Nuclear Power and Sustainable Development

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NUCLEAR POWER AND SUSTAINABLE DEVELOPMENT

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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FOREWORD

In September 2015, all Member States of the United Nations adopted a development agenda for the next 15 years to end extreme poverty, fight inequalities and injustices, and protect the planet. At the core of the agenda are the 17 Sustainable Development Goals (SDGs), which address the most important challenges of our time. Producing and using energy in ways that support human development over the long term, in all its social, economic and environmental dimensions, is at the core of the SDG dedicated to energy. Nuclear power has a long record of contribution to a diversified energy supply by providing electricity in a resilient and sustainable manner. The accident at the Fukushima Daiichi nuclear power plant in March 2011 revived anxiety about nuclear power and reminded the world that safety can never be taken for granted. Long term actions and near term measures were undertaken to ensure the resilience of nuclear power plants to external hazards and to strengthen overall nuclear safety. More than five years after the accident, it is clear that nuclear energy will remain an important option for many countries. Countries choosing nuclear power as part of their sustainable energy strategies note that it broadens the resource base, expands electricity supplies, is ahead of other energy technologies in internalizing externalities, increases the world's stock of technological and human capital, and avoids air pollution and greenhouse gas emissions.

Nuclear power has a place among other solutions and needs to be accessible to countries interested in making it part of their sustainable energy strategies. Nuclear power is a choice that rests with sovereign countries together with the responsibility to use it safely and securely. The IAEA provides assistance and information to countries that wish to introduce nuclear power. It also provides information for broader audiences engaged in energy, environmental and economic policy making. This publication explores the possible contribution of nuclear energy to addressing the issues of sustainable development through a large selection of indicators. It is a substantially revised edition relative to the 2006 information booklet in terms of structure and content. In the new edition, the sections are written in connection with the SDGs across the main dimensions of sustainable development: the economic, environmental and social dimensions.

CONTENTS

1. INTRODUCTION

Since the 1992 United Nations Conference on Environment and Development held in Rio de Janeiro, there has been a growing recognition of the importance of energy in achieving the goals of sustainable development. None of the 40 chapters contained in the Agenda 21 document [1] adopted unanimously by 178 countries at that conference was dedicated to energy. Energy was not included in the United Nations Millennium Development Goals (MDGs) for 2000–2015.

The Commission on Sustainable Development addressed energy for the first time during its ninth session in 2001. Over the subsequent decade, however, energy has become increasingly acknowledged as one of the key issues in sustainable development, culminating in the declaration by the United Nations General Assembly of 2012 as the International Year of Sustainable Energy for All. In September 2015, the international community approved the post-2015 development agenda with a new set of sustainable development goals (SDGs), fully recognizing energy as a fundamental pillar on its own. Energy is now seen as a precondition for sustainable economic growth and improved human well-being, affecting health, education, jobs and gender equality. Moreover, energy also needs to be produced and consumed sustainably if the devastating impacts of climate change are to be averted.

The importance of energy rests on the recognition of the many trade-offs and linkages between energy and sustainable development. A critical issue in the sustainable use of energy is the incorporation of the full social costs in energy prices and the desirability of reaping large societal benefits (e.g. derived from the global abatement of greenhouse gas (GHG) emissions). In addition, the various dimensions of sustainable development are often linked through energy related concerns. A first critical example is the management of the natural resource base and the desirable mix of non-renewable and renewable energy resources (since in the case of the latter, exhaustible resources will be consumed at the front end of a renewable technology's life cycle). In addition, the nature and magnitude of emissions from fossil fuel combustion into the atmosphere (GHG, sulphur oxides (SO_x), nitrogen oxides (NO_x), fine particulate matter (PM2.5), etc.) affect the carrying capacity of ecosystems at the regional and global level, and can also be largely detrimental to people's health. Furthermore, access to energy resources — particularly to modern energy services provided by electricity, liquefied petroleum gas stoves and more efficient and lower emission biomass stoves — has been recognized as an essential need of the world's poor. Yet, over 1.1 billion people are without access to electricity and 2.9 billion people lack clean cooking facilities (i.e. facilities that do not use firewood) [2]. Finally, granting physical access to modern energy services (e.g. via a connection to the electrical grid) will accomplish little if consumers are unable to afford those services. The cost of energy from alternative sources is therefore crucial if those sources are to play a role in sustainable development. Furthermore, scaling up energy supply to pursue (rapid) economic development paths in developing countries (as seen, for example, in China's recent past) will pose challenges to finite resources and the carrying capacity of ecosystems on an altogether different scale. Striking a balance between economic growth, quality of life and the exploitation of natural resources is necessary to provide decent energy services for developing regions with growing populations.

Given the complexity and multiplicity of energy systems worldwide, there is no uniform solution to make them more sustainable, while simultaneously addressing environmental, social and economic imperatives. Since there is no technology without risk, waste generation or interaction with the environment, the role of every energy technology needs to be assessed on an equal footing. Despite the lack of consensus on the compatibility of nuclear energy with sustainable development, nuclear technologies are regarded by many as a viable option to satisfy specific needs.

This publication explores the possible contribution of nuclear energy to addressing the issues of sustainable development by using a large selection of indicators. The publication also addresses some misconceptions and misleading statements regularly associated with the development and operation of nuclear power plants (NPPs). These perceptions often result from a combination of exaggerations and statements that are demonstrably false. Examples include the misconceptions that nuclear power costs more than other electricity generation options, it is impossible to finance new nuclear power stations, there is no solution for storing and disposing of radioactive waste, the costs of managing radioactive waste is prohibitive, the remaining uranium resources will run out in a few years and that nuclear power poses substantial radiation risks to the public, consumes too much water, takes up too much land or contributes to air pollution. Throughout the publication, these statements are compared with objective, scientific information and are put into perspective with the respective merits and shortcomings of alternative sources of energy.

Section 2 presents the scope and the scale of energy challenges and depicts the potential role of nuclear power in sustainable development. Section 3 is devoted to the economic dimension of sustainable development and covers issues ranging from economic competitiveness to financing and the long term availability of energy resources. The potential contribution of nuclear power as a means to strengthen energy supply security is also addressed. Section 4 is devoted to the environmental dimension of sustainable development. The section reviews the potential of various technologies to mitigate local and regional air pollution and GHG emissions, and compares their impacts in terms of waste generation, land use and water consumption. Section 5 looks at the social dimension, including impacts on health and employment. Intergenerational equity concerns of radioactive waste disposal, safety, proliferation and public concerns are also tackled. Section 6 summarizes the conclusions of this publication.

2. THE CONTEXT FOR NUCLEAR POWER IN SUSTAINABLE ENERGY DEVELOPMENT

2.1. THE CONCEPT OF SUSTAINABLE DEVELOPMENT

The 1987 United Nations report Our Common Future [3] provides what has arguably become the most widely accepted definition of sustainable development: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (see chapter 2, para. 1 [3]). The report, commonly referred to as the Brundtland Report[1], notes that the definition of sustainable development relies on two key notions (see chapter 2, para. 1 [3]):

— “The concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given; and
— “The idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs.”

The concerns central to the concept of sustainable development today can be seen as resulting from the definition provided by the Brundtland Report. Broadly, they can be characterized as concerns regarding:

— The depletion of finite resources;
— The carrying capacity of ecosystems;
— Intergenerational equity;
— Intragenerational equity;
— Material needs for human development;
— Non-material needs for human development.

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[1] The report Our Common Future was released in October 1987 by the World Commission on Environment and Development chaired by Gro Harlem Brundtland.

The issues arising in the context of these concerns are typically listed under three headings, corresponding to the three "pillars" described in the Johannesburg Declaration on Sustainable Development [4] issued by the United Nations World Summit on Sustainable Development in 2002:

— The economic pillar of sustainable development relates to the maintenance, accumulation and use of different categories of capital: human-made (e.g. infrastructure, machinery), natural (e.g. mineral resources, forests, clean air and water) and social/human capital (e.g. institutions, knowledge);
— The environmental pillar embraces the preservation of natural resources and biodiversity and the protection of habitats and ecosystems. A major concern is to ensure that natural capital, including the carrying capacity of ecosystems (as determined by the nature of critical biogeochemical cycles) is not depleted;
— The social pillar encompasses 'needs' as defined in the Brundtland Report [3]. These needs are not limited to the basics of food, water, energy, shelter and health, but are extended to areas such as education, leisure, culture, political activities, good governance, competent institutions, social relations and justice — both intra- and intergenerational.

Sustainable development is characterized by the notions of strong sustainability and weak sustainability [5]. The key difference between these two concepts lies in the willingness to accept the possibility of substitution between different forms of capital: natural (e.g. mineral resources, carrying capacity of ecosystems), human-made (e.g. infrastructure, machinery) and social/human (e.g. institutions, knowledge). Proponents of strong sustainability argue that certain types of natural capital cannot be replaced by human-made or social/human capital. Depletion of these types of natural capital represents an irreversible loss and needs to be avoided. In contrast, proponents of weak sustainability believe that human-made and social/human capital can substitute indefinitely for natural capital. Section 3.1 will argue that the notion of weak sustainability is important for understanding the ability of uranium resources to meet future demands.

As an approach, sustainable development conjectures that market signals alone — at least in their current form — do not incentivize sustainable patterns of production and consumption. Competitive markets would generate an efficient outcome if all natural resources and an ecosystem's carrying capacities could be priced in a way that reflected actual resource scarcity and the preferences of current and future generations. For example, ranking two alternative electricity generation technologies according to their full social costs by embedding the costs of associated externalities in terms of land use, GHG emissions or solid waste generation, would be equivalent to ranking them in terms of their social desirability.[2] The fact that sustainable development proponents consider impacts in terms of land use and other biophysical indicators and do not focus simply on relative prices as the ultimate indicator of what is socially desirable reflects their scepticism regarding purely market driven mechanisms of societal choices.

Another potential asset of the sustainable development approach is its frequent reliance on life cycle assessment as the appropriate methodology for evaluating the impacts of a product or technology on the natural environment. Life cycle assessment involves the evaluation of the environmental impacts of a system through all the stages of its life cycle ('cradle to grave'). Setting system boundaries is critical for the consistency and reproducibility of life cycle assessment studies. Upstream (and downstream) processes incur indirect impacts along the supply chain of the technology in construction and manufacturing (and decommissioning and dismantling) whereas direct impacts are incurred during the operation of the technology (i.e. delivery of the services it provides). Although variations can be found in the existing literature on the grouping of the processes, the important condition for a valid and credible life cycle assessment is the inclusion of all relevant actions in producing the end product.

The sustainable development issues arising in the context of the three pillars are complicated by the interlinkages, meaning that they are inextricably intermeshed and that actions in one area have impacts on one or more other areas. The need for an integrated approach to peace, development and environment was already highlighted in the Brundtland Report [3]. Similarly, the necessity of an integrated approach to these issues has long been acknowledged by political leaders, scientists, high level panels, global United Nations conferences and summits. In September 2015, the United Nations adopted the post-2015 development agenda seeking to provide an action plan up to 2030 for people, the planet and prosperity. The core item of the agenda is a set of new global SDGs that build on the MDGs (2000–2015), with the intention of completing what the MDGs did not achieve. The new comprehensive agenda aims to shift the world onto a sustainable path where environmental sustainability, social inclusion and economic development are equally valued. In particular, the SDGs extend beyond the social sector and incorporate goals on environmental quality (relating to climate change, biodiversity loss and deforestation and oceans) and sustained economic progress (sustainable energy sources, building sustainable cities and

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[2] Accounting for external costs and benefits of electricity generation can make a significant difference between the private and social costs of electricity produced by different technologies. Economic theory suggests the internalization of externalities as a way to improve socioeconomic welfare.

promoting sustained economic growth). Although the 17 SDGs are presented as separate elements, stronger or weaker connections link them through a large number of targets (169) (Fig. 1). The integrated nature of the SDGs balances the three dimensions of sustainable development: the economic, social and environmental.

The framework of sustainable development has been widely employed to evaluate different energy systems. For instance, concerns over the depletion of finite resources might be reflected in reserve–production ratios. Concerns over the carrying capacity of ecosystems can be found in analyses of emissions from energy chains and assessments of waste management challenges posed by various technologies. More recently, the term nexus has been increasingly used to describe interdependencies in managing resources. For instance, the energy–water–food nexus refers to synergies and trade-offs between the use of energy and water and the production of food (see Section 4.6). Overall, both the preoccupations and techniques of sustainable development have been widely employed for the purposes of the comparative evaluation of energy systems and will be employed throughout the remainder of this publication.

The place of nuclear power in sustainability issues has generated substantial controversy so far because of its trade-offs between low carbon electricity and concerns related to the risks of accidents as well as environmental and human health issues associated with radioactive waste management.

Discussions on this topic were particularly intense during the ninth session of the United Nations Commission on Sustainable Development in 2001. The debate between Member States that consider nuclear power an essential component of their sustainable development strategies and those that consider nuclear power fundamentally incompatible with sustainable development was long and thorough.

