

Morocco's path to a climate-resilient energy transition: identifying emission drivers, proposing solutions, and addressing barriers

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Abstract. Morocco is currently at a critical juncture, facing a pivotal decision regarding its future energy transition and standing at the crossroads of its energy trajectory. The dilemma lies in whether to prioritize energy efficiency (reducing energy consumption and promoting the adoption of electric vehicles) and energy sobriety (limiting the frequency of using energy-consuming equipment) or to pursue the decarbonization of the grid through enhancements in fossil and nuclear production, gradually transitioning to a 100% renewable mix. In an effort to foster a broader contemplation, this study illuminates these concepts, encompassing an analysis of the CO₂ emission drivers utilizing the Kaya equation and an exploration of the challenges and opportunities associated with the net-zero challenge and a successful energy transition, including critical materials and policy landscapes. Furthermore, the study delves into Morocco's advancements across these three pillars of the energy transition.

Keywords: Climate resilience, Energy transition, Grid decarbonation, Energy efficiency, Energy sobriety, Kaya equation, Morocco.

1 Introduction

Climate change has become an undeniable reality, with tangible consequences extending to our vital systems. The regional impacts [1, 2] are particularly concerning, exerting significant influence on crucial aspects such as our energy systems [3], food security [4], and water supply [5]. In fact, the persistent rise in temperatures is affecting both the production and consumption of energy ([3], Chapter 5). Simultaneously, alterations in climate patterns are disrupting precipitation and weather conditions [1, 2], posing a direct threat to food security by disturbing agricultural cycles and heightening the risks of food shortages [4]. Moreover, water resources face increasing challenges due to modifications in rainfall patterns and glacier melting, directly impacting water supply and jeopardizing the overall sustainability of our societies [5].

A study [1] aims to examine areas that are becoming hotter and facing drought, with a particular focus on Africa, considering its historically low emissions but limited economic capacity to mitigate and adapt to climate change [2]. Morocco, with its conditional target reliant on foreign assistance, is assessed as “almost sufficient” but still falls

short of the Paris Agreement goal [6, 7]. The study also explores the consistency and sources of uncertainty in Coupled Model Intercomparison Project Phase 6 (CMIP6) models based on Shared Socio-Economic Pathways (SSPs) and analyzes changes compared to CMIP5, whose projections are based on Representative Concentration Pathways (RCPs) ([1], Sect. 2.2; [3], Chapter 2, Sects. IV and 2). The study examines the projected average temperature change worldwide, considering the CMIP6 HadGEM3-GC31-LL climate model ([1], Table 1), according to the average trajectory of future greenhouse gas emissions challenges in terms of mitigation and adaptation to climate change, specifically “SSP2-4.5”, over a given period (2015–2100) compared to the historical period (1850–2014). While the global average temperature is increasing, the rate of warming is not uniform across the globe. Firstly, continents are expected to warm more than coastal areas ([1], Sect. 4.4). Secondly, temperatures are increasing more rapidly at high latitudes, especially in and near the Arctic, than in regions near the equator ([1], Sect. 4.5). However, this does not apply uniformly to the Arctic and Antarctica ([1], Sect. 4.6). The study shows that Morocco's average temperature was relatively stable during the pre-industrial phase but has steadily increased since the 1990s when Morocco increased its coal capacity and began importing

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gas from Algeria to replace oil ([3], Chapter 1, Sects. III and 2). It also indicates that, according to the SSP scenario, the speed and increase in annual temperature in Morocco differ. While in the SSP1-2.6 scenario, Morocco could stabilize its annual temperature around 1.72 °C at best, in the unfavorable SSP5-8.5 scenario, Morocco's annual temperature could increase to over 6.25 °C between the historical reference period (1980–2009) and the far future (2070–2099). Overall, warming in Morocco ranges from 0.81 °C to 6.25 °C, depending on the CMIP6 climate model, scenario, and time horizon (near-, mid-, and far-future) ([1], Fig. 7 and Table 2). The study also presents the projected percentage change in precipitation by the end of the 21st century (2015–2100) compared to the historical period (1850–2014) based on the SSP2-4.5 climate change trajectory. An increase in precipitation is expected in many places worldwide in the future ([1], Sect. 4.7). However, regional heterogeneity in the magnitude of precipitation increase is significant. It is noted that equatorial regions and some tropical areas will receive more precipitation ([1], Sect. 4.8). Additionally, due to the descent of dry air from high-pressure systems, desert areas (mainly between 15° and 35° latitude north and south of the equator) receive little precipitation. The presence of semi-permanent subtropical anticyclones leads to the descent of air, making it warm and dry in subtropical regions. The Mediterranean region is particularly vulnerable to climate change, with a predicted decrease in precipitation of about 5–35% by 2100 in an SSP2-4.5 scenario. With amplified Mediterranean drought, decreases in precipitation have been observed in southern Africa, western Australia, Chile, and Central America/Mexico ([1], Sect. 4.9). The HadGEM3-GC31-LL climate model shows that most of the precipitation increase is projected to occur at high latitudes, especially in the Arctic, where warmer oceans increase the amount of evaporating water in the air. Moderate precipitation is predicted for mid-latitudes ([1], Sect. 4.10). However, despite the increasing complexity and sophistication of climate models in simulating Earth's climate, scientists still face a shortage of data or poor-quality data in many regions. This affects their ability to understand various aspects of the climate system, estimate trends in drought occurrence, etc.; therefore, validating climate models is challenging. This is particularly true at the regional scale, where the specifics of local climate are inherently chaotic. As a result, it is strongly recommended that analyses use multiple model ensembles unless the underlying assumptions and biases of each individual model are perfectly understood. The accuracy of climate projections also depends on the different scenarios of future socio-economic development integrated into them (e.g., whether greenhouse gas emissions will decrease or increase). This adds another layer of uncertainty to projections. Understanding whether the “change” is the result of natural variability (i.e., quasi-random internal variability of the coupled atmosphere-ocean-land-ice system) and non-human-origin periodic “forcing” events (i.e., volcanic eruption or solar activity) or if the projected change reveals statistically trends compared to natural variability is crucial for climate change projection ([1], Sect. 4.11).

These impacts of climate change, evident in areas experiencing heightened temperatures, droughts, or flooding, are primarily attributed to global warming. This phenomenon refers to the increase in the Earth's overall temperature, largely caused by the accumulation of GreenHouse Gases (GHGs) in the atmosphere during the Industrial Era. The main human activities responsible for these additional anthropogenic emissions encompass the combustion of fossil fuels (such as coal, oil, and natural gas), deforestation, agricultural practices, and alterations in land use.

Given this reality, it is crucial to urgently implement measures aimed at reducing GHG emissions, which contribute to global warming. These measures should also encompass mitigation and adaptation strategies for climate change, all while reinforcing the resilience of our essential systems ([3], Chapter 1).

To address the challenges posed by harder-to-abate sectors, including the transportation sector (which relies on fossil fuels for cars, trucks, ships, trains, and planes), industrial processes, agriculture, waste management, and deforestation leading to the destruction of carbon sinks [8], it becomes imperative for the energy generation sector to achieve net-zero emissions at an earlier stage. For instance, the Kaya formula, developed by Japanese economist Yoichi Kaya in 1993 and documented in his book [9], offers potential solutions to decrease carbon dioxide (CO₂) emissions associated with the energy sector. The formula underscores the relationship between Gross Domestic Product (GDP), population, and global energy consumption, providing insights for achieving necessary emission reductions.

A key approach to mitigate emissions and address the impacts of climate change [1, 2] involves the decarbonization of the electrical grid with the aim of decreasing the carbon intensity in the global energy mix (CO₂/energy consumption). Achieving this goal is feasible through three primary technological pathways ([3], Chapter 1):

- Implementation of Carbon Capture and Sequestration (CCS) technologies in existing power plants offers a means for the electricity sector to continue utilizing fossil fuels while reducing emissions [10]. However, current CCS technologies are costly and can diminish net generator efficiencies, leading to increased fuel consumption per unit of electricity produced. Additionally, the sustainability of CCS is questioned due to the finite nature of fossil fuel resources.
- Another strategy involves the expansion of carbon-free resources, such as nuclear energy. Despite its potential, public resistance persists due to various tragic incidents associated with nuclear power.
- The integration of renewable energy resources (e.g., wind, solar, hydro, geothermal, biomass, and marine energy) into the grid presents a promising avenue, as these sources generate electricity without relying on fossil fuels. The associated costs of these technologies have significantly decreased over the past decade [11]. Nevertheless, challenges, both technological and economic, are prevalent [3]. Additionally, the demand

for critical materials required for renewable technologies is expected to rise [12]. Various policy instruments, including carbon pricing, emission trading, reduction of fossil fuel subsidies, and simplified regulations promoting low-carbon energy integration, have been proposed as political and economic measures to address these challenges.

The second approach involves adopting technologies that require less energy to fulfill the same function. This includes practices such as enhancing building insulation, utilizing energy-efficient light bulbs, transitioning to electric vehicles, and opting for transportation modes with lower emissions. The goal is to reduce the energy intensity of the economy, measured as the ratio of energy consumption to GDP.

The third approach to emission reduction is energy sobriety, emphasizing the use of less energy through behavioral adjustments and habit changes. Examples include opting for walking or cycling for short distances instead of driving, utilizing public transportation or carpooling, turning off lights and electronic devices instead of leaving them on standby, minimizing the consumption of animal products, and selecting products with minimal plastic packaging ([3], Chapter 1). This strategy aims to enhance economic production per capita, measured as the ratio of GDP to population.

When compared to other nations, Morocco's conditional target, reliant on international assistance, is assessed as "almost sufficient." This evaluation suggests that it has not yet aligned with the Paris Agreement's temperature limit of 1.5 °C [7], but with modest enhancements, it holds the potential to meet the stipulated requirements [6, 7].

Considering these factors, this work aims to answer the following primary research questions: (1) What are the factors driving and influencing CO₂ emissions levels in the energy sector? (2) What are the essential features of the three pillars of energy transition – namely, grid decarbonization, energy efficiency, and energy sobriety – that contribute to orchestrating a paradigm shift towards a sustainable and green energy transition? (3) What obstacles and potential opportunities exist in addressing the net-zero challenge and ensuring a successful energy transition?

2 Drivers of CO₂ emissions in the energy sector

Four essential components, delineated in the widely recognized equation (Fig. 1) referred to as the "Kaya equation" [9], play a pivotal role in determining total CO₂ emissions. The breakdown of the Kaya identity equation is illustrated in Figure 1. Specifically, total CO₂ emissions are shaped by population (i.e., the overall number of individuals) and CO₂ emissions per person (i.e., the per capita effect). The quantity of CO₂ emitted per person is influenced by two factors: technology (i.e., the amount of CO₂ emitted per dollar spent) and income, or GDP per capita (i.e., individuals with higher income levels tend to emit more CO₂). Technology,

in turn, is affected by energy intensity (i.e., the amount of energy expended per unit of GDP) and carbon intensity (i.e., the amount of CO₂ released per unit of energy). Consequently, the interplay of population, GDP per capita ("GDP/population"), energy intensity ("energy/GDP"), and carbon content ("CO₂/energy") determines the overall environmental impact in terms of total CO₂ emissions. Figure 2 illustrates the temporal evolution of the four elements and their relative changes, consequently influencing the total annual CO₂ emissions – the ultimate outcome. The substantial upsurge in GDP during this timeframe underscores its pivotal role as a primary driver of emissions, surpassing even the impact of population growth. The ability of nations to swiftly reduce their energy and carbon intensity sufficiently to offset this significant rise in GDP (and population growth) dictates whether CO₂ emissions undergo substantial growth, stabilization, or decline. A dramatic increase in CO₂ emissions may occur if improvements in energy or carbon intensity are modest (or absent in certain scenarios). Hence, one of the fundamental parameters shaping the Kaya identity equation is GDP or average income per person.

In Morocco, from 2006 to 2016, energy-related CO₂ emissions increased by more than a third, reaching 55.3 MtCO₂ since 1990. In 2016, 64% of the total emissions were linked to oil, while coal contributed 31%, with the remaining portion originating from natural gas and other sources (refer to Fig. 3). Oil consumption spans various sectors, whereas emissions from coal usage primarily stem from power generation.

Most of Morocco's energy-related CO₂ emissions stem from power generation and transportation. In 2016, the power sector contributed 39%, while the transport sector accounted for 31% of the total emissions. The remaining emissions were distributed across industry (13%), residential and commercial buildings (12%), and agriculture (5%). Over the past decade, emissions have seen significant growth in all sectors, except for industry, which has remained relatively stable. Between 2006 and 2016, there was a 31% increase in power generation emissions, 63% in transport, 1.5% in industry, 58% in residential and commercial, and 58% in agriculture (refer to Fig. 4).

Since 1990, the surge in CO₂ emissions in Morocco can be attributed to a 40% increase in population and a substantial 90% rise in GDP per capita, as illustrated in Figure 5. The correlation between Morocco's economic expansion and CO₂ emissions is evident, although the emissions have recently exhibited a slower growth rate compared to the overall economy. Notably, against the backdrop of expanding renewable energy and increased utilization of natural gas in power generation, Morocco observed a noteworthy 7% reduction in carbon intensity during the period of 2011–2016 (Fig. 5). In contrast to member countries of the International Energy Agency (IEA), Morocco exhibits a relatively high carbon intensity in its economy, as depicted in Figure 6. However, the per-capita emissions in Morocco are significantly lower than those of any IEA member due to the country's low energy consumption per capita, as illustrated in Figure 7.

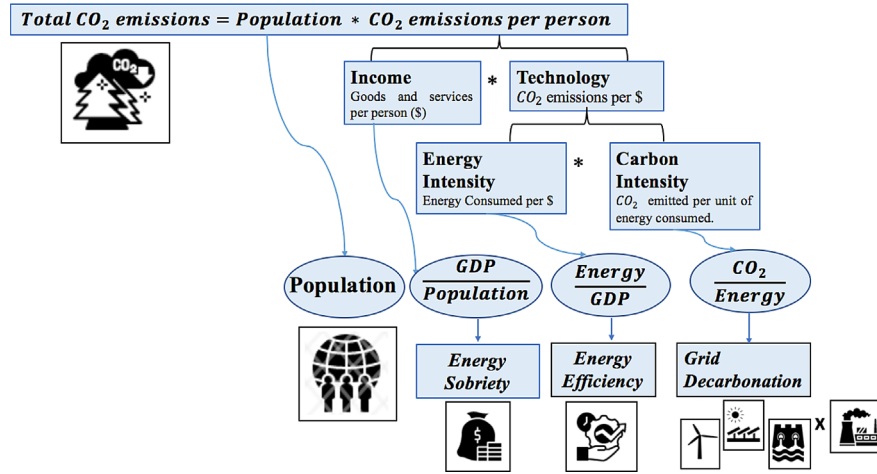


Fig. 1. Factors influencing CO₂ emissions, as depicted in the Kaya equation. Source: Self-generated, adapted from “Our World in Data” [13].

