1 Energy Economics and Current Energy Systems

In this introductory chapter, we first present the discipline of energy economics, including a discussion on the analysis of policy instruments. We then describe the importance of energy for an economy, provide a synopsis of current energy systems using statistics on global energy consumption and greenhouse gas (GHG) emissions, and discuss some of the most pressing environmental and economic problems that are shaped by the prevailing fossil fuel-dominated energy systems.

1.1 What Is Energy Economics?

Economics is the study of how societies take decisions related to the production and consumption of goods and services to satisfy their needs in an efficient and sustainable manner, given scarce resources. These decisions are made within an economic system, with the goal of answering the following questions:

1. Which goods and services should be produced?,
2. How should we produce these goods and services?, and
3. For whom should these goods and services be produced?

The answers to these three questions are decided by different agents based on the type of economic system, that is, the markets in a market economy approach, the state in a planned economy approach, or both the market and state intervention in a mixed system. The last approach, that is, the mixed economic system is the one adopted by many societies around the world.

If we now consider the energy sector, we can also identify three fundamental questions that we should answer in this sector:

1. Which energy sources and energy services (such as heating, cooling, or lighting) should be produced?
2. Which technologies and energy sources should be used to produce goods and energy services?
3. For whom should the energy sources and services be produced?

Energy economics is the application of the principles of economics to the study of how energy sources can be managed and used in an efficient and sustainable way to produce goods and energy services. Moreover, energy economics helps to answer the three questions previously mentioned and helps to understand the role of the state in

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the management of energy sources that are scarce and partially non-renewable and polluting. Energy economics can also be used to study how the state can intervene in the energy sector through policies to promote more efficient and sustainable use of scarce resources and/or to promote more access to energy sources. As we will explain in Chapter 2, the functioning of energy markets is characterised by market failures, that is, situations wherein market forces such as demand and supply by themselves are not able to provide efficient and sustainable outcomes in terms of prices and quantities that maximise the welfare of society. In this context, state intervention is needed in the functioning of the energy markets to correct this failure. Therefore, an economic analysis of these policy instruments used by the state is essential. The discipline of energy economics includes an economic analysis of both the functioning of the energy markets and energy-related markets and of state intervention in these markets, that is, of policy instruments.

Economic analysis of energy systems can be based on using a microeconomic approach that studies the behaviour of individual agents such as consumers and firms, or on using a macroeconomic approach that provides an analysis of the economic issues at the aggregate level of an economic system. In this book, we provide an exposition based on a microeconomic approach that is integrated with some insights from econometric studies, that is, studies that use statistical and mathematical methods to evaluate issues in energy economics.

Although energy economics is largely oriented towards analysing issues from an economic efficiency perspective, it is also important to take into consideration equity-related issues such as access to energy, the impact of policy on income and wealth distributions, and the impact of pollution and climate change on the well-being of society. In this context, it is relevant to differentiate between positive and normative approaches in economics. Positive approaches provide insights into how economic systems function, that is, how households and firms make decisions, whether the allocation of resources is efficient, and how scarce resources are allocated among different economic agents. Normative approaches, on the other hand, shed light on the desirability of economic outcomes from society's point of view, for instance, whether the distribution of energy resources is equitable, or whether the impact of an energy policy instrument such as a carbon tax is equitable. Therefore, this approach involves making a value judgement.

In energy economics, we mainly use the scientific method, that is, models of energy markets as well as of the behaviour of different economic agents are developed. These models are tested using empirical analysis with real data. A model is a simplified representation of the real world and is based on a set of basic principles, as well as on some assumptions that allow the modeller to describe and analyse economic situations. The modeller emphasises empiricism, that is, evidence-based analysis. This type of analysis uses data and econometric methods to develop and test theories, and to evaluate the effectiveness of energy and climate policy, while being careful to distinguish between correlations and causality.

Moreover, these models are based on concepts of optimisation, in which economic agents are choosing, under some constraints, the best outcomes for themselves. Of course, in the real world, we can observe deviations from this optimal behaviour that we call ‘behavioural anomalies’, whereby economic agents may not always optimise their decisions. The models can be represented either using graphs or with some simple mathematical functions as well as more complex systems of equations. In this book, we will primarily use graphs with the goal of illustrating economic decision-making using intuition.

1.2 The Role of Energy in an Economic System

Energy is a pivotal driving force for any economic system, and its use is vital for enhancing the welfare of all agents within these systems.

The ultimate objective of any economic system is to enhance the well-being of both current and future generations of a society while taking into account the limits of natural resource availability as well as the Earth’s constraints. Well-being is directly dependent on both material living conditions and on subjective perceptions of the quality of life. Energy is an essential determinant of both of these elements of well-being.

Energy plays a crucial role as a production factor in several sectors, such as the industrial, transportation, services, and residential sectors. Energy is used to run machines that transform materials into finished products, as well as to fuel vehicles, ships, trains, and aeroplanes to transport people and goods. Households use energy to produce energy services such as heating, lighting, cooking, and cooling which are crucial to satisfy their basic needs. Energy is also essential for the functioning of critical infrastructure such as telecommunications and health care, as well as important utilities such as power generation and water supply. More generally, access to affordable

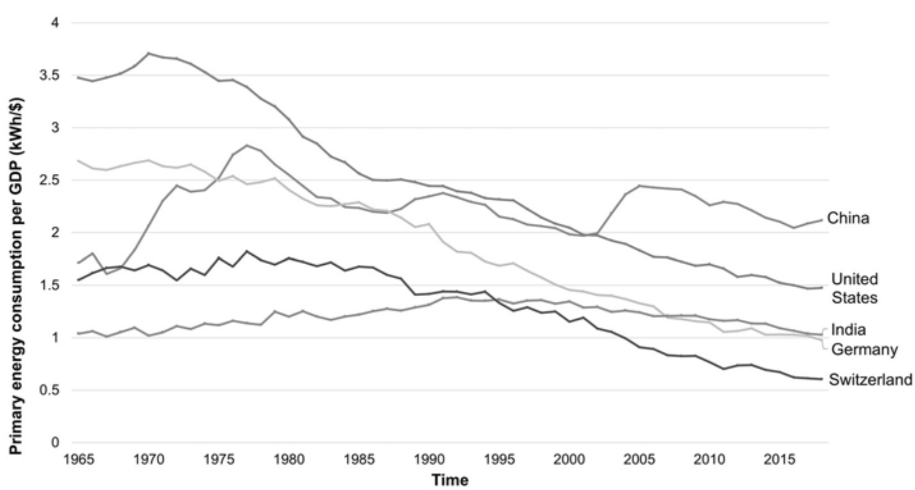

Figure 1.1 Energy intensity (1965–2018)
adapted from Our World in Data [1], sources of data include EIA [2] and the Energy Institute [3]

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and sustainable energy sources is crucial to promote innovations, and productivity growth, which ultimately influences economic growth and enhances living standards.