Finally, the Member States agreed to disagree on the role of nuclear power in sustainable development, but also agreed that the "choice of nuclear energy rests with countries" (chapter 1, para. 20 [7]). One year later, the Plan of Implementation of the World Summit on Sustainable Development [4] called for a series of actions to promote the widespread availability of clean and affordable energy, specifically the promotion of renewable energy resources, efficiency improvements and advanced energy technologies, including cleaner fossil fuel technologies. In this context, nuclear power belongs to the category of advanced energy technologies.

For the sake of clarity, this publication retains the traditional approach to sustainable development that revolves around three pillars: the economic, environmental and social pillars. Naturally, there is an implicit correspondence between those three pillars and the aforementioned SDGs. The pillars serve as

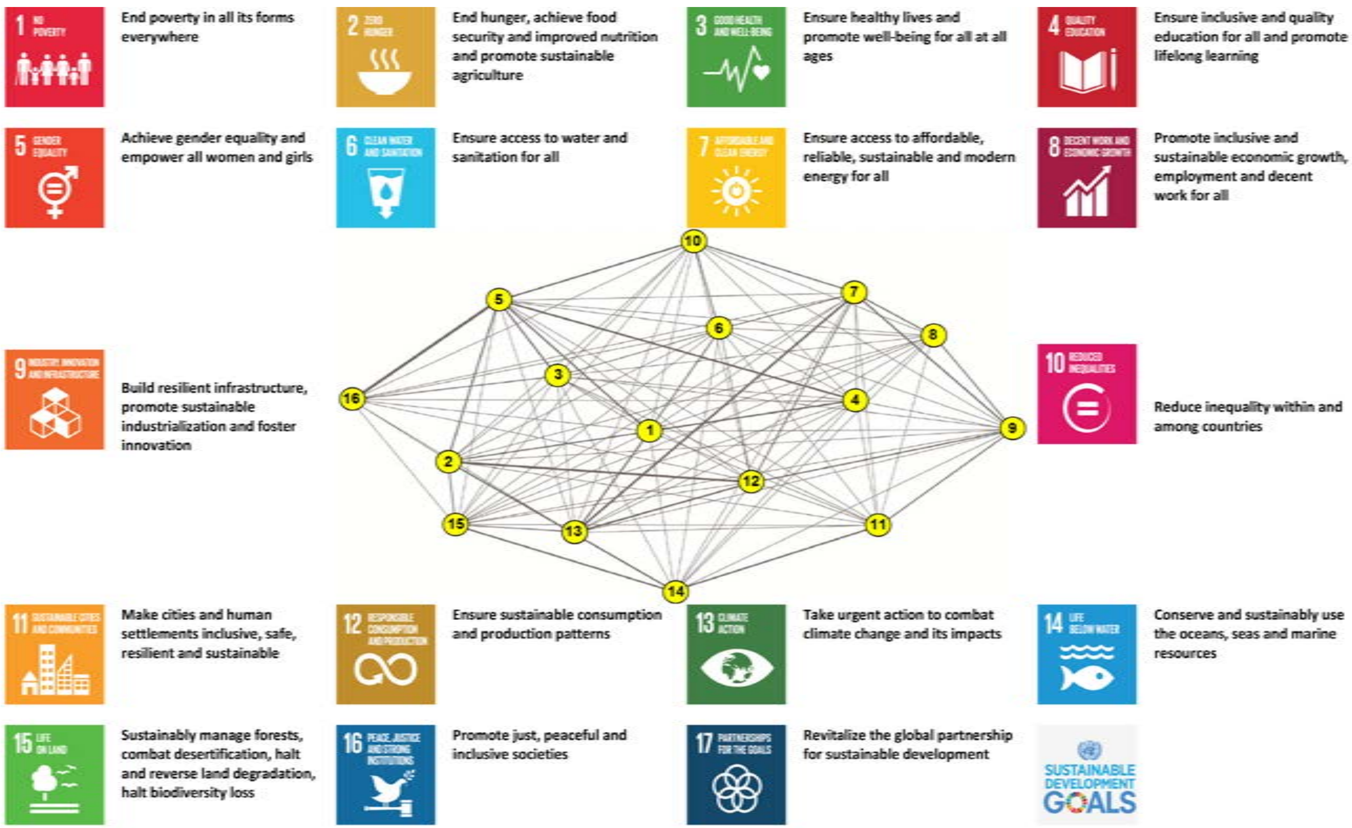

FIG. 1. The United Nations SDGs and their interlinkages. Source: Adapted from Ref. [6] with permission. Note: The width of the lines indicates the ratio of targets linking the two goals (i.e. the number of links between the two goals divided by the sum of the targets under the two goals).

constitutive dimensions across the SDGs in relation to nuclear energy and in comparison with available alternatives (Fig. 2).

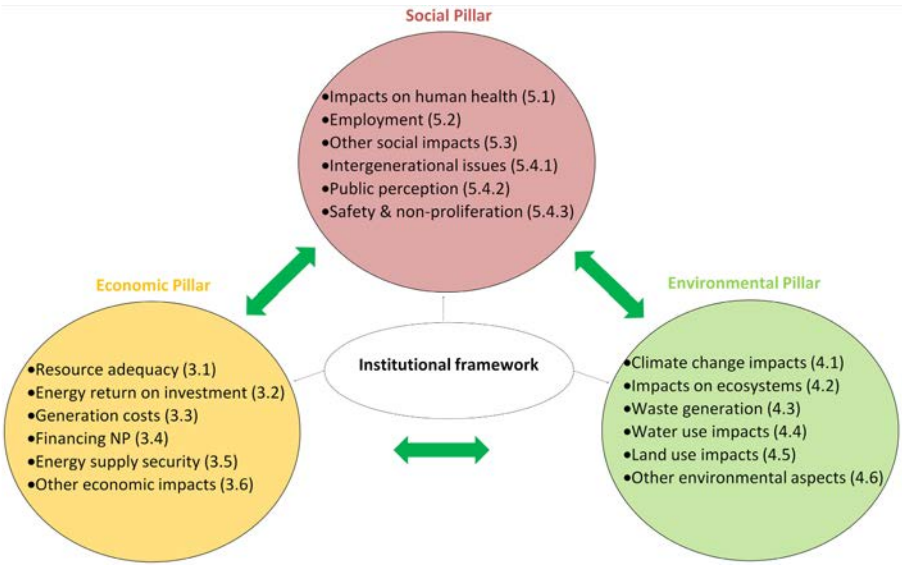

FIG. 2. Three pillars of sustainability as they relate to nuclear energy.

Sections 3, 4 and 5 are devoted to the three pillars. The underlying comparative assessments are based on different methodological tools, including sustainability indicators, life cycle assessments and external cost approaches, and avoid subjective or ad hoc judgments.

2.2. THE SCOPE FOR ENERGY IN SUSTAINABLE DEVELOPMENT

One of the two key concepts underlying the definition of sustainable development as put forward in the Brundtland Report [3] is “the concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given” (see chapter 2, para. 1 [3]). It includes access to important resources and services at the individual and household level (e.g. health, water, sanitation, energy), but also social aspects such as human security, social inclusion and dignity. These needs are best reflected in the United Nations MDGs defined in 2000 for the period up to 2015. The specific and time bound objective of the MDGs was to dramatically reduce extreme poverty in its many facets. Notwithstanding the fact that there was no specific MDG relating to modern energy services, it has been increasingly recognized that no development goal can be achieved without affordable, accessible and reliable energy services.[3] The strong linkages between access to energy and poverty reduction — as well as climate change — is also reflected in the Secretary-General's Vision Statement entitled Sustainable Energy for All, which was released in November 2011 [8]. Three linked objectives to be reached by 2030 are set in this initiative: ensuring universal access to modern energy services, doubling the rate of improvement in energy efficiency and doubling the share of renewable energy in the global energy mix.

Following the United Nations Conference on Sustainable Development (Rio+20) in June 2012, a process was initiated to formulate a set of new global SDGs. In August 2015, the United Nations Summit on Sustainable Development communicated for the first time a dedicated goal on energy (SDG 7): "Ensure access to affordable, reliable, sustainable and modern energy for all" [9]. SDG 7 includes the following targets (7.1 to 7.3) and means of implementation (7a and 7b) [9]:

> "7.1 By 2030, ensure universal access to affordable, reliable and modern energy services
>
> "7.2 By 2030, increase substantially the share of renewable energy in the global energy mix
>
> "7.3 By 2030, double the global rate of improvement in energy efficiency
>
> "7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil fuel technology, and promote investment in energy infrastructure and clean energy technology
>
> "7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries and small island developing States and landlocked developing countries, in accordance with their respective programmes of support".

[3] For example, the MDG to achieve universal primary education is linked to energy availability in that study after dusk requires illumination; many children, especially girls, do not attend primary school because they have to carry wood and water to meet family subsistence needs. The MDG to reduce child mortality is linked to energy via the health impacts of unboiled water and respiratory illness caused by indoor air pollution from traditional fuels and stoves, both of which directly contribute to infant and child disease and mortality.

Energy is also included in the clusters of several other SDGs. One example is SDG 13 on climate change, where energy related indicators can measure progress in achieving the target that aims to integrate climate change measures into national policies, strategies and planning. Thus, besides promoting sustainable energy for all, the goal also calls to head off the rapidly growing dangers of climate change by curbing GHG emissions from energy, industry, agriculture, built environment and land use change. Besides climate change, SDG 7 on energy is interlinked with other goals and targets, as illustrated in Fig. 3.

Energy is essential for economic development and for improved human well-being. However, current energy systems face several major challenges that need to be addressed urgently and comprehensively.

The first major challenge is the lack of both energy access and the energy needed to fuel the emerging economies. Despite significant efforts made by national governments and the international community, primary access to non-solid fuels barely rose, at 58% in 2010 and 59% in 2012 (meaning that access was gained by about 125 million additional people). Overall, the global access deficit to non-solid fuels amounted to 2.9 billion people in 2012. Similarly, the global electrification rate rose from 83% in 2010 to 85% in 2012, an estimated increase of 222 million people, mainly in urban areas [2]. About 1.1 billion people worldwide are still estimated to live without electricity. Without access to basic, affordable labour saving devices and adequate lighting, these people, and especially the women and girls among them, are deprived of economic and educational opportunities.

Furthermore, large regional disparities are observed: the access deficit to non-solid fuels remains overwhelmingly concentrated in south and east Asia and sub-Saharan Africa, predominantly in rural areas. The slow progress in gaining access to energy is mainly due to population growth in these regions.[4] Overall, there are deep inequalities in energy use that constrain the pursuit of improving human well-being: in 2013, more than 50% of the planet's population consumed less than 60 gigajoules (GJ) per capita, whereas 10% of the population used nearly 200 GJ per capita (Fig. 4). In other words, one citizen of the United States of America still consumes on average five times more energy every year than a Brazilian citizen and 11 times more than an Indian citizen. Yet, the ever increasing consumption does not necessarily lead to ever increasing levels of

[4] Population growth was, however, outpaced by global electrification rates — 222 million people gained access to electricity as compared to a population increase in 2010–2012 of 138 million — mainly driven by significant advances in India.