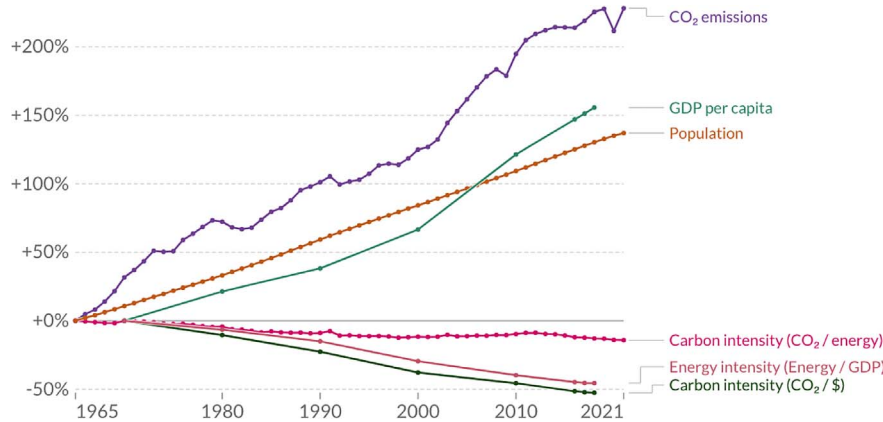
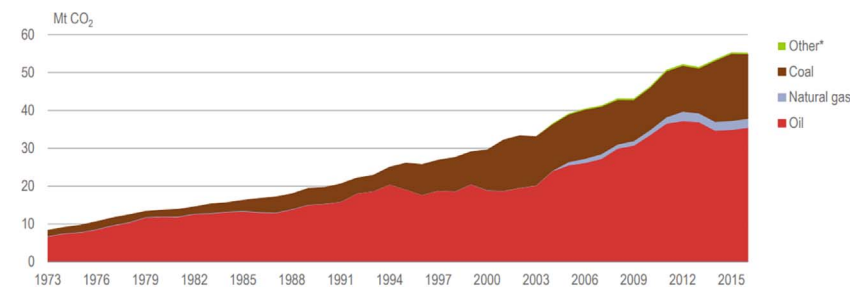


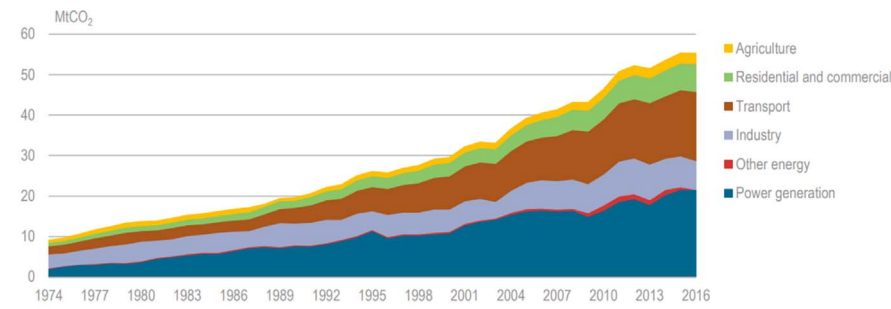
Fig. 2. Worldwide percentage variations in the four factors of the Kaya equation influencing total CO₂ emissions, encompassing emissions from both fossil fuels and industry. Changes in land use are not considered. Source: Data derived from “Our World in Data” [13].



* Other includes biomass and waste.

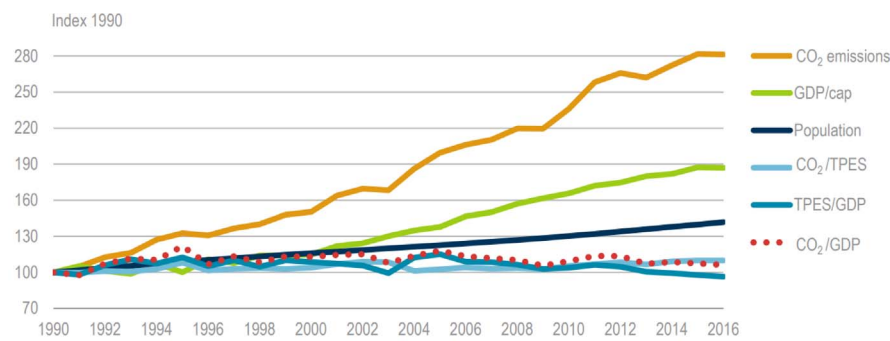
Source: IEA (2018), *CO₂ Emissions from Fuel Combustion 2018*, www.iea.org/statistics/.

Fig. 3. Emission breakdown by fuel from 1973 to 2016. From 2006 to 2016, global energy-related CO₂ emissions rose by over a third to 55.3 Mt CO₂ since 1990. In 2016, 64% of emissions were from oil, 31% from coal, primarily linked to power generation. Source: International Energy Agency (IEA) [14].



Source: IEA (2018), *CO₂ Emissions from Fuel Combustion 2018*, www.iea.org/statistics/.

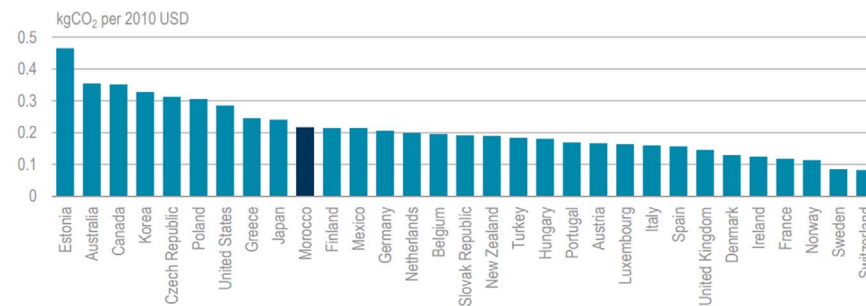
Fig. 4. Sector-wise emissions from 1973 to 2016. In Morocco, power generation and transportation dominate energy-related CO₂ emissions. In 2016, the power sector contributed 39%, and transport accounted for 31%. Other sectors included industry (13%), residential/commercial buildings (12%), and agriculture (5%). Emissions increased significantly in all sectors over the past decade, except for a stable trend in industry. Between 2006 and 2016, there was a 31% increase in power generation emissions, 63% in transport, 1.5% in industry, 58% in residential/commercial, and 58% in agriculture. Source: International Energy Agency (IEA) [14].



Note: Real GDP in USD 2010 prices and PPP.

Source: IEA (2018), *CO₂ Emissions from Fuel Combustion 2018*, www.iea.org/statistics/.

Fig. 5. CO₂ emissions linked to energy and their primary influencing factors, spanning the period from 1990 to 2015. Morocco's CO₂ emissions surged since 1990 due to a 40% population increase and a 90% rise in GDP per capita. Although emissions grew more slowly than the economy recently, a significant 7% reduction in carbon intensity occurred from 2011 to 2016, driven by the adoption of renewable energy and increased use of natural gas in power generation. Source: International Energy Agency (IEA) [14].

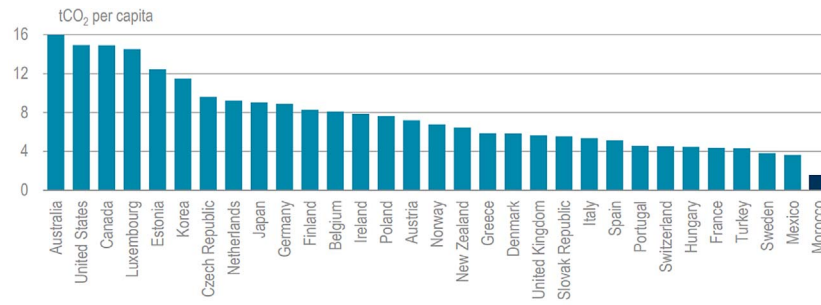


Source: IEA (2018), *CO₂ Emissions from Fuel Combustion 2018*, www.iea.org/statistics/.

Fig. 6. CO₂ emissions associated with energy per unit of GDP in Morocco and member countries of the International Energy Agency (IEA) for the year 2016. Source: International Energy Agency (IEA) [14].

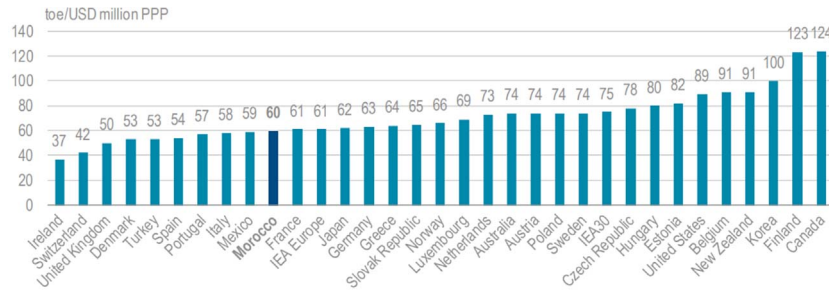
In comparison to IEA member countries, Morocco exhibits the tenth-lowest level of energy intensity, falling below both the IEA average and just slightly under the IEA Europe average, as depicted in Figure 8.

In a baseline scenario, GHG emissions from energy-related activities are projected to increase from 51 MtCO₂eq in 2010 to 139 MtCO₂eq in 2040. Figure 9 demonstrates that emissions from the energy sector,



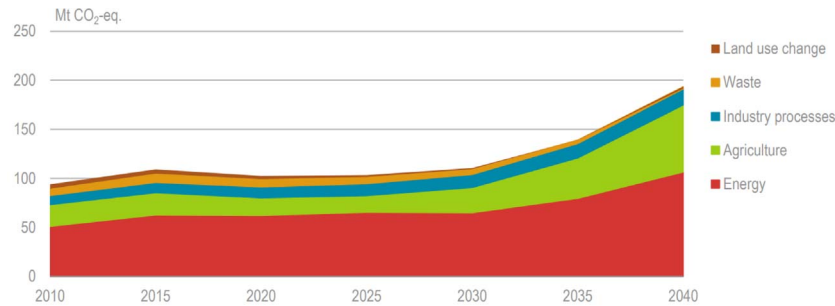
Source: IEA (2018), *CO₂ Emissions from Fuel Combustion 2018*, www.iea.org/statistics/.

Fig. 7. Per capita CO₂ emissions from energy use in Morocco and member countries of the IEA for the year 2016. Source: International Energy Agency (IEA) [14].



Source: IEA (2018a), *World Energy Balances, 2018*, www.iea.org/statistics/.

Fig. 8. Intensity of energy (Total Final Consumption per Gross Domestic Product) in member countries of the IEA for the year 2016. Source: International Energy Agency (IEA) [14].



Notes: "Energy" - Energy use in the end-use sectors (buildings, transport, industry, agriculture, etc.) and energy transformation (power generation etc.); "Agriculture" - N₂O and CH₄ emissions from agricultural soil and agricultural processes such as fermentation and animal manure.

Source: Government of Morocco, Third National Communication to the UNFCCC, 2016.

Fig. 9. GHG emissions from various sources in Morocco's baseline scenario. Source: International Energy Agency (IEA) [14].

particularly in the transport sector (constituting 27% in 2010), are anticipated to be the primary catalyst for future GHG emission growth.

If the non-conditional target is met, GHG emissions from energy-related activities are projected to double only to 106 MtCO₂eq by 2040, thereby staying below the Business As Usual (BAU) emissions level, as shown in Figure 10.

2.1 Income effect "GDP/population"

Figure 11 illustrates the correlation between per capita CO₂ emissions and GDP per capita. Generally, there is a robust

association between CO₂ emissions and income. As income rises, emissions typically increase due to heightened utilization of energy-intensive goods and services, including power, heating, transportation, and other energy-dependent items. This pattern is often observed as nations pursue economic growth, particularly by emphasizing energy-intensive sectors like manufacturing and construction, as highlighted in studies such as Caron *et al.* [15].

Populations with lower economic status exhibit lower emissions, primarily because they lack access to modern energy and technology. In the absence of contemporary energy sources for heating and cooking, individuals resort

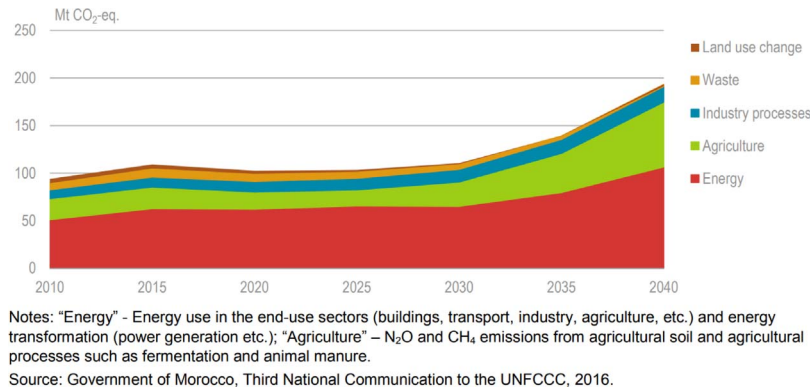


Fig. 10. GHG emissions in Morocco categorized by source in the non-conditional scenario. Source: International Energy Agency (IEA) [14].

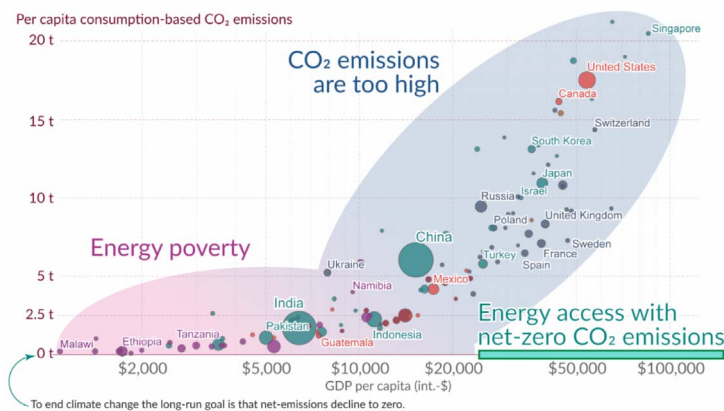


Fig. 11. The comparison of per capita CO_2 emissions to GDP per capita globally. Data source: "Our World in Data" [13].

to using solid fuels such as firewood, dung, and crop waste. This reliance on traditional fuels not only has detrimental effects on the health of those experiencing energy poverty, contributing to indoor pollution as noted by Sahoo *et al.* [16], but also results in adverse environmental impacts. Crespo *et al.* [17] highlight the connection between poverty and deforestation, attributing it to the dependence on fuelwood as a source of energy.

Moreover, the absence of energy access compels individuals to endure poverty. Devoid of electricity, essential amenities such as refrigeration, washing machines, dishwashers, and even basic night lighting become inaccessible.

Per capita CO_2 emissions tend to be elevated in regions with improved living standards, as higher GDP per capita correlates with better living conditions. Conversely, in areas where child mortality is minimal, children enjoy enhanced access to education, and hunger is scarce, emissions tend to be higher.

The necessity for energy access is fundamental to a comfortable lifestyle, but in a world where fossil fuels dominate as the primary energy source, access to modern energy contributes significantly to carbon emissions. Our current generation faces a dual mission: as a substantial portion of the global population still grapples with poverty, efforts must persist in alleviating energy poverty. Yet, success in

this endeavor hinges on simultaneously reducing GHG emissions. The pivotal factors in advancing on both fronts are the source and affordability of energy. To transition towards the ideal scenario depicted in the lower-right corner of Figure 11 – marked by a green rectangle, where emissions are net-zero and energy poverty is eradicated – we must develop large-scale energy alternatives to fossil fuels that are economical, safe, and sustainable. Without such transformative technologies, we find ourselves confined to a world with limited options: low-income countries struggling to meet the demands of the present generation, high-income countries jeopardizing the ability of future generations to meet their needs, and middle-income countries falling short on both fronts. This predicament is particularly pertinent in carbon-emitting industries, notably transportation (shipping, aviation, and road transportation), and heating, as well as in sectors like cement manufacturing and agriculture [18].

In contrast to fossil fuels, nuclear and renewable energy sources produce markedly lower amounts of CO_2 . Nevertheless, their share of global electricity production has seen a modest increase over the last three decades, moving from 36% to 38%, as illustrated in Figure 12. Despite this shift, every nation is yet to achieve widespread production of clean, safe, and affordable energy. Until

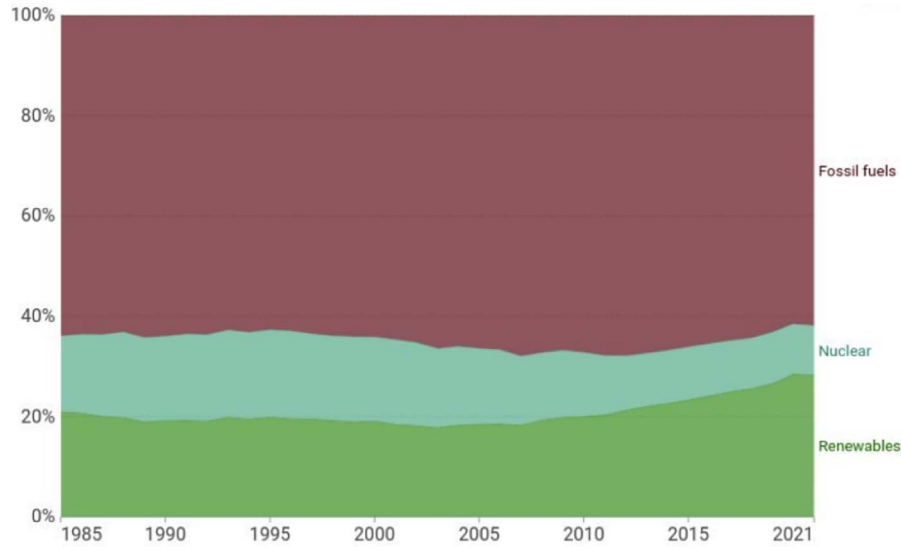


Fig. 12. Worldwide generation of electricity from fossil fuels, nuclear, and renewable sources. Data source: “Our World in Data” [13].