While energy is an essential input in the production processes for goods and services, its role in contributing to production has generally declined over time, that is, reduced the total amount of energy consumed per unit of gross domestic product (GDP). For instance, in Figure 1.1 [4], we illustrate the values of energy intensity between 1965 and 2018 for a sample of Organisation for Economic Co-operation and Development (OECD) and non-OECD countries. We find that in general, energy intensity levels have declined over this period. This improvement does not imply, however, that the importance of energy has diminished; on the contrary, energy remains one of the main elements in promoting the well-being of all economic agents. This decline simply reflects technological gains over time, which have changed how societies use energy.

1.3 Energy Systems and CO_2 Emissions

1.3.1 Total Energy Consumption

In Figure 1.2, we present a graph that illustrates the trends in the total final energy consumption by source for the world. Upon looking at the graph, we observe a general reliance on the current energy systems on fossil fuels (coal, oil, and natural gas), which naturally leads to environmental and economic problems. Moreover, a large share of the global electricity supply is also generated using fossil fuels. Additionally, we observe that energy consumption is steadily increasing. This development is largely driven by an increase in energy demand in the growing developing countries, whereas in industrialised countries, it has mostly been stable.

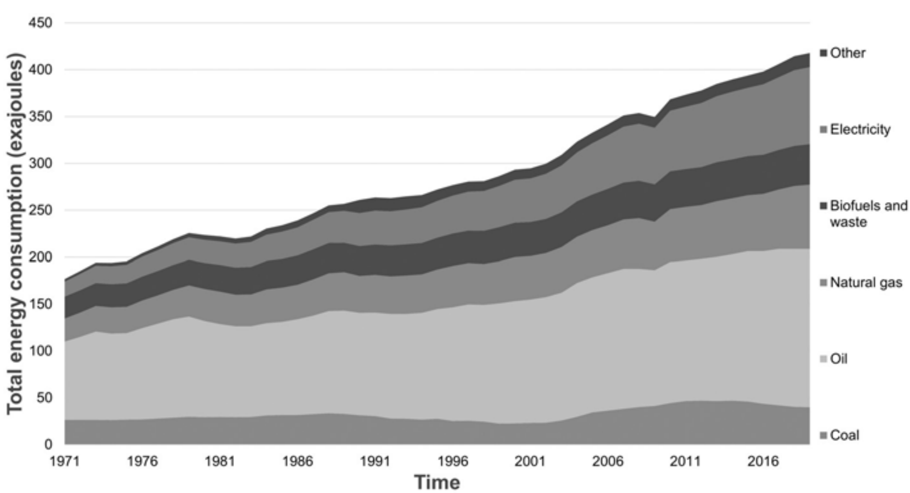

Figure 1.2 Total final energy consumption by source for the world [5]

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One must note that the path being followed by the developing countries today, in terms of their growth in energy consumption, is one that has already been traversed by the current industrialised countries. Indeed, several industrialised countries experienced a significant increase in total energy consumption from the middle of the twentieth century, similar to the trend currently observed in China and India as well as in other developing countries. However, this increase was followed by a stabilisation, and in recent years a slight decrease in energy consumption. In the beginning, the growth in total energy consumption in industrialised countries was driven by the increase in population levels and in life expectancy that these countries witnessed, as well as by their economic growth. In the past decades, factors such as technological change, energy and climate policy measures, and low fertility rates have led to the stabilisation in levels of energy consumption. It is natural to expect this transformation in developing and emerging countries as well. However, as we will discuss later in this chapter, ensuring sustainable development in these countries would require that this increase in total energy consumption is largely met with renewable energy sources, and not by using fossil fuels.

Figure 1.3 presents a map that shows the total per capita energy consumption around the world, as of 2022. We see a clear divide between developing and developed countries with respect to per capita energy consumption. The value of this energy metric in several developed regions of the world, especially in the United States, Canada, Russia, Australia, Saudi Arabia, and the Nordic countries is much higher compared to that in the currently developing, or lower-income economies. We can observe that most countries in Africa, as well as several parts of South America, South Asia and

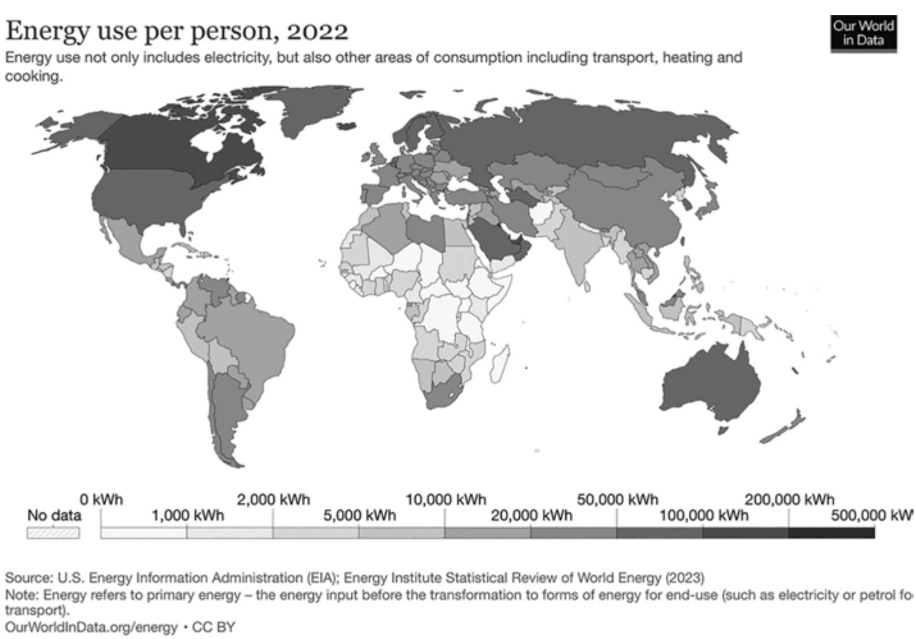

Figure 1.3 Total per capita primary energy consumption around the world (2022) [6]

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Southeast Asia, have much lower levels of energy consumption compared to North America, Australia, and much of Europe.

