Physics – Uspekhi **65** (11) 1119 – 1128 (2022)

CONFERENCES AND SYMPOSIA

PACS numbers: **88.40.–j**, **88.50.–k**, 92.60.Ry

FORUM 'USPEKHI-2021': CLIMATE CHANGE AND GLOBAL ENERGY ISSUES
(Joint Scientific session of the Physical Sciences Division, Chemistry and Materials Sciences Division,
Division of Earth Sciences and Division of Energetics, Machinery, Mechanical Engineering
and Control Processes of the Russian Academy of Sciences, January 19, 2021)

Integration of climate variability and climate change in renewable energy planning

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DOI: https://doi.org/10.3367/UFNe.2021.07.039080

Contents

Abstract. **The trajectory outlined in the Paris Agreement to keep global warming below 2 °C dictates not only the timing but also the speed at which the transformation of our energy system must take place to decarbonize energy production. Complying with the Paris Agreement requires reducing the carbon content of energy by about 75% and therefore making a rapid transition from fossil production to production based on low-carbon technologies. Among these technologies are those based on renewable energies. The variability of the climate itself induces a fluctuating or even an intermittent production of variable renewable energy (solar, wind, marine), challenging the balance of the electricity grid. In this context, to speak of energy transition is to face the problem of increasing the penetration of low-carbon energy production while limiting the variability so as to ensure the socio-technical feasibility and economic viability. The problem is not simple, and the delicate balance between urgency (drastically reducing emissions) and utopia (choosing a strategy for low carbon energies and analyzing opportunities and obstacles) needs to be clearly defined.**

Keywords: climate change, climate change mitigation, energy transition, renewable energies, renewable energy integration

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Received 30 May 2021
Uspekhi Fizicheskikh Nauk **192** (11) 1191 – 1202 (2022)
This paper is published as submitted by the authors

1. Climate change and mitigation

The climate is warming up. Figure 1a (from [1]) shows the time evolution of the temperature anomaly since the pre-industrial level from 3 sets of observations (black, purple and green lines). Regardless of warming trend due to human activities, the climate shows strong natural variability at multiple scales, including intra-seasonal and inter-annual scales. Indeed, the climate system is an extremely complex system whose elements (atmosphere, hydrosphere, cryosphere, geosphere, biosphere including human societies) interact. It evolves over time under the effect of its own internal dynamic elements and due to external forces such as orbital variations, solar evolution and cycles, major volcanic eruptions. The natural fluctuations are partly organized, in time and space. They are called 'modes of variability', among those, the El Nino Southern Oscillation (ENSO) (e.g. [2] for a review), the North Atlantic Oscillation (NAO) (e.g. [3] for a review). Figure 1d attributes observed temporary temperature bumps (black line) to four major El Niño events and two major volcanic eruptions. On top of the natural variability a significant trend showing evidence of a global warming has accelerated since the 1980's. It is caused by anthropogenic forcings such as altering the composition of the atmosphere (e.g., greenhouse gas, aerosols) and land use changes. In 2020, the climate has warmed by about 1.25 °C compared to the pre-industrial levels due to the anthropogenic greenhouse gas emissions.

Indeed, since the pre-industrial period, the carbon dioxide (CO_2) concentration have increased from about 300 to about 415 parts per million (ppm). Before the industrial era, the CO_2 concentration oscillated between 180 and 300 parts per million, following the Milankovitch cycle of about 100,000 years. If we examine the problem on geological time