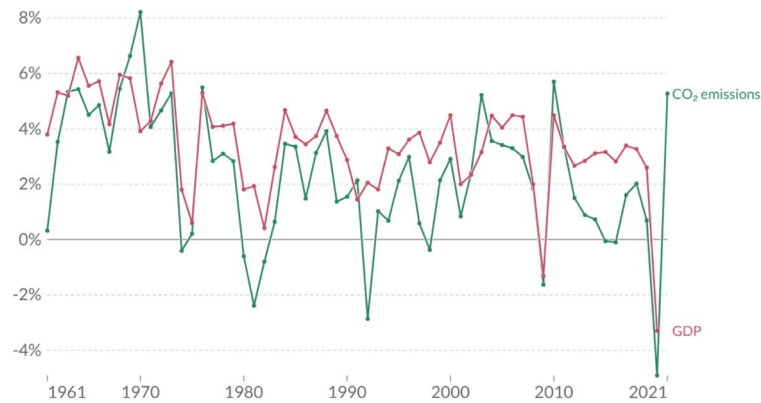


Fig. 13. Percentage change in both Global Gross Domestic Product (GDP) and carbon dioxide (CO₂) emissions. Data source: “Our World in Data” [13].

substantial progress is made in advancing these technologies, the world remains dependent on current unsustainable alternatives, including energy poverty and GHG emissions.

Embracing energy sobriety (refer to Sect. 3.4), entails the intentional decision to curtail a portion of production or consumption while striving to minimize the impact on overall well-being. This approach offers a means to reduce per capita GDP. For instance, implementing a restriction on the manufacturing of vehicles exceeding three tons can effectively lower GDP without substantially compromising the comfort of the population, as individuals can still choose lighter alternatives.

Per capita CO₂ emissions exhibit a considerable sensitivity to economic shocks, primarily due to the pivotal role of energy demand in fostering economic growth, as depicted in Figure 13. A recent illustration of this sensitivity is evident in the aftermath of the coronavirus pandemic, leading to substantial albeit temporary declines in global CO₂ emissions. However, the impact of economic shocks on emissions

trends varies across countries, influenced by factors like energy mix, grid decarbonization, as well as considerations of energy efficiency and sobriety.

2.2 Energy intensity “Energy/GDP”

Energy intensity serves as a metric gauging the efficiency of an economy in utilizing energy resources. It quantifies the amount of energy required to produce goods and deliver services, relative to the attainment of a monetary unit. This energy is employed in various processes, including the transformation of raw materials, initiation of chemical processes, and transportation of goods and people over extended distances – all integral components intertwined with the progression of wealth development.

In the scenario where a country’s economy is constructed around industries or activities that are less energy-intensive, the energy intensity of that country would be lower. Figure 14 illustrates the global distribution of energy intensity.

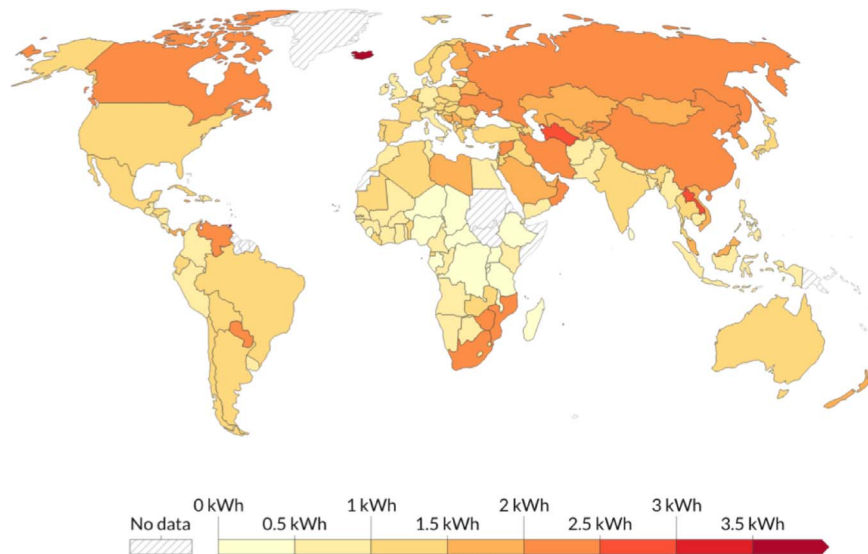


Fig. 14. Global energy intensity, denoting the primary energy consumption per unit of gross domestic product, in the year 2018. Data source: “Our World in Data” [13].

The comprehensive energy intensity can be computed by multiplying the energy intensity specific to each economic sector by its relative weight in the overall economy. This methodology mirrors the determination of the average carbon content of energy, achieved by multiplying the carbon content associated with each energy type by its proportion in the energy mix. This computation unveils three avenues for enhancing the energy efficiency of GDP: (i) prioritizing less energy-intensive sectors within the economy; (ii) emphasizing energy efficiency measures; and (iii) ameliorating the energy intensity of predominant sectors through a form of restraint or sobriety.

Initially, certain industries inherently demand more energy per unit of economic output; for example, the chemical, paper, and metal sectors necessitate a substantial amount of energy for each euro “produced,” while services and electronics have comparatively lower requirements. Broadly, when there is a greater reliance on human labor compared to machine utilization, the energy intensity of the produced service or good tends to be lower. Consequently, influencing an economy’s energy intensity is attainable by prioritizing specific sectors, particularly those that heavily rely on “human resources.”

Secondly, we have the opportunity to influence energy intensity by enhancing the energy efficiency of goods or services within the same sector (refer to Sect. 3.3). Various policies are in effect to promote energy-efficient products, including requirements to inform consumers about the energy efficiency of items through labels on home appliances and to provide a Diagnosis Performance Energy (DPE) for housing. Achieving a reduction in a company’s energy expenditures translates to enhanced overall efficiency.

Lastly, enhancing the energy intensity of GDP can be achieved by curbing energy consumption in activities with a limited connection to GDP (see Sect. 3.4). For instance, lowering the setpoint temperature for home heating or

imposing a lower maximum speed on highways significantly reduces energy consumption with minimal repercussions on GDP.

2.3 Carbon intensity “CO₂/energy”

Carbon intensity serves as a metric indicating the level of carbon emissions in an energy mix. It is calculated by assessing the amount of CO₂ released per unit of energy generated. This metric is significantly influenced by the composition of the energy mix, specifically the ratio of fossil fuels to low-carbon alternatives.

Typically, only fossil fuels such as coal, oil, and gas release CO₂ upon combustion. However, when considering the entire cycle of energy production and consumption, emissions are associated with all energy sources today. The energy we utilize for daily activities – such as transportation, heating, lighting, operating equipment, and cooking – is not inherently present in its usable form. Instead, primary energy sources must be obtained from living organisms or subsurface reservoirs (oil, gas, coal, uranium, wood) or harnessed from natural elements (wind, sun, gravity, tides). These sources are then converted into usable forms of energy (heat, electricity, gasoline, fuel oil, etc.) and transported to end users, constituting what is referred to as final energy. When determining the carbon content of energy, the entire life cycle is considered, encompassing the upstream stages: extraction and refining (for fuels), transportation, and eventual distribution to end users. Additionally, emissions resulting from the construction and decommissioning of manufacturing facilities should be incorporated into the assessment.

Figure 15 illustrates the global carbon intensity. A country’s carbon intensity can be reduced (refer to Sect. 3.2) if it derives a significant portion of its energy from renewable sources such as hydropower, wind, solar, and biomass, a scenario often observed in lower-income countries heavily

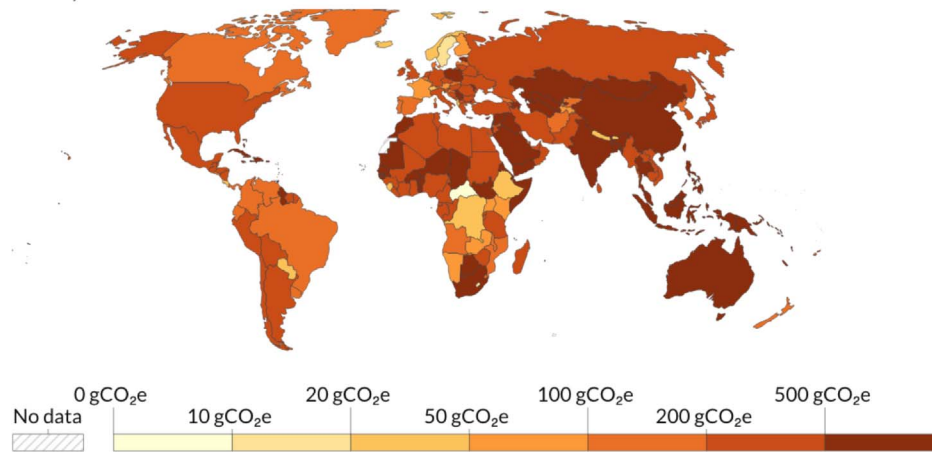


Fig. 15. Global carbon intensity of electricity, denoting the quantity of grams of CO₂-equivalents emitted per kilowatt-hour (kWh) of electricity, for the year 2021. Data source: “Our World in Data” [13].

reliant on biomass as a fuel source. Another avenue for reducing carbon intensity is a substantial reliance on nuclear energy. Additionally, effective carbon capture and storage from CO₂ emissions produced by fossil fuels is a commonly proposed solution, albeit infrequently implemented on a large scale. An example is the preference for gas over coal in the energy mix, given that gas typically generates less CO₂ per unit of energy than coal.

2.4 Population

Regarding population, a common expectation is that a larger population will lead to increased emissions. The conventional perspective often attributes escalating CO₂ emissions to “uncontrolled” population growth. However, global emissions display significant inequality, with low-income nations, characterized by the most substantial population growth, contributing a relatively minor percentage to global emissions. Conversely, high-income countries, characterized by slower population growth, disproportionately contribute to the overall emission levels.

3 Pillars towards a sustainable energy transition model: grid decarbonation vs. energy efficiency vs. energy sobriety

3.1 Pathway to 1.5 °C

In adherence to the 1.5 °C scenario – representing an energy transition path aligned with the climate goal to restrict the global average temperature increase to 1.5 °C by the end of this century relative to pre-industrial levels – electricity generation is projected to increase more than threefold from 2020 to 2050. In this scenario, 91% of the total electricity supply is anticipated to be derived from renewable sources, a substantial increase from the 28% observed in 2020 (see Fig. 16). This pathway prioritizes readily available technological solutions that can be scaled up to meet the 1.5 °C goal.

The expansion outlined in the 1.5 °C Scenario aims to increase the share of renewable energy in Total Final Energy Consumption (TFEC) from 28% in 2020 to 91% by 2050. This envisioned transformation positions electricity as the predominant energy carrier, constituting over 50% of TFEC (see Fig. 17). The transition is facilitated by the deployment of renewable energy, advancements in energy efficiency, and the electrification of various end-use sectors. Furthermore, the scenario foresees notable roles for modern biomass and hydrogen, accounting for 16% and 14% of TFEC by 2050, respectively. An intriguing aspect is that 94% of hydrogen production is anticipated to be sourced from renewables, indicating a growing dependence on clean energy sources.

Maintaining a steady total primary energy supply, advancements in energy efficiency, and the rise of renewables contribute to stability (Fig. 18). The share of renewable energy in primary supply is projected to surge from 16% in 2020 to 77% in 2050, marking a substantial 61% net gain. This transformation hinges on end-use electrification, renewable fuels, and direct uses. Vital for global climate goals, achieving this level of renewable energy penetration demands substantial investment, policy backing, and ongoing innovation.

To achieve a significant reduction in global CO₂ emissions by 2050, the primary focus should be on substantial declines in renewables’ usage for power generation, as well as direct applications in heat and transportation. Coupled with energy conservation and efficiency measures, these strategies would contribute to over half of the necessary cuts in global CO₂ emissions. Additionally, a 19% reduction would result from the direct electrification of various end-use sectors, while 12% would come from employing hydrogen and its derivatives, including synthetic fuels and feedstocks (Fig. 19). The remaining CO₂ emissions until 2050 must be captured and stored through methods like carbon capture and storage (CCS) or carbon capture and utilization (CCU). Alternative carbon removal measures, such as bioenergy with carbon capture and storage (BECCS), direct air capture, soil carbon sequestration,

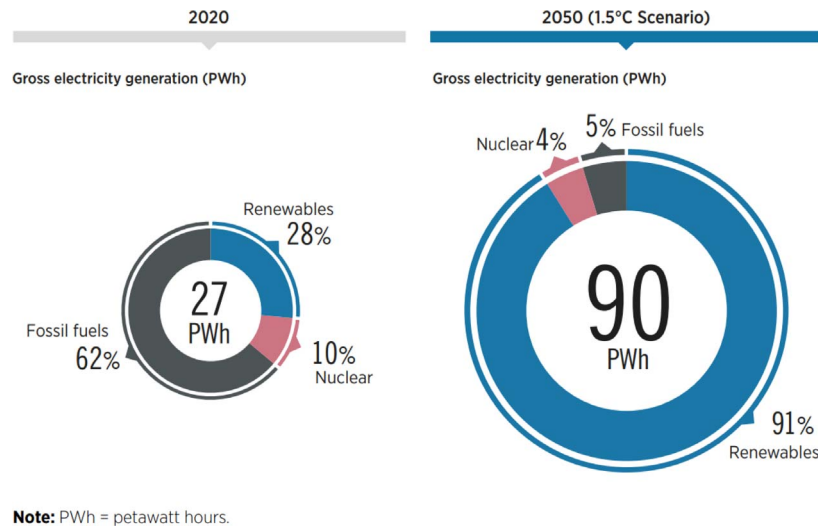


Fig. 16. Under the 1.5 °C scenario, there is a requirement for power generation to increase by over threefold by the year 2050. Source: International Renewable Energy Agency (IRENA) [19].

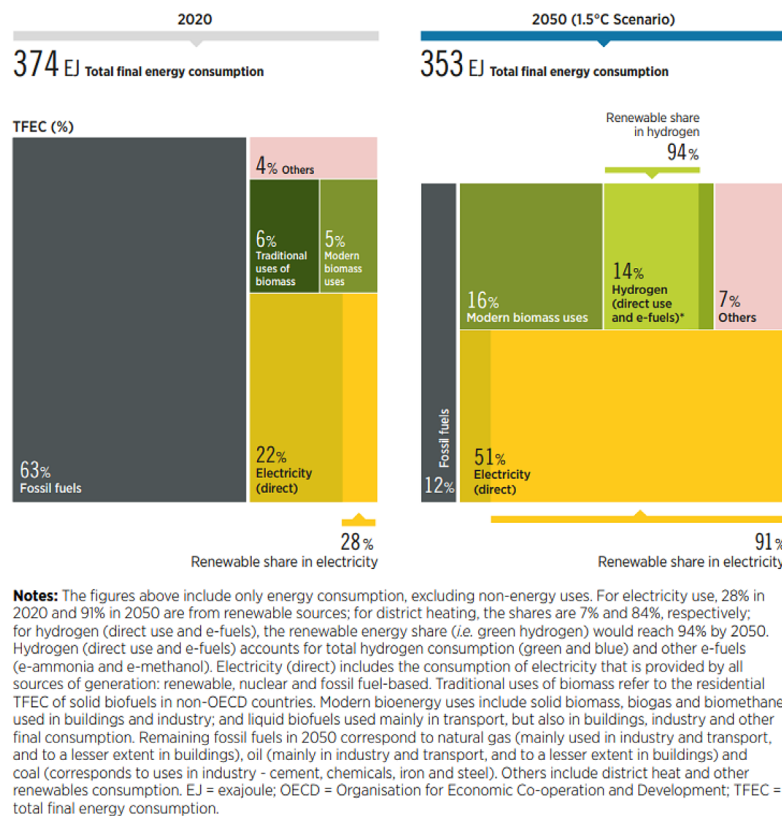


Fig. 17. Distribution of TFEC among different energy carriers from 2020 to 2050 in alignment with the 1.5 °C scenario. Source: International Renewable Energy Agency (IRENA) [19].

enhanced mineralization, ocean-based CO₂ removal, afforestation, or reforestation, would also play crucial roles.

