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

M. Cobal (✉)
Chemistry, Physics and Environment Department, University of Udine, Udine, Italy
e-mail: Marina.Cobal@cern.ch

V. Lughi
CENMAT, Materials and Natural Resources Department, University of Trieste, Via Valerio 6A, 34136 Trieste, Italy

S. Fantoni et al. (eds.), *Quantitative Sustainability*,
https://doi.org/10.1007/978-3-031-39311-2_8

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].

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

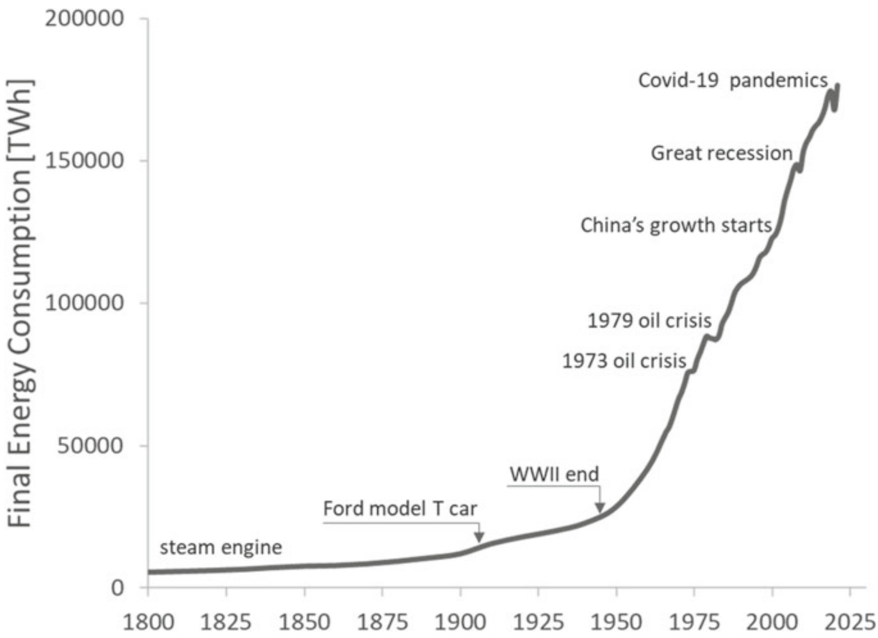

Fig. 8.1 Historical global energy consumption and major industrial and geopolitical landmarks that greatly influenced energy consumption (data retrieved from [1])

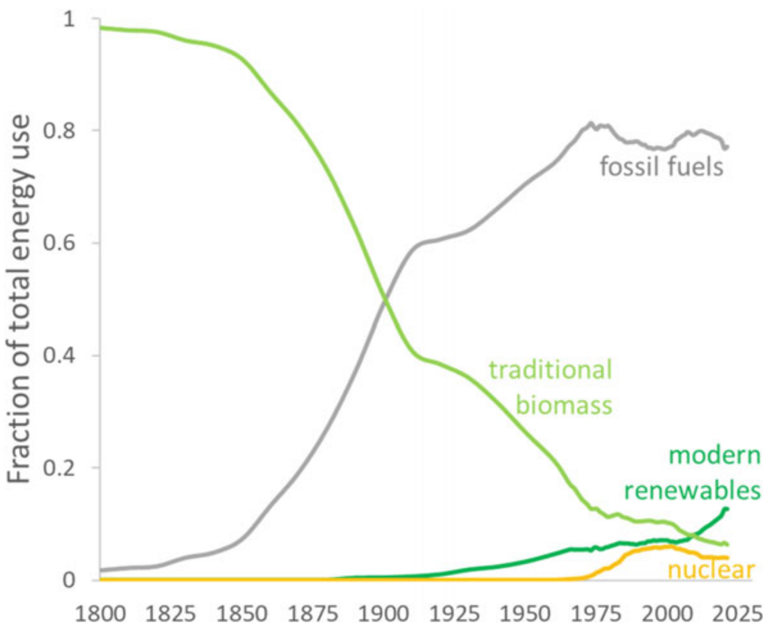

Fig. 8.2 Fraction of the total energy use, by energy source (data re-elaborated from [1])

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

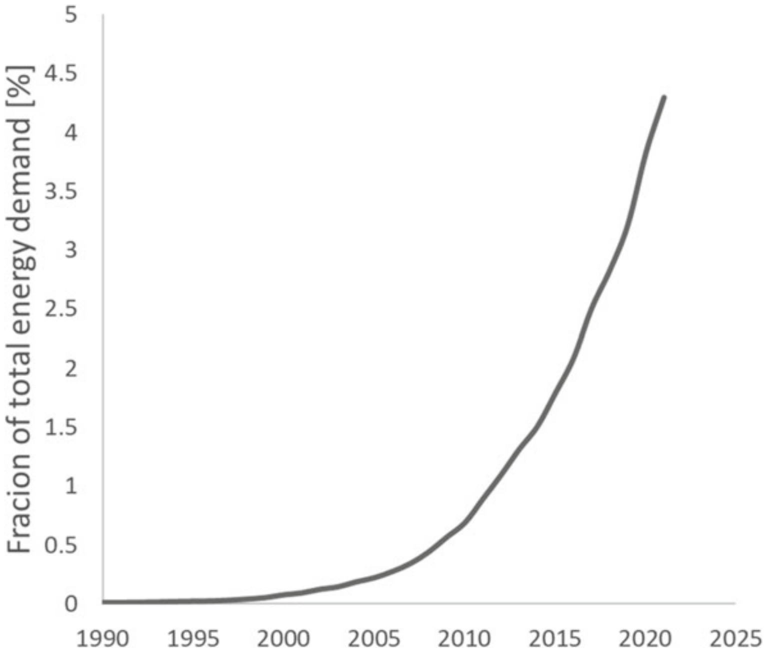

Fig. 8.3 Combined fraction of the total energy use for solar photovoltaics and wind power (data re-elaborated from [1])

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.