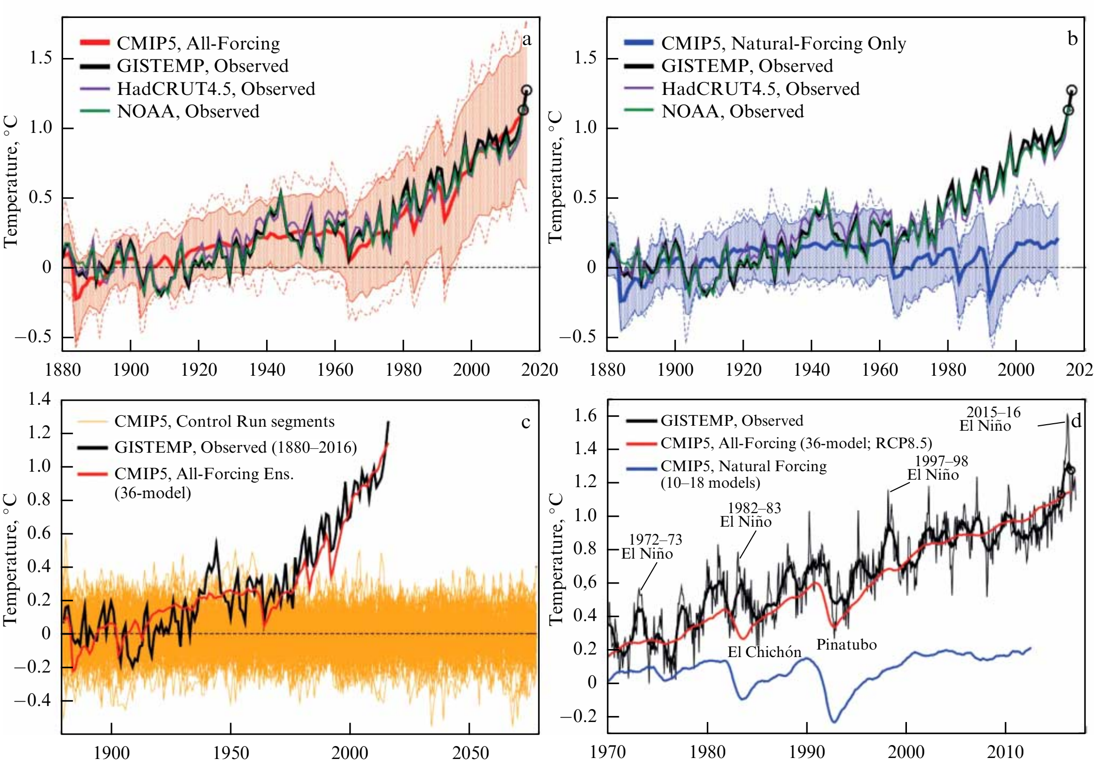

Figure 1. Observed global-mean temperature anomalies vs. Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (°C; 1881–1920 reference period). (a) CMIP5 All-Forcing (anthropogenic plus natural forcing) grand ensemble mean of individual ensemble means from 36 models (thick red curve); ±2 std. dev. (red shading) and minimum-maximum spread (dashed red) of annual means across individual simulations; and observed GISTEMP (black), HadCRUT4.5 (purple) and NOAA (green) anomalies. (b) As in (a) but for natural forcings (18 models; blue curves and shading). (c) Observed (GISTEMP; black) and All-Forcing grand ensemble mean (red) anomalies compared to 200-year segments from 36 CMIP5 control runs (orange). (d) 12-month running mean anomalies for GISTEMP observations (thick black; monthly anomalies are thin black) and CMIP5 All-Forcing (red) and Natural Forcing (blue) grand ensemble means. GISTEMP observed annual means (Jan-Dec) for 2015 and 2016 are highlighted by circles in panels (a), (b), and (d). See also online supplement materials. Source: [1].

scales, our age is characterized by an extraction of oil, the emblematic fuel of industrial countries, about to peak globally (depending on its type, conventional or nonconventional), while at the same time the climate system is subject to a increase of the atmospheric greenhouse gas concentration, inducing a radiative forcing of the order of 2 W m^{-2} relative to pre-industrial levels [4, 5].

In addition to observations and theory, control simulations and historical simulations from Earth System Models (ESMs) are essential in attributing ongoing changes to human activities. Figure 1 compares the observed global mean temperature anomalies of three observational datasets to historical simulations of the CMIP5 models using on the one hand the combined anthropogenic and natural forcings (Fig. 1a), or natural forcings only (volcanic eruptions, variation in solar radiation) (Fig. 1b) [1]. All time series are referred to a benchmark of 1901–1960. Observations after around 1980 are found to be inconsistent with simulations using only natural forcings (indicating detectable warming) and also consistent with simulations using combined anthropogenic and natural forcings, implying that warming is mostly attributable to anthropogenic forcing in agreement with previous studies and assessments [6–10].

Other observable manifestation of the human origin of global warming by the increase in greenhouse gas concentrations is the global sea level rise as well as the sea ice extent. The cooling of the stratosphere, the layer of the atmosphere that typically extends between 10 and 50 km altitude, above the effective radiation level (about 6 km altitude) is also of human origin, partly due to the increase of greenhouse gas in the troposphere, the layer between the Earth surface and the stratosphere, and partly amplified due to the stratospheric ozone depletion between 1979 and the mid-1990's (Table 1) [8]. The key to understanding the cooling of the stratosphere is that most of the greenhouse gas is concentrated at low altitude, in the troposphere, where the greenhouse gas block more of the heat implying less heat goes to higher altitudes. There is a level in the atmosphere called the effective radiation level at the effective radiation temperature (around 252 K) located in the middle troposphere at about 6 km altitude. Since an increase in greenhouse gases results in an increase in the temperature gradient, temperatures will therefore 'pivot' around this fixed point: the atmosphere below this point will heat up, and the atmosphere above will cool down. Such temperature trend is however altered because of the opposing effects of stratospheric ozone recovery and increases in other greenhouse gases [18].

While it is certain that global warming will continue if net greenhouse-gas emissions are not stopped, the future climate is not strictly foreseeable since the trajectory will largely depend on the peoples and actions that the nations of the planet will take to reduce greenhouse gas emissions. Scenarios have been produced using demographic and socio-economic assumptions converted into greenhouse gas emissions, as a representation of possible futures for a prospective purpose [19]. It is customary not to consider one, but several scenarios.

Table 1. Estimates of trends and 90% confidence intervals of global temperature, measured by satellite radiosondes and microwave sounders, in the lower troposphere (LT) (0–5 km), the mid troposphere (MT) (5–10 km) and the lower stratosphere (LS) (10–50 km). Source: IPCC (2013) [8].

Data set	Trends in °C per decade (1979–2012)		
	LT	MT	LS
HadAT2 [11]	0.162 ± 0.047	0.079 ± 0.057	−0.436 ± 0.204
RAOBCORE 1.5 [12]	0.139 ± 0.049	0.079 ± 0.054	−0.266 ± 0.227
RICH-obs [12]	0.158 ± 0.046	0.081 ± 0.052	−0.331 ± 0.241
RICH-tau [12]	0.160 ± 0.046	0.083 ± 0.052	−0.345 ± 0.238
RATAPAC [13]	0.128 ± 0.044	0.039 ± 0.057	−0.468 ± 0.225
UAH [14]	0.138 ± 0.043	0.043 ± 0.042	−0.372 ± 0.201
RSS [15, 16]	0.131 ± 0.045	0.079 ± 0.043	−0.268 ± 0.177
STAR [17]		0.123 ± 0.047	−0.320 ± 0.175

Scenario development for the 2001 and 2007 IPCC reports was sequential. These socio-economic scenarios, organized into 4 families (A1, A2, B1 and B2), were translated in terms of greenhouse gas and aerosol emissions, then used as input data for models simulating the climate future [20]. The A1 storyline describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. The B1 storyline describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. The climate scenarios emerging from these simulations were in turn used in impact models (e.g. on ecosystems or hydrology), then finally used in socio-economic studies on the impacts and adaptation to climate change.