Since 2010, a significant transformation in the competitiveness of renewable power generation has occurred. The global weighted average levelized cost of electricity (LCOE)

for newly commissioned utility-scale solar PV projects has witnessed an impressive 88% decline over the 12-year period from 2010 to 2021. During the same period, onshore wind, Concentrated Solar Power (CSP), and offshore wind also experienced substantial reductions in LCOE, with declines

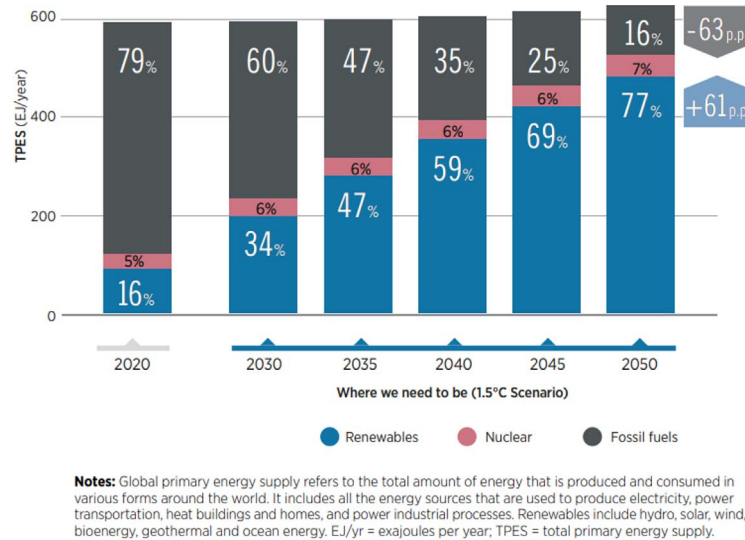


Fig. 18. Evolution of primary energy supply across energy carrier groups from 2020 to 2050 in the 1.5 °C scenario. Source: International Renewable Energy Agency (IRENA) [19].

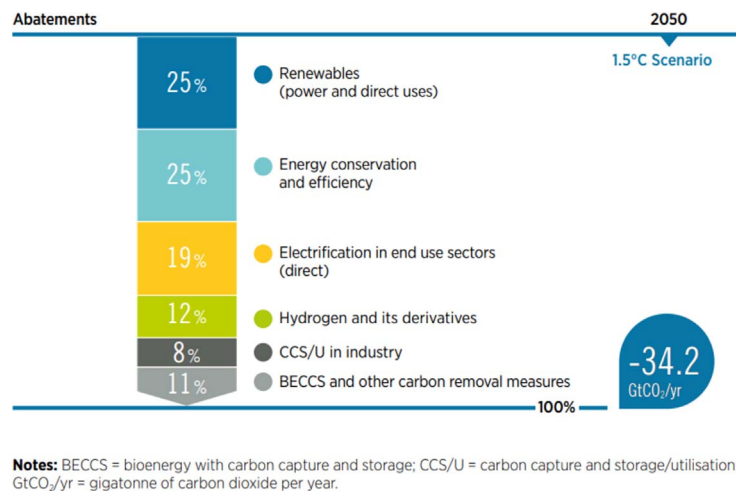


Fig. 19. Carbon dioxide emission reduction in 2050 within the context of the 1.5 °C scenario. Source: International Renewable Energy Agency (IRENA) [19].

of 68%, 67%, and 60%, respectively. In 2021 alone, the LCOE for utility-scale solar PV decreased by 13% year-on-year, while onshore and offshore wind saw reductions of 15% and 13%, respectively (Fig. 20).

The power sector, responsible for 40% of CO₂ emissions in 2022, stands as a significant contributor to global emissions. Achieving its decarbonization by 2050 is a challenging yet imperative goal in the fight against climate change and the reduction of worldwide GHG emissions. A crucial aspect of this decarbonization involves transitioning from fossil fuels to renewables for electricity generation, a move facilitated by electrification. In the Planned Energy Scenario (PES), the share of renewables in power generation rises from 28% in 2020 to 46% in 2030 and surpasses 70% by 2050 (Fig. 21). However, the current plans outlined in the PES fall short of meeting the 1.5 °C temperature

target. The gap between our trajectory and the necessary path to limit global temperature increase to 1.5 °C is widening with each passing year.

From the present until 2050, investments of USD 130 trillion (for the PES Scenario) and USD 150 trillion (for the 1.5 °C Scenario) would be necessary, as illustrated in the Figure 22.

3.2 Grid decarbonation

3.2.1 Scenarios of renewable energy integration

North Africa, encompassing Algeria, Egypt, Libya, Morocco, Tunisia, and Sudan, stands out as the largest energy market on the African continent. The region, consisting mainly of middle-income nations (excluding Sudan),

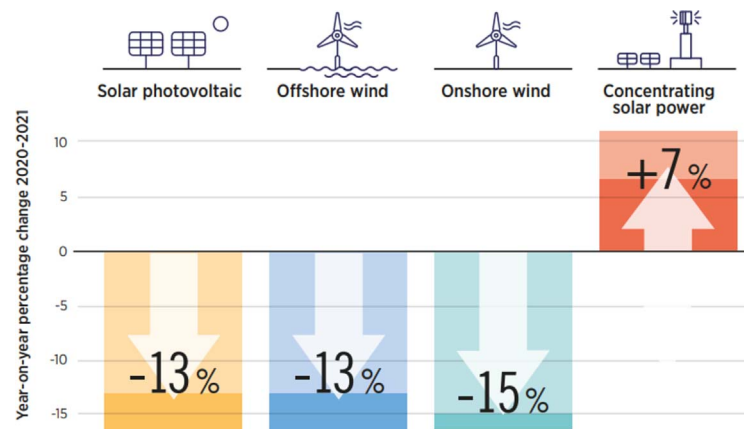


Fig. 20. Shift in global weighted average levelized cost of electricity across technologies, 2020–2021. Despite the pandemic, renewable electricity costs sustained their remarkable decline, continuing a historic trend. Source: International Renewable Energy Agency (IRENA) [19].

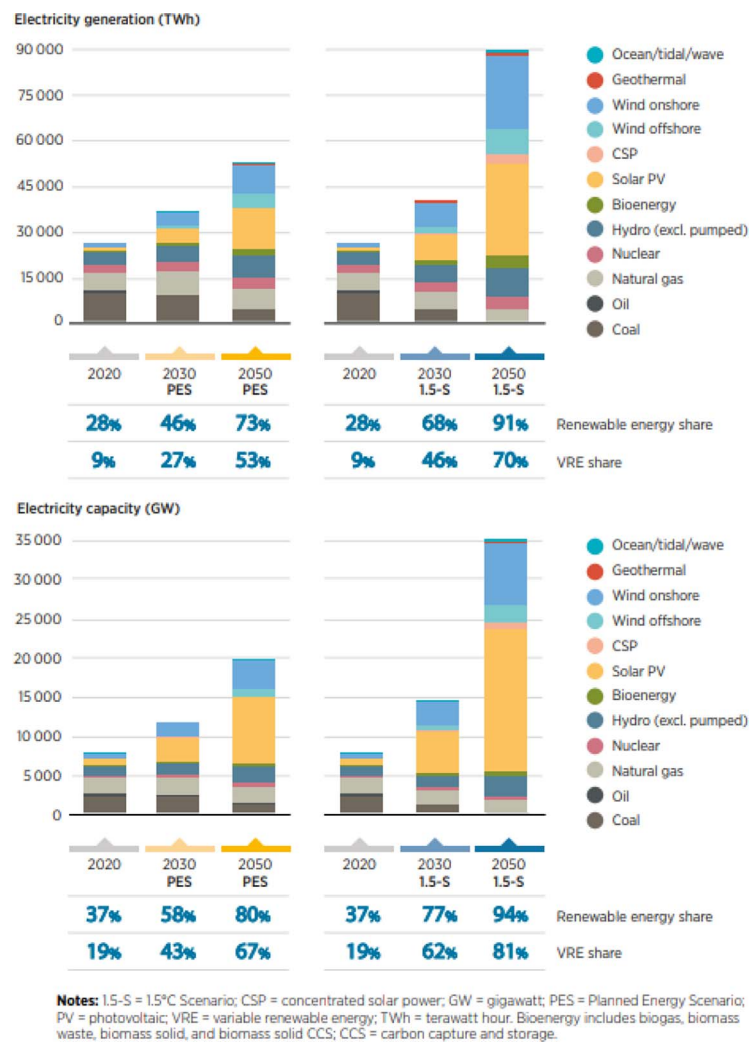


Fig. 21. Comparing global power generation mix and installed capacity across energy sources: anticipated energy scenario vs. 1.5 °C scenario for the years 2020, 2030, and 2050. Source: International Renewable Energy Agency (IRENA) [19].

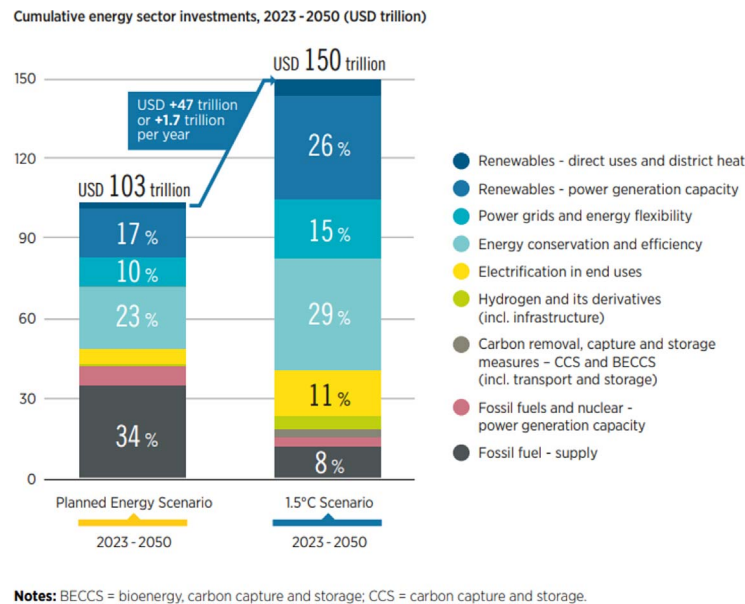


Fig. 22. Worldwide investment across technological pathways: Planned Energy Scenario (PES) and 1.5 °C Scenario from 2023 to 2050. Source: International Renewable Energy Agency (IRENA) [19].

boasts superior socio-economic and human development indicators, industrialization, and widespread access to modern energy compared to other African regions. Benefiting from a unique geographical position, North Africa enjoys robust trade connections with its southern neighbors and Europe through the Mediterranean Sea. Furthermore, its distinctive energy landscape distinguishes it from the rest of the continent. North Africa holds substantial untapped potential for utility-scale solar and wind power, complementing its existing hydropower capacity. Additionally, the region has implemented decentralized, off-grid solutions in remote areas and presents considerable market opportunities in countries with limited electricity access, notably Libya and Sudan. Given these factors, North Africa is poised to become one of the most dynamic energy markets in Africa, particularly in the realm of renewable energy, in the foreseeable future.

Algeria, Libya, Egypt, and Sudan possess considerable hydrocarbon resources, establishing them as enduring exporters of both oil and natural gas. The fossil fuel sectors in these nations have played a pivotal role in driving their economic growth, serving not only as domestic energy sources but also as commodities for international trade. In contrast, Morocco and Tunisia have limited domestic oil and gas reserves, resulting in historically substantial expenses on energy imports. Consequently, these two countries boast the region's most diversified economies, rooted in sectors such as agriculture, manufacturing, textiles, tourism, and services. Notably, Morocco holds significance as a major producer of phosphate and phosphate rock, critical minerals essential for various technologies associated with the ongoing energy transition.

With the exception of Sudan, North African nations have attained some of the highest levels of access to modern energy across the African continent. Algeria, Egypt, Morocco, and Tunisia have effectively reached

near-universal access to both electricity and clean cooking fuels and technologies. However, variations exist in the quality, affordability, and stability of this access within and among these countries. Libya, on the other hand, has regressed in this regard due to political instability since the 2010s, with electricity access hovering around 70%, marked by persistent instability. Sudan, with an electricity access rate of 55%, finds itself among African countries with substantial populations lacking fundamental access to electricity.

Traditionally, Algeria, Egypt, and Libya have predominantly depended on fossil fuels to fulfill almost all their energy requirements (refer to Fig. 23). A noteworthy exception is Egypt, where hydropower has played a significant role in the power sector since the 1960s. Morocco and Sudan exhibit relatively diverse energy mixes, although their reliance on coal and oil, respectively, contributes to making their electricity compositions more carbon-intensive compared to nations that lean more heavily on natural gas for power generation, such as Algeria, Egypt, and Tunisia. Despite this, the electricity sectors of these countries have a longstanding association with hydropower. Recently, Morocco has introduced large-scale wind and solar projects to its energy portfolio [3], while Sudan has incorporated the household use of traditional bioenergy.

The distinctive geography and climate of North Africa position it as a region with substantial potential for renewable energy, especially in the realms of solar and wind power. With an annual average solar irradiation of approximately 22,100 kWh/m² and notable wind speeds averaging 7 m/s, reaching 9.5 m/s in Algeria and Libya (refer to Fig. 24), the region stands out as a promising hub for harnessing clean energy sources.

In 2016, Algeria, Egypt, Libya, Morocco, Sudan, and Tunisia, along with 189 other member states of the United Nations Framework Convention on Climate Change

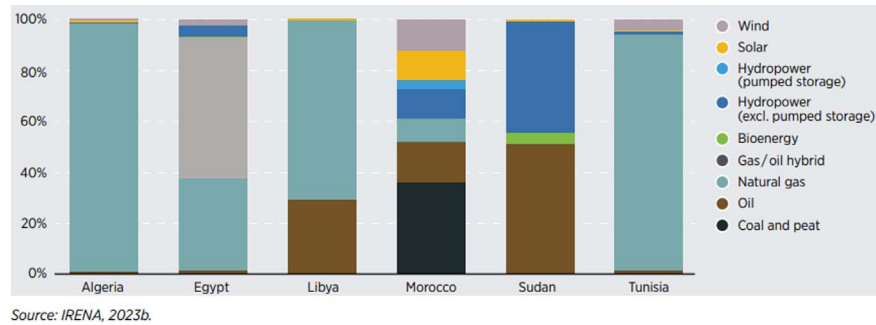


Fig. 23. Electricity generation capacity in North Africa by nation and energy source in the year 2020. Source: International Renewable Energy Agency (IRENA) [20].

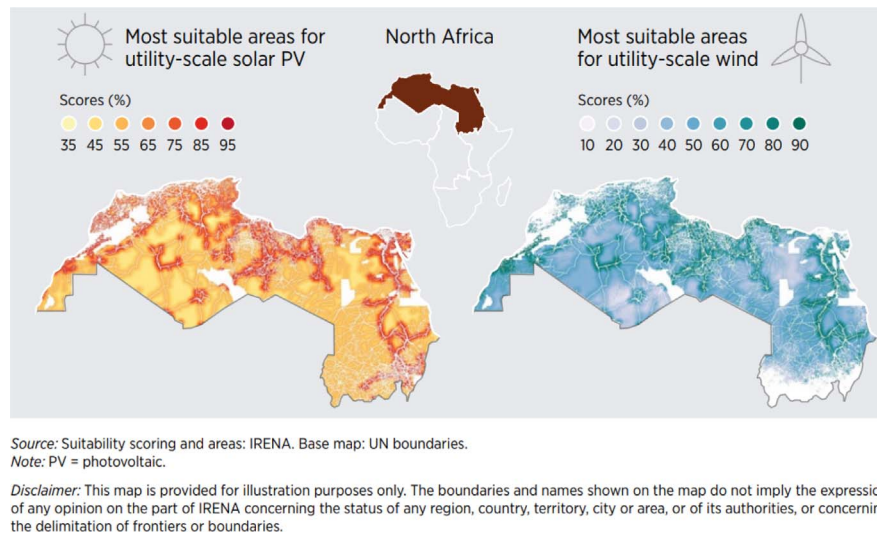


Fig. 24. Optimal regions in North Africa for large-scale photovoltaic and wind energy projects. Source: International Renewable Energy Agency (IRENA) [20].

(UNFCCC), collectively endorsed the Paris Agreement. As part of their commitment, these countries are obligated to present their Nationally Determined Contributions (NDCs) every five years. These NDCs outline the specific mitigation and adaptation measures they undertake to align with the goals of the agreement. With the exception of Libya, which has not yet ratified the Paris Agreement, all North African nations submitted their initial NDCs between 2016 and 2017. In 2021, Morocco, Sudan, and Tunisia submitted updated NDCs, while Egypt did so in July 2022, ahead of COP22. Algeria, however, has not submitted an updated NDC as of now. Notably, all the NDCs from the region incorporate both unconditional and conditional targets for the expansion of renewable energy capacity by 2030.