1 NO POVERTY — **Access to modern and sustainable energy is fundamental for poverty alleviation.**	2 ZERO HUNGER — **Helps achieve secure and equal access to productive resources, sustainable food production and increased investment in rural infrastructure.**	3 GOOD HEALTH AND WELL-BEING — **Contributes to reducing death and illness from air, water and soil pollution as well as contamination.**	4 QUALITY EDUCATION — **Basic energy services are required to provide better education to all.**
Ex.: Electrification in poor rural areas increases access to basic services. More sustainable energy use worldwide reduces the vulnerability and exposure of the poorest to extreme climate events.	*Ex.: Improved electricity access and cleaner, more efficient and affordable fuels contribute to more sustainable and modern agriculture, thereby reducing hunger worldwide.*	*Ex.: Energy services are needed to improve access to medical facilities for care. Lower reliance on coal-based electricity cuts ash volumes and improves air quality in urban areas.*	*Ex.: Lighting allows studying after dusk while improved access to information and communication technologies facilitates long distance learning.*
5 GENDER EQUALITY — **Supports women's equal rights to economic and natural resources and helps curtail violence against women and girls in public places.**	6 CLEAN WATER AND SANITATION — **Facilitates access to safe drinking water and sanitation, improvement of water quality and expansion of wastewater treatment**	8 DECENT WORK AND ECONOMIC GROWTH — **Energy industries which require skilled labour and generating large revenues are set to develop to meet ever rising energy needs worldwide.**	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE — **Developing a reliable energy infrastructure is a prerequisite for industrial value creation and wealth redistribution, and an opportunity to innovate.**
Ex.: Availability of modern energy services frees up girls' and young women's time from household activities (gathering firewood, crop processing by hand, etc.).	*Ex.: While water remains essential for most forms of energy production, improved designs of e.g. efficient cooling systems decrease wasteful resource use.*	*Ex.: The transition to more sustainable development patterns is an opportunity to stimulate economic activity, create employment and improve the living conditions of the poorest.*	*Ex.: High energy prices due to intense energy use alter international competitiveness. Energy efficiency investments stimulate innovation, technology diffusion and economic activity.*
10 REDUCED INEQUALITIES — **Getting energy prices right reduces income inequalities and their corrosive effects on health, social cohesion, growth, education and crime.**	11 SUSTAINABLE CITIES AND COMMUNITIES — **Urban areas are the largest basins of energy consumption because of high population densities and concentration of economic activities.**	12 RESPONSIBLE CONSUMPTION AND PRODUCTION — **Promoting resource and energy efficiency and sustainable infrastructure delivers a better quality of life for all.**	13 CLIMATE ACTION — **With roughly two thirds of all anthropogenic greenhouse gas emissions, the energy sector is the major contributor to climate change.**
Ex.: Poverty indicators are highly correlated with lack of access to electricity, suggesting that income and energy inequality can be jointly addressed.	*Ex.: Efficient and advanced transport vehicles, network or distributed low-carbon electricity and district heating and cooling mitigate greenhouse gas and fine particle emissions.*	*Ex.: A global shift to energy efficient light bulbs would save US $120 billion annually. Rationalizing inefficient fossil fuel subsidies eases pressure on public budgets and brings environmental benefits.*	*Ex.: In 2012, low carbon technologies, including nuclear, hydropower and renewable energy sources, avoided around 6 Gt of GHG emissions.*
14 LIFE BELOW WATER — **Energy production and use directly affect oceans' chemistry and biodiversity. Oceans buffer impacts of climate change.**	15 LIFE ON LAND — **Energy production and use affect forests and can lead to land degradation, desertification and biodiversity losses.**	16 PEACE, JUSTICE AND STRONG INSTITUTIONS — **Transparent, effective institutions and improved civil society involvement are necessary to implement efficient energy and sustainable policies.**	17 PARTNERSHIPS FOR THE GOALS — **Only global partnerships between governments, the private sector and civil society can help address energy challenges to meet all SDGs.**
Ex.: Offshore oil exploitation can generate oil spills. Fossil fuel burning leads to climate change which increases water temperature and indirectly generates ocean acidification.	*Ex.: Damage to ecosystems and losses arise from land use change and contamination from wastes from energy related activities such as mining, drilling and fuel transport.*	*Ex.: A more equitable redistribution of resource wealth lessens poverty and stimulates economic growth in energy producing countries.*	*Ex.: The Green Climate Fund's mandate is to catalyse both public and private finance to limit greenhouse gas emissions (and climate adaptation) through country driven approaches.*

FIG. 3. Examples of linkages between the Sustainable Development Goals and energy (SDG 7).

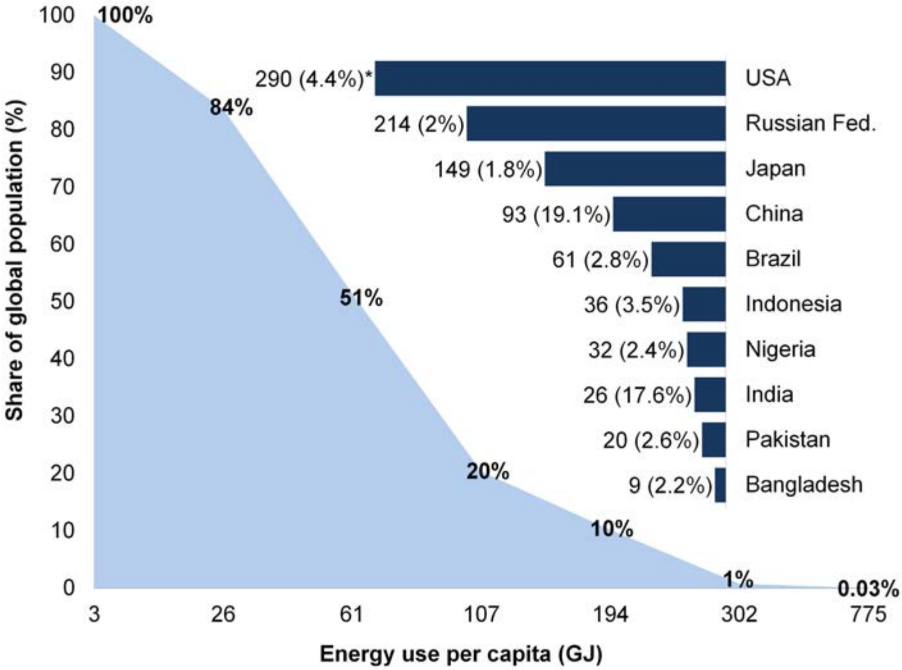

*FIG. 4. Energy use in the top 10 countries by population: Average per capita energy use and the share in global population in 2012. Source: Based on Ref. [10]. Note: *Average per capita energy use (the share of global population).*

well-being as measured by the United Nations Human Development Index [5] [11]. The correlation between the Human Development Index and per capita energy use starts to level off at around 125 GJ per year [12].

Nevertheless, an expansion of the energy supply will certainly be needed over the next decades to reduce the gap between developed and developing countries. Beyond basic access at the household level, energy is also a precondition for economic development. Poor communities take better advantage of the modern world's opportunities as their income and living conditions rise but this requires higher energy use and a higher production capacity. Given that sustainable development places importance on the material needs of communities, improving the material living standards of the world's poor will (barring large scale global redistribution of wealth) require economic growth. Historically, the

[5] A composite index based on measures of health, longevity, education and economic standards of living.

availability of reliable, high density energy resources has been a key driver of growth, resulting in turn in increased demand for energy services.

The second major challenge is that energy related emissions need to be reduced to prevent adverse health effects and serious impacts on ecosystems, land and water. Already in the early phases of industrialization, energy production caused high levels of local air and water pollution [13]. Advances in scientific capabilities in recent decades revealed even more subtle environmental and human health effects associated with energy production [14]. Fossil fuel combustion is responsible for substantial emissions of air pollutants and plays a major role in the formation of PM2.5, ground level ozone and acid rain primarily impacting public health and ecosystems, but also impairing agricultural productivity and degrading materials and structures [13, 15].[6]

Energy use is also a major contributor to the release of long lived heavy metals such as lead and mercury and other hazardous materials into the environment [13]. Energy related air pollution (including poor indoor air quality from the use of solid fuels for cooking and heating) causes millions of deaths every year with a disproportional burden experienced in low and middle income countries [15]. Moreover, the extraction, transport and processing of primary energy sources are associated with impacts on land, water and ecosystems [13]. In addition, the evidence from climate science collected over the past few years indicates that the earth's climate is warming owing to the increasing concentrations of GHGs, especially CO_2. These result from human activities, mainly the burning of fossil fuels, and significantly threaten ecological and socioeconomic systems. Distressing impacts of climate change (e.g. sea level rise, changing intensity of extreme weather and climate events) can be attenuated if the increase in global mean temperature is kept below 2°C relative to pre-industrial levels.

The third major challenge is that the provision of energy services raises concern about the socially desirable level of depletion of non-renewable energy sources and the resulting efforts to improve resource efficiency in energy systems. This relates to the simple idea of running out of exhaustible resources. Constrained choices are another source of concern for future generations that will have to rely on less accessible resources (i.e. more unconventional hydrocarbons may have to be tapped).

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[6] In contrast to conventional energy sources, the assessment of environmental impacts of unconventional resource extraction and use has received little attention to date. Pioneering studies indicate that the extraction and use of some unconventional oil resources might generate more than twice as much life cycle emissions per barrel than those generated by conventional oil.

The use of alternative, more sustainable primary energy sources may be preferable to fossil fuels. In addition, considering scarce resources and the related negative externalities, the promotion of energy conservation measures remains an essential component of the full policy and technology portfolio necessary for sustainable development.

Recycling of exhaustible resources (i.e. uranium) might also become more attractive as the cost of extracting such resources may increase, and the costs of recycling might place an upper limit on the price escalation of extraction. Admittedly, the physical depletion of resources as emphasized in the 1972 book Limits to Growth [16] is now deemed less pressing than the implications of burning fossil fuels for the environment and human health.

Fourth, security of uninterrupted provision of energy needs to be ensured. According to Ref. [13] this security is:

> "defined as access to adequate supplies of energy when needed, in the form needed, and at affordable prices, energy security remains a central priority for all nations concerned with promoting healthy economic growth and maintaining internal as well as external stability."

Nonetheless, the definition of energy security is strongly country dependent. For the highest income countries, energy security is related to import dependency, price volatility, the sources and costs of supply and an ageing infrastructure, whereas emerging economies have additional vulnerabilities such as insufficient capacity, high energy intensity and rapid growth in demand [17]. For many countries, introducing or expanding nuclear power could increase the diversity and resilience of energy and electricity supplies because of abundant and relatively evenly distributed uranium reserves around the planet (see Section 3).

Throughout modern history, energy has been central to economic development and social progress. It directly impacts the well-being of people and communities and it is essential to economic growth, employment, health, security and education. It also affects ecosystems and is linked to climate change. Clearly, energy systems need to be overhauled with a view to favour sustainable conditions of human development, to reduce political tensions due to insecurity of supply and to attenuate adverse environmental and human health impacts [17].

2.3. THE SCALE OF THE ENERGY CHALLENGE

The energy challenge to sustainable development lies in the necessity to deliver growing amounts of modern energy services compatible with economic development. The scale of this challenge is illustrated through the following review of energy–development linkages, drawing upon past trends and depicting some of the key drivers of the projected energy demand.

2.3.1. Historical patterns of energy use

Over the past 40 years, population, gross domestic product (GDP), primary energy consumption and CO_2 emissions have consistently increased in most countries and at the global level [18] (Fig. 5). Global energy consumption has been growing at a much slower rate than GDP primarily because of overall energy efficiency improvements and shifts in the structures of economies. Yet these global aggregates hide a more contrasted picture: around 84% of the world's population still live in developing countries (as of 2012), whereas around half of the global income is received by the wealthiest 20% [19] of the people, who also consume more energy and produce more CO_2 emissions (although the share of high income countries in the primary energy consumed is declining, mainly due to the growing share of middle income countries — with China as the prime example) [2].

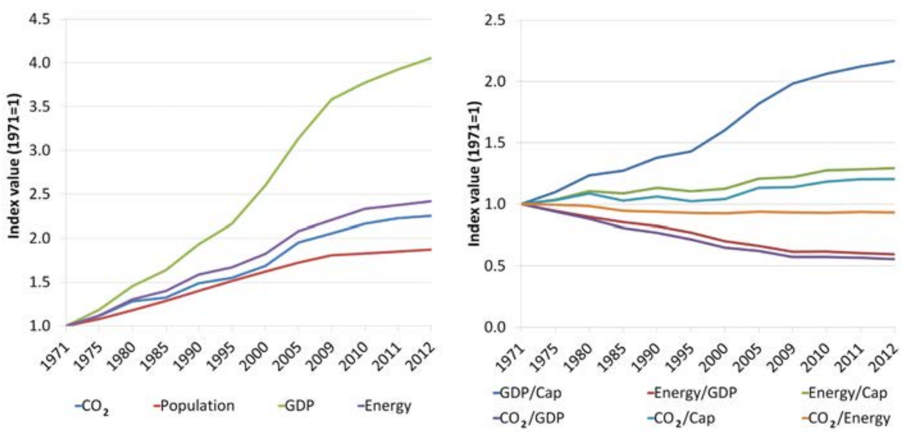

FIG. 5. Trends in four basic indicators (CO_2 emissions, global population, GDP, energy consumption) and the relationships between them in 1971–2012. Source: Based on Refs [10, 18, 20].

In addition to structural changes in the world economy, improvements in energy efficiency (i.e. reduced primary energy use for a given amount of final energy consumption, thereby translating into less energy per unit of GDP) are essential to decouple energy demand from economic growth. The evolution of this relationship is best captured by the energy intensity indicator — the amount of energy needed to produce one unit of GDP (Energy/GDP in Fig. 5). In high and middle income countries, primary energy intensity improved by nearly 1.3% a year between 1971 and 2012. Although energy demand and economic growth remain tightly connected in emerging economies (e.g. Brazil, Nigeria), the decline in energy intensity is an established and long standing trend [21]. On a global scale, the combination of decreasing energy intensity and increasing share of non-fossil energy sources have resulted in a modest decarbonization of the energy system and a marked reduction in the carbon intensity of GDP (CO_2/energy and CO_2/GDP). Nevertheless, if energy development is to follow a sustainable track, continuous improvements in both energy and carbon intensities (energy/GDP and CO_2/energy) are needed to accompany growing energy use.