The preparation of the 5th IPCC report in 2013 was based on a parallel approach [21]. Four trajectories of emissions and concentrations of greenhouse gases, ozone and aerosols, as well as land use called RCP (Representative Concentration Pathways) [19]. The four RCP scenarios for the evolution of greenhouse gas concentrations have been translated in terms of radiative forcing, i.e. modification of the planet's radiative balance. The radiative balance represents the difference between the solar radiation received and the infrared radiation re-emitted by the planet. The RCP scenarios each correspond to a different evolution of this forcing on the horizon 2300. The higher the value of the radiative forcing, the more the earth-atmosphere system accumulates energy and heats up. Figure 2 from [22] shows the greenhouse gas emissions from fossil fuels and cement for the 4 RCP scenarios (thick lines). The 4 scenarios go from 2.6 W m^{-2} to 8.5 W m^{-2} of radiative forcing. Figure 2 shows that depending on the scenario, the warming could be 1 °C to more than 5 °C on average compared to pre-industrial. Of these reference scenarios, the climate projections were carried out using the RCP as input, while in parallel the emission scenarios (thin lines in Fig. 2) developed on socio-economic assumptions are compared with the RCP scenarios.

To characterize the evolution of the temperature of the atmosphere in response to a given radiative forcing, two indicators are used traditionally, climate sensitivity at equilibrium (ECS), which is defined as the global mean surface air temperature increase that follows a doubling of atmospheric CO_2 concentrations, and the transient climate response (TCR), which is defined to account for this transient response of the climate system.[1] To assess the climate sensitivity and its uncertainty, instrumental recordings, climate simulations and paleoclimatic recordings are used [8, 23]. The measurements give estimates for the transient response (TCR) of about 1.3 °C and the equilibrium response (ECS) of 1.5 to 2.0 °C, which is in the lower range of projections from CMIP5 climate models which have predicted an ECS between 2.1 to 4.7 °C and a TCR between 1.1 and 2.6 °C [8]. Figure 3 summarizes the variability of estimates of climate sensitivity across data sources [8].

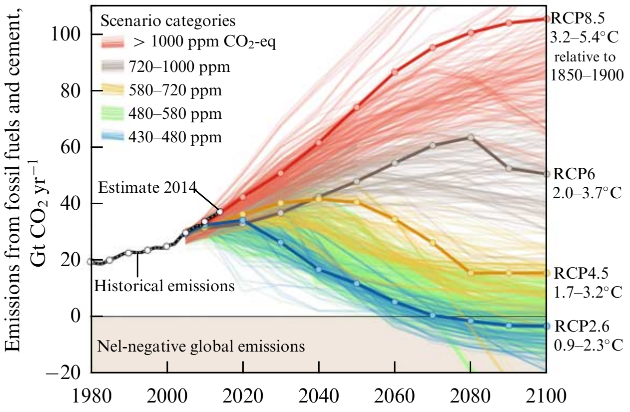

Figure 2. Emissions from fossil fuels and cement (Gt CO_2 yr^{-1}) in the Representative Concentration Pathways (RCPs) (lines). Over 1000 IPPC scenario categories from the IPCC 5th Assessment Report are shown, which summarize the wide range of emission scenarios published in the scientific literature and are defined on the basis of CO_2-eq concentration levels (in ppm) in 2100.The estimate at 2014 is displayed by a red dot, showing that we are currently on the red RCP8.5 pathway. Source: [22].

Cloud feedback impact on the climate sensitivity is by far the most uncertain, both in its understanding, its measurement and its modeling. There are nevertheless other sources of uncertainty. First there are the fast feedbacks with the water vapor feedback on the one hand. Indeed, the water vapor content changes with warming. This is because warmer air can contain more moisture, as predicted by the Clausius–

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[1] TCR is the global surface temperature change averaged over a 20-year period centered at the doubling point of atmospheric carbon dioxide concentration; TCR characterizes the rate of surface temperature response to greenhouse gases. (*Translator's note.*)

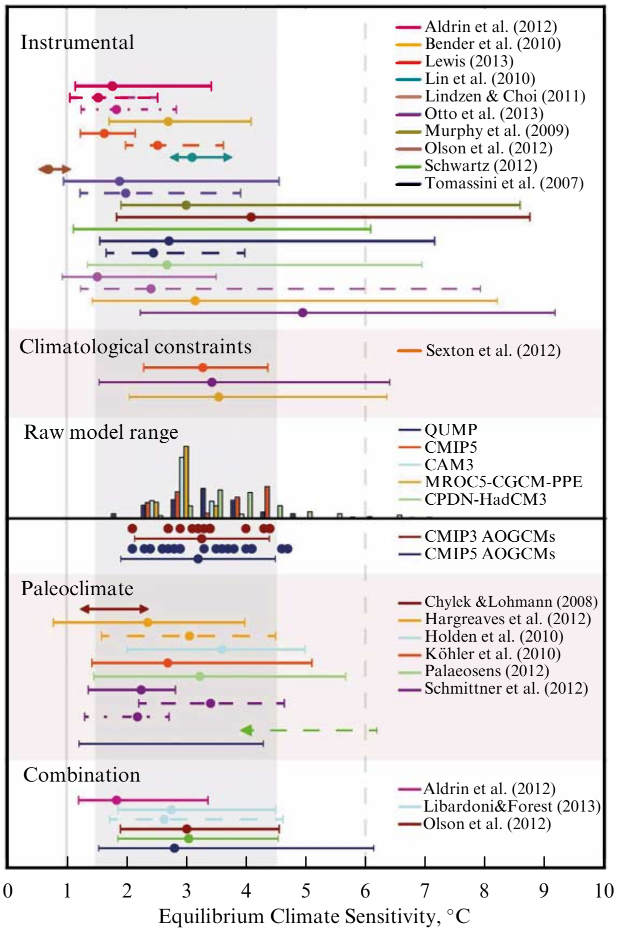

Figure 3. Probability density functions, distributions and ranges for equilibrium climate sensitivity. The grey shaded range marks the likely 1.5 °C to 4.5 °C range, and the grey solid line the extremely unlikely less than 1 °C, the grey dashed line the very unlikely greater than 6 °C. Source: IPCC (2013) [8].