Morocco stands out with the most ambitious and intricately outlined Nationally Determined Contribution (NDC) in the region. The country aims to achieve a notable milestone by 2030, with 52% of its installed capacity attributed to renewable power plants. This target, initially established in its first NDC, has been consistently maintained in the updated version. Furthermore, it finds reinforcement in Morocco's "Stratégie Bas Carbone à Long Terme – Maroc

2050" (Long-Term Low-Emission Development Strategy or LT-LEDS) [21]. Nearly half of Morocco's renewable energy objectives are unconditional, while the remainder is contingent upon external financial and policy support. Fulfillment of all conditions would result in a tripling of Morocco's installed capacity for renewables within this decade.

Following the release of the Intergovernmental Panel on Climate Change (IPCC) assessment reports, which include the first [22], second [23], and third [24] reports, dedicated to scrutinizing scientific data on climate change such as temperature increases in comparison to the pre-industrial era, the carbon budget, impacts, and potential solutions to mitigate climate change, various scenarios for the integration of renewable energy in Morocco have been previously documented. These scenarios consider different levels of renewable penetration, accounting for factors such as the influence of thermal and Battery Energy Storage (BES), production and storage technology rental costs, spatio-temporal complementarity, and the effects of climate change. These studies have been detailed in prior publications [3].

Morocco is confronted with a crucial decision concerning the composition of its future electricity generation: how to transition from fossil fuel production to diminish energy dependence. The key question is whether to augment the generation of renewable energy and, if so, which technology to employ and where to implement it. There is a dilemma in prioritizing intermittent and variable renewable sources like Photovoltaic (PV) and wind power over continuous production sources like CSP with Thermal Energy Storage (TES) or PV with BES. Although the latter options can provide consistent output at a substantial scale, they come with higher investment and operational costs. This dilemma extends beyond the choice between variable sources (wind, PV, and CSP) without storage and also encompasses dispatchable sources, especially when integrated into the electricity mix with varying degrees of storage. For instance, when considering the same storage capacity, the question arises: is it more cost-effective and poses a lower production-demand adequacy risk to replace conventional production during peak consumption periods with CSP using thermal storage or PV with battery storage? This decision-making process becomes especially critical as the penetration of renewable energy increases, requiring careful consideration of both economic factors and the evolving dynamics of production and demand.

When shaping its electricity mix, Morocco faces the decision of whether to account for correlations between different technologies and regions, or solely focus on correlations between technologies within the same geographical area. Alternatively, the country may opt to consider only spatial complementarities within a specific technology, or altogether disregard these complementarities. An additional consideration is the impact that the integration of CSP and storage – both thermal and battery – would have on the advantages derived from these complementarities.

Renewable technologies are often cited as crucial contributors to a low-carbon energy supply, representing a substantial advantage due to the significant reduction in the deployment costs of solar and wind power observed from 2010 to 2019 [22]. Despite this, these low-carbon technologies, reliant on climatic conditions, are significantly influenced by climate change itself. Consequently, a critical question arises: are the optimal energy mixes in Morocco more vulnerable to the impacts of climate change or to cost considerations?

Moreover, given that climate projections are currently limited to a daily time step, the question arises: does overlooking intra-day variations in temperature, irradiance, and wind speed significantly influence the determination of optimal energy mixes? Additionally, an exploration into the vulnerability or resilience of various technologies to climate change is essential. Identifying the necessary conditions for cultivating climate-resilient renewable energy mixes becomes imperative, as does understanding the primary sources of uncertainty in forecasting future renewable energy compositions. Moreover, it begs investigation of whether thermal storage enhances the resilience of CSP in the face of climate change. Lastly, what impact does climate change exert on the geographical distribution of renewable energy capacity?

Bouramdane *et al.* [3] delve into these inquiries and present a series of preliminary and plausible scenarios. It is noteworthy that these scenarios are non-prescriptive, meaning they refrain from prescribing what should be done, and that's why multiple scenarios are considered instead of just one. In Chapter 3 of her work [3], Bouramdane *et al.* specifically examine the impact of various thermal storage durations when coupled with CSP, along with the concept of time-space complementarity. This exploration aims to understand how these factors can mitigate the adequacy risk associated with variable Renewable Energies (REs), namely wind and PV, within the Moroccan electricity system. In Chapter 4 of her work [3], Bouramdane *et al.* explores the impact of coupling BES and TES with PV and CSP technologies. They particularly focus on scenarios with extended storage duration and increased rental costs, along with the incorporation of diversification. The study aims to elucidate how these factors collectively influence the Moroccan energy mix, incorporating wind energy, and to what extent they contribute to the reduction of variability, specifically in terms of adequacy risk. In the concluding Chapter 5 of the study [3], an assessment is made regarding the impact of climate change on resources. The study also explores the implications for capacity factors and demand by the end of the 21st century, drawing comparisons to historical observed forcing. Notably, the findings suggest that while there are some indications of a potential impact in high-penetration energy mixes, these effects are minor when contrasted with the anticipated cost reduction effect on capacity pathways projected by climate models. Conversely, the study indicates that climate change is unlikely to have a discernible effect on optimal energy mixes characterized by low proportions of REs. However, a crucial takeaway is that the future impact of each technology is considered highly uncertain. The study comprehensively discusses the sources of uncertainty and outlines the primary options for cultivating climate-resilient Renewable Energy mixes.

Several critical factors come into play when deciding on the optimal solar field technology, orientation, storage capacities (both in combination with PV and CSP), and associated costs (covering both production technology and storage). Additionally, considerations extend to the dilemma of choosing between storage and spatio-temporal complementarities, the prevalent climate conditions (whether historical, current, or future), and the targeted level of renewable penetration. The intricate interplay of these factors, as discussed in [3], significantly influences the prioritization of specific technologies and their deployment in particular regions.

Smart grids emerge as crucial contributors to climate change mitigation. These sophisticated energy systems integrate diverse technologies and communication networks, revolutionizing electricity generation, transmission, distribution, and consumption. Their significance lies in efficiently incorporating renewable energy sources, implementing demand response programs – encouraging consumers to adjust electricity usage based on price signals or grid conditions –, and facilitating electric vehicle integration through smart charging and grid balancing. These measures

collectively lead to a substantial reduction in carbon emissions [25]. Nevertheless, as the importance of smart grids grows, so does their susceptibility to cyberattacks. Leveraging advanced Information Communication Technologies (ICTs), smart grids face potential cybersecurity threats. It is imperative to address these vulnerabilities and implement robust cybersecurity measures to guarantee the security and resilience of smart grid systems. Cyberattacks on smart grids can lead to system shutdowns, cascading failures, damage to consumer loads, and financial consequences. A recent investigation conducted by Bouramdane [25] delves into the realm of cyberattacks on smart grids. This study examines various cyberattack types and their consequences, offering insights supported by real-world case studies and quantitative models. To identify optimal cybersecurity solutions, the study introduces a Multi-Criteria Decision-Making (MCDM) approach using the Analytical Hierarchy Process (AHP). Additionally, the study explores the incorporation of artificial intelligence (AI) techniques in smart-grid security, presenting potential advantages and challenges. Emphasizing the utmost importance of “security effectiveness” in evaluating smart grid cybersecurity, the study identifies “access control and authentication” and “security information and event management” as critical components. Furthermore, it highlights “deep learning” as the most effective AI technique, providing valuable insights for making well-informed cybersecurity decisions in the smart grid sector.

The rising temperatures could pose additional challenges to Morocco’s power generation and distribution infrastructure. With the anticipated increase in frequency, intensity, and extent of heat waves [26], certain components of the energy system are likely to face growing impacts, as detailed in ([3], Chapter 5). The IEA also addresses this concern in its report [27].

Solar PV are sensitive to temperature, and their efficiency tends to decrease as temperature rises. High temperatures can lead to a reduction in the overall power output of a solar PV system. Moreover, increased cloud cover due to climate change can affect solar irradiance levels ([3], Chapter 1). Solar panels and associated infrastructure can be vulnerable to extreme weather events such as hurricanes, tornadoes, and severe storms [26]. Physical damage to the PV installations can result in disruptions to power generation. Coastal solar installations may face challenges from sea level rise and increased storm surges [26], potentially leading to damage or submersion of solar PV systems [28–30].

Based on the IEA’s projections, relying on the IPCC climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), the majority of existing solar PV capacity in Morocco is anticipated to face an increase of over 20 days per year with a maximum temperature exceeding 35 °C under a low-emissions scenario (2 °C or SSP1-2.6). Meanwhile, under a high-emissions scenario (above 4 °C or SSP5-8.5), this could escalate to over 40 days in the time frame 2080–2100 compared to the period 1850–1900 (refer to Fig. 25). This projected impact surpasses the world average. In a global assessment, only one-third of the global solar PV capacity is expected to be exposed to over

20 additional days with a maximum temperature above 35 °C in a low-emissions scenario (below 2 °C), while two-thirds would face over 40 more days under a high-emissions scenario (above 4 °C). During hot weather exceeding 35 °C, solar panel temperatures may rise up to 70 °C, causing a reduction in solar PV efficiency by 13.5–22.5%. This could result in a notable decrease in generation output unless adaptation measures or technological enhancements are implemented.

Climate change can alter wind patterns, affecting the speed and consistency of wind at specific locations. This can impact the overall energy output of wind turbines, as they demand a certain level of wind speed for optimal performance ([3], Chapters 1 and 5). In fact, wind turbines are designed to withstand a certain range of wind speeds, but extreme weather events such as hurricanes and typhoons can exceed these limits and cause damage to wind turbine infrastructure ([3], Chapter 1). Offshore wind farms may be vulnerable to rising sea levels and increased storm surges [26]. Submersion or damage to offshore wind turbines can result in disruptions to power generation. Changes in global wind patterns may also lead to shifts in the geographic distribution of favorable wind resources, potentially requiring adjustments in the placement of wind farms [3]. Similar to solar PV systems, wind turbine efficiency can be influenced by temperature changes. Extremely high or low temperatures can affect the performance of turbine components, leading to changes in power output ([3], Chapter 1). Changes in precipitation patterns, such as increased rainfall or drought conditions, can affect the foundation stability of wind turbines. Flooding or soil erosion can pose risks to the structural integrity of wind farms [31, 32].

Wind power plants in Morocco are anticipated to experience a rise in the number of days with a maximum temperature surpassing 35 °C across all climate scenarios. Under a low-emissions scenario (below 2 °C), half of the installed capacity is expected to encounter an increase of over 20 days, while under a high-emissions scenario (above 4 °C), half would likely see an increase of over 60 days by the end of the century (refer to Fig. 26). This projection notably surpasses the world average, where only 15–20% of wind power plants are estimated to face an increase of more than 20 days in a low-emissions scenario (below 2 °C), and over 60 days in a high-emissions scenario (above 4 °C). The heightened exposure to hot weather poses challenges to wind power generation, as elevated temperatures can diminish the lifespan of battery cells and other electronic components and impairs the performance of lubrication oil in the turbine gearbox. In extreme heat conditions, such as temperatures exceeding 45 °C, a standard wind turbine may shut down completely.

Alterations in precipitation patterns, such as changes in rainfall intensity, frequency, and distribution, can affect water availability in rivers and reservoirs. This, in turn, influences the potential for hydropower generation. Many hydropower systems depend on snowmelt as a water source. Changes in temperature and precipitation patterns can influence the timing and magnitude of snowmelt, affecting the flow of water into rivers and reservoirs. Extreme weather events, such as floods or droughts, can impact

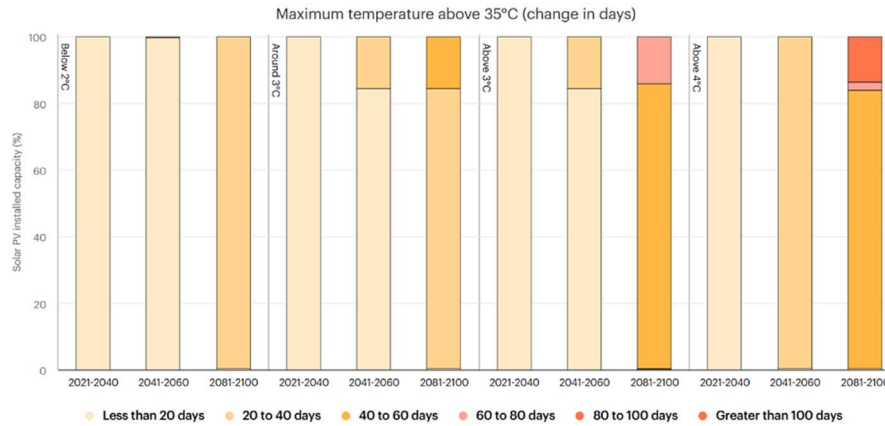


Fig. 25. Moroccan solar PV systems subjected to elevated temperatures under various climate scenarios from 2021 to 2100. Source: International Energy Agency (IEA) [27].

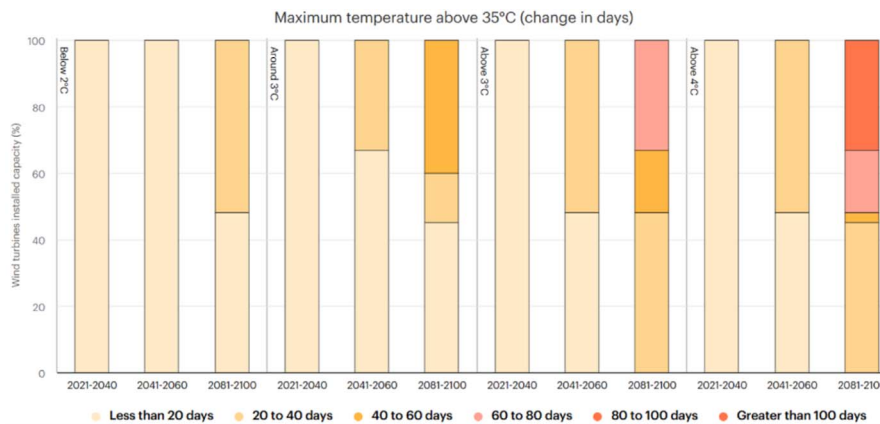


Fig. 26. Moroccan wind power plants subject to increased temperatures under various climate scenarios from 2021 to 2100. Source: International Energy Agency (IEA) [27].

the operational efficiency and structural integrity of hydropower infrastructure. Floods can damage facilities, while droughts can reduce water levels, affecting power generation. Changes in precipitation and temperature patterns can complicate reservoir management. Variability in inflow patterns may require adjustments to reservoir release schedules to meet both energy generation and water supply demands. Changes in reservoir management practices can have downstream effects on ecosystems, affecting aquatic habitats and water quality. Coastal hydropower installations may be vulnerable to sea level rise and storm surges, potentially leading to damage or submersion of infrastructure [33, 34].

Historical observations reveal a progressive aridification trend in Morocco. Cumulative rainfall declined by 16% from 1961 to 2017, notably dropping by 43% in spring and 26% in winter. While the northwest region receives the highest annual average precipitation of up to 1200 mm, the south-east witnesses less than 50 mm per year on average. This diminishing precipitation in southern Morocco contributes to the encroachment of the Sahara Desert. Projections indicate a continuing decline in mean annual precipitation in

Morocco, ranging from 10% to 20% during 2036–2065 compared to 1981–2018, with some regional variability. Long-term projections forecast a 30% reduction in precipitation in the central region, while the Sahara region could experience a 50% decrease in precipitation. The decrease in precipitation raises concerns about increasing droughts, both in frequency and intensity. Climate projections indicate a heightened risk of severe droughts, especially in central and southern regions. Despite the current temperate Mediterranean climate north of the Atlas Mountains, the majority of Morocco is expected to transition to an arid climate by the end of the 21st century. In the energy sector, reduced precipitation and more frequent droughts are impacting hydropower generation (Fig. 27). Climate-induced changes contributed significantly to the decline in hydropower output from 3631 GWh to 1260 GWh between 2010 and 2020. If GHG emissions are not mitigated, the IEA's climate impact assessment projects that 90% of Morocco's existing hydropower plants will face a significantly drier climate, with a notable increase in consecutive dry days in a high-emissions scenario (above 4 °C) (left and right panels of Fig. 28). This exceeds the world average, where only 20% of hydropower plants would experience a

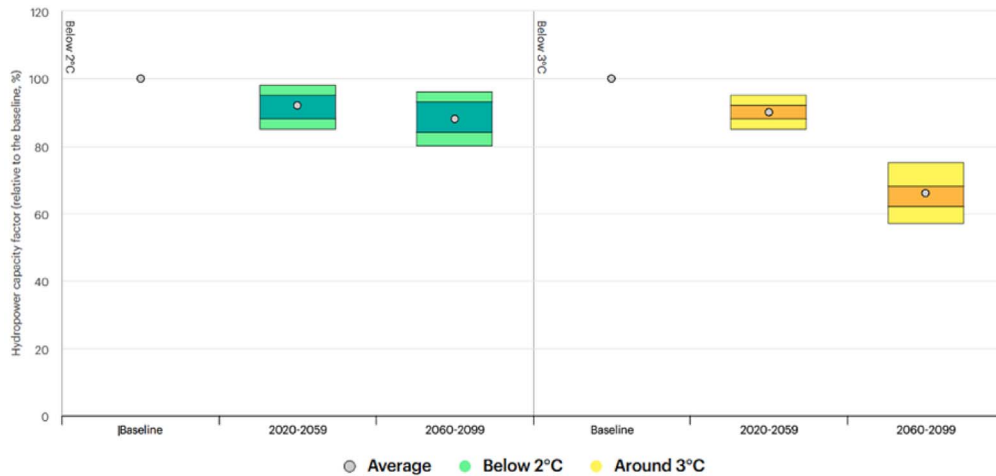


Fig. 27. Variations in hydropower capacity factors in Morocco across different climate scenarios from 2020 to 2099. Source: International Energy Agency (IEA) [27].