Despite sustained efforts worldwide and increasing efficiency of extraction, conversion and utilization of energy sources, the total global energy requirement has increased by a factor of 2.4 between 1971 and 2013, from 231 to 568 exajoules (EJ). With considerable regional and national variations, the growing world economy has relied to a large extent on abundant fossil fuels, growing on average at 2.1%/year, and the combined share of coal, gas and oil has been around 80% of global energy consumption over the last four decades.

Figure 6 illustrates the sustained use of fossil fuel with a gradual increase in energy supplied from renewables (mainly biomass), nuclear and hydropower sources. In most countries, new renewable generation capacity (wind and solar) recorded a tremendous increase in the last decade driven by rapid cost reductions and continued public support. Although growing, these renewables, centred principally in the power sector, still remain insignificant in the total global energy supplied (1% in 2013).

During the 21st century, coal saw the fastest progression of all energy resources in absolute quantities of energy supplied, largely pushed by Chinese and, to a lesser extent, Indian demands. Recently, some European countries have also recorded a renewed interest in coal based power generation incentivized by lower coal prices. These market trends are mainly supported by higher exports of natural gas from the USA thanks to enhanced shale gas extraction [22] and by sluggish carbon price signals from the European Emissions Trading System. Without more stringent measures to tackle local pollution and reduce CO_2 emissions, the departure from the dependence on fossil fuels, especially on coal, remains difficult.

In the early decades of its history, nuclear power was seen as a high-tech, abundant, cheap and safe energy source in most countries. Its share in primary energy supply has grown from just 0.5% in 1971 to nearly 7% at the end of the 1990s, and then declined to 5% in 2013.

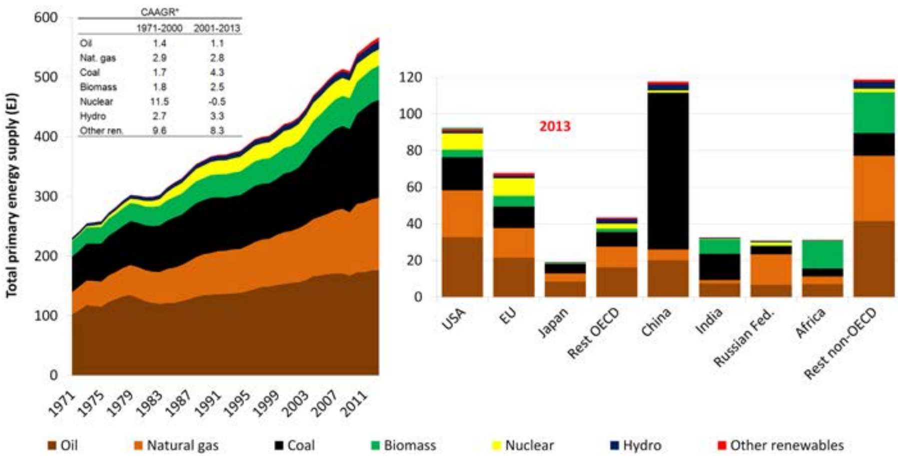

FIG. 6. Global and regional primary energy supply. Source: Based on Ref. [10]. Note: CAAGR — compound average annual growth rate.

In the last decades, the promising features of nuclear power have swung to the opposite side, driven by a variety of factors. Poor project management and consequent costly and lengthy duration of new constructions accompanied by slowing electricity demand in the Organisation for Economic Co-operation and Development (OECD) countries led to the slowdown of nuclear programmes in the late 1980s and 1990s [23]. In addition, three large accidents (Three Mile Island, Chernobyl and Fukushima Daiichi) shattered the safety image of nuclear power and led to changing regulatory requirements and procedures, resulting in enhanced safety of existing plants, but also in more expensive nuclear power.

In the last decade, however, the nuclear industry has been regaining momentum: the highest number of reactor units (70) since 1989 was under construction in 2015. Expansion, as well as near and long term growth prospects, remain centred in Asia, particularly in China. Of the total number of reactors under construction, 46 are in Asia, as are 32 of the last 40 new reactors that have been connected to the grid since 2004 [24].

Another characteristic trend of the past decades is the increasing share of electricity in total final energy, from 9% in 1971 to 18% in 2012. Electricity is recognized to be an essential input for the productive, household and social sectors, reducing poverty and accelerating economic development. Figure 7 illustrates the link between poverty, income levels and access to electricity. It is important to note that this correlation gets weaker at higher income levels — an important indicator of sizeable potentials for efficiency improvements in richer industrialized States.

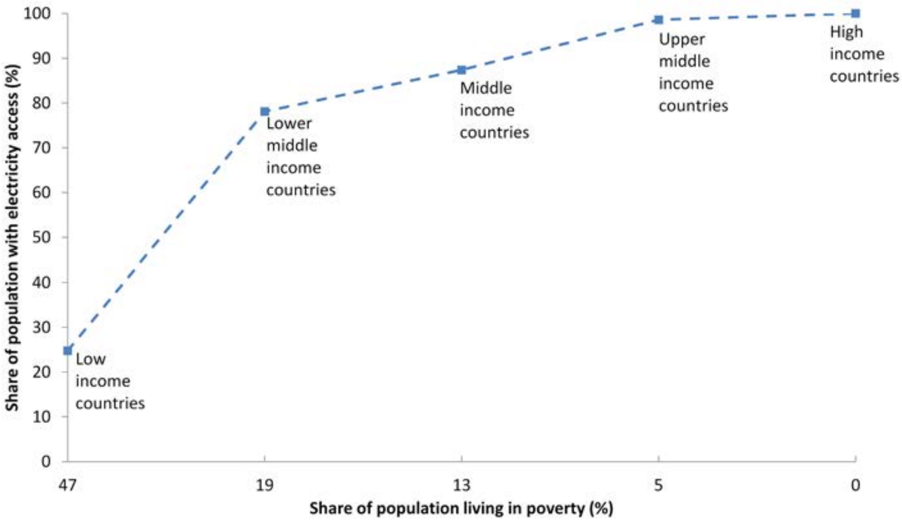

FIG. 7. Access to electricity versus poverty levels in 2012. Source: Adapted from Ref. [25]. Note: Share of the population living in poverty reflects the share living on less than US $1.90 a day at 2011 international prices. The grouping of countries by income levels matches the categories of the World Bank.

The relative importance of different fuels in electricity generation is very diverse across the countries and so are the associated socioeconomic and environmental impacts. Thermal sources dominate in China and India (nearly 80% of all energy sources), hydro provides more than half of the electricity in Latin America, whereas the European Union (EU) has the highest share of nuclear power (27%) (see also Section 2.3.2). In 2014, the highest shares of electricity provided by nuclear were found in France (76.9%), Slovakia (56.9%) and Hungary (53.5%).

2.3.2. Projected trends in energy use

Rising demand for energy is driven by population, economic growth and urbanization. Although population is a fundamental driver of energy demand, the relationship is not linear and results from numerous factors ranging from economic growth to household sizes or the population's age structure. Currently, the world population is estimated at 7 billion people. The Medium Fertility population growth forecast of the United Nations Population Division projects an increase in global population to 9.7 billion by 2050 [26] (Fig. 8). However, the pace of change over the last three decades suggests a slowdown in the future: from 0.9%/year during the period to 2035 to 0.6% during the subsequent 15 years (the population expanded by 1.4% annually between 1980 and 2015). Key contributors to global population growth include Africa, India and south-east Asia.

The provision of adequate, high quality energy services is a necessary condition for economic growth. In turn, economic growth is another key driver of the demand for energy services and the corresponding upstream energy conversion and resource use. The relationship between energy use and economic growth is thus not unidirectional. On the one hand, a reorientation of the economy towards less energy intensive sectors (decoupling) is already taking place in most high and middle income countries. On the other hand, increasing production in middle and low income countries will require more energy inputs, while rising incomes will increase the demand for services that require energy such as heating, cooling and mobility. More generally, the demand for energy will vary at different stages of economic development depending on the availability of resources and technologies within a particular economic, social, institutional and cultural context.

As such, projections for energy demand are highly sensitive to underlying assumptions about the rate of GDP growth. The International Energy Agency (IEA) assumes that global GDP will increase at an average overall rate of

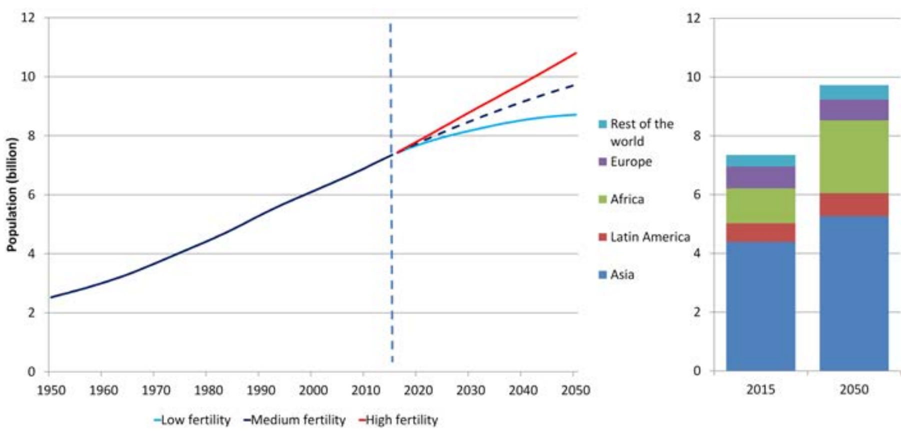

FIG. 8. World population 1950–2050 at global and regional levels. Source: Based on Ref. [26]. Note: Medium fertility estimates are shown in the regional chart.

3.4%/year between 2012 and 2040 (based on GDP expressed in 2013 US $ in purchasing power parity terms) [27] (see Table 1). By 2040, this translates into more than a doubling of the global economy, mainly pushed by fast growing economies in sub-Saharan Africa and Asia (led by India). Albeit at lower levels, economic activity is set to expand at a relatively firm rate in the USA, whereas growth in Europe is projected to be slow. Overall, over the next quarter of a century, growth rates of GDP and population in non-OECD countries are seen to exceed those of OECD countries. Similar trends in income and demand for (commercially supplied) energy are expected in per capita terms.

TABLE 1. ECONOMIC GROWTH BY REGION 2012–2040
(Based on Ref. [27])

	Compound average annual growth rates of real GDP (%)				
	1990–2012	2012–2020	2020–2030	2030–2040	2012–2040
OECD	2.2	2.2	2.0	1.7	1.9
Americas	2.6	2.6	2.2	2.0	2.2
Europe	1.9	1.7	1.9	1.6	1.7
Asia and Oceania	1.9	1.9	1.8	1.3	1.7
Non-OECD	4.9	5.3	4.9	3.7	4.6
Eastern Europe/ Eurasia	0.8	2.8	3.5	2.7	3.0
Asia	7.5	6.3	5.4	3.9	5.1
Middle East	4.4	3.7	3.9	3.3	3.6
Africa	4.0	5.1	4.8	4.4	4.7
Latin America	3.4	3.1	3.5	3.0	3.2
World	3.3	3.7	3.6	3.0	3.4

Urbanization is another major demographic driver of energy demand as urban areas will accommodate most of the growing population. Currently, approximately two thirds of final energy is used in urban areas [28]. According to the United Nations, the population living in urban areas globally is projected to increase by 60% between 2014 and 2050, going from 3.9 billion in 2014 to 6.3 billion in 2050 [29] (Fig. 9). Urbanization rates generally go hand in hand with rising income and growing energy needs, as well as improved access to energy services. Thus, urban infrastructure and residents will both drive consumption and increase the demand for global resources. This also implies that energy sustainability challenges — access to modern and clean energy services, security, reliability and resilience of systems, pollution reduction, efficiency improvements and clean supply — need to be addressed primarily in urban settings as emphasized by SDG 11 on Sustainable Cities and Communities.

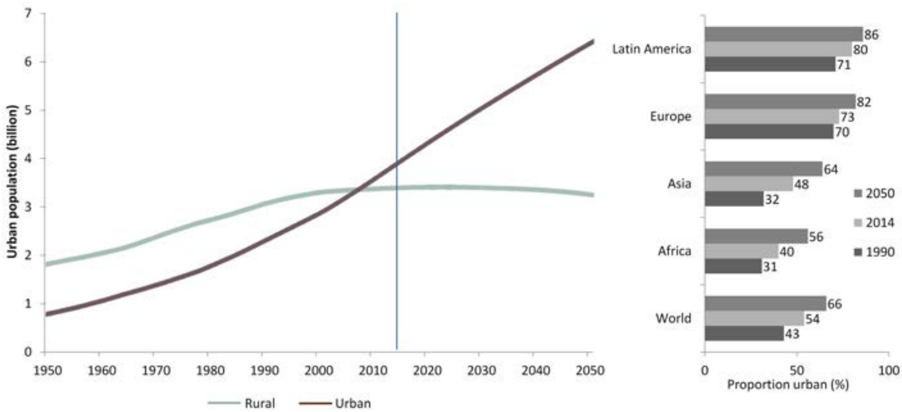

FIG. 9. Urbanization trends. Source: Based on Ref. [29].