1.3.2 Energy Consumption by Sector

For both industrialised and developing countries, it is important to evaluate the overall trends in aggregate energy consumption as well as in energy consumption by sector; this is helpful to identify the sources for the variations that we observe in aggregate consumption. Thus, in Figures 1.4 and 1.5, we will provide information regarding the structure of energy consumption by sector in a high-income country, Switzerland, and in a developing country, India, between 1990 and 2010. It is important to note that India has experienced an increase in total energy consumption over this period, compared to Switzerland, where levels of total energy consumption have stagnated.

Figure 1.4 shows the energy consumption in Switzerland split up by sector, including the residential sector, industry, services, and transport, for the years 1990 and 2020. We observe that the transport and residential sectors have contributed to a large share of the total consumption, while the shares of industry and commercial/public services are comparatively lower, and roughly of similar magnitudes to one another. Furthermore, this trend persists over time. In Switzerland, the buildings sector constitutes around 45 per cent of the total end-use energy demand [7]. This is tantamount to the case in several other industrialised countries, in which energy consumption in buildings for the provision of heating, cooling, lighting, and other energy services, constitutes a large chunk of energy demand.

Figure 1.5 illustrates the shares of energy consumption by sector for India, a large developing country, again in 1990 and 2020. These shares are different with respect to the shares that characterised an industrialised country such as Switzerland. In India,

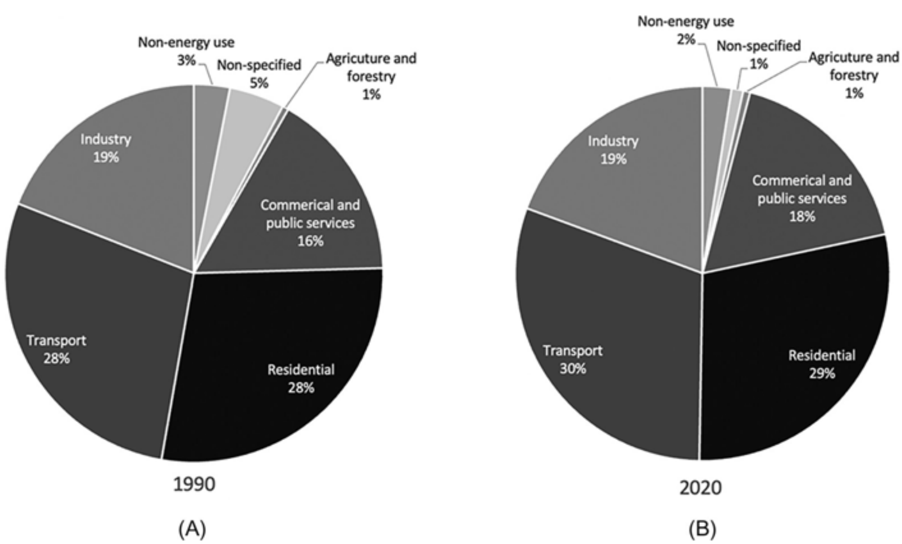

Figure 1.4 Total energy consumption by sector for Switzerland [5]

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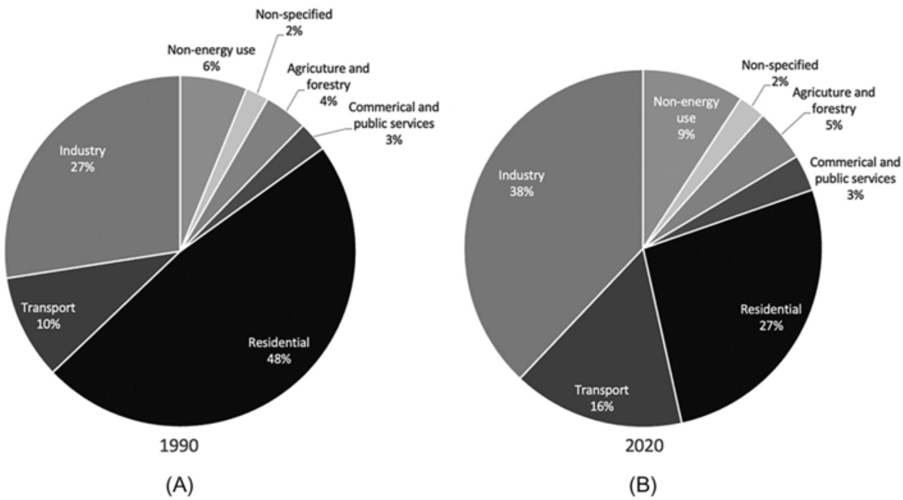

Figure 1.5 Total energy consumption by sector for India [5]

the shares of energy consumption across the industrial and transport sectors have grown rapidly, whereas, in Switzerland, we observe a general stagnation. As we can also observe that as of 2020, the industrial sector is responsible for the largest share of energy consumption, followed by the residential and transportation sectors. However, in the near future, India is likely to experience a significant increase in energy consumption in the buildings as well as the transportation sectors, due to both the installation of heating and cooling systems in buildings (primarily air-conditioning) and due to the increase in the number of private vehicles as levels of population and urbanisation skyrocket [8–10].

1.3.3 Energy Demand in the Future

The increase in energy demand in the future will be determined partly by increases in per capita income and urbanisation, and partly by increases in population. In the next decades, the world population is projected to increase to over 10 billion. This large increase in the world population, especially in developing countries, will naturally lead to an increase in demand for energy as well as energy services. For instance, in developing and emerging countries, energy demand in the transport sector can be expected to increase considerably in the next decades, especially as economic growth picks up. This increase will be amplified in emerging economies such as India and China in which population levels are still increasing (even if population growth rates have stagnated), while the number of vehicles owned per household is relatively low [9]. Currently, the population of countries that are classified as industrialised countries is estimated at around 1.2 billion. The combined population of China and India alone currently reaches a staggering 2.8 billion, with upward trends expected in both nations. Accordingly, the potential for an increase in vehicle ownership and energy demand in developing and emerging markets, mostly based in Asia and Africa, is enormous.