Clapeyron law [24]. This evolution takes place with a fixed relative humidity, therefore an increasing absolute humidity. The second rapid feedback comes from the thermal gradient which increases in the polar regions and decreases in the tropics. Finally, there are slow feedbacks like changing the albedo. Ice caps and snow-covered surfaces have high albedo, if they retract due to global warming, darker surfaces are exposed to solar radiation therefore amplifying the warming. Finally, global warming tends to melt the frozen soils of the permafrost in which 1700 Pg of carbon is sequestered, nearly double the current atmospheric carbon reservoir [25]. The uncertainty also stems from poorly understood aerosol-induced cooling [26]. Compared to CMIP5, a large subset of models participating in CMIP6 predict values exceeding 5 °C. The difference is attributed to the radiative effects of clouds, which are better captured in these models, but the underlying physical mechanism and thus how realistic such high climate sensitivities are remain unclear [27].

A necessary condition for the climate sensitivity to be used to calculate the response of the climate system to another value of CO_2 change is that the change in global average surface temperature be proportional to the change in CO_2 (linear relationship). This is shown in Fig. 4a which represents the global average temperature change from the pre-industrial era as a function of the cumulative concentration of CO_2 since the pre-industrial era [8]. There is a quasi-linear relationship between the 2 variables framed by an envelope reflecting the uncertainty of this relationship between the CMIP5 models. This result is nonetheless deceptively simple because strongly nonlinear mechanisms are at play. However, it reflects that global warming depends almost linearly on the amount of carbon emitted, rather than on the details of the particular emission scenario. This is because the most important factor in global warming is the total amount of carbon emitted since the pre-industrial era, not the detail of the rate of carbon emitted each year. For instance, despite the significant reduction of CO_2 emissions in 2020 due to the COVID-19 pandemic (−6.4% globally from 2019) [28, 29], only a small effect of COVID-19 pandemic is expected on global emissions in 2030 and negligible beyond [30].

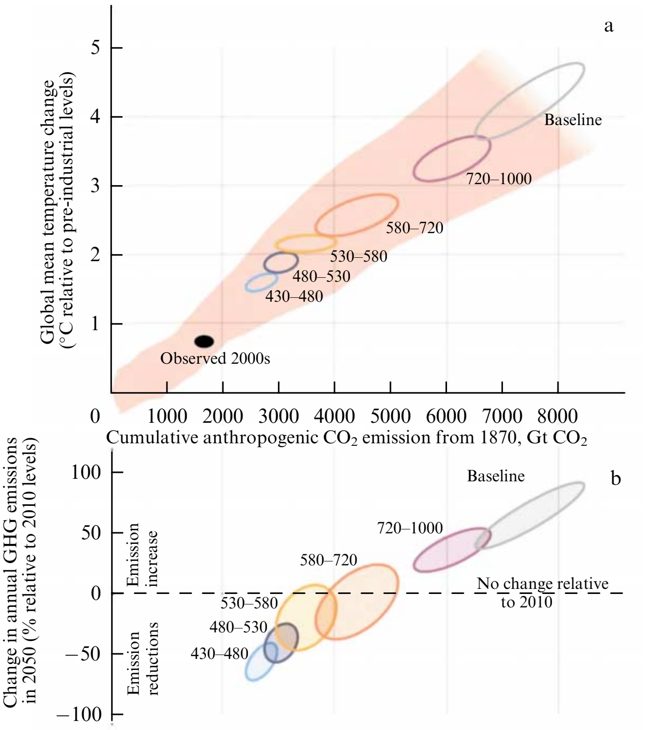

Figure 4. (a) Increase in the average global surface temperature at the time when global CO_2 emissions reach a given net cumulative, plotted against this cumulative, obtained from several data sources. The colored area represents the dispersion of past and future projections obtained using different climate and carbon cycle models taking into account the historical series of emissions and the four RCPs for the entire period up to 2100; it fades as the number of available models decreases. The ellipses represent the ratio between the total anthropogenic warming in 2100 and the cumulative CO_2 emissions from 1870 to 2100, obtained using a simple climate model (median climate response) according to the categories of scenarios used by the WG3. Regarding temperature, the minor axis of the ellipses corresponds to the impact of different scenarios for climatic factors other than CO_2. The solid black ellipse represents the emissions observed up to 2005 and the temperatures observed during the decade 2000–2009 with the corresponding uncertainties. (b) Relationship between the cumulative CO_2 emissions of the scenario categories and their associated variation in annual GHG emissions by 2050 compared to 2010. Source: IPCC (2013) [8].

Figure 4b shows the emission reduction between 2050 and 2010 needed to ensure compatibility with the emission scenarios [8]. Let us consider the limit of 2 °C of 'acceptable' global warming set in Copenhagen during the COP15 in 2009 and was at the center of the negotiations at COP21 in 2015, which led to the Paris agreement. This threshold was partly motivated in reference to a period in the past, when this average temperature was reached with existing but limited climatic consequences. However, as the evolution of the climate is not linear, there is no certainty that beyond a global warming of 2 °C climatic runaway will not occur, in response to phenomena still poorly appreciated such as increased CO_2 and methane emissions into the atmosphere caused by melting permafrost or the collapse of the Antarctic ice caps. Caution therefore encourages compliance with this limit of 2 °C, which is not absolute but which, if exceeded, would increase the risk of a bifurcation with potentially dramatic consequences. Moreover, the IPCC's special report on a global warming of 1.5 °C concludes with high confidence that "climate-related risks for natural and human systems are higher for global warming of 1.5 °C than at present, but lower than at 2 °C" [31]. The motivations to limit global warming to 1.5 °C rather than 2 °C are thus strong, especially for more vulnerable populations such as those island populations. Taking into account the uncertainty on the cumulative CO_2 emissions for each scenario, it appears that the emission scenarios making it possible to limit global warming to less than 2 °C this century are characterized by a reduction in global greenhouse gas emissions by 40 to 70% in 2050 compared to 2010. These emission levels are expected to be close to or below zero in 2100.