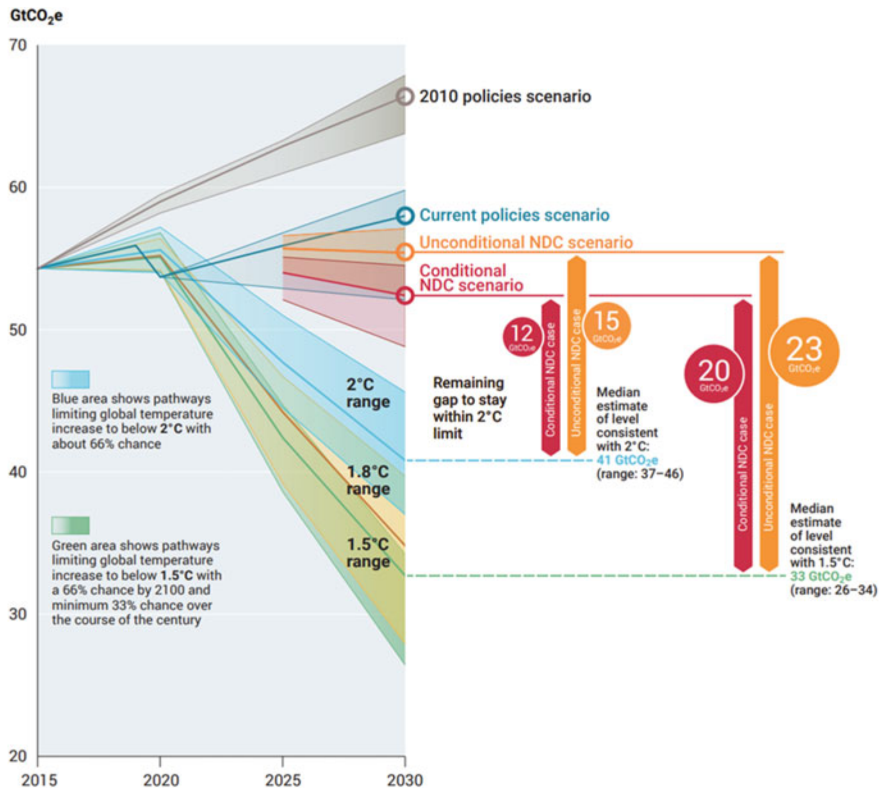

Fig. 8.4 Annual Greenhouse gas (GHG) emissions (Reproduced from [11] with permission). The green, yellow and blue ranges identify the annual GHG emission trends required to comply with different scenarios of temperature increase mitigation (under 1.5, 1.8, and 2 °C, respectively). The red and orange 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.

References

1. H. Ritchie, M. Roser, P. Rosado, “Energy”, published online at OurWorldInData.org (2022) Retrieved from: https://ourworldindata.org/energy on January 15th, 2023
2. “Climate Change 2022—Mitigation of Climate Change”, Sixth Assessment Report of the Intergovernmental Panel on Climate Change, United Nations Environmental Program, 2022
3. Y. Lu, The current status and developing trends of industry 4.0: a review. Inf. Syst. Frontiers (2021). https://doi.org/10.1007/s10796-021-10221-w
4. M. Ghobakhloo, M. Fathi, Industry 4.0 and opportunities for energy sustainability. J. Clean. Prod. **295**, 126427 (2021). https://doi.org/10.1016/j.jclepro.2021.126427
5. “Global Energy Review 2021”, International Energy Agency (2021)
6. “Renewables 2022—Global Status Report”, International Energy Agency (2022)
7. A. Renda et al., European commission, directorate-general for research and innovation. Industry 5.0, a transformative vision for Europe : governing systemic transformations towards a sustainable industry. Publications Office of the European Union (2022), https://doi.org/10.2777/17322
8. R. Zafar et al., Prosumer based energy management and sharing in smart grid. Renew. Sustain. Energy Rev. **82**, 1675–1684 (2018). https://doi.org/10.1016/j.rser.2017.07.018
9. “World Energy Outlook 2022”, International Energy Agency, November 2022
10. R. Ortt et al., Implementing Industry 4.0: assessing the current state. J. Manuf. Technol. Manag. **31**, 825–836 (2020). https://doi.org/10.1108/JMTM-07-2020-0284
11. United Nations Environmental Program, Emission and Gap Report 2022: Closing Window-Climate crisis calls for rapid transformation of societies. Nairobi (2022)

12. "Nuclear Power and Secure Energy Transitions", International Energy Agency (2022)
13. "The Role of Critical Minerals in Clean Energy Transitions", International Energy Agency (2022)
14. T. Capper et al., Peer-to-peer, community self-consumption, and transactive energy: a systematic literature review of local energy market models. Renew. Sustain. Energy Rev. **162**, 112403 (2022)