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To satisfy this surge in demand, it will be crucial to promote sustainable private and public transportation modes such as electric cars, motorcycles, buses, and trucks, or vehicles with engines fuelled by renewable energy sources. It is also critical that the electrification of the transport system, to whichever extent it takes place, should be based on clean sources of electricity.

1.3.4 Greenhouse Gas Emissions

The main cause for the persistently high level of GHG emissions that we have observed over the past 20–30 years is that both the energy sector and the other sectors of modern economies are largely dominated by the use of fossil fuels. As of 2020, the composition of GHG was carbon dioxide (74.4 per cent), methane (17.3 per cent), nitrous oxide (6.2 per cent), and fluorinated gases (or F-gases) (2.1 per cent) [11].

1.3.4.1 Sources of Greenhouse Gas Emissions

It should be noted that the energy sector is the major contributor to GHG emissions, as shown in Figure 1.6 constituting almost 73 per cent of global GHG emissions. The agricultural sector is another important source of global emissions, being responsible for approximately 20 per cent of total emissions.

In this section, we will mainly present statistics on carbon dioxide (CO_2) emissions because of its dominant role in global warming. CO_2 is produced both from natural processes (such as during volcanic eruptions) and from anthropogenic sources (such as deforestation, land use changes, and the burning of fossil fuels). We must note that other pollutants are also significant contributors to climate change. For example, methane is a highly potent GHG, wherein one tonne of methane emission is equivalent to approximately 30 tonnes of CO_2 emissions [13]. This gas is released through natural sources and human activities, especially agricultural activities (such as rice cultivation and livestock breeding). With around 130 million tonnes of emissions from the energy sector on the global scale, methane also poses a serious threat to the climate [14].

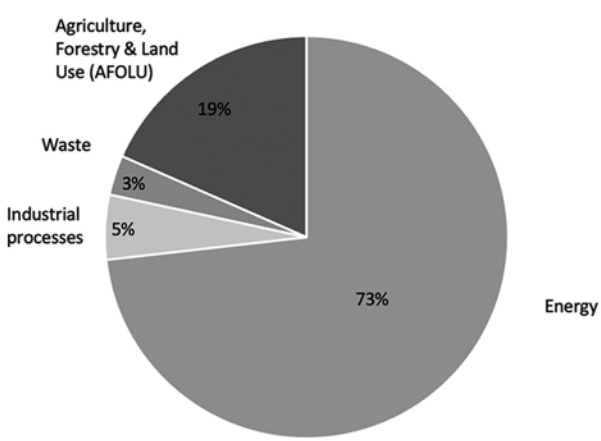

Figure 1.6 Global greenhouse gas emission by sector in 2016 [12]

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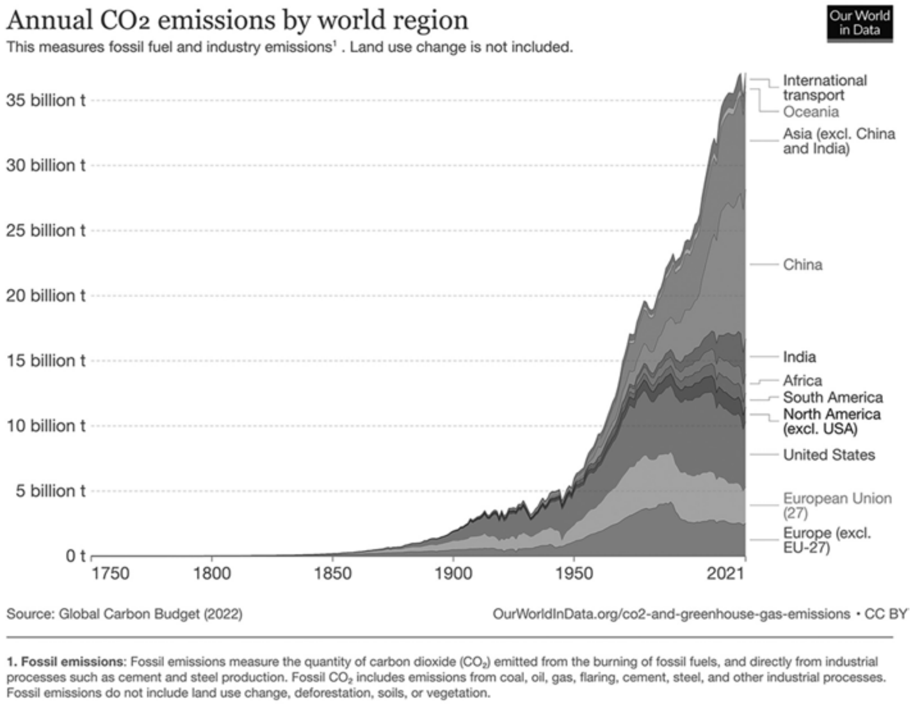

Figure 1.7 Annual fossil fuel carbon dioxide emissions (2023) [15]

Figure 1.7 illustrates world CO_2 emissions due to fossil fuel combustion from 1750 to 2020, by region. In the last 40–50 years, world CO_2 emissions grew steadily. However, if we look at the heterogeneity across regions, we can see that in the last decade, the amount of CO_2 emissions that arose in industrialised countries tended to decrease, whereas it has shown an uptick in the emerging-market and developing countries, as can be expected. It is also important to note that several industrialised countries, despite showing declines domestically, are still contributing to the global increase in CO_2 emissions through their imports, that is, CO_2 emissions generated in the production of goods that are imported from other countries.

Table 1.1 presents information regarding the per capita CO_2 emissions (measured in metric tonnes, as of 2020) for a sample of countries, as a result of burning fossil fuels for energy and cement production excludes land use change. This table presents information on emissions generated within the boundary of a country. However, as also previously discussed, these statistics fail to account for the emissions embedded in the import or export of goods and services, that is, the emissions being produced elsewhere, for example, due to goods that are imported. This is a significant omission in the accounting of emissions; for some industrialised countries, the inclusion of the embedded emissions in the total CO_2 emissions per capita is likely to lead to a large increase in their level of emissions. Per capita CO_2 emissions were relatively high in Australia, Canada, South Korea, Japan, and the United States, and to a lesser degree in countries such as China and Germany. Many of these countries use fossil

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Table 1.1 CO_2 emissions (measured in metric tonnes per capita in 2020) [16]

Country	CO_2 emissions
Australia	14.77
Brazil	1.94
Canada	13.60
Switzerland	4.04
China	7.76
Germany	7.26
Spain	4.28
France	3.95
United Kingdom	4.60
Indonesia	2.07
India	1.58
Italy	4.73
Japan	8.03
South Korea	10.99
Mexico	3.04
Norway	6.73
Russia	11.23
United States	13.03
South Africa	6.69

fuels intensively. Naturally, population size also plays a crucial role in determining the quantity of emissions. As previously discussed, India emits relatively low levels of CO_2 compared to industrialised countries, on a per capita basis.