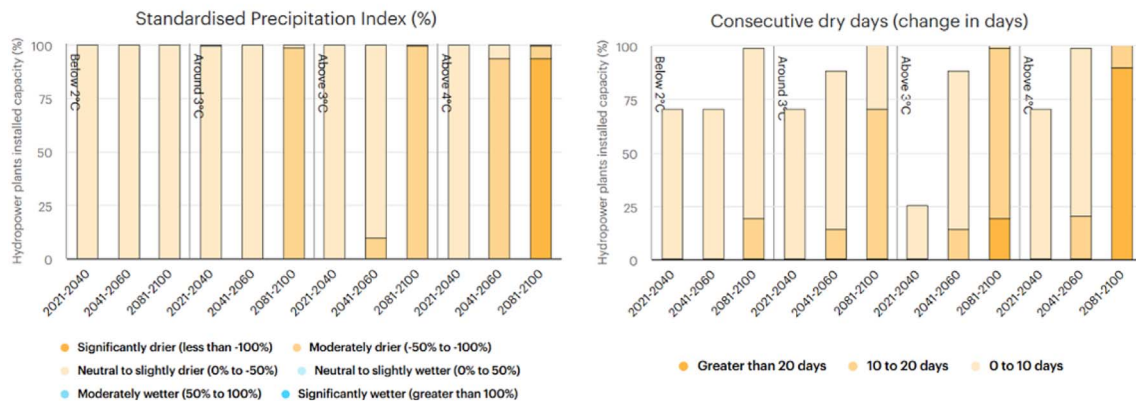


Fig. 28. Moroccan hydropower plants facing increased aridity under various climate scenarios from 2021 to 2100. Source: International Energy Agency (IEA) [27].

similar rise in consecutive dry days. The anticipated increase in aridity could result in a hydropower capacity factor drop exceeding 30% between 2060 and 2099 compared to 2010–2019. Mitigating GHG emissions could potentially limit the decrease in the hydropower capacity factor to 10% between 2060 and 2099 compared to 2010–2019, according to the IEA's assessment. Anticipating the projected decrease in precipitation, Morocco has expanded the capacity of its pumped storage hydropower plants, which are less dependent on precipitation than other types. Pumped storage hydropower's ability to operate in a closed loop, storing and pumping water between lower and upper reservoirs, might mitigate the impact of lower precipitation. The Office National de l'Électricité et de l'Eau Potable (ONEE) has initiated projects for pumped storage hydropower, including the construction of Abdelmoumen (350 MW) and plans for El Menzel II (300 MW) and Ifasha (300 MW).

Morocco's ambitious initiative to diversify its electricity generation through a substantial expansion of solar power technologies, including PV panels and CSP, may face

challenges due to the anticipated rise in dust and sandstorms in the region. Coarse sand particles have the potential to cause damage to CSP mirrors, leading to scratching or breakage. Additionally, small particles can accumulate on solar mirrors, forming a soiling layer that diminishes their efficiency in power generation. Without regular cleaning, solar PV panels may experience efficiency losses of up to 30% within six months, equating to a daily electricity generation reduction of 13–15%. Identifying optimal sites for solar power plants and implementing comprehensive maintenance plans to counteract the escalating prevalence of dust and sandstorms will be crucial in mitigating these adverse impacts on the electricity systems [27].

Rising temperatures associated with climate change can lead to an increased demand for air conditioning and cooling. Hotter weather may result in more prolonged periods of high energy demand for cooling systems, especially in regions with higher temperatures. Conversely, in some regions, milder winters may reduce the need for heating, potentially leading to a decrease in energy demand for heating systems. Extreme weather events, such as hurricanes,

floods, or storms, can cause damage to energy infrastructure. The subsequent recovery efforts may result in a temporary spike in energy demand for reconstruction and repair activities. Climate change can influence economic activities through various channels, including changes in agriculture, water availability, and supply chain disruptions. These changes can, in turn, affect energy demand in industrial and commercial sectors ([3], Chapter 1 and 5; [35, 36]).

Transmission lines can be vulnerable to extreme weather events such as hurricanes, tornadoes, ice storms, and severe storms. These events can lead to physical damage, including line breakage, tower collapse, or conductor damage. Increased frequency or intensity of extreme weather events may require more frequent maintenance and repair activities, leading to potential disruptions in the continuity of electrical service. Coastal transmission lines and substations may be at risk of inundation due to rising sea levels. This can lead to corrosion, degradation of materials, and increased vulnerability to storm surges. Sea level rise can contribute to changes in soil conditions and land use, affecting the stability and maintenance requirements of transmission line infrastructure. Elevated temperatures can affect the efficiency of transmission lines by increasing line losses and reducing their overall capacity. Higher temperatures may also lead to equipment failures and increased thermal stress on components. Changes in temperature patterns may alter energy consumption and peak demand, influencing the load on transmission lines. Changes in precipitation patterns, such as increased rainfall or more frequent and intense storms, can lead to landslides, flooding, or soil erosion, affecting the stability of transmission line towers and foundations. Wildfires can pose a significant threat to transmission lines, especially in regions with dry and hot conditions. Burning vegetation may lead to conductor damage, tower collapse, or the need for proactive shutdowns to prevent further damage. Increased wildfire risk may prompt utilities to implement preventive measures, such as temporary shutdowns or more extensive vegetation management, impacting the reliability and availability of transmission lines. Ice storms and heavy snowfall can lead to the accumulation of ice or snow on transmission lines, increasing their weight and potentially causing sagging or structural damage [37, 38].

3.2.2 Role of hydrogen

The Moroccan Ministry of Energy, Mines, and Environment, through the National Hydrogen Commission, outlined a comprehensive roadmap for the country's green hydrogen sector in 2021. The roadmap envisions a substantial increase in green hydrogen demand, estimating consumption to range between 14 TWh and 30 TWh by 2030 and between 156 TWh and 307 TWh by 2050. To meet this demand, the government plans to add 2 GW of renewable energy capacity. The roadmap aligns Morocco's renewable energy potential with the growing green hydrogen market, aiming not only to satisfy domestic demand but also to become a leading exporter of green hydrogen. The development of green hydrogen is expected to result in emissions reductions ranging from 10 MtCO₂e to 20 MtCO₂, contributing to environmental sustainability.

The roadmap is structured into short, middle, and long-term phases, each with specific objectives. In the short term (2020–2030), the focus is on local utilization in industries and exports to countries committed to decarbonization. The middle term (2030–2040) involves cost reduction, environmental regulations, and the exportation of synthetic liquid fuels. The long term (2040–2050) anticipates improved profitability and widespread local use in various sectors. The action plan emphasizes technology development, investment in industrial clusters, infrastructure optimization, and market and demand strategies. Morocco aims to position itself as a global leader in green hydrogen by contributing to decarbonization efforts and meeting rising demand [39, 40].

In a recent extensive assessment of hydrogen production technologies in Morocco, Bouramdane *et al.* [41] employed the MCDM approach, specifically utilizing the AHP methodology. The evaluation took into account factors such as technological feasibility, economic viability, environmental impact, and social acceptance. The study identified highly effective technologies, such as Autothermal Reforming with Carbon Capture and Storage, deemed suitable for hydrogen production in Morocco. Technologies with moderate performance, including PV and CSP, demonstrated promise, while those with lower performance may encounter challenges meeting specified criteria. The study highlights the significance of stakeholder perspectives, especially in scenarios involving renewable penetration, in influencing the suitability of different technologies.

A German fuel and gas distribution company is contemplating the importation of green hydrogen from Morocco to cater to a network of hydrogen refueling stations (HRS) and industrial plants within the country, as depicted in the left panel of Figure 29. The graphic on the right panel of Figure 29 illustrates potential locations for a hydrogen production plant, each presenting distinct advantages and disadvantages. The ultimate selection of the production plant's location hinges on a comprehensive analysis.

3.2.3 Fossil fuels

In an effort to reduce dependence on Russian gas, the European Union (EU) is turning towards American Liquefied Natural Gas (LNG) and prolonging the operational lifespan of coal- and gas-fired power plants. However, this shift implies a postponement in the plans to reduce GHG emissions, as the decarbonization of electricity generation is imperative by 2050 to align with the temperature target set by the Paris Agreement [42, 43]. Notably, LNG, being predominantly shale gas, emerges as a less favorable option concerning climate change due to its considerably higher carbon footprint compared to Russian gas. Obtaining Russian gas through pipelines is evidently more cost-effective and straightforward than importing gas via ship from Qatar or the United States. Moreover, while the United States boasts substantial natural gas production, consumption is equally significant. Even with potential production expansion, existing liquefaction terminals may prove inadequate to meet domestic demand and accommodate exports to Europe. The construction of new facilities



Fig. 29. A detailed pre-feasibility analysis conducted for a German fuel and gas distribution company exploring the possibility of importing green hydrogen from Morocco. Source: Alexec Consulting.

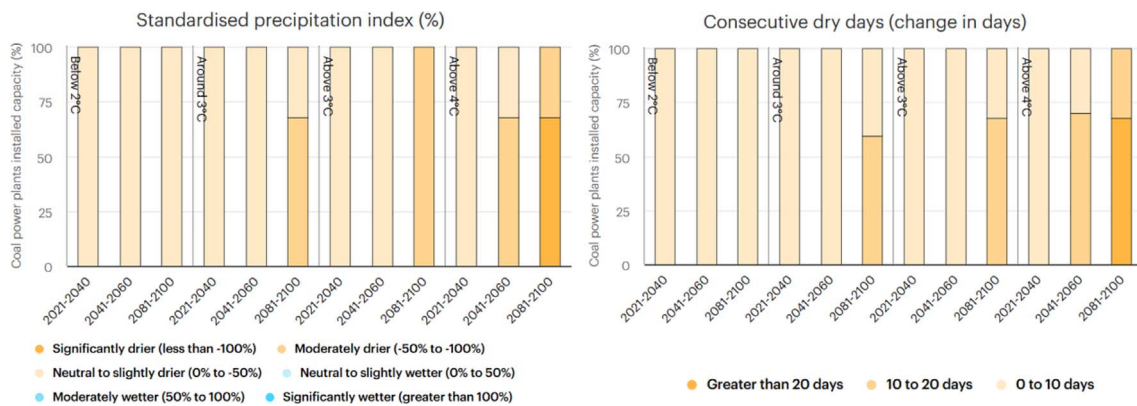


Fig. 30. Moroccan coal power plants facing increased aridity under various climate scenarios from 2021 to 2100. Source: International Energy Agency (IEA) [27].

presents a considerable logistical challenge, requiring years of planning and execution.

Coal power plants, constituting approximately two-thirds of Morocco's current electricity generation, are anticipated to confront more arid conditions in the upcoming decades. Nearly 70% of Morocco's coal power plants could be exposed to a significantly drier climate, witnessing an increase of over 20 consecutive dry days in the period 2061–2100 if climate change remains unmitigated (above 4 °C) (left and right panels of Fig. 30). This heightened exposure is notably higher than the global average, where less than 2% of coal power plants are expected to become significantly drier or experience an increase of over 20 consecutive dry days. The projected rise in aridity under a high-emissions scenario poses challenges for coal power plants, especially those relying on water for cooling, which accounts for over 80% of the total installed capacity of coal-fired power plants in Morocco. Morocco's strategic initiative to replace coal power plants with natural gas

combined-cycle power plants emerges as a potential solution to enhance power system resilience against water stress. The national plan aims to install an additional 2,400 MW of natural gas power plant capacity by 2030 and completely phase out coal-fired plants by 2050. Shifting to natural gas power plants, known for emitting fewer GHGs and requiring less cooling water per MWh compared to coal-fired counterparts, not only strengthens climate resilience but also aligns with efforts for climate change mitigation.

3.2.4 Role of carbon capture and sequestration (CCS) to achieve net zero CO₂ emissions

The current rate of global warming surpasses the pace at which the global economy is decreasing its emissions. Despite the signing of the Paris Agreement in December 2015, aiming to limit the temperature increase to 1.5 °C above pre-industrial levels, net GHG emissions have increased rather than decreased since then, with a minor

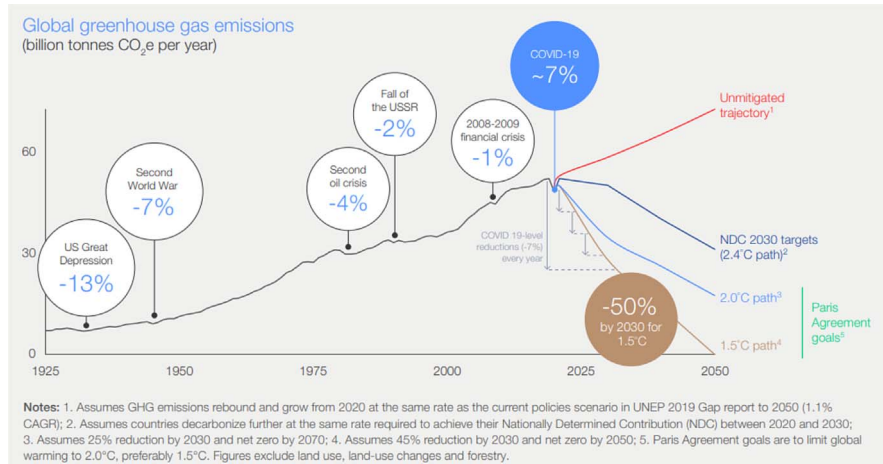


Fig. 31. The emissions pathway required to achieve the objectives outlined in the Paris Agreement. Source: World Economic Forum (WEF) [44].

dip due to the COVID-19 pandemic. In the past year, total estimated emissions rose by nearly 2 billion tonnes compared to 2015, constituting an approximately 5% increase. To meet the goals set in the Paris Agreement, as highlighted by the United Nations (UN) IPCC, a substantial decline in global net anthropogenic CO₂ emissions of 40–60% by 2030 (compared to 2010) is necessary. Achieving this 2030 target implies reducing emissions at a rate equivalent to the pandemic-induced drop, amounting to approximately 7% each year (see Fig. 31).

Since 1990, when the IPCC released its inaugural report, human activities have resulted in more GHG emissions than all historical records before that period. To initiate climate restoration, it is imperative to permanently remove these accumulated emissions. Consequently, achieving net-zero emissions by 2050 is not the ultimate endpoint. Beyond the mid-century point, global emissions must transition to a net-negative state, and Carbon Dioxide Removal (CDR) emerges as the sole pathway to realizing this objective (see Fig. 32).

Figures 31 and 32 encapsulate the necessary actions to fulfill the objectives of the Paris Agreement: a 50% reduction in emissions by 2030, achieving net-zero emissions by 2050, and transitioning to net-negative emissions beyond 2050.

CCS involves capturing the CO₂ emitted from highly polluting sources and injecting it underground instead of releasing it into the atmosphere. The IPCC emphasized in its 2018 special report on 1.5 °C [42] that achieving the goal of limiting global warming to 1.5 °C requires “rapid and far-reaching” transformations in various sectors, including land use, energy, industry, buildings, transportation, and cities. The report indicates that global net CO₂ emissions should decrease by approximately 45% from 2010 levels by 2030 and reach “net-zero” by 2050 to stay within the 1.5 °C limit with “no or limited overshoot.” Consequently, any remaining emissions must be compensated for by actively removing CO₂ from the atmosphere.

