (e.g., food, drugs, trade, transportation, tourism, international finance);
- the optimal dimension of the specific rules on energy production/distribution/consumption, in light of their impact on the social fabric and on the supply chains in globalized localities;
- which are the appropriate incentives to drive governments, business and social organizations to comply with the rules aiming to achieve the SDGs;
- the individual and social costs of sustainable rules—who they favor, who penalize, where, in what time range;
- the design of rules of responsibility—effective, not declaimed—for those who favor global warming, or for those who, even at an international level, disregard their promises;
- which is the actual wiggle room to propose rules embedding an 'accountability by design' model, doing away with the legal vagueness of the present situation and setting up legal mechanisms responsive to the different contexts where the rules should apply. Behind and beyond the above one should be aware that the present situation shaped by initiatives such as the SDGs, CSR obligations, and loose commitments to flight climate change nurture the Western rhetoric, blur the agendas and practices of a plurality of actors (from states to NGOs, from multinationals to citizens), and end up by raising an equal amount of expectations and disappointments.

Part VIII
Protection of the Earth Habitats with Space Tools

This part aims to be an introduction to the activities that TLQS intends to carry out in the field of environmental management prevention, using the methodologies and tools already developed for space investigations.

The Italian research groups belonging to the National Institute of Astrophysics (INAF) and in particular those operating in Friuli Venezia Giulia are very active in this area.

TLQS offers a unique opportunity to combine their knowledge with those of scientists working in the fields of climate change (group 3), data science and intelligent algorithms (group 4), and marine economics (group 1).

Sustainability and prevention are intimately connected. In the field of environmental management, it is clearly necessary to move from policies that intervene after the fact to treat damage, to interventions aimed at preventing that damage. This is true not only for anthropogenic climate change, but also for environmental disasters unrelated to human activity; there can be no sustainability without prevention. Chapter 13, *Protection of the Earth habitat with Space tools*, by F. Fiore and S. Ivanovski, provides two examples where prevention plays a crucial role: (i) space weather and (ii) minor bodies of the solar system.

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Chapter 13
Protection of the Earth Habitats with Space Tools

Fabrizio Fiore and Stavro Ivanovski

Sustainability and prevention are intimately connected. In the field of environmental management is it clearly necessary to move from policies that intervene after the fact to treat damage, to interventions aimed at preventing that damage. This is true for both anthropogenic climate change but also for environmental disasters unrelated to human activity: there can be no sustainability without prevention. In the following we give two examples where prevention plays a crucial role.

Space Weather

Modern society has become increasingly dependent on reliable technologies in the fields of communication, navigation, power grid systems, which can be vulnerable to energetic solar events. The latest US government research on the economic impact of the occurrence of another major geomagnetic storm like the"super storm" of 1859 shows potential costs on the nation's technological infrastructure (power grid, satellites, GNSS receivers, etc.) of about 15–20 trillion US$. Even minor events can do enormous damage, as in the case of the loss of about 40 Starlink satellites due to a relatively small solar event on February 3, 2022. The solar wind is the ultimate source of energy and is responsible for virtually all the magnetospheric dynamics. Describing and quantifying the solar wind energy transfer to the Earth's magnetosphere-ionosphere system is one of the fundamental questions in space physics. For these reasons, the space weather (SWE) and the solar physics are primary themes in the road-maps of the European Union and European Space Agency

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(ESA). The study of solar activity, the solar wind and its interaction with the earth's magnetosphere, ionosphere, troposphere and atmosphere is mainly done using space infrastructures. The main objectives are the understanding of solar phenomena and the transport of solar wind energy events to the Earth, the detailed modelling of these phenomena, the ability to make timely predictions, and therefore the possibility of implementing strategies to mitigate the effects of solar phenomena on terrestrial infrastructures. In this context, the priority scientific activities are the following:

- Studying architectures, satellite techniques and innovative methods aimed at spatially and temporally resolved monitoring of SWE events.
- Analysis and modelling of events that enable preventive prevention and prevention in real time.
- Design of a network capable of connecting and making the scientific segment (analyses and models) work efficiently together with the operational one (observations, monitoring and interventions).