1.3.4.2 Which Countries Contribute Most to Global CO_2 Emissions?

The atmosphere can be considered, as discussed in more detail in Chapter 2, to be a global common resource, that is, a scarce resource that can potentially be exploited by everyone. More specifically, the atmosphere is a major sink for GHG emissions. As a sink, it has a limited capacity to 'absorb' emissions, and once that limit is surpassed, the ill effects of climate change become apparent, as we have already started to observe (through heatwaves, extreme weather events such as droughts and floods, a rise in global sea levels, and melting of glaciers).

Related to the use of the atmosphere as a sink, it is important to keep in mind that the industrialised countries, in which approximately 20 per cent of the current world population lives, have contributed to more than 50 per cent of the global cumulative emissions [12]. Therefore, the atmosphere has been exploited as a sink mostly by industrialised countries. In the discussion on climate policy strategies to address these ongoing (and expected) problems, it is also vital to know the actors that have contributed the most to the exploitation of this sink thus far.

1.3.5 The Relationship between Carbon Dioxide and Global Warming

As discussed and illustrated in the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report [17], there has been a positive relationship between cumulative CO_2 emissions and the global surface temperature change since 1850. We should note that more than 90 per cent of scientists and researchers studying the Earth's climate support the notion of global temperatures increasing and acknowledge that the primary cause of this increase is anthropogenic emissions, that is, emissions produced as a result of activities of humans.

1.4 Main Problems Resulting from the Current State of Energy Systems

The current state of the world described in the previous section leads us to identify four major problems with present-day energy systems. We broadly classify these problems as: environmental and economic issues that can have both global and local effects, the non-renewable nature of resources, security of supply and geopolitical problems, and lastly, the inefficiency in the use of energy. In this section, we will discuss their importance and explain how they may pose a threat to the idea of sustainable development.

1.4.1 Environmental and Economic Problems

1.4.1.1 Environmental Problems and Global Effects

The current energy systems, dominated by fossil fuels, are creating global and local environmental problems. Globally, GHG emissions arising from fossil fuel combustion trigger climate change. Some changes have already started to materialise, such as extreme natural events, heat waves, the spread of infectious diseases, the occurrence of climate-related migration, and a reduction in production efficiency, and these changes are expected to intensify in the next few decades. Therefore, environmental problems at the global level pose serious threats to population health and give rise to potentially negative effects on production activities, on the levels of GDP, as well as on the well-being of all living beings. It is important to note that the effects of these environmental issues are likely not to be felt with an equal level of intensity by everyone around the world and that there exist strong disparities between different regions, with developing countries being affected relatively more by climate change.

Several studies in the scientific literature have analysed the long-term economic consequences of climate change. One of the first comprehensive studies on the economic impact of climate change on GDP was published in 2006 by Nicholas Stern. The report found that '... if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5 per cent of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20 per cent of GDP or more' [18]. Two recent studies by Burke et al. (2015) [19] and by Kalkuhl and Wenz (2020) [20] analyse the regional impact of climate change on GDP. Both studies affirm that the negative impact on GDP is likely to be substantial, and could be more than 20–30 per cent for some developing countries by 2100. Additionally, both studies also clearly underline the stark heterogeneity of the impact of climate change on GDP, with emerging markets and developing countries likely to suffer more from climate change [19]. Of course, we have to keep in mind that these are long-run-oriented studies, and these results are derived on the basis of making certain modelling assumptions and do not factor in considerable uncertainty. Therefore, these results should be taken with a grain of salt. The main advantage of these studies is that they shed light on the possible effects of climate change and its heterogeneity, which is helpful for policymakers.

1.4.1.2 Environmental Problems and Local Effects

Apart from global problems, fossil fuel-dominated energy systems also have local impacts on human health and the environment. One of the most obvious negative effects is air pollution, which manifests through an excessive accumulation of Particulate Matter 10 (PM10), PM2.5, ozone, and other pollutants and is brought about by the burning of fossil fuels. Air pollution is also dubbed as the silent killer; with approximately 7 million deaths per year [21] being attributed to outdoor and indoor air contamination, it is one of the major environmental risks to human health. The level of air pollution varies considerably between regions of the world, and also between urban and rural areas within the same country. Its negative effects on health and well-being can also cause an indirect decrease in GDP. Being mindful of the heterogeneous effects once again, we should keep in mind that the most polluted urban areas in the world are located in developing and emerging countries, as can be observed from Figure 1.8, which plots average PM2.5 concentrations in some of the most polluted capital cities of the world in 2019 and 2020. According to guidelines from the World Health Organisation, annual average concentrations of PM2.5 should not exceed 5 $\mu g/m^3$ [22], and as we can see, these cities perform far worse in terms of air pollution.

1.4.2 Non-renewable Energy Sources

The second problem with current energy systems is their heavy reliance on the use of non-renewable energy sources, which is likely to lead to a scarcity of these resources. Furthermore, the projected increases in the use of these scarce resources (such as coal, oil, and natural gas) can lead to an increase in their prices, and thus potentially create social tensions and economic problems in society as well as across borders. Of course, to some extent, rises in prices can at least partially be stemmed by technological change in production and consumption activities. However, it is clear that our dependence on essentially unreplenishable sources of energy to fuel our lives not only has a severe environmental impact, but it can also have several economic and social implications.