Article 2 of the Paris Agreement [32] expresses the commitment of parties to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. In order to achieve the long-term temperature goal set out in Article 2, the Parties strive in Article 4 to achieve a global peak in greenhouse gas emissions as quickly as possible, and this in order to achieve a balance between sources and sinks of anthropogenic emissions during the second half of this century.

To keep global warming below 2 °C, it is necessary to reduce by approximately 50% the CO_2 emissions between 2050 and 2010 (Fig. 4b), in parallel to a reduction of emissions from other greenhouse gases such as methane and nitrous oxides. To analyze the evolution of global CO2 emissions as part of climate change mitigation policies, Kaya's equation relates anthropogenic carbon dioxide emissions (CO_2) associated with energy use to demographic, economic and energy parameters [33]. The total level of emissions can be expressed as the product of four factors: population (POP), gross domestic product per capita (GDP/POP with GDP the gross domestic product), energy intensity of the economy (E/GDP where E is the primary energy consumption) and carbon content of energy (CO_2/E). This equation is used to analyze or simulate the evolution of global CO_2 emissions in the context of technologic, market and demographic policies to fight against global warming. Note that, while stressing the role of the carbon-content of energy and energy efficiency, the possibility to reduce emissions by switching to a more sober lifestyle leading to a reduction of consumption is hidden in the GDP-per-capita term. The following formulation of the Kaya equation is thus one tool focusing on the market economy, while other measures of welfare could be used in addition.

$$\underbrace{\mathrm{CO_2}}_{\mathrm{CO_2\ emissions}} = \underbrace{\frac{\mathrm{CO_2}}{E}}_{\substack{\text{Carbon content}\\ \text{of energy}}} \times \underbrace{\frac{E}{\mathrm{GDP}}}_{\substack{\text{Energy intensity}\\ \text{of the economy}}} \times \underbrace{\frac{\mathrm{GDP}}{\mathrm{POP}}}_{\substack{\text{Gross domestic}\\ \text{product per capita}}} \times \underbrace{\mathrm{POP}}_{\text{Population}}. \quad (1)$$

To reduce by approximately 50% the global CO_2 emissions from energy use between 2050 and 2010 and considering a world demographic change of +35% [34], an average annual world GDP growth of 3% [35] and a decrease of the energy intensity of the world economy by about 10% per decade [36], the carbon content of the energy should decrease by 75% in 40 years. Keeping in mind that it depends on the success of energy-intensity reduction measures and on the decarbonation of nonenergy uses such as from land use, such a figure reflects the magnitude of the challenge that needs to be addressed in terms of energy transition. It is a radical transformation towards carbon-free energy production. It also means sharing the burden of this reduction on other terms in the Kaya equation. Taking Western Europe as an example, three different economy sectors are involved in CO_2 emissions: electric power production, transportation and heating of buildings. Most of what follows is related to electric power production, which is probably the line of business with the highest expectations, and where large-scale transformations are already under way. Transportation is, however, a challenging sector, since few technological solutions exist to reduce greenhouse-gas emissions.

2. Transition pathways to low-carbon energy technologies for electricity

As discussed in the previous section, policies to reduce emissions associated with electricity production can be divided in three categories: carbon-intensity reduction, increase in energy efficiency, and reduction of consumption. In the following sections, we choose to focus on the first, because this is where there is much to learn from meteorology and climate sciences. This choice thus reflects a disciplinary bias rather than a political choice.

To understand the issues, it is important to bear in mind the carbon footprint of energy production systems. Table 2 shows the carbon footprint of energy supply systems from the 5th assessment report [37]. It has lower values for fossil fuel-based technologies than in the IPCC special report on renewable energies and climate mitigation [36] because more recent technologies are analyzed (e.g., pulverised coal). The values are expressed in gCO_2eq per kWh (CO_2 equivalent is a measure combining emissions from different greenhouse gas over a reference time of 100 years, depending on the differing lifetimes that these gas remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation). Low-carbon technologies have a much lower carbon footprint than fossil energy technologies. For example, in median value, photovoltaic technologies are nearly 10 times less emitting than gas. Among the so-called low-carbon technologies, it is usual to distinguish nuclear energy from renewable energies since the fuel used for nuclear power is not renewable.

Despite the urgency of the shift from fossil fuel driven economy toward a carbon-neutral economy, it is obvious that the post-fossil technologies are not fully operational at global scale and for today's energy use. Nuclear fusion is not available and it is uncertain it will ever be. Conventional nuclear fission, including Generation IV with optimized fuel cycles, displays barriers and challenges [38] but is probably part of the solution, though may not be the solution that it would be chosen by the peoples as one of the challenges of fission nuclear path is its radioactive spent nuclear waste that can accumulate for more than the civilizational epoch [39].

Table 2. Life cycle CO_2 equivalent from selected electricity supply technologies. Arranged by decreasing median (gCO_2eq per kWh) values. The values cover the full life of the source, from material and fuel mining through construction to operation and waste management. Advances in efficiency, and therefore reductions in CO_2e since the time of publication, have not been included. CCS stands for carbon capture and sequestration. Source : IPCC (2014) [37].