The IPCC’s sixth assessment report [24] underscores the direct relationship between the cumulative volume of CO₂

emissions from human activities and observed and future warming, emphasizing the imperative of achieving global net-zero CO₂ emissions to curb global warming. Despite fossil fuels continuing to dominate the global energy supply [11], making complete elimination of GHG emissions unattainable, the necessity of carbon “sinks” becomes apparent. Forests play a crucial role, especially when managed sustainably. Achieving carbon neutrality will depend on employing strategies for negative emissions, encompassing various approaches to extract CO₂ from the atmosphere and store it in “geological, terrestrial, or ocean reservoirs, or in products.” These approaches include “nature-based solutions” like reforestation and land-use modifications, along with industrial processes such as Carbon Capture, Utilization, and Storage (CCUS) of CO₂ [45, 46].

Carbon Capture and Storage (CCS) technologies, integral to carbon capture, present cost-related challenges that may render electricity generation from fossil fuels economically unfeasible. Safety concerns arise from storing substantial amounts of CO₂ in a single location, as potential leaks could result in environmental contamination if not managed effectively. Despite its importance, carbon capture and storage alone prove insufficient in adequately addressing climate change. While emissions from fossil fuel use in heat and power generation contribute only a small fraction to total GHG emissions, significant portions come from transportation, agriculture, and other related industrial activities, areas not currently covered by carbon capture and storage initiatives.

3.2.5 Renewable energies vs. fossil fuels vs. nuclear

In the highly dynamic fossil fuel markets, traditional fossil fuel generators exhibit diminished initial expenses but incur substantial ongoing fuel costs, often exerting significant influence. In contrast, renewable technologies, characterized by elevated initial investment outlays, minimal operational and maintenance costs, and the absence of fuel expenses, are particularly sensitive to variations in capital costs and financing conditions ([3], Chapter 1, Sects. I and 2).

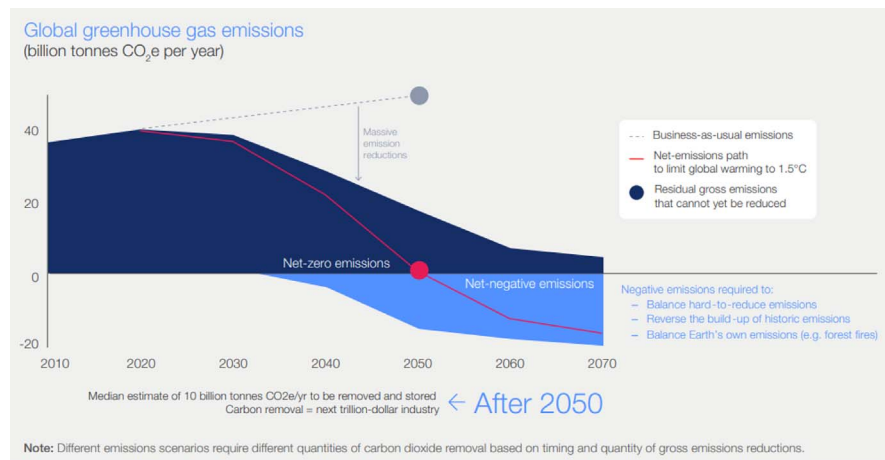


Fig. 32. Moving past net-zero – Negative emissions necessitated by carbon removals. Source: World Economic Forum (WEF) [44].

In contemplating a shift away from the most environmentally impactful fossil fuels, nuclear energy emerges as a viable alternative, warranting examination in conjunction with renewable technologies. Nevertheless, the escalating costs associated with nuclear power contrast with the diminishing expenses linked to renewable technologies. Additionally, both nuclear and fossil fuel facilities demand substantial quantities of cooling water ([3], Chapter 1, Sects. I and 2).

Moreover, fossil fuels (or nuclear reactors) exhibit significantly higher carbon footprints (or safety concerns) compared to renewable technologies. Wind turbines, PV panels, and CSP plants harnessing wind and solar energy, introduce concealed carbon footprints and safety issues due to the industrial manufacturing processes involved, which emit GHGs. The production of PV cells, for instance, involves the use of various hazardous, carcinogenic, flammable, and explosive substances. Environmental consequences associated with wind turbines include noise from blade rotation, equipment noise from the gearbox and generator, visual intrusion, and bird strikes. Hydro (utilizing the power of moving water), geothermal (tapping into heat generated within the Earth), and biomass (extracting energy from organic material in plants and animals) all entail environmental impacts, such as dam inundation, the release of offensive chemicals, competition for food resources, and the use of wood for cooking and heating. CSP plants obstruct natural landscape views, utilize non-recyclable materials, and involve hazardous compounds that, when burned at high temperatures, can persist in the environment for an extended duration, posing risks to human health. In contrast, nuclear power plants release no GHGs during operation, emitting approximately the same amount of carbon dioxide (CO₂)-equivalent emissions per unit of electricity over their lifetime as wind power, and about one-third of the emissions per unit of electricity compared to solar power ([3], Chapter 1, Sects. I and 2).

3.3 Energy efficiency

Energy efficiency entails the principle of accomplishing a given task with reduced energy consumption, thereby

avoiding waste during energy production or utilization. Enhanced efficiency leads to reduced waste, while diminished efficiency results in increased waste. Embracing energy efficiency yields numerous advantages, including a decrease in GHG emissions, reduced dependence on energy imports, and lower costs at both individual and societal levels [47, 48]. Across various sectors like buildings, transportation, manufacturing, and energy production, there exists substantial potential for improvements in efficiency [49].

Prior to integrating renewable energy technologies, architects and building designers are striving to elevate building efficiency, with the ultimate goal of creating zero-energy buildings. Moreover, there is a focus on retrofitting existing structures to achieve energy and cost savings. Retrofitting measures span from straightforward initiatives like adopting LED light bulbs and energy-efficient appliances to more extensive endeavors such as enhancing insulation and implementing weatherization techniques [50].

Cogeneration systems, often known as Combined Heat and Power (CHP) systems, utilize the “waste” heat generated by power plants to supply heating, cooling, and/or hot water to adjacent buildings and businesses, thereby enhancing the overall energy efficiency of electricity generation [51]. Another approach to amplify the efficiency of energy generation, distribution, and consumption is through the implementation of the smart grid [52].

Water supply and treatment facilities demand a significant quantity of electricity for their operation. Nonetheless, a substantial portion of the energy is squandered due to neglect and the absence of an energy management program capable of handling data, overseeing and calculating usage, and promoting energy conservation [53].

Creating neighborhoods with mixed-use developments and providing secure and convenient options for walking, biking, and public transportation is crucial in diminishing the reliance on private car travel [54].

Automobiles with higher fuel efficiency consume less fuel to travel the same distance, leading to substantial reductions in both pollution and operational expenses. Plug-in hybrids and fully electric vehicles exemplify exceptional fuel efficiency [55]. Additionally, the implementation of carbon pricing is crucial for averting the buildup of heat-trapping

GHGs in the atmosphere. This can take the form of a tax on the carbon content of fossil fuels or on their carbon dioxide (CO₂) emissions [56].

Through technological advancements and thoughtful design, the aforementioned strategies significantly enhance energy efficiency. However, the effectiveness of these technologies is heavily contingent on their implementation. A technology boasting high efficiency serves little purpose if it cannot be readily acquired, installed, or adopted by businesses and consumers. For instance, if public transportation is stigmatized within society, its utilization may be limited. The potential energy savings offered by high-efficiency technologies often go unrealized due to various sociological, cultural, and economic factors [57, 58]. Addressing these issues is equally critical in the quest to enhance energy efficiency within our economy.

3.4 Energy sobriety

The energy scenarios, which investigate the pathways toward substantial global carbon neutrality goals, underscore the challenges inherent in achieving such objectives without incorporating the concept of energy sobriety [59].

While the concept of energy sobriety is not new, specific elements have been addressed within the realm of behavioral theories, such as in the fields of behavior change or sustainable lifestyles [60]. However, these considerations lack a comprehensive global, systemic, or political perspective.

Initially, sobriety can be perceived as an aspiration – a vision of a society where every inhabitant can fulfill their basic needs while adhering to the inherent limits of the planet and abstaining from the current reckless depletion of its resources. Achieving sobriety involves a comprehensive reassessment of the influence and functioning of our techno-economic systems, encompassing both macro aspects (such as the consumer society in a broad context) and micro aspects (individual consumption habits).

Energy sobriety can be defined as a blend of collective and individual measures aimed at altering the attributes of the energy services we employ and discontinuing or diminishing our reliance on those that inherently demand the highest energy consumption.

Sobriety policies, as defined by the IPCC, encompass a collection of measures and daily practices designed to circumvent the need for energy, materials, soil, and water. These policies are crafted with the goal of ensuring the well-being of all while operating within the constraints of planetary boundaries.

This expansive definition gives rise to several fundamental questions.

Firstly, there exists an incomplete understanding of planetary boundaries [61]. A comprehensive study [62], grounded in diverse environmental indicators such as carbon emissions, material extraction, and water supply, reveals that no country presently satisfies its population's basic needs within ecological limits set by planetary boundaries. Achieving this necessitates a profound restructuring of all societal systems with a focus on frugality. When considering the specific issue of climate change, its magnitude is unequivocal. The equitable allocation of the world's finite carbon budget, while ensuring environmental safety and

meeting essential development needs for all, stands as a pivotal challenge in ongoing negotiations [7, 63]. Despite the long-standing inclusion of the concept of climate and social justice in IPCC reports [7], explicit attention to climate justice emerged more prominently in the 2018 special report [42]. This report accentuates the constraints of the limited carbon budget and underscores the North's responsibility for contributing to emissions.

An additional challenge involves the identification of essential versus supplementary energy services. Addressing this matter requires contemplation of individual needs and desires, entailing the navigation of political and personal compromises in the pursuit of a universally applicable solution, which can prove to be complex.

To implement the concept of energy sobriety, the *néga-Watt Association* [64, 65] has defined categories of sobriety actions based on their nature. These categories include:

- **Sobriety in use:** involves reducing the duration or frequency of highly energy-intensive activities, such as taking fewer long trips.
- **Substitution sobriety:** focuses on satisfying needs in alternative ways by replacing energy-intensive services with much less intensive alternatives, such as using fans instead of air conditioners for cooling buildings in the summer.
- **Dimensional sobriety:** requires moderating certain desires and adjusting the capacity of consumed services to align closely with current needs. For instance, choose a refrigerator with an optimal volume for daily needs rather than an oversized, flashy fridge that is rarely filled.
- **Collaborative sobriety:** aims to share energy services whenever possible, thereby reducing the overall volume of energy consumption. An example is participating in car-sharing initiatives.

3.4.1 Distinguishing sobriety from efficiency

Certain authors interpret the notion of energy efficiency in a broad sense, encompassing anything that can diminish energy demand. They argue that this perspective inherently includes the concept of sobriety through the application of effectiveness to behavior. However, this viewpoint represents a somewhat limited understanding of sobriety. Both approaches are grounded in distinct concepts regarding how to minimize energy demand, yet they can be viewed as complementary. For instance, in the realm of mobility (or communication), a demonstration of sobriety might involve choosing a bicycle over a car (or limiting a company's data production and storage needs). In contrast, an illustration of efficiency could entail transitioning from a conventional thermal vehicle to a hybrid one (or storing data in a high-efficiency data center) [66].

3.4.2 Obstacles and limits to sobriety behaviors

Sobriety can draw upon a diverse array of knowledge fields, including sociology, psychology, economics, philosophy, and political science. Researchers frequently inquire about the persistence of a crucial question: despite the growing

acknowledgment of environmental constraints, why has the adoption of sobriety not become more prevalent? What underlies the ideological preconceptions and occasionally intense emotional reactions encountered by sobriety, hindering its widespread acceptance?

The rationale behind this phenomenon can be traced to the prevailing social paradigm in our societies, which propagates and upholds values such as materialism, consumerism, individualism, and the pursuit of power. Additionally, many existing economic and development models often promote tendencies toward excessive scale and the encouragement of a mindset of “always more”. This is further compounded by socio-technical contexts and historical planning decisions that restrict users to specific choices within a limited range of energy services. Resistance to altering daily practices, as well as the lack of clear visibility and tangibility regarding the energy impact of our choices across various levels, also contribute to this explanation.

This underscores the significance of taking into account social inequality and the notable disparities in consumption levels. It is essential to recognize the contrast between individuals facing challenges in accessing basic energy services and those engaging in conspicuous, energy-intensive behaviors when contemplating the concept of sobriety.

Sobriety continues to evoke a sense of ambivalence. While the dominant paradigms mentioned earlier remain highly influential, there are discernible faint signals indicating a gradual advancement of sobriety in people’s perspectives.

In practical terms, this ambivalence manifests through somewhat contradictory trends. Cities witness a rise in bicycle usage alongside the unprecedented popularity of high-consumption vehicles for mobility. While certain major projects with substantial energy footprints, like coal power plants, have been abandoned, numerous others, such as natural gas infrastructure, continue to progress. It’s noteworthy that shifts towards sobriety do not appear solely motivated by economic considerations, like financial savings. Various co-benefits play a role, including a sense of better life control, improved health, the pursuit of social connections, increased resilience, support for local employment, concerns for animal welfare, biodiversity preservation, and more [67].

4 Breaking down barriers to accelerate the energy transition

Advancing the net-zero challenge necessitates overcoming obstacles and constraints associated with the adoption of decarbonization policies. Simultaneously, it is crucial to guarantee that no individual or group is excluded from this transition.

4.1 The role of critical minerals in clean energy transitions

A clean energy system represents a substantial departure from one reliant on traditional hydrocarbon resources ([3], Chapter 1). Notably, the transition to cleaner energy sources introduces new challenges related to critical

minerals that impact energy security [68] (SMRY [12]). For instance, solar PV plants, wind farms, and electric vehicles (EVs) necessitate a greater quantity of minerals compared to their fossil fuel-based counterparts. Specifically, an electric vehicle requires six times the mineral inputs of a conventional vehicle, and an onshore wind farm demands nine times the mineral inputs of a gas-fired power plant ([12], Fig. 3). As the proportion of renewable energy sources in the energy mix has expanded, the average mineral requirements for a new unit of power production capacity have increased by 50% since 2010 ([12], Fig. 1).

The utilization of mineral resources varies depending on the technology involved. Essential minerals such as lithium, nickel, cobalt, manganese, and graphite are integral to the performance, lifespan, and energy density of batteries. Rare earth elements are crucial for permanent magnets, which find application in wind turbines and electric car motors. Additionally, copper and aluminum play vital roles in electricity networks, with copper forming the basis for various electricity-related technologies. Comparing the “Stated Policies Scenario (SPS)” to the “Sustainable Development Scenario (SDS)” – aimed at climate stabilization well below a global temperature rise of 2 °C – reveals a substantial increase in the share of total demand for clean energy technologies in the next two decades. This surge reaches over 40% for copper and rare earth elements, 60–70% for nickel and cobalt, and nearly 90% for lithium in the SDS. Notably, electric vehicles (EVs) and battery storage have already surpassed consumer electronics in terms of lithium consumption (Fig. 33).

As per the Sustainable Development Scenario (SDS), the demand for minerals in renewable energy technologies is projected to quadruple by 2040. Achieving net-zero global emissions by 2050 would necessitate a six-fold increase in the amount of minerals required in 2040 compared to the present (Fig. 34).

Although numerous projects are in different stages of development, several vulnerabilities exist that could elevate the risk of market tightness and increased price volatility.