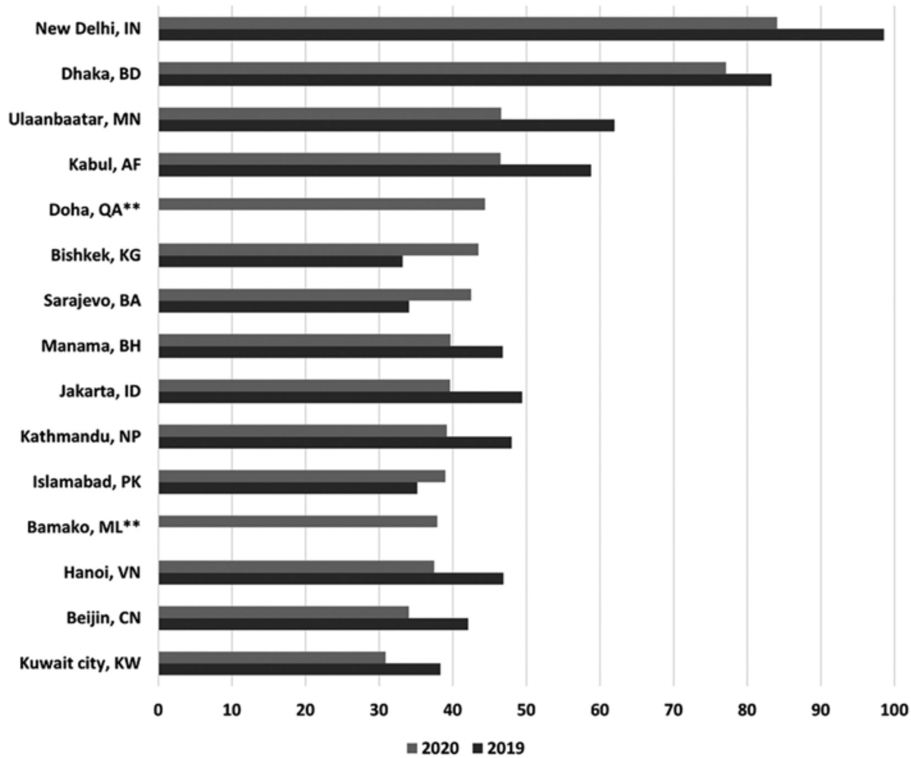

Figure 1.8 Average PM2.5 concentrations in the most polluted capital cities in the world in 2019 and 2020. ** Data for Doha and Bamako for 2019 was unavailable. [23–25]

1.4.3 Geopolitics and Security of Energy Supply

The third problem with current energy systems arises due to geopolitical circumstances. Oil reserves are primarily located in the Middle East (48 per cent) and in Central and South America (18 per cent), while gas reserves are concentrated in the Middle East (40 per cent) and in the Commonwealth of Independent States (Russia and eleven other republics that were formerly part of the Soviet Union (Commonwealth of Independent States (CIS))) (30 per cent). The consumption of oil and gas is predominantly concentrated in the OECD countries and in emerging economies such as China and India. Moreover, as previously discussed, a significant increase in energy demand can be foreseen in many developing countries. Such an increase in energy demand can lead to geopolitical tensions, which can negatively affect the security of energy supply for many industrialised and developing countries.

1.4.4 Inefficiency in the Use of Energy

The fourth and last problem is related to the efficiency of the use of energy. Current economic systems are wasteful in their use of energy, and this is a pivotal problem. Improving energy efficiency is the low-hanging fruit for ameliorating the extent of the

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other three problems discussed above, and for helping transform the current energy system. A study by the management consultancy firm McKinsey from 2009 calculated that in the United States, energy demand could be reduced by 23 per cent by improving energy efficiency, which amounts to savings of $1.2 trillion within a decade [26]. These findings are based on the adoption of a bottom-up approach (an engineering-based methodology that focuses on isolating the end-uses of energy, as well as detailing technological choices). On the other hand, using a top-down approach that analyses possible synergies between sectors and based on the estimation of econometric models, Alberini and Filippini (2018) [27] found that the potential for energy demand reductions through energy efficiency measures in the American residential sector was around 20 per cent of current demand, whereas Filippini and Hunt (2011) [28] estimated that across all the OECD countries, the potential energy demand reduction through energy efficiency measures was also around 20 per cent.

1.5 The Way Ahead: Energy Transition

The four problems that we discussed in the previous section clearly indicate that the current energy systems based on fossil fuels are not sustainable. Societies recognise that the solution to these compelling problems lies in the transformation of energy systems into those based on renewable energy sources and on the use of energy-efficient technologies. The ultimate goal is to develop a sustainable energy system, that is, an energy system that provides energy and energy services to the economic system while minimising the negative impact on the environment, considering the welfare of future generations. In this context, the term ‘energy transition’ is important to discuss.

1.5.1 Energy Transition

Energy transition refers to a structural change in the current energy system with respect to supply and demand. On the supply side, the energy transition implies a shift away from traditional fossil fuels such as coal, oil, and gas towards more sustainable and renewable energy sources, such as solar energy, wind energy, and hydropower. On the demand side, the energy transition involves the adoption of energy-efficient technologies, investments in digitalisation to optimise energy consumption, as well as making changes to consumption behaviour. Through the energy transition, governments want to achieve an energy system dominated by electricity produced from renewable energy sources within the next two to three decades. This implies, for instance, the electrification of some important sectors, such as land transport and heating. Other sectors, such as air transport, or some sub-sectors within the industrial sector are likely to substitute oil and gas and their derivative products with renewable energy sources such as biogas or hydrogen obtained using renewable sources (‘green hydrogen’).

Initially, the thrust on achieving an energy transition was mainly driven by concerns over climate change. During the last few years, governments and societies around the

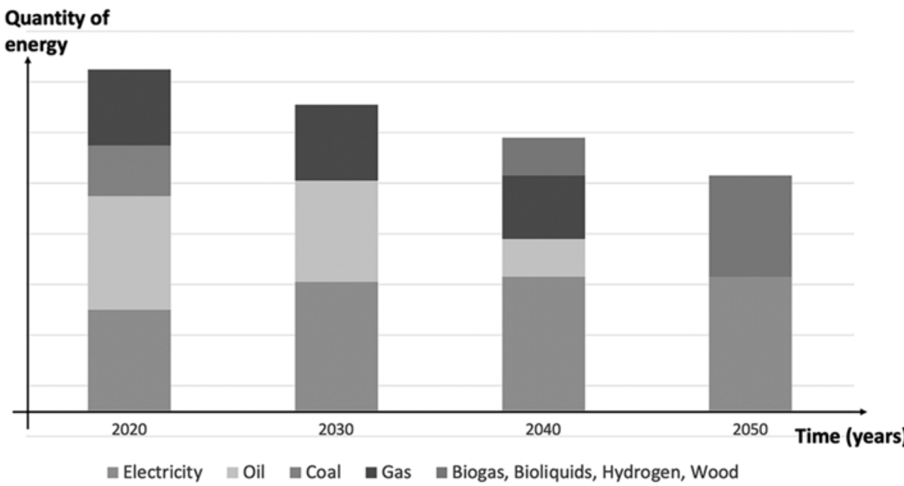

Figure 1.9 Energy transition and changes in the energy mix

world have realised that an energy system based on renewable energy can provide three other very important benefits, that is, an increase in the level of security of supply, an improvement in the level of air quality and, therefore, a reduction in the number of premature death and health costs due to air pollution, and the facilitation of energy access (particularly in developing countries) through decentralised systems.