The future development of urban energy use is characterized by specific opportunities and challenges. Key drivers of urban energy use amenable to urban policy making, such as urban form and density (e.g. transport systems), the quality of the built environment (e.g. energy efficient buildings) and urban energy systems (e.g. cogeneration), present vast opportunities for improvements [28]. For example, in the long term, all end use energy fuels consumed in urban areas need to be of zero emission[7] quality, as exemplified by electricity or (eventually) hydrogen. However, this challenging strategy can only maintain urban air quality if other measures to reduce air pollution are successful (e.g. minimal pollution levels at the point of production of these fuels, potentially with waste heat redirected for district heating) emphasizing the importance of a holistic view of the issues. Obvious sustainable choices on the supply side such as locally harnessed renewables (solar and wind), however, face strong limitations in large cities because of the mismatch between the high urban energy demand density and the low renewable supply densities, implying the need for large scale imports of energy generated elsewhere [28]. On the demand side, the potential for energy efficiency improvements in urban areas remains enormous and deserves the highest priority for policy action.

Two key publications of the IEA: the World Energy Outlook (WEO) [27] and Energy Technology Perspectives (ETP) [30] are based on the aforementioned drivers. The central scenarios of the IEA — the New Policies Scenario in WEO and the comparable 4°C scenario in ETP — project a 37% increase in global primary energy supply by 2040 (to 766 EJ) and a 50% growth between now and 2050 (to 834 EJ), equivalent to an average 1.1% annual increase. These projections are based on a detailed representation of announced (but not yet implemented) policies, such as the progressive removal of subsidies supporting fossil fuel consumption, the public support for renewable deployment and climate change mitigation policies[8] [27]. These policies still fall short of curbing trends of fossil fuel use and global energy related CO_2 emissions that by 2050 are projected to increase by almost 29% and 21%, respectively. Nuclear energy production is projected to increase by 72% (from 2461 terawatt-hour (TW·h) in 2012 to 4443 TW·h in 2050) although its share in global primary energy supply barely rises from 5% in 2012 to 6% in 2050 [30].

Demand for electricity grows faster than any other form of final energy. In 2050, it is projected to reach twice the level of electricity generation in 2012. Much of this growth is expected to occur in non-OECD countries and regions (China, India, sub-Saharan Africa, south-east Asia), stimulated by more dynamic economic and population growth and expanding access to electricity (Fig. 10). By 2040, more than half of the electricity is still projected to be produced from

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[7] The zero emission requirement is important to consider in the context of ‘carbon-neutral’ biofuels that produce unacceptable levels of pollution (e.g. NO_x or ozone (O_3)) when used by millions of automobiles in an urban environment.

[8] Examples are regulations in the USA to cut GHG emissions from power plants, the EU’s 2030 policy framework for climate and energy policies, and changes in energy subsidy schemes (for fossil fuels and renewable energy) in many countries.

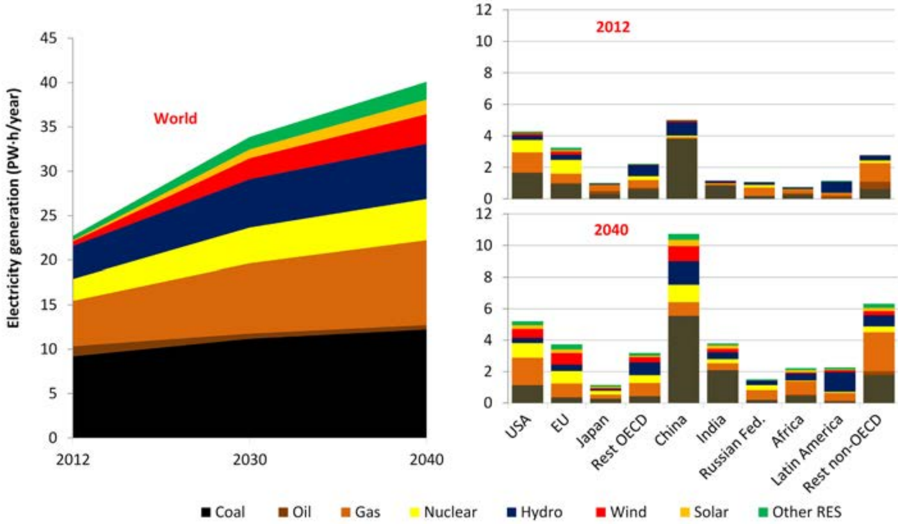

FIG. 10. Fuel mix in electricity generation in the World Energy Outlook New Policies Scenario 2014. Source: Ref. [27]. Note: RES — renewable energy sources.

fossil fuels. Addressing the heavy reliance of fossil fuel based power generation together with the associated adverse environmental and human health impacts will be a challenge to sustainable development in itself.

2.4. TOWARDS A SUSTAINABLE ENERGY SYSTEM

Energy is central to nearly every major challenge and opportunity the world faces today and, as illustrated in Section 2.2, energy relates to every goal of the new 2030 United Nations Agenda for Sustainable Development. An energy system is sustainable if energy services are delivered adequately, at an affordable cost, in a secure and environmentally benign manner and in conformity with social and economic development needs. Only a deep transformation of energy systems can meet SDGs, match growing energy needs and address energy poverty. The multiple issues at stake, ranging from social inequality to sustainable resource use, security, reliability and resilience of systems, pollution reduction, conservation of ecosystems and climate protection are all part of a necessary integrated approach to such challenges.

Existing differences in levels of economic development across countries translate into different starting points towards more sustainable energy systems [31]. Universal access to energy services is of utmost importance for many low income countries, in parallel with measures to foster economic growth.

Middle income countries and fast growing economies need to develop their energy systems while progressively decoupling economic growth from energy consumption and GHG emissions. High income countries and advanced economies are engaging on a decarbonization track and encourage the uptake of the most efficient energy technologies. Improved energy efficiency and diffusion of cleaner energy technologies might also take place in low income countries, but trade-offs in meeting different SDGs may exist and priorities in implementation measures need to be set. These priorities ought to be set in accordance with national and regional circumstances, bearing in mind the combination of costs, benefits and risks associated with various aspects of energy supply (e.g. supply cost, resilience to disruptions, long term import dependency and GHG mitigation), and in accordance with other SDGs related to health, food, education and so on. Carefully designed national and local policies, including targets and indicators to track progress, are critical for the transformation of energy systems.

When designing their national strategies, countries need to weigh mindfully the risks and costs of potential technology lock-in, a persistent concern in the energy sector owing to long lead times and the durability of infrastructure. Among paramount transformations towards a sustainable development trajectory is the shift towards a low carbon economy and especially a low carbon power sector. This change also generates ancillary benefits in terms of poverty alleviation, economic development, energy security, improved health, climate change mitigation and ecosystem protection. Stringent GHG mitigation scenarios — e.g. the 450 Scenario in IEA WEO 2014 and the 2°C scenario in IEA ETP 2014 — are meant to illustrate such changes in development paradigms. These scenarios rest on a set of measures to limit the average global temperature rise to 2°C: targeted sectoral efficiency improvements, restrictions on the construction and operation of inefficient coal fired power plants, curbing methane emissions in upstream oil and gas production, and the partial phase-out of subsidies supporting the ending of the use of fossil fuels in the near term. Beyond the 2020 time horizon, the full removal of subsidies supporting the consumption of fossil fuels, the strengthening of energy performance standards and a progressive introduction of carbon pricing mechanisms become indispensable [27].[9] These measures bring about appreciable savings in energy consumption and lead to major shifts in power generation mixes: the significant increases in the electricity generated from low carbon sources, including renewable energy sources, nuclear and fossil fuel technologies with carbon dioxide capture and storage (CCS),

[9] In these scenarios, CO_2 emission charges start at US $20/t in 2020 and reach US $140/t in 2040 in OECD countries, and increase from US $10/t in 2020 to US $125/t in 2040 in other major economies.

progressively substitute for fossil fuel based electricity generation without CCS. In such stringent mitigation scenarios, the role of nuclear power is significantly strengthened: by 2050, nuclear generation capacity increases more than twofold (from 383 gigawatt (electrical) (GW(e)) in 2015 to 930 GW(e)).

The transformation of energy systems will follow a gradual process and will evolve as uncertainties on future developments and scientific advances (e.g. on costs and performance of CCS based technologies, renewable energy sources, advanced nuclear reactors and the associated infrastructure) are resolved. The policy challenge lies in the necessary enhancement of ambition and in the pace of implementation. For this purpose, strong governmental support is essential where markets would otherwise fail to direct investments towards low carbon energy solutions and set their levels adequately. Governments have a vital role to play in defining incentives and regulations, in giving adequate price signals and in setting other conditions that will drive markets towards outcomes compatible with a more sustainable management of energy use and concomitant objectives of global public good[10] nature, such as energy security and climate change.

3. THE ECONOMIC DIMENSION

3.1. RESOURCE ADEQUACY

The depletion of finite resources is a key concern in the sustainable development framework. Adequate energy supply in an economy is vital for fast and sustainable rates of economic growth. As such, resource adequacy contributes primarily to SDG 8 on Decent Work and Economic Growth and to SDG 9 on Industry, Innovation and Infrastructure (see Figs 1 and 3). In this context, the availability of uranium resources relative to that of other primary non-renewable energy resources is explored in this section.

The question of uranium resource adequacy can be addressed by analysing: (a) the quantities of physical resources available from different sources (conventional versus unconventional) and (b) the energy that can be extracted from a given quantity of uranium during different types of fuel cycle. Insofar as the potential deployment of different reactor technologies and fuel cycles raises

[10] Public goods concern the provisioning of benefits that do not have exclusive ownership rights and that are non-rival in use (one person’s consumption does not affect another person’s consumption).

the limits of the second point, it can arguably be regarded to support the view of nuclear generated electricity as a weakly sustainable energy source (i.e. one for which human-made capital such as knowledge and infrastructure can substitute even as it is physically depleted).

In addition, uranium is only one of the types of material that can be used to fuel nuclear reactors. Thorium, which is roughly four times as abundant in the earth's crust as uranium, is an alternative to uranium. Its possible utilization in various reactor types has been demonstrated, including in light water reactors, the type which accounted for 85% of the reactors connected to the grid as of 31 December 2014. From the mid-1950s to the mid-1970s, a considerable interest in thorium based fuel cycles arose, but it then waned in the face of a better understanding of uranium deposits and their availability.

The physical availability of uranium resources is typically characterized by resource deposits expressed in terms of both the estimated cost of recovery and the degree of confidence in the quantities reported [32]. Identified resources are known or inferred to occur based on direct evidence, and undiscovered resources are expected to occur on the basis of evidence that is mainly indirect. Together they make up the total conventional resources insofar they are restricted to "those that have an established history of production where uranium is a primary product, co-product or an important by-product" (Ref. [33] p. 477). As far as unconventional resources are concerned, uranium from these resources, such as uranium associated with phosphate rocks, non-ferrous ores, carbonatite, black shale and lignite, is recoverable only as a minor by-product [33]. Exploiting lower grades of uranium is expected to raise uranium costs. However, a better integration of temporal (productivity growth in mining) and accumulative (learning based) cost mitigating processes as well as the evolution of demand would be needed to better understand and mitigate uranium cost escalation, as demonstrated by a recent study [34]. Under rather conservative assumptions on the dynamics of these processes, the rate of increase of such costs is significantly attenuated and may even decline.

Figure 11 shows the evolution of the ratio of proved reserves to production and consumption (R/P and R/C, respectively)[11] in 2001, 2007 and 2013 for the main fossil fuels and uranium. Calculating such ratios yields a figure in years

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[11] This ratio includes proven resources of oil, natural gas and coal (quantities with reasonable geological and engineering information certainty recoverable in the future from known reservoirs under existing economic and operating conditions), and identified uranium resources (reasonably assured resources and inferred resources recoverable at a cost of less than US $130/kg U or US $260/kg U). This ratio excludes unconventional resources such as tar sands, shale oil, deep offshore oil and shale gas.