Technology	Min.	Median	Max.
Currently commercially available technologies			
Coal — pulverised coal	740	820	910
Biomass — cofiring with coal	620	740	890
Gas — combined cycle	410	490	650
Biomass — dedicated	130	230	420
Solar PV — utility scale	18	48	180
Solar PV — roof top	26	41	60
Geothermal	6.0	38	79
Concentration solar power	8.8	27	63
Hydropower	1.0	24	2200
Wind offshore	8.0	12	35
Nuclear	3.7	12	110
Wind onshore	7.0	11	56
Pre-commercial technologies			
CCS — coal — pulverised coal	190	220	250
CCS — coal — integrated gasification combined cycle	170	200	230
CCS — gas — combined cycle	94	170	340
CCS — coal — oxyfuel	100	160	200
Ocean (tidal and wave)	5.6	17	28

Dams all over the world produce a large amount of electricity, but a large part of the resource is already exploited [40], and their impact on the biosphere is far from negligible [41]. Biomass is heavily limited by the regeneration rate of forests, thus can hardly be considered carbon neutral [42]. Hydrogen is but an energy vector, whose impact depends on the primary energy source. Finally, it must be said that wind and solar energy have seen an impressive development in the last two decades, with both exponential reductions in cost, and a strong growth rate of implementation and final electricity production [43]. Yet, their business model is still dependent on favorable tax policies or complicated subventions. They also come with limitations that will benefit from research to be overcome. One of these limitations is the variability and intermittency [44]. Indeed, when addressing energy production, a major issue is the fluctuating nature of the capacity factor which measures how often an energy production plant is running at rated power. In the US, nuclear has the highest capacity factor of any other energy source producing power more than 92% of the time in 2016. It is twice as large as a coal (48%) or natural gas (57%) plant and almost 3 times more often than wind (35%) and solar (25%) plants [45]. While the capacity factors of conventional technologies depend on energy markets and on operation and maintenance constraints, the capacity factors of wind and solar technologies is mostly the result of varying meteorological conditions. The latter results both in a mean capacity factor being much smaller than 100% but also in the variance of the capacity factor being large. The variability and intermittency of renewable energy sources are a serious issue for their massive deployment and integration in the grid [46].

Energy storage systems aim at providing a buffer against short-term fluctuations in output from renewable energy sources. For instance, compared to solar photovoltaic production, concentration solar plants include heat storage that doubles the capacity factor [45]. Buffered renewable energies using storage systems is therefore one pathway to be investigated from a technological but also an economic perspective [47]. However, the problem of electricity storage cannot be tackled solely by batteries (putting aside the question of the sheer number of batteries needed), one reason being that electricity needs to be stored on very disparate time scales, from an hour to a year (another reason being the concerns associated with the possibility to recycle batteries). Also, solar and wind energy require, per kWh of produced electricity and compared to classical (fossil and nuclear) ways of producing energy, much more steel, concrete (wind only), rare metals such as copper, or silver (solar only), not mentioning rare earths for the wind turbines [48]. Finally, the space required per kWh is also several orders of magnitude larger compared to classical electricity production methods [49], which is preoccupying when one knows that land use change is one of the main causes of biodiversity loss [50].

The impact of climate change on renewable energy sources and low-carbon energy supply itself is also at stake [51]. Hydropower and thermoelectric power together contribute 98% of the world's electricity generation at present [52]. These power-generating technologies both strongly depend on water availability, and water temperature for cooling also plays a critical role for thermoelectric power generation. Climate change and resulting changes in water resources will therefore affect power generation while energy demands continue to increase with economic development and a growing world population. Worldwide, reductions in usable capacity for 61–74% of the hydropower plants and 81–86% of the thermoelectric power plants are projected for 2040–2069 [53]. The energy demand for heating and cooling buildings is also changing with global warming. Over all continental areas the energy demand trends for heating and cooling were weak (of less than 10%) from 1941–1960 to 1981–2000, and get stronger (of more than 10%) from 1981–2000 to 2021–2040. The increasing trends in cooling energy demand are more pronounced than the decreasing trends in heating [54]. However, quantification of global warming impacts on future energy demand is still highly uncertain whereas it is a key for accurate energy planning. Regarding wind and solar energy sources, the impact should be marginal if global warming does not exceed 2 °C (losses $< 5\%$), but a rapid deterioration beyond 2 °C could be significant in some regions [55].

3. Climate variability and renewable energy source integration

3.1 Variable renewable energy integration phases and challenges

Several countries are establishing renewable-energy targets for their electricity supply, for reasons including the limitation of their carbon footprint. Because solar and wind tend to be more variable and uncertain than conventional sources, meeting these targets involves changes in power-system planning and operation. Grid integration is the practice of developing efficient ways to deliver variable renewable energy to the grid. Robust integration methods maximize the cost-effectiveness of incorporating renewable energies into the power system while maintaining or increasing system stability and reliability. Grid integration spans a variety of issues, including [56–58]:

- new renewable energy generation;
- new transmission;
- increased system flexibility;
- planning for a high renewable energy future.

Increasing the share of variable energy production in the network is not straightforward. The adaptation of the network to renewable energy integration can, roughly, be divided into 6 phases with respect to the share of the variable energy production in the network [59]. In phase 1, the low penetration of renewable is not an issue for the network. In phase 2, conventional control systems such as thermal power plants and hydropower are sufficient to integrate variable energies without having to transform the network. From phase 3, investments must be made to transform the network to make it smarter and more flexible to manage the supply-demand balance with a much more variable net energy demand. Flexibility means strengthening storage facilities, or erasing or reducing consumption. It is also through the massive collection of energy consumption and production data and their real time processing in a more sophisticated energy-management system. Two other phases (phases 5 and 6) are necessary steps towards a 100%-renewable energy mix. Phase 5 implies that structural surpluses emerge and that electrification of other sectors become relevant. Phase 6 assumes bridging seasonal deficit periods and supplying nonelectricity applications and the emergence of synthetic fuels. Flexibility resources can mitigate the challenges from renewable-energy integration in different phases and allowing the system to integrate more renewable energies.