Figure 1.9 is an illustration of a possible pathway of the transition of an energy system for a typical industrialised country from fossil fuels towards an energy system based on renewable energy sources and electricity produced using renewable energy. Starting from an energy system dominated by oil, gas, and coal, the transition results in an energy mix that is dominated by renewable energy sources such as biogas, hydrogen, biofuels, and wood and electricity produced from renewable energy sources.

An important point to note regarding the energy transition is the relevant decrease in total energy consumption due to the adoption of more energy-efficient technologies and the electrification of the transport and heating sectors. This is likely to be the case for industrialised countries. In developing countries, we expect a similar transformation towards renewable energy sources and an increase in overall energy efficiency, but we also expect an increase, and not a decline, in total energy consumption. This increase will be driven mostly by economic growth and population increases.

Regarding the transformation of the electricity sector in industrialised countries illustrated in Figure 1.10, we see that at the end of the transition process, the electricity production mix will be mainly based on hydropower, wind energy, solar energy, and geothermal energy. Of course, the electricity production mix is likely to be different across countries depending on their characteristics. We foresee this transformation taking place also in developing countries, although with a different path between 2030 and 2050.

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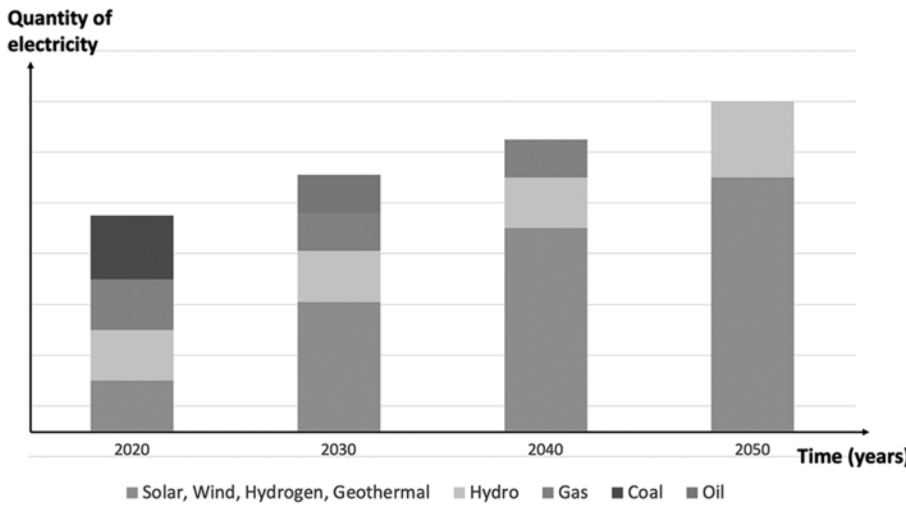

Figure 1.10 Electricity production mix for an industrialised country

Generally, it is expected that the electrification of sectors such as transport and heating will increase the electricity demand. Therefore, the energy transition implies that the suppliers will also increase electricity production, largely based on renewables. Note that in order to reach a well-functioning electricity system relying mainly on renewable energy sources such as solar energy and wind energy, which are characterised by intermittence in production due to meteorological factors, it is essential to:

- have a well-developed and interconnected electricity network that gives the possibility to move electricity from one region to another with flexibility, depending on the demand,
- have a well-developed electricity distribution network that enables the flexible and dynamic management of demand and supply using digitalisation (smart grids, smart meters, and smart appliances) as well as local storage facilities such as community-level batteries, and
- have a backup technology, such as gas-based power plants functioning with hydrogen, or technologies such as storage hydropower plants or large batteries that can be used during periods of supply shortages, which are mainly operated at the national level.

Some policymakers use the term ‘energy transition’ in combination with the term ‘net zero’. This refers to a transition that is used to achieve an energy system characterised mainly by renewable energy sources, along with a small proportion of fossil fuel-based energy essential for sectors in which renewables cannot be employed. However, since the energy transition also implies achieving climate neutrality, that is, an energy system that produces zero CO_2 emissions, emissions from the sectors that still use fossil fuels must be captured and stored in dedicated repositories underground.

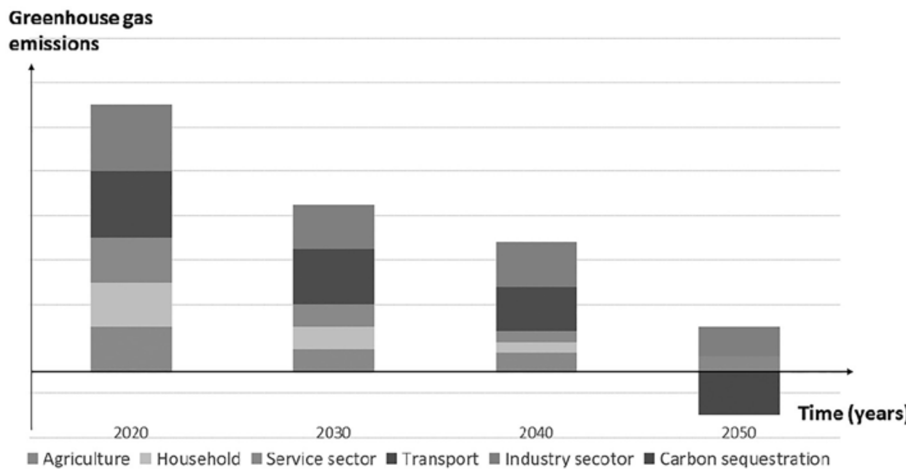

Figure 1.11 Energy transition and greenhouse gas emissions

In Figure 1.11, we illustrate the development of GHG emissions over time. Towards the end of the energy transition process, emissions are likely to be low, and, as discussed previously, they can be eliminated using carbon capture and sequestration technologies. For instance, emissions from industrial processes such as steel and cement production are likely to be captured from the production sites, and then transported and stored deep underground in geological formations.