- The production of several energy transition minerals exhibits a high degree of geographical concentration, unlike oil or natural gas. The top three producers control over three-quarters of the global output for lithium, cobalt, and rare earth elements. Notably, a single country may contribute nearly half of the total global production. For instance, in 2019, the Democratic Republic of the Congo (DRC) and China accounted for 70% and 60% of global cobalt and rare earth element production, respectively ([12], Fig. 5). Processing operations witness even higher concentration levels, particularly with China having a strong presence. Approximately 35% of nickel refining, 50–70% of lithium and cobalt refining, and almost 90% of rare earth element refining occur in China ([12], Fig. 6). Chinese companies have also made substantial investments in international properties in Australia, Chile, the DRC, and Indonesia. The pronounced concentration levels and intricate supply chains amplify the risks associated with physical

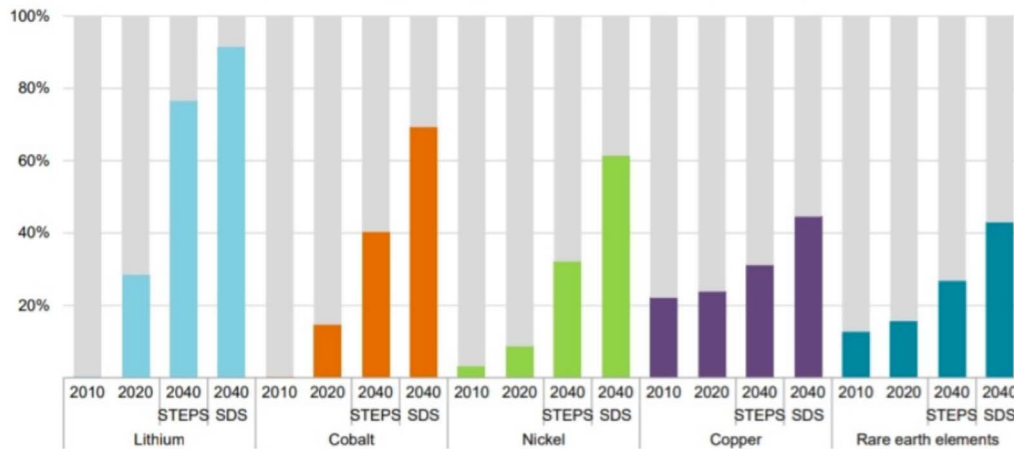


Fig. 33. The proportion of total demand for specific minerals attributed to clean energy technologies. Source: International Energy Agency (IEA) [68].

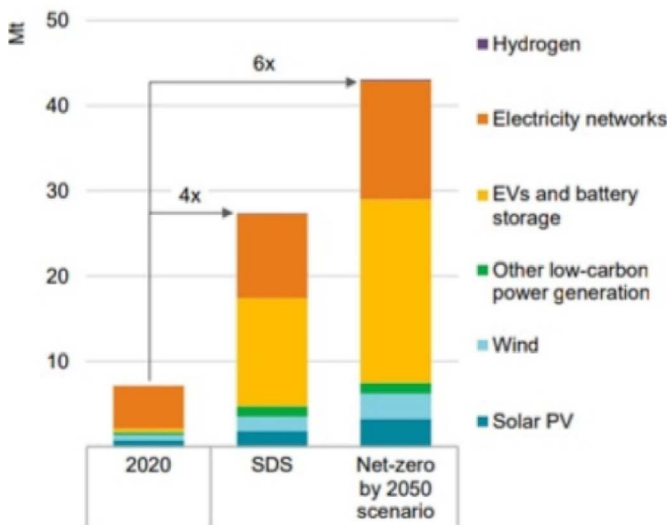


Fig. 34. The breakdown of mineral demand for clean energy technologies is provided for each scenario. Source: International Energy Agency (IEA) [68].

disruptions, trade restrictions, or other alterations in key producing countries. In the short term, there is little indication that the geographical concentration of production will shift (Fig. 35).

- Significant lead times characterize the development of mining projects, as indicated by the IEA [68], with an average duration of 16 years from discovery to initial production (Fig. 36). These prolonged lead times raise apprehensions regarding suppliers' capacity to swiftly increase supply in response to surges in demand, potentially prolonging market tightness and contributing to price volatility.
- The apprehensions regarding resources primarily revolve around quality rather than quantity. Extracting metals from lower-grade ores demands more energy, resulting in elevated manufacturing costs, increased GHG emissions, and higher volumes of waste.

- The predominant portion of current output volumes originates from regions characterized by either low governance standards or high emissions intensity (Fig. 37).
- The impact of climate change is rendering mining assets increasingly susceptible to vulnerabilities. Copper and lithium, in particular, face heightened sensitivity to water stress due to their substantial water requirements. Over half of the current lithium and copper output is concentrated in regions experiencing water stress. Moreover, crucial production areas, including Australia, China, and Africa, are also susceptible to severe heat or flooding (Fig. 38), presenting additional challenges in maintaining a dependable and sustainable supply.

4.2 The broader policy landscape

Tailwinds refer to non-climate change policy events, encompassing shifts in economic or social conditions, discoveries, and innovations that can propel and ease the transition to net-zero energy. For instance, the anticipated costs for newly contracted solar PV and onshore wind projects witnessed a 50% and 20% reduction, respectively, from 2015 to 2020. Nations should consider such market developments when crafting net-zero strategies [69]. Innovation and substantial public support, such as public investment or feed-in tariffs, have driven investments in renewable energy. The momentum of efficiency gains is propelled by learning by doing and increased private-sector investment. Consequently, renewable energy has become as, if not more, profitable than fossil-fuel-based energy in many countries, attracting heightened private investments and research. This dynamic fosters a virtuous circle between innovation and production. With increased private investment and research, there is potential for a gradual reduction in government support, particularly feed-in tariffs, which have already been reduced or eliminated in certain nations. Between 2000 and 2020, global renewable energy production surged by 63%, while OECD countries experienced an 82% increase [69].

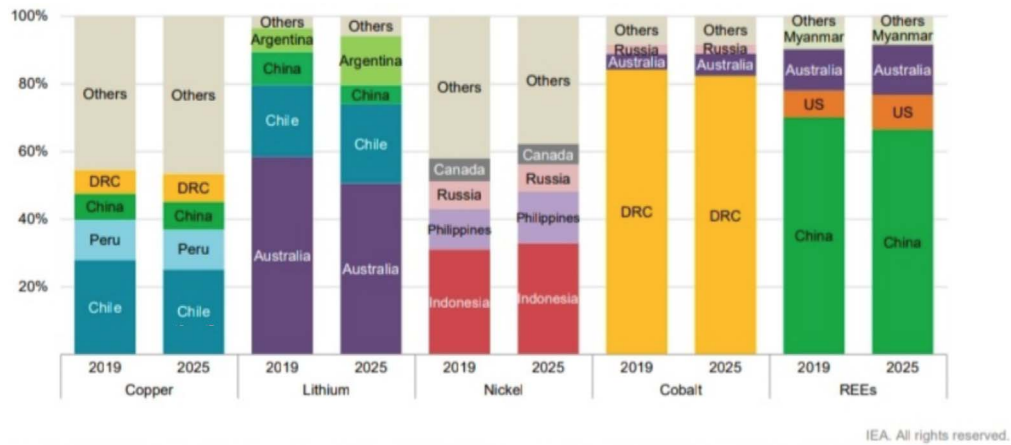


Fig. 35. Primary nations in mineral production from 2019 to 2025. Source: International Energy Agency (IEA) [68].

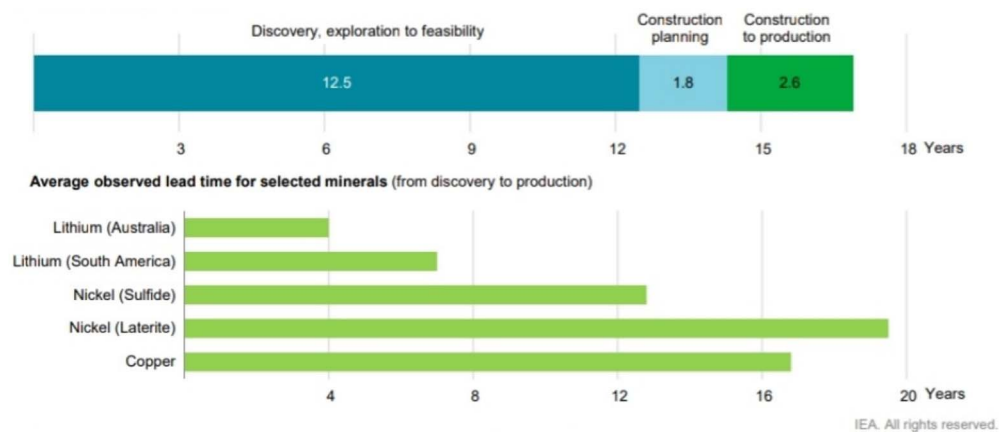


Fig. 36. The mean duration from discovery to production worldwide, spanning from 2010 to 2019. Source: International Energy Agency (IEA) [68].

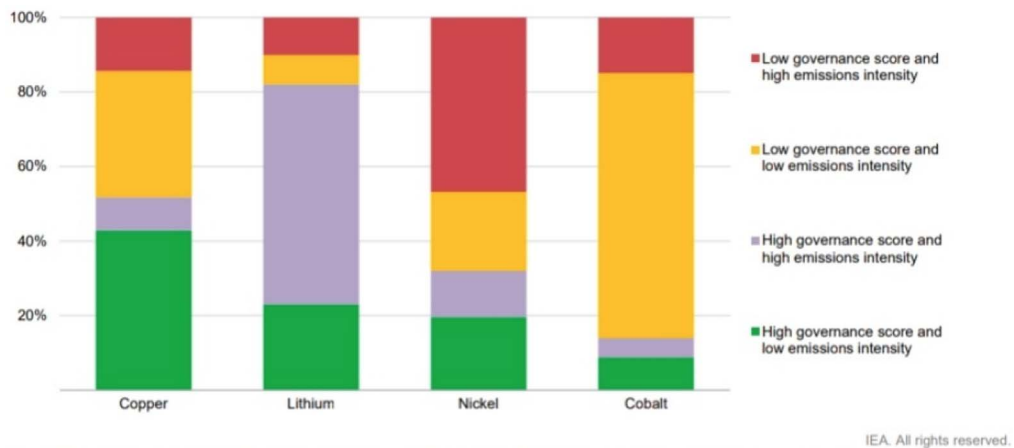


Fig. 37. Distribution of selected minerals in terms of governance and emissions performance in 2019. Source: International Energy Agency (IEA) [68].

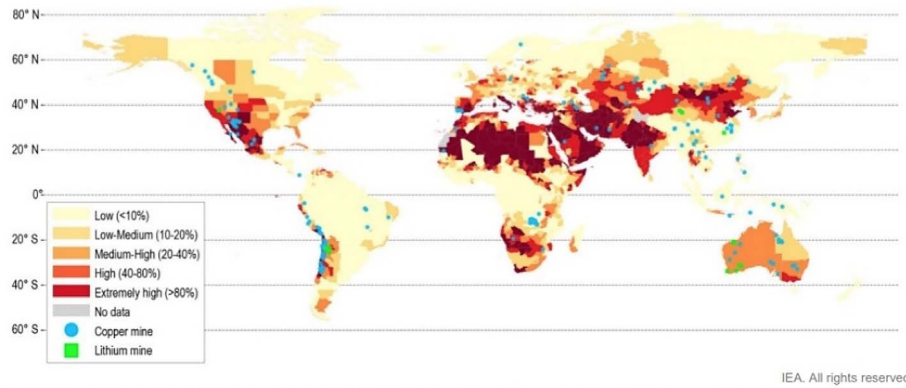


Fig. 38. Mining sites for lithium and copper, along with water stress levels, in the year 2020. Source: International Energy Agency (IEA) [68].

Headwinds encompass events beyond the scope of climate change policy, such as shifting political conditions, discoveries, economic crises, or conflicts that have the potential to impede or even derail the climate transition. The Ukrainian conflict, for instance, has introduced uncertainty, disrupted supply lines, diminished grain production, and critically damaged energy markets, already under strain due to the post-COVID crisis. The European gas market has particularly suffered, and potential future shortages might compel a temporary retraction from European countries' decarbonization goals, particularly concerning access to natural gas as a transitional fuel while renewable energy sources are developed. The reduced availability of natural gas has led to the reopening of coal mines, posing a threat to decarbonization efforts. As a consequence, policies need to address the impacts of climate change, such as vulnerability to heatwaves, droughts, wildfires, and other climate-related losses and damages [26]. This involves mitigating climate change effects by identifying optimal locations for renewable energy power plants [3]. Adaptation to climate change is also imperative [3], while concurrently managing the energy crisis. The development of reliable energy systems, based on diverse and complementary renewable sources, along with mature storage methods, is increasingly crucial.

5 Conclusion and discussion

This study delves into the breakdown of the Kaya equation, analyzing the distinct contributions of various factors in driving emissions. It explores the potential for transitioning to a sustainable energy model through three key pillars: (i) grid decarbonization achieved by incorporating REs or combining fossil fuels with CCS or nuclear power; (ii) enhancing energy efficiency; and (iii) practicing energy sobriety.

While the initial two pillars predominantly entail technological aspects, sobriety necessitates essential behavioral changes. Determining the most effective, widely accepted, environmentally beneficial, cost-effective, and technically feasible option among these choices remains a crucial consideration for contemporary societies.

Considering the extensive range of technical, economic, environmental, and social factors involved, making a choice among grid decarbonization, energy efficiency, and energy sobriety seems challenging. Nevertheless, it is imperative to progress within a cohesive framework and communicate the significant and promising issues and challenges that these aspects present for Morocco to a wider audience of professionals.

Advancements in technology have expanded the array of low-carbon electricity generation resources, offering a potential solution to meeting energy demand while addressing the challenges of climate change. This is notably advantageous, as indicated by a recent report from the International Renewable Energy Agency (IRENA) [70], which reveals an 82% decrease in the global cost of utility-scale solar PV between 2010 and 2021. The cost of various renewable energy sources has seen a general decline, with CSP costs decreasing by 4% and onshore wind costs dropping by 35%.

Morocco's Nationally Determined Contribution (NDC) [71] outlines a target of achieving 52% renewable installed capacity in the power sector by 2030. In contrast, Morocco's National Climate Plan [72] explicitly outlines plans to construct new coal plants, enhance Liquefied Petroleum Gas (LPG) imports for industrial use, and increase natural gas utilization in the industrial sector by 2030. However, in alignment with 1.5 °C-compatible pathways, Morocco is compelled to reduce its reliance on fossil fuels from 81% in 2019 to a range of 2–9% by 2030. This necessitates a complete phase-out of coal from the national power mix by 2030, and natural gas must be phased out between 2028 and 2034. Consequently, achieving complete decarbonization of the power sector is projected between 2035 and 2038 [73]. The country faces the risk of being burdened with stranded, carbon-intensive assets requiring substantial upfront investments [6, 26].

Carbon capture mitigates the release of carbon into the atmosphere, making it a recognized solution to combat climate change and global warming. However, despite its benefits, CCS is not without certain drawbacks.

Beyond the advancement of renewable energy, Morocco's policy initiatives encompass energy efficiency measures in challenging-to-abate sectors, such as building insulation and the adoption of energy-saving light bulbs. The overarching objective is to achieve a 20% reduction in overall energy

consumption by 2030. Additionally, Morocco has taken modest steps to encourage the adoption of electric vehicles [74], exemplified by the installation of the initial charging stations along the highway connecting Tangier and Agadir. Several automotive manufacturers have also introduced and marketed their inaugural modern electric models [75].

Agrivoltaic systems and water desalination initiatives offer various benefits, including the capacity to enhance the resilience of agricultural land to climate change. This is particularly relevant for farms situated in dryland ecosystems where challenges such as escalating temperatures and water scarcity are already prevalent issues [76].

Energy sobriety, which involves diminishing energy consumption by altering consumption styles, usage patterns, and behaviors, stands as a pivotal factor in maintaining competitiveness [24]. Sobriety manifests in various forms: The restraint of use involves reducing the duration, frequency, or extent of employing energy-consuming devices; substitution sobriety entails replacing appliances with less energy-intensive alternatives; dimension sobriety involves adjusting the size and utilization of appliances according to needs; and collaborative sobriety revolves around shared equipment use to conserve energy.

Peak power shaving is a strategy employed by consumers to diminish energy load, resulting in cost savings on utility bills by transitioning activities from peak to off-peak hours. This may involve operating industrial machines or washing machines during nighttime rather than peak hours. Additionally, avoiding peak rates can be achieved by temporarily reducing power consumption through “load shedding” during peak times. In some cases, businesses authorize the network manager to disconnect their power temporarily during peak demand, when supplies are both scarce and expensive, in exchange for financial compensation ([77, 78], 3, Chapter 1, Sects. I and 2).

Enhancing a building's energy performance typically involves a combination of energy sobriety and energy efficiency. While energy sobriety promotes sensible energy consumption practices, energy efficiency focuses on utilizing objects with low consumption or exceptionally high energy performance [66]. For instance, in the context of heating, a prudent energy sobriety approach involves avoiding overheating rooms and opting for wearing a sweater in winter. Simultaneously, an energy efficiency approach seeks to optimize energy consumption by choosing a heating method with high energy performance, such as installing a gas condensing boiler or a heat pump.

In conclusion, we analyze the challenges and prospects linked to the net-zero challenge and the achievement of a successful energy transition. This encompasses critical considerations such as essential materials, the policy landscape, costs and opportunities, and supporting the energy transition in developing countries, among other factors.

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