Italian research groups and in particular also the group at INAF—Osservatorio Astronomico di Trieste, INAF-OATs in Friuli Venezia Giulia are active in all these areas. INAF-OATs is leading a study funded by ESA (and including several other Italian and European teams, Politecnico di Milano, Universita' di Trento, University of Maribor and SKYLABS d.o.o, a Slovenian SME), to design a distributed architecture of nano-satellites to monitor solar energetic events such as Coronal Mass Ejections (CME) and Solar Energetic Particles (SEP). CME are rather common, occurring from once per day at solar minimum to several per day at solar maximum. More extreme SEP events are rarer, occurring from once every few per months to a few per months. These events worsen the radiation environment around the Earth, representing a hazardous condition for both technological systems and humans. CUBE (CME Catcher Carousel) will monitor the magnetospheric response to CME and SEP at reconnection sites and near the poles using a constellation of nano-sats. The main objective of the constellation is to identify incoming CME and SEP events, measure them at different magnetospheric locations and altitude to quantitatively understand the energy transport toward the Earth. The baseline mission analysis, to be confirmed during the study, includes two 6U CubeSat on circular SSO and eight 12U CubeSats on two highly energetic circular orbit, ~60000 km radius, phased 90 deg away from one another. All units will be equipped with magnetometers, plasma analyzer, and particle monitors capable of measuring magnetic field strength of a few nT, proton spectra from a few tens keV to a few hundred MeV, and electron spectra up to a few hundred keV.

Minor Bodies of the Solar System

Another important issue on which the OATs team decided to contribute, in the spirit of the sustainability of our Planet, is the Prevention for asteroid impacts. That the impact of an asteroid against our planet is a likely hypothesis is certainly not new.

The Chelyabinsk meteor, which fell in Russia in 2013 with an energy release equal to 30 times the Hiroshima atomic bomb, reminded us all too well, while in 1994 the impact of the comet Shoemaker-Levy 9 (2 km large) on Jupiter has generated a crater so large that it is clearly visible from the Earth. Defense against asteroid impacts on Earth includes three fundamental points:

- identification of potentially dangerous asteroids;
- tracking and evaluation of the risk of the impact on the Earth;
- response to a possible threat

The first two points are covered by the Space Situational Awareness programs of ESA, NASA, etc. About the third point, we are in a phase of great increase in activity. On November 23, 2021, the DART probe was launched by NASA carried out the first impact experiment with an asteroid to study the deflection capacity of its orbit on September 26th 2022. The probe also hosted an experiment of the Italian Agency of Space (ASI), LiciaCube, a 6U CubeSat that detached from the mother probe before impact and filmed the impact itself with its two cameras, LUKE and LEIA. The DART impact on the small moon Dimorphos orbiting the asteroid Dydimos was definitely spectacular, as both LiciaCube images as well as HST, JWST and ground-based telescopes have testified. The impact has changed the period of Dimorphos by about 32 min or slightly less than 5%, showing that this technique can be capable to deflect hazard asteroids that may risk hitting the Earth. In such dangerous situations the ability to predict the event with as much time as possible is the most important key to success. In fact, the angle of deflection, and the relative energy of the impact. will be the smaller the greater the distance of the dangerous asteroid from the earth. The discovery, monitoring and characterization of near Earth asteroids is therefore the key to the success of these prevention activities.

ESA is also preparing the HERA probe, which will be launched in 2026, which will have the task of reaching the asteroid hit by DART and studying the long-term effects of the impact. INAF-OATs is involved in both LiciaCube and HERA and is active both in the modelling of the event and in the design and programming of new experiments in the field.