The transformation of the current energy system into a system dominated by renewable energy sources and characterised by net zero GHG emissions generally implies additional costs in comparison to a system based on both renewable and non-renewable sources. However, it is important to keep in mind that this transformation is likely to also bring significant benefits to society. Of course, costs and benefits may vary a lot across different countries due to differences in their initial energy systems, their economic structures, and the socioeconomic characteristics of their populations. Generally, we distinguish between direct benefits and co-benefits of an energy transition. The direct benefits are obtained from the avoided negative climate change impacts, such as damages due to natural extreme events, agricultural yield losses, and adverse effects on labour productivity. Co-benefits result from the reduction of air pollution, greater biodiversity, enhanced water quality, and improved security of supply. It is, therefore, important to consider both costs and benefits (including these co-benefits) in all discussions about the energy transition, even though some benefits, such as the increase in air and water quality, as well as an increase in the security of supply, are not easy to estimate from an economic point of view.

The energy transition is an extremely essential but also challenging goal for societies to achieve. To reach this goal, we need to continue to invest in research and development activities to further enhance the exploitation of renewable energy sources, increase the level of energy efficiency, and digitalise the electricity sector. To ensure that they reach this ambitious goal, governments around the world are trying to design and implement effective energy and climate policies. In the second part of this textbook, we will discuss the most important policy measures that can be adopted by policymakers to address market failures and promote the energy transition. Of course, the ultimate goal is to choose a strategy to achieve the energy transition by maximising the difference between benefits and costs and by minimising possible negative distributional issues related to this transition.

Type of renewable energy sources for the energy transition

As we mentioned, to achieve the energy transition, we need to invest in renewable energy. In this box, we briefly describe different forms of renewable energy. Renewable energy is a form of energy that can be constantly replenished and is drawn from natural sources (such as water, biomass, sunlight, wind, steam or hot water within the Earth, or even waves). It can be used for electricity generation, space and water heating and cooling, cooking purposes (mostly in developing countries), and transport. Renewable energy sources should be distinguished from non-renewable energy sources, which are mostly drawn from fossil fuels (such as coal, gas, and oil) as well as from nuclear fuels that are exhaustible energy stocks, and thus only available in finite quantities.

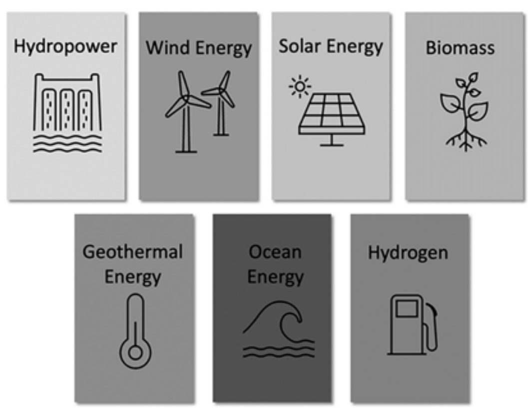

Figure 1.12 Types of renewable energy [29]

Figure 1.12 provides a snapshot of these main renewable energy sources. Hereon, we will briefly describe some of these forms of energy.

- **Solar energy:** In recent years, solar energy has become a very important form of renewable energy. Using the rays of the Sun as an energy source remains one of the most promising forms of clean energy. There are broadly three types of solar energy systems: photovoltaic (photovoltaic (PV))-based electricity systems, concentrated solar power-based electricity systems, and heating and cooling systems for water and spaces. PV-based systems use solar panels to

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directly convert sunlight to electricity. Smaller solar PV systems can power small appliances and individual homes, while many solar panels may be needed to produce electricity for several homes. Concentrated solar power systems are based on mirrors that reflect sunlight to a power tower, in order to focus it onto receivers that convert this to heat. This heat can either be used for electricity generation or stored. It is primarily used in very large power plants.

- **Wind energy:** Utilising the daily wind cycle to generate mechanical power or electricity is also one of the most common forms of renewable energy. Wind-based electricity is generated using wind turbines. They can be located on both land (onshore) and offshore. Wind turbines can either be individual structures or clumped together in what is called a wind farm. While individual turbines can generate enough electricity to power single homes, wind farms are needed for large-scale production.
- **Hydroelectric power:** Hydropower was one of the first renewable sources of energy used for electricity generation. Hydroelectric plants are located on or near a water source, and electricity is produced with the help of turbines. Run-of-the-river systems are those in which the water force of the current of a river causes a turbine to rotate, which then converts the mechanical energy to electrical energy. Storage systems, on the other hand, are built to accumulate water in reservoirs, from where it is released through turbines as and when needed to generate electricity.
- **Biomass energy:** Biomass is a renewable organic material, the source of which are plants and animals. Biomass energy is commonly used in many developing countries for the purposes of cooking and heating, but it is also used in many developed countries for transport (e.g., in the form of ethanol, which is a component of vehicle fuel in many countries) as well as electricity generation (by direct combustion, bacterial decomposition, or conversion to a gas or liquid fuel). Biomass sources can include wood, agricultural residue or crops, organic material in municipal solid waste, and animal manure.
- **Geothermal energy:** Geothermal energy is produced from the heat within the Earth. It can be used to heat buildings as well as to generate electricity.
- **Tidal/ocean energy:** Tidal energy is produced by the rise and fall of the ocean tides, as well as currents. Tidal electricity is generated with the help of tides turning turbines, similar to wind-based electricity. Tidal energy is at a relatively nascent stage of development compared to the other types, with very few commercial tidal power plants operating in the world.
- **Hydrogen:** Hydrogen is an energy carrier that is useful to store energy produced from other energy sources. It can be produced from a variety of renewable energy sources, and in this case, the it is a clean fuel, as well as non-renewable sources such as natural gas and nuclear power. Furthermore, it can be used for transportation as well as in electricity generation.

There are four main advantages of using renewable energy sources:

- Production of electricity is mostly devoid of polluting emissions.
- Resources used to produce these energy types are available at the local level (e.g., wind energy and solar energy), and they mostly use local technologies and know-how.
- The production costs are increasingly competitive.
- Countries can achieve a relatively high level of independence in generation with respect to other countries, and thus reduce the risk of international political crises arising due to energy shortages.

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