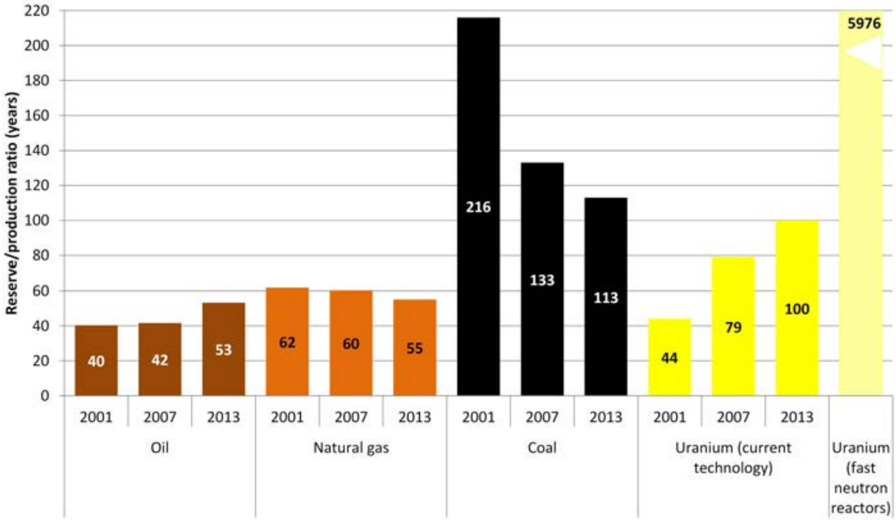

FIG. 11. Reserve/production ratios of key energy resources and reserve/consumption ratio for uranium. Source: Based on Refs [33, 35, 36]. Note: Consumption rather than production figures are used for uranium because consumption has exceeded production since 1990, mostly owing to the crowding out of the fresh uranium supply by uranium from secondary sources, including the Megatons to Megawatts programme [37]. Consumption may therefore be regarded as a more accurate reflection of likely future depletion of the resource. Identified uranium resources recoverable at below US \$130/kg are used to calculate R/C for uranium. At 2013 levels of consumption, identified uranium resources recoverable at below US \$260/kg would be sufficient for 129 years of supply for the global nuclear power fleet.

which can be regarded as an estimate of the durability of proved reserves (i.e. their longevity). In this sense, they can be viewed as simple measures of sustainability. The central message of the figure is that estimates for uranium reserves have been increasing steadily over the years: at the 2013 level of uranium requirements (59 270 tonnes (t) U), identified resources are sufficient for 100 years of supply as compared to 44 remaining years estimated in 2001.

The currently prevalent technology is based on a once through fuel cycle (OTFC) and uses only a small percentage of the energy content of the reactor fuel. The use of fast reactors (FRs) operated in a closed fuel cycle (discussed further in this section) could increase uranium resource efficiency by at least a factor of 60 [35] extending the longevity of conventional resources to nearly 6000 years at current rates of consumption. The increasing value of the uranium R/C ratio can also be regarded as a positive signal to investors in uranium exploration and mining. Conversely, the dynamics of the R/P ratio are less favourable for natural gas and especially for coal for which the estimates of reserves have decreased by almost 50% since 2001. The R/P and R/C ratios are not to be interpreted as absolute longevity, i.e. depletion time. When a 'comfortable' volume of reserves (sufficient for a few decades) is identified, exploration efforts tend to decline. This is especially true for coal because its future use has become uncertain.

Figure 12 provides estimates of years of uranium resource availability according to three resource categories and two reactor and fuel cycle types at the 2013 level of uranium requirements. Using current reactor technologies, the entire conventional resource base, including inferred, prognosticated and speculative resources recoverable at a cost between US $40/kg and US $130/kg, is expected to be sufficient for nearly 170 years of exploitation. The largest availability, which essentially decouples nuclear energy from resource availability, reflects the use of conventional and some unconventional resources as well as the large scale deployment of FRs.

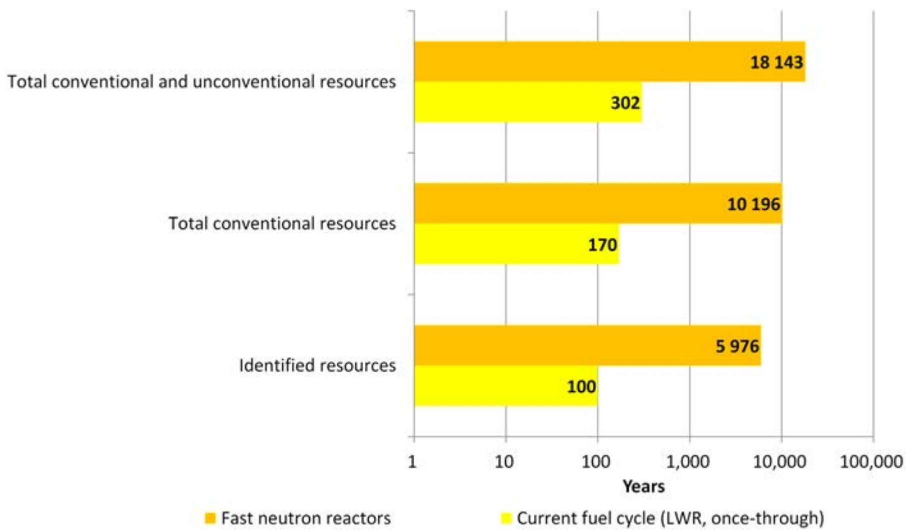

FIG. 12. Physical resources for nuclear fuel in years of resource availability (below US $130/kg) at the 2013 utilization level. Source: Based on Refs [33, 35]. Note: LWR — light water reactor.

The spent fuel produced by nuclear reactors can also be regarded as a resource and not solely as waste. In OTFCs, spent nuclear fuel still contains some 95% of its original energy content [38]. Reprocessing of the unused fissile material can reduce the requirements for natural uranium by approximately 10–15%, mainly through the use of the plutonium extracted from spent fuel and recycled in mixed oxide (MO_X) fuel. This type of fuel is currently used in fewer than 10% of reactors worldwide. Reprocessing also reduces the volume, heat production and long term radiotoxicity of the remaining waste that requires disposal. However, unless these aspects are taken into consideration, currently, the high reprocessing cost and low uranium prices undermine the reprocessing option as well as the economic value of retrievability, a concept used to express an intention to retrieve the waste from a geological repository in the future for potential reuse [39]. The availability of more advanced technologies for waste treatment or a decision to recycle spent fuel in future reactors might increase this value and support the principle of intergenerational equality also regarding the option of retrievability (see also Section 5.4.1).

The vast majority of reactors currently in operation were designed to produce and use so-called thermal neutrons to bring about fission whose energy ultimately drives a station's turbines. In contrast — and as the name suggests — the so-called FRs produce and use neutrons which are faster (and thus more energetic) than thermal neutrons. These fast neutrons can 'burn' (fission) a broader range of the isotopes present in a reactor's fuel than is possible using thermal neutrons. They can also convert some non-fissionable isotopes in the fuel into isotopes which can then undergo fission. Taken together, these characteristics of fast neutrons result in FRs' effectively releasing far more of the energy present in a given quantity of uranium than do their thermal neutron based counterparts. In doing so, they also improve the management of high level radioactive waste by effectively converting (transmuting) those isotopes responsible for the most challenging radiotoxicity issues associated with such waste. Effectively, this approach enhances the recovery of energy from finite uranium supplies and minimizes the volume, heat load and lifetime of the most hazardous radioactive waste.

Currently, three experimental FRs (out of 15 constructed) with thermal power ranging from 40 to 65 megawatt (thermal) MW(th) and one commercial size prototype (out of seven constructed) with electrical output of 1470 megawatt (electrical) (MW(e)) are being operated worldwide [40]. Research on FR technology continues under a number of initiatives. International initiatives include the Generation IV International Forum and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) that assists participating Member States in assessing, developing and implementing innovative nuclear energy systems [41]. National initiatives include programmes in China, India, Japan, the Republic of Korea, the Russian Federation and other countries with the goal of having the first FR demonstration plants in operation around 2025–2030.

The Russian Federation currently operates the most powerful commercial FR (the BN-600 in Beloyarsk); it is constructing the BN-800 and has recently launched a federal target programme entitled New Generation Nuclear Power Technologies for 2010–2015 with Outlook to 2020 aimed at the development of several FR technologies as well as the related fuel cycles [42].

In Europe, a strategic and technological pathway for FR has been defined including the development of sodium cooled FR as a first track aligned with Europe's prior experience and two alternative FR technologies to be explored on a longer timescale: the lead cooled FR and the gas cooled FR.

Furthermore, in contrast with nuclear fission, which is the basis for currently operating reactors as well as future FRs, nuclear fusion promises to be a non-depletable energy source. In fission, heavy nuclei are fragmented releasing energy through a chain reaction, whereas fusion involves two light nuclei fusing together to form a larger one. A small part of the reactants' mass is converted into energy.

Fusion research entered a new era in 2006 with the agreement to construct an International Thermonuclear Experimental Reactor (ITER). ITER brings together States and organizations representing half of the world's population, including China, the EU, India, Japan, the Republic of Korea, the Russian Federation and the USA. The construction of ITER started in 2008 at the Cadarache facility in France. It will be the first fusion reactor and will produce 500 MW of fusion power, ten times more than the input auxiliary heating power. Beyond ITER, various countries have national programmes to build demonstration fusion reactors to supply electricity to their grids. Depending on the technology development road map adopted and the availability of funding, it is plausible that fusion research and development (R&D) will lead to successful fusion ignition experiments within a decade or so and commercially viable fusion reactors generating electricity by the second half of this century.

In conclusion, fissile resources of uranium (and thorium) are plentiful and pose no limitation to the sustainability of nuclear power. Furthermore, the reprocessing and recycling of unused fission material generated in reactors can extend the availability of identified resources to several thousands of years depending on the reactor configuration and fuel cycle. From the perspective of exhaustible resources, nuclear power is therefore unique in the sense that technology improvements can multiply the useful output while using a finite energy resource.

3.2. ENERGY RETURN ON INVESTMENT

The role of abundant, cheap and high quality energy sources (mostly oil, gas or electricity) in the development of modern civilizations is widely recognized. The energy returned on energy invested (EROEI) and similar concepts (e.g. energy payback time, energy money returned on invested [43]) provide a measure of the energetic efficiency of technologies and fuels. EROEI can be defined as the

> “ratio of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question” (Ref. [44] p. 1).

A typical example of its application would be the ratio of the energy contained in a given quantity of biofuel relative to the energy required to grow, harvest and process that quantity of fuel. The focus on EROEI as a metric has perhaps gained particular currency in the context of the recent public discussion as to whether corn based ethanol is a net energy gainer or not, i.e. whether its EROEI is greater than 1. It is important to note, however, that EROEI is not fixed: its values are likely to fall as easily accessed and processed forms of (often fossil) energy are exhausted or to increase when processes are improved, as happened with steel production and uranium enrichment [43, 45].

Nevertheless, an EROEI above the physical threshold of 1, meaning that more energy is being produced than is being consumed, is a desirable attribute of any energy chain — the greater the value, the better. Clearly, an EROEI value of less than 1 would challenge the viability of an energy chain. Published estimates of the ratio of EROEI for conventional oil and gas indicate that when the quality of reserves is taken into account, there has been a substantial decline over time: the EROEI was over 100 in 1930, dropping to 30 in 1970 and to some 11–18 in 2005 [46]. Therefore, it is not surprising that sharp increases in extraction costs over the past decade were recorded, particularly in the oil industry. Calculated EROEI values for coal appear to have so far remained relatively stable since coal reserves are further from being depleted, although in some countries, such as in China and the USA, decreasing EROEI trends have been observed [45, 47]. Similarly, given the relative abundance of uranium fuel sources and the small role played by the fuel in electricity generating costs, the EROEI of nuclear energy exhibits relative stability and will likely continue to do so over the long term.

The EROEI is also an indicator for comparing power supply technologies as it describes the overall life cycle efficiency, i.e. the ratio of electrical energy produced by a given power source to the amount of energy needed to build, fuel, maintain and decommission that power plant. Nonetheless, the scientific work in this area is rather scarce and inconsistent. One of the key methodological problems is the lack of a clear definition of spatial and temporal boundaries of the system, i.e. which of the energy inputs over the entire life cycle of a system are to be classified as investments. Furthermore, renewable energy sources have been treated inconsistently by weighting or multiplying the output energy by a factor of three (justified as ‘primary energy equivalent’) but comparing it with the unweighted output of other energies such as conventional plants [43]. Using a strictly consistent physical definition (exergy output for the energy returned), a recent study provides independent and comparable results for the various technologies summarized in Fig. 13 [43]. In this study, ‘unbuffered’ refers to raw generation without storage. However, some energy generation techniques need buffering (wind energy, photovoltaic (PV), concentrating solar power (CSP)) using technological solutions such as storage systems and overcapacities, which are included in the system borders, replacing the flexible usage of mined fuel with fuel based technologies. Fuelled energy sources already store energy in the fuel, so no additional buffering is necessary. Buffered sources include pumped hydro

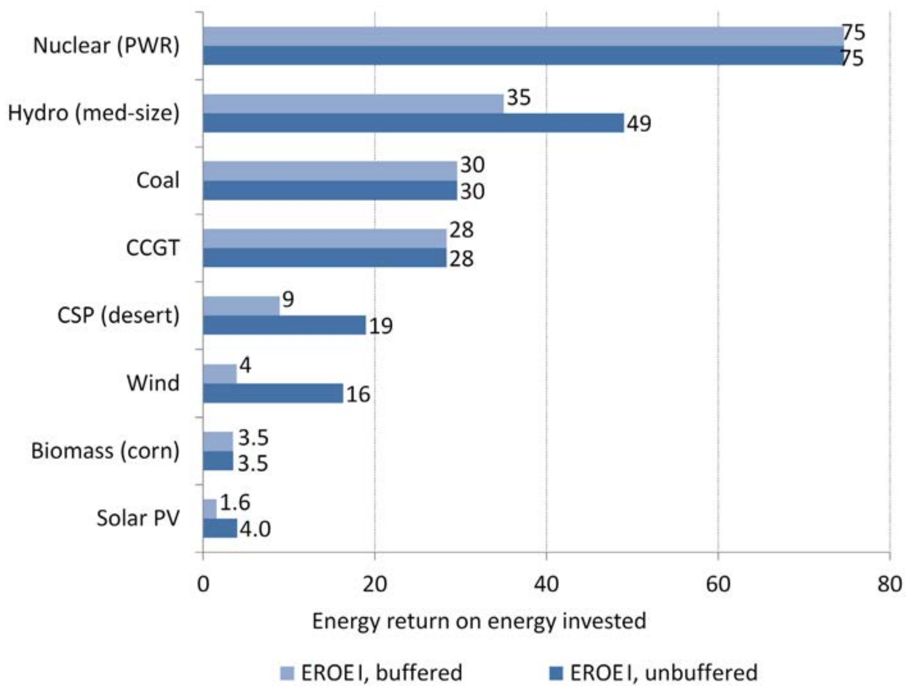

FIG. 13. EROEI for selected technologies. Source: Adapted from Ref. [43]. Note: PWR — pressurized water reactor: Enrichment 83% centrifuge, 17% diffusion; Coal: transportation not included; CCGT — combined cycle gas turbine; CSP — concentrating solar power: grid connection to Europe not included; Wind: location is Northern Schleswig-Holstein, Germany (2000 full hours); Biomass: maize, 55t/ha per year harvested (wet); Solar PV — solar photovoltaic: roof installation, south Germany.

storage where it is needed to buffer the difference in peaks between production and consumption.