Major challenges from the integration of high shares of PV and wind energy in power systems come from the variable, uncertain and location-specific nature of the renewable-energy production and the need for a constant balancing of the demand-supply. This results in 'integration costs' or in additional system costs that are not reflected by the marginal costs of renewable energies [60]. For systems historically dimensioned to face the variability of the demand only, variability in the renewable energy production may lead to local power shortages due to the low capacity credit of renewable energies or to increased transmission congestion and over-produced generation leading to curtailment. Today, short-term balancing issues can be in part mitigated by accurate forecasts of energy demand and supply at various time horizons [61–65] and must be compensated at all times via ancillary services over a broad range of frequencies [66, 67], e.g., by an increased flexibility of the conventional generation systems such as coal plants or combined cycle gas turbines [68, 69]. Compensation for variable energy supply can also be enabled via demand-response mechanisms [70]. On the other hand, this increased variability brings higher price instability along with a reduction of wholesale prices. In the long run falling prices associated with the low marginal costs of renewable energies may 'erode' the returns of both renewable and conventional producers, pushing the latter out of the market. The latter are, however, essential to smooth out the fluctuations of renewable-power output and ensure system stability, unless nonfossil flexibility solutions take over. Therefore, the possibilities for a future large-scale renewable penetration are still controversial [71–73].

3.2 Focus on the issue of the variability of the renewable production

To evaluate the needs for and the viability of solutions, the variability of the renewable energy production is analyzed in a number of studies for different temporal and spatial scales, locations and renewable energy sources [74, 75]. Let us illustrate the role played by the variability of the renewable production by the following mean-variance analysis approach. The notion of 'risk' associated with the variability of indices such as the renewable energy production, generation costs or electricity prices is introduced. The advantage of this type of simplified approach is that it allows for prospective investment sensitivity studies while avoiding having to model the conventional scheduling problem [76]. The down side is that it makes it hard to associate a system cost to the optimized mixes. Nevertheless the approach helps stress the impact of renewable energy variability on optimal mixes. The 2015 actual Italian energy mix (Fig. 5b) compliant with the 2020 European directive and reached 6 years in advance, is revisited. Two objectives must be sought. The first aims at maximizing the average penetration of variable renewable energies (the ratio of the average production over the average demand) as one path to reduce the carbon footprint of energy production. The second objective is to minimize the variability of the penetration in order to prevent imbalances in the network and to minimize the costs incurred by the commissioning of dispatchable energy-production systems such as thermal power plants. In addition, a constraint on the total capacity (or alternatively of total variable renewable energy costs) is added when considering the recommissioning of an existing mix. The result is a set of Pareto-optimal renewable energy mixes whose value can be represented by a two-dimensional mean-variance chart.

An example is given in Fig. 5a for the case of Italy [76]. The points under or to the right of the frontier are by definition sub-optimal. The area above or to the left of the frontier cannot be reached. The frontier shows that there is a trade-off between maximizing the renewable energy penetration and minimizing the variance of the renewable energy production. The more the renewable energy variance is problematic for the energy system, the more weight should be given to the objective of minimizing the variance, thus limiting the variable renewable energy penetration. Depending on the weight put on the variance, the resulting variable renewable energy mixes vary greatly. This is illustrated by two optimal mixes represented in Fig. 5c and 5d. The first represents an optimal mix for which more weight is given to