Space is Really Interdisciplinary

We have seen that the use of artificial satellites enable the acquisition of crucial data on the Sun and its interaction with the Earth, both using remote sensing and solar particle detection, and provide a way to monitor and even deflects potentially dangerous asteroids. Space based satellite architectures have also been revolutionary for Earth system observations. Satellite architectures have enabled and enable the acquisition of quantitative climate change information considering all components of the Earth system, providing meteorological, terrestrial, oceanographic, and cryosphere data on both local and global scales. Earth observation data must be combined with in situ environmental measurements to build a digital twin of the

Earth, using complex models, high-performance computing and artificial intelligence. This replica of the planet will provide an accurate representation of Earth's past, present and future changes, enabling the development of"what if" simulations to support decision making. Europe is a leader in Earth observation, which can support space-based green transition solutions for society and business. Both ESA and the EU are engaged in long-standing space programs to monitor climate change, and lead the ecological transition, enabling the EU to achieve its goal of becoming carbon neutral by 2050. Space has untapped potential to help achieve better understanding through modelling, enabling predictive predictions, and supporting policy formulation needed for implementation and monitoring. Space can also offer sustainable and commercial solutions for a green and decarbonised economy. All of this implies that space activities cut across many of the themes presented in this book, and thus these can stimulate interdisciplinary collaborations.

The Laboratory for Quantitative Sustainability

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'*Measuring the immeasurable*', to quote the famous book by Bell and Morse (2008), is the challenge of The Laboratory on Quantitative Sustainability (TLQS).

The idea of setting up a new laboratory for measuring sustainability in the city of Trieste came about after discussions between scientists from the Trieste International Foundation for the Progress and Freedom of Science (FIT) and the National Institute of Oceanography and Applied Geophysics - OGS.

The basic idea is to mobilise all the multidisciplinary scientific capacity of a science city like Trieste to respond to a major global challenge: measuring sustainability with rigorous quantitative scientific methods.

In 2022, a project proposal was submitted to the Italian Ministry of University and Research, involving research institutes (OGS, FIT, ICTP, FIF, INAF) and universities (Trieste, Udine, SISSA) with the support of relevant governmental organisations (Port Network Authority of the Eastern Adriatic Sea, Corps of the Port Captaincies - Coast Guard) and private companies (Illycaffè).

The project was approved for funding by the Ministry for the four-year period 2022–2025 as a distributed laboratory for quantitative sustainability research.

The term 'quantitative sustainability' refers to the application of scientific methods to represent and quantitatively analyse the UN Sustainable Development Goals using high performance computing and artificial intelligence tools to study the components of the science of sustainability, to make short- and medium-term predictions about the health of the Planet and the people who inhabit it, and to assess the impact of policies and technologies on economy and ecosystems.

The research activity concerns scientific modelling applied to the following topics:

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- study of the Blue Planet for the sustainability of the sea economy;
- food and biodiversity for the health of the Planet and its inhabitants;
- climate change and the environment;
- energy transition and industrial processes;
- new data science at the service of sustainability and human;
- protection of the Earth habitats with Space;
- sustainability and social sciences, the right to sustainability, attention to diversity and inclusion, the relationship between sustainability and social equity.

Given the scope of the topics covered, the multidisciplinary approach, which aims to combine hard sciences, natural sciences and social and economic sciences, is of paramount importance.

Even more important is the systematic use of new technologies, such as high-performance computing, big data analysis and machine learning. Successful applications in the fields of applied physics, engineering, geosciences and medicine could form the basis for new stimulating applications for sustainability goals.

Sustainability is addressed in all its three basic components: environmental, economic and social, with innovative tools and models that can stimulate interdisciplinary interaction.

The idea is to bridge the gap between research and science, governance, and the productive sector by promoting a circular model of development instead of a linear one, which is often destructive. Thus, generating wealth to our societies, helping social inclusion and above all protecting our environment.

This is a great challenge, for the whole scientific community and especially for the city of Trieste. The forces deployed are of the highest scientific calibre, as are the research infrastructures mobilised in the form of laboratories, computing centres and modelling capacities.

We therefore hope for a full success of the project, which may prove useful for policy makers and other stakeholders dealing with sustainability.

We are confident that at the end of the project the immeasurable will be a little better measured.

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