Investing energy to build and operate nuclear, hydro, coal and natural gas power systems is one order of magnitude more effective than PV and wind power over their respective operational lifetimes. In particular, when backup is considered, alternatives such as solar energy and wind turbines do not appear to be nearly as cheap energetically as do the rest of the technologies. When the EROEI is considered, any transition to these alternatives would require massive investments of fossil fuels because these technologies are "dependent upon (i.e. constructed and maintained using and therefore subsidized by) high ERO[E]I fossil fuels" (Ref. [45] p. 150) and because of likely extensive and energy intensive storage infrastructures to partially offset inherent intermittency.

According to the EROEI indicators, nuclear power and run-of-river hydro offer the best returns. Indeed, the EROEI for nuclear power has been rising rapidly as the industry switches from the gas diffusion enrichment of uranium to centrifuge enrichment, estimated to be 35 times more energy efficient. Since the electricity used for uranium enrichment is added to the invested energy, it reduces the EROEI remarkably. For comparison, an NPP using 100% gas diffusion would have an EROEI of 31 whereas with 100% centrifuge enrichment, the EROEI would be of the order of 106, according to the analysis employed in Ref. [43]. The switch from diffusion to centrifuge increases the overall energy efficiency of nuclear power by a factor of 3.4.

The analysis of the EROEI highlights some of the merits of nuclear power and gives support to its potential role in a future sustainable energy mix for at least two reasons: (1) the EROEI of major fossil fuels has been decreasing over time, suggesting that technological advances are falling short of offsetting depletion effects, and (2) most renewable energy sources exhibit relatively low EROEI values pertaining to low capacity factors and aspects such as the employment of oil, natural gas and coal in the production, transport and implementation of wind turbines and PV panels [45]. Nevertheless, an adequate and thorough assessment of the sustainability of power technologies will also factor in other types of externalities.

3.3. GENERATION COST

Access to modern forms of energy, including electricity, can provide for a range of services to improve health, convenience and general conditions of life. However, such human development improvements can only be enabled if they are affordable. Affordability is a core element of SDG 7 on Energy (see Figs 1 and 3). Keeping prices at levels that allow consumers to benefit from energy and electricity services is therefore a social imperative of sustainable development. It is also desirable that such affordability results from the inherent cost characteristics of generating those services, as opposed to being the result of subsidies, although there are circumstances in which such subsidies may be justified (e.g. production subsidies for new technologies, such as feed-in tariffs for renewable energies and consumption subsidies to support access for the poor). Low electricity prices can also make industries and businesses more competitive internationally and result in higher overall productivity of the entire economy by boosting economic growth, creating jobs, sustaining higher wage levels and improving public welfare, thus contributing to SDG 8 on Decent Work and Economic Growth and to SDG 9 on Industry, Innovation and Infrastructure. Economic sustainability also requires the adequate pricing of goods and services, including energy and electricity, at levels compatible with the recovery of supply cost. Sufficient returns on investments are necessary to fund future capital spending and thereby avoid underinvestment and subsequent poor quality services.

NPPs have a front loaded cost structure, a feature shared with most renewables. They are relatively expensive to build but relatively inexpensive to operate. Unlike fossil based generating capacities, the low share of fuel costs in the total generating costs of nuclear power protects plant operators and their clients against resource price volatility. Thus, existing well run NPPs continue to be a generally profitable source of electricity. For new construction, energy choices at the national level are not expected to be made on a one size fits all basis. Suitable energy choices will reflect national circumstances encompassing resource availability, expected growth rates in energy demand and the regulatory framework, market structure and investment environment of a country. Energy security considerations may also play a part. Some but not all of these factors will be reflected in the costs of different energy sources. No less than the shares of other energy sources, the share of nuclear energy in a country's energy mix, specifically in its electricity generation mix, will be determined by a range of factors that are not limited to generating costs. Nonetheless, cost remains an important factor.

The full cost of nuclear power needs to be examined at two different levels. First, the direct explicit costs of generating 1 kW·h of electricity levelized across the lifetime of the power plant plus the related system costs need to be calculated. However, the levelized cost of electricity (LCOE) may not be indicative of prices in the markets, as cost and price formation are two distinct processes.

In particular, the current prevalence of out-of-market payments[12] may drive considerable differences between electricity prices and costs [48].

Second, the social costs, including all externalities, which currently remain unaccounted for despite being predominantly positive in the case of nuclear power, need to be considered. For instance, avoided CO_2 emissions are unrewarded social benefits (equivalent to the gap between the private and social costs of fossil competitors). As such, these benefits remain invisible to potential investors and cannot guide their decisions.

The IEA and the OECD Nuclear Energy Agency (NEA) regularly prepare studies on the projected costs of electricity generation. The latest study presents LCOE calculated on the basis of a common methodology using data supplied by countries and organizations [49]. Figure 14 shows the results for a range of major electricity technologies using three discount rates: 3% (corresponding approximately to the social cost of capital), 7% (corresponding approximately to the market rate in deregulated or restructured markets) and 10% (reflecting expected returns on investment in a higher risk environment). Higher discount rates make technologies with large upfront investment costs relatively more expensive. The large cost ranges in Fig. 14 reflect regional disparities influenced by market structure, the policy environment and resource endowments.

At the 7% discount rate, coal and nuclear sources largely overlap between US \$75 and US \$100/MW·h, whereas gas turbine costs are above US \$100/MW·h in all countries except New Zealand and the USA. At the 10% discount rate, the range of LCOE from nuclear power (US \$49–144/MW·h) remains in line with the costs of other baseload technologies, and below those of renewable energy sources. At the 3% discount rate, nuclear power, along with the lower fraction of large scale hydropower, is the cheapest option for generating electricity (the calculated median is US \$53/MW·h). Similarly to other capital intensive low carbon technologies, the overall cost of an NPP depends significantly on the cost of capital. As such, the LCOE of an NPP remains sensitive to lead times and capacity factor variations. Meanwhile, the relative costs of coal and natural gas fired generation are heavily contingent on fuel costs and the price of CO_2 emissions. A 50% increase in natural gas prices increases the cost of electricity generation by 35% while a carbon price of US \$90/t CO_2 increases the cost of coal generated electricity by 53%, both at the 7% discount rate. Contributions to decommissioning and waste disposal funds are collected and accumulated throughout the operating lifetime of NPPs and thus are internalized to a large extent.

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[12] Payments that are supplementary to the revenues earned in wholesale energy markets: taxes, levies and other charges (the ‘government wedge’).

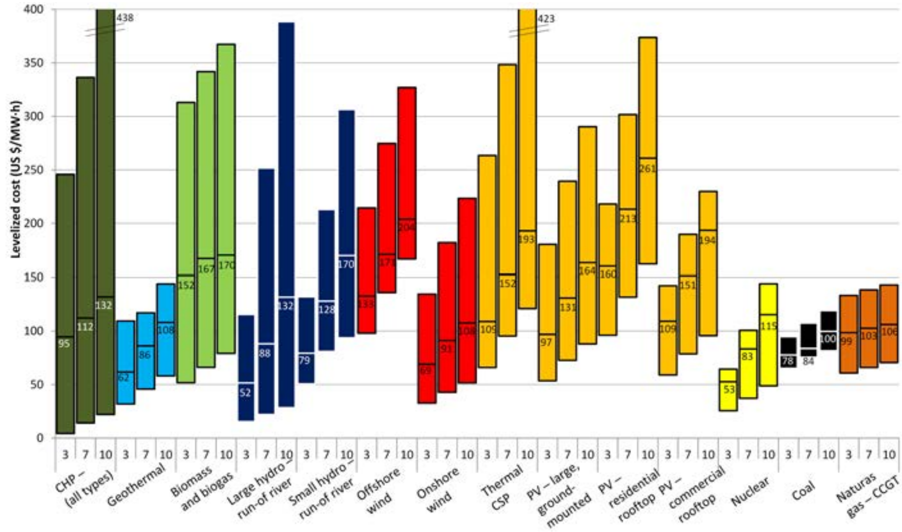

FIG. 14. Levelized costs of electricity generation associated with new construction at 3%, 7% and 10% discount rates. Source: Ref. [49]. Note: The bars represent the low and high ends, the horizontal lines and the value in each bar indicates the median; Carbon cost is US \$30/t CO_2; CHP — combined heat and power; CSP — concentrating solar power; PV — photovoltaic; CCGT — combined cycle gas turbine.

The levelized costs shown in Fig. 14 reflect the estimated actual costs of power generation but exclude system costs that arise from the additional investments and services needed to supply electricity at a particular load and specified level of reliability. System costs include investments required to expand and augment transmission capacities and distribution grids on the one hand, and short term balancing and long term adequacy costs to ensure the stability and reliability of electricity supply on the other. System costs are important to consider because they are ultimately paid by consumers as part of the transmission and distribution costs in their electricity bills or by taxpayers if there is some form of government support. The grid connection costs for intermittent renewables are 3 to 10 times higher than those of dispatchable technologies such as nuclear, coal and gas, and their balancing costs increase sharply with their shares in the power mix (Fig. 15). This means that for renewables, the system costs alone are close to the total levelized costs of gas, coal and nuclear electricity. Adding these system costs to levelized costs reinforces the cost effectiveness of coal, gas and nuclear based power generation. Nevertheless, depending on case specific circumstances, the expansion of renewables in the power system may entail some cost decreases if the need for other generation capacity is reduced and the associated fuel costs, CO_2 or other pollutant emission costs are lower.

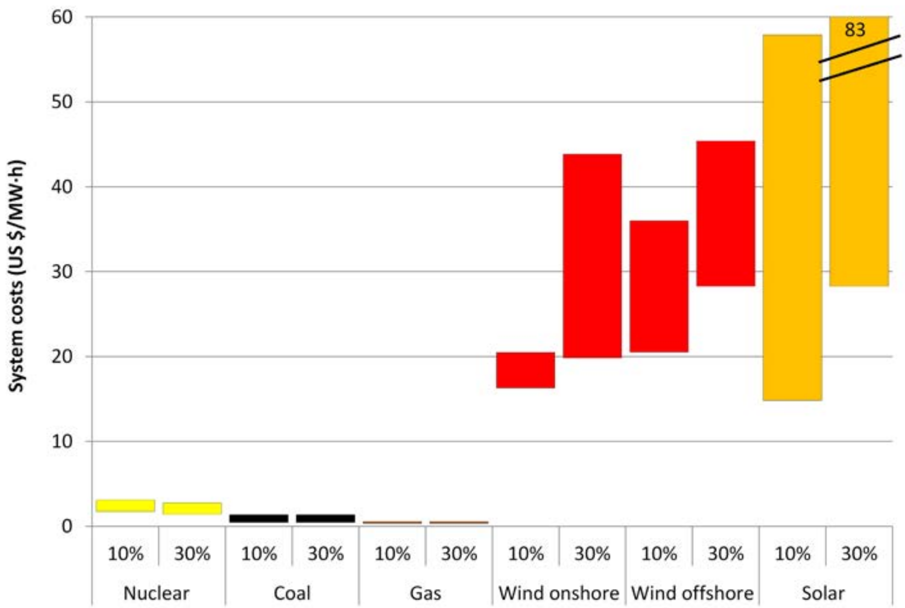

FIG. 15. Ranges of system costs (backup, balancing, grid connection, reinforcement and extension) of selected technologies at their 10% and 30% shares in the grid in selected countries (Finland, France, Germany, Republic of Korea, United Kingdom and the USA). Source: Based on table ES.2 in Ref. [50]. Note: The bars represent the low and high ends.