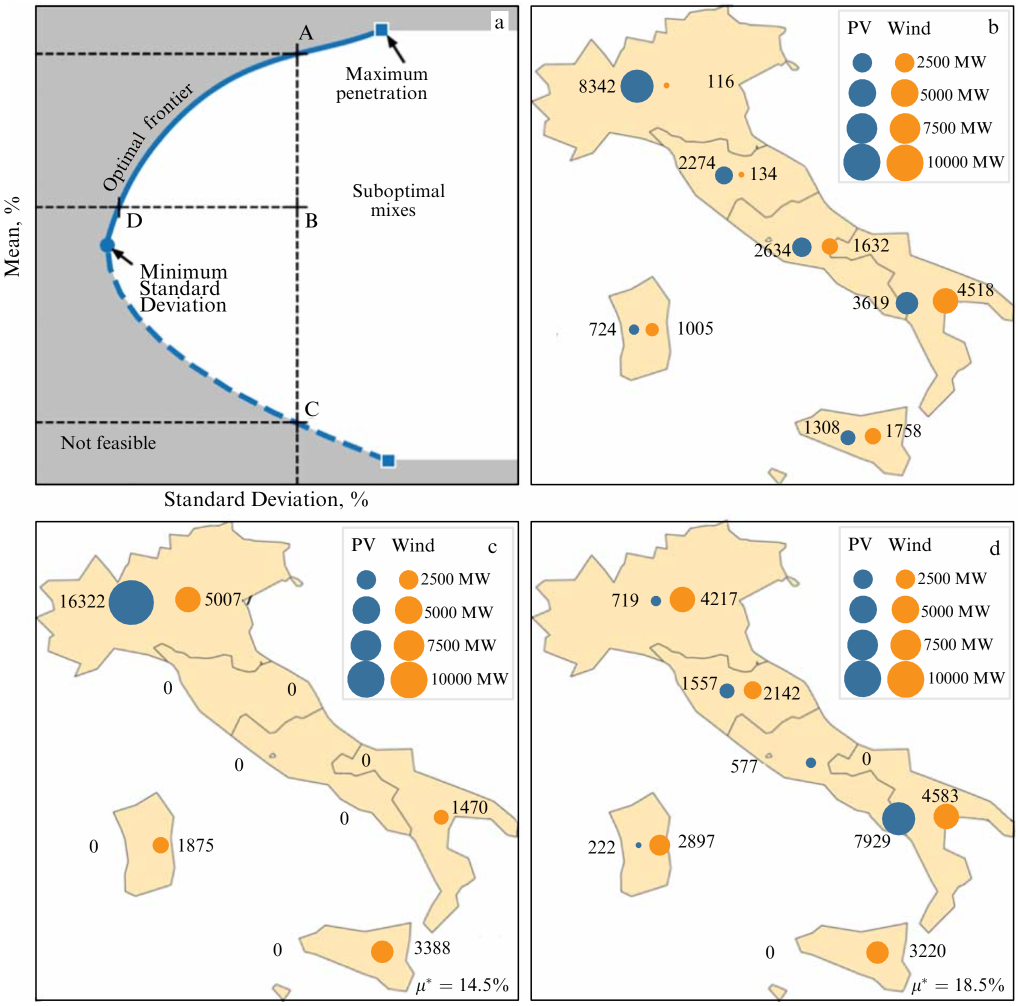

Figure 5. (a) Example of the optimal frontier of a mean-variance optimization problem. It is one-dimensional and represented by a plain blue line. In this example, the optimal frontier is bounded below by a minimum-variance optimal mix (blue dot) below which the variance may only increase. The optimal frontier is bounded above by a maximum-penetration optimal mix above which higher penetration mixes are not feasible due to the constraints of the problem. The point B is an example of suboptimal mix, since a higher mean penetration is achievable for the same variance (point A) and a lower variance is achievable for the same mean penetration (point D). The dashed blue line is obtained by minimizing the variance for a range of target mean penetration values. These solutions are, not Pareto optimal as point C yields the same variance as point A but achieves a lower mean penetration. Thus, A 'dominates' C. (b) 2015 wind (orange) and PV (blue) installed capacities in Italy; (c) minimum standard-deviation scenario from E4Clim; (d) high penetration scenario from E4Clim. (Adapted from [76].)

the variance, which encourages technologies in regions for which the capacity factor varies little. The second maximizes the penetration and puts an emphasis on technologies and regions with high capacity factors on average. While being sub-optimal in the sense of the efficient frontier, the actual Italian energy mix (Fig. 5b) therefore appears to be a compromise between the 2 simulated scenarios. A detailed description of the mean-variance analysis is given in [76] with various applications in [77, 78]. As reviewed by [60], to design optimal mixes while precisely accounting for the costs of energy systems with high shares of variable renewable energies, economic studies instead attempt to minimize costs or to maximize welfare, although it remains a challenge to combine the long-term investment problem with the short-term scheduling problem while taking flexibility, balancing and grid investments into account.

An essential point is that this variability may be partly smoothed out by aggregating the production from different units of a farm and from sites at different locations (spatial diversification), or by exploiting the complementarity between energy sources (technological diversification). Spatial diversification is all the more effective if the different production sites are weakly or negatively correlated. In the midlatitudes, mesoscale weather patterns are associated with a relatively quick decline in wind-speed correlations with distance, but synoptic weather systems and persistent atmospheric regimes are responsible for correlations at synoptic scales of about 1000 km or more [79, 80]. The major part of the variability of the solar resource, on the other hand, is associated with the diurnal and the seasonal cycle and is thus highly correlated in space. However, a fraction of the solar-resource variability is associated with clouds and decorrelates quickly with distance [81]. Spatial diversification is thus only applicable at sufficiently large scales, whenever the renewable energy variability is sufficient. The benefits of spatial diversification for solar energy is also assessed by a number of authors [74, 75, 87, 88], while [89] study the joint smoothing from the distribution of both wind and solar energy in Europe. Technological complementarity may also help reduce the renewable energy-production variability. In

Europe, for instance, wind and solar productions have negatively correlated seasonal cycles [90–95]. Most studies mentioned so far are based on an existing or a uniform distribution of renewable energy capacities. Instead, this renewable energy mix may be optimized in order to leverage weaker correlations between production sites to minimize the variability of the production/production-demand mismatch once aggregated by an interconnection network. To this end, the distribution of renewable energy capacities may be optimized technologically, geographically or both.

Finally, because they avoid modeling the full power-plants dispatch problem, these mean-variance analyses cannot replace modeling the coupled problem of long-term investment in renewable capacities (and divestment in conventional power plants) and short-term dispatch of the dispatchable production (including dispatchable renewables). However, they capture the impact of renewable-energy variability in a conceptually and computationnaly simple way that allows for multi-scenario sensitivity studies focusing on the role of this variability.

4. Conclusions and upcoming challenges

Anthropogenic greenhouse gas emissions are responsible for a change in the climate with impacts on life and populations that we already observe and that will continue to increase if nothing is done to mitigate it by reducing emissions and restoring carbon sinks like forests. Together with sobriety and efficiency measures, reducing the carbon-content of the primary energy that we consume is one way to reduce greenhouse gas emissions. This means replacing most fossil fuels with low-carbon energy sources like wind and solar or nuclear energy. While both nuclear energy and renewable energy sources emit little greenhouse gas compared to fossil fuels, increasing their use raises a number of challenges. Focusing on variable renewable energies like wind and solar energy sources, one major challenge is that of their variability which makes more difficult ensuring the energy system's adequacy and the ability to balance energy demand and production at all times.

In this article, dispatchable renewable energy sources like hydropower, geothermal energy or biomass, for both electrical or thermal energy production are not addressed as they do not raise issues regarding their integration. However, when focusing on reducing greenhouse gas emissions by variable renewable energies integration in a specific region, we risk to miss the big picture. To truly address the viability of such an energy transition on a global scale we indeed need to consider constraints associated with energy, material resources, environmental impacts and society. For instance, the possibility of a massive transition to low-carbon energies such as wind and solar energies, while continuing to increase global energy consumption is questioned by the availability of raw materials [96]. Rivers that are impounded by dams for hydropower suffer physical, chemical, and biological alterations [97–99]. The production of biomass on an industrial scale leads to expansion of agricultural areas or to the change of use of those already existing, leading to the increase of food and feed prices but also causes the degradation of the environment (e.g., consumption of water resources and decrease of biodiversity) [100, 101]. On the other side, embarking on the energy transition path will also help improve social well-being [102] and contribute to job creation, among other positive externalities [103]. Regional integrations and cooperations in the energy market are necessary to mitigate climate change cost-effectively. Cross-border regulations require the convergence of national regulations for interconnections to function effectively.

This work was conducted in the frame of the Energy4Climate Interdisciplinary Center (E4C) of Institut Polytechnique de Paris and Ecole des Ponts ParisTech and is supported by the 3rd Programme d'Investissements d'Avenir [ANR-18-EUR-0006-02].

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