The levelized costs shown in Fig. 14 also exclude external costs such as environmental and health damage costs imposed on society as a result of the deployment of a particular form of generation, but not borne by the power plant operators. From a policy perspective, it is desirable to internalize such external costs (i.e. to ensure that they are reflected in the costs paid by generation owners) so that investment decisions would then be more closely aligned with socially desirable outcomes. For example, imposition of a carbon tax per kg of CO_2 emitted reduces the attractiveness of fossil fuelled generating technologies. In the absence of mechanisms to internalize these external costs, it is at least useful to quantify them as a first step towards inferring what a level playing field would look like if the costs paid by plant owners included all of the external costs associated with the plant's technology. A quantification of the impacts in monetary terms has become the core of many research projects, and their results provide relevant indicators for policy.

An extensive European study gives a sense of the magnitude of average external cost for selected existing generating technologies in the EU between 2005 and 2010 and for new generating technologies with CCS for 2025 [51]. The study monetizes (i.e. assigns a monetary value to) the externalities arising from the impacts on human health, biodiversity, crops and materials of familiar air pollutants such as ammonia (NH_3), NO_x, sulphur dioxide (SO_2) and particulates and the health impacts of heavy metals and radionuclides.

Figure 16 shows the results for a range of electricity generation technologies. The estimated external costs cover the entire life cycle (i.e. construction and decommissioning as well as the fuel cycle). The nuclear life cycle does not include radionuclides released from accidents at the power plant and from waste disposal. However, the external costs of both types of radionuclide releases are assessed to be small [51].

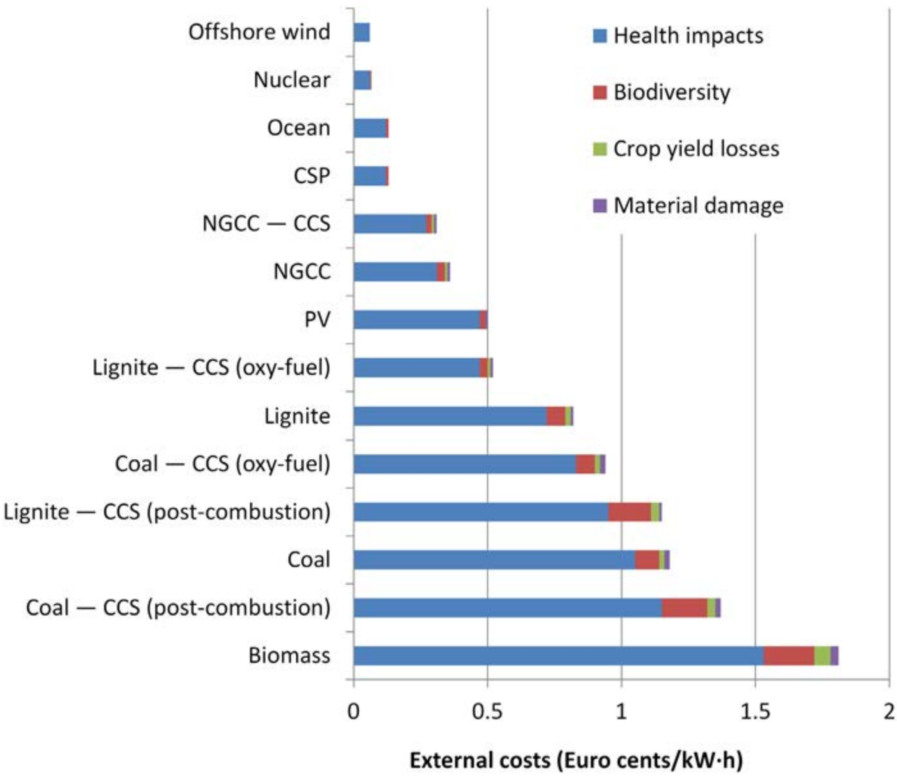

FIG. 16. Estimated average external costs in the EU for selected electricity generation technologies. Source: Ref. [51]. Note: Unit damage costs of emissions in 2010 are used for the calculation of external costs from existing technologies. External costs of future technology configurations with CCS (2025) are estimated by deriving unit damage costs of emissions in 2020. CSP — concentrating solar power; NGCC — natural gas combined cycle; CCS — carbon dioxide capture and storage; PV — photovoltaic.

Fossil based electricity generation has considerably higher external costs than nuclear power and renewable technologies. Through safety and environmental regulations, the nuclear industry has already internalized the bulk of its potential external costs.[13]

As mentioned earlier, cost is an important factor, although a plethora of other factors ought to also be considered in deciding whether to construct an NPP (such as available alternatives, the structure of electricity demand and market structure as well as regulatory and investment environments). Other things being equal, nuclear power's front loaded cost structure is less attractive to a private investor in a liberalized market that values rapid returns than to a government that can consider the longer term, particularly in a regulated market that ensures attractive returns. Private investment in liberalized markets will also depend on the extent to which energy related external costs and benefits have been internalized. In contrast, governmental investors can incorporate such externalities directly into their decisions. All these factors, including regulatory risks, political support and public acceptance, vary across countries.

3.4. FINANCING NUCLEAR POWER

Even if nuclear power is demonstrated to be an economically efficient option to diversify a country's energy supply portfolio and to reduce negative externalities, the financing of an NPP project presents its own unique challenges. With an average NPP taking five to seven years to build and costing approximately US $3.5–5.5 billion per plant [52], the upfront capital investment costs can be considerable to most economies. New models supporting the financing of nuclear projects have emerged in both regulated and deregulated electricity markets. A potential package of instruments in favour of low carbon technologies, negotiated under the new UNFCCC (United Nations Framework Convention on Climate Change) climate agreement (the Paris Agreement [53]) to enter into force in 2020, could also facilitate investments in nuclear power. Nonetheless, a clear commitment at the national level and a long term governmental strategy for nuclear development providing sufficient confidence to investors remains critical in raising the finance.

[13] There is insufficient information for estimating the incremental costs of the enhanced safety measures resulting from the international and national safety action plans after the Fukushima Daiichi accident. However, when spreading the one-time investment costs of improved safety measures over the long lifetime of NPPs, the LCOE of nuclear power is not likely to increase significantly.

The magnitude of the investment needed is often presented by the overnight cost indicator that seeks to capture the capital costs incurred if an NPP could be built instantaneously (or overnight), thereby abstracting from costs such as escalation and interest during construction (IDC). The most recent data on the overnight costs for nuclear power projects are US $1800–6600/kW(e) — with the mean around US $4500/kW(e) (Fig. 17). The variations in the investment cost levels can be explained by factors ranging from site characteristics and plant types/sizes to country specific financial, technical and regulatory conditions. The high end estimates are recorded in Western Europe and the USA whereas the lowest estimates are reported for China and the Republic of Korea. Particularly high overnight investment costs are encountered when constructing a first of a kind reactor and costs tend to decline when moving towards the construction of a fully mature nth of a kind plant. For instance, a potential saving of 10% in the total design and construction costs was recently estimated if a nuclear fleet[14] of up to eight new reactors was to be built by 2030 in the United Kingdom [54].

Overall or total capital costs also include both escalation and financing cost, mostly IDC. Given the large upfront capital requirements and lengthy construction periods associated with a nuclear project, IDC can be substantial: with a typical profile of spending on a nuclear plant construction, IDC could amount to US $1 billion over a five year construction period if financed at an interest rate of 5% and to as much as US $2.8 billion over a seven year period if financed at an interest rate of 10% [55]. On the one hand, IDC could be reduced if the construction period were shortened and if the nuclear industry were able to improve its performance to deliver "on time and to budget" (Ref. [52] p. 12). Alternatively, IDC could be reduced significantly if the required financial resources were obtained at lower cost. This cost reflects various risk factors such as construction risks (cost and duration), electricity price and regulatory risks (nuclear safety regulation) that can impact planning and construction times. It remains crucial to clearly define the roles and responsibilities of different stakeholders involved in a nuclear project (vendors, utility, host country, local supply chain participants and regulators) so that the risks can be better allocated among them.

Table 2 provides a summary of emerging models to reduce the riskiness of a nuclear project and examples of their successful implementation.

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[14] A fleet is defined as two or more pairs of reactors relying on the same reactor technology and common design of the conventional island and the balance of plant.

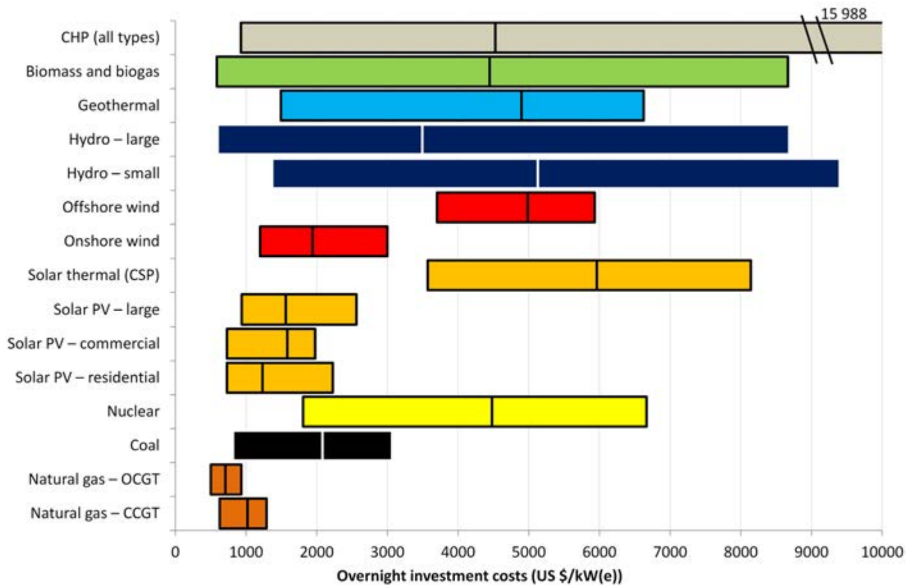

FIG. 17. Overnight investment cost estimates for selected electricity (and heat) generation technologies. Data source: Based on Ref. [49]. Note: CHP — combined heat and power; CSP — concentrating solar power; PV — photovoltaic; OCGT – open cycle gas turbine; CCGT — combined cycle gas turbine.

TABLE 2. ACTIONS SUPPORTING THE FINANCING OF A NUCLEAR PROJECT
(Based on Refs [52, 55, 56])

Action	Features	Example
Government-to-government financing	Financing is procured at government-to-government level, and its availability is specific to certain countries	• Implemented by the Russian Federation in a number of countries, including Bangladesh, Belarus, India, Viet Nam, Nigeria. • Implemented by China in Pakistan.

TABLE 2. ACTIONS SUPPORTING THE FINANCING OF A NUCLEAR PROJECT (cont.)

Action	Features	Example
Loan guarantees provided by host country governments or export credit agencies (ECAs*)	Guarantees may assure lenders of receiving full repayment of the loan and any interest owed on the guaranteed amount or they may protect the lender against a portion of potential losses	• Loans backed by the US Department of Energy and furnished by the Federal Financing Bank for developing the Vogtle 3 and 4 reactors in Georgia, USA. • UK Treasury guaranteed debt may finance 65% of the expected total costs of the Hinkley Point C nuclear project prior to operation. • The ECA's financing has been the key source of nuclear financing in the past and continues to play a role in most nuclear financing models.
Mechanisms to reduce electricity market risks	Mitigates uncertainties in long term electricity prices and hence assures lower interest rates by including an agreement to purchase some or all of the electricity generated by the NPP at a fixed price	• The UK's Contract for Difference effectively fixes the price of electricity at a strike price for the first 35 years of the Hinkley Point C project; consumers are committed through legislation to pay or receive the difference between the market price and the strike price, depending on which one is higher. • The total cost of the Akkuyu NPP project in Turkey is backed by a 15 year power purchase agreement for 70% of the electricity generated by the first two units and 30% of the last two units at an average price of US cents 12.35/kW·h. • The Mankala model (Finland), in which a consortium of electricity consumers (shareholders) benefit from the equivalent of a long term supply contract and stable electricity rates.

TABLE 2. ACTIONS SUPPORTING THE FINANCING OF A NUCLEAR PROJECT (cont.)

Action	Features	Example
Vendor financing in the form of equity stake	Addresses short term financing constraints on raising large amounts of long term debts	• The United Arab Emirates contract provides for equity shares for the Emirates Nuclear Energy Corporation and the Korea Electric Power Corporation for the design and construction of four 1.4 GW(e) NPPs. • ROSATOM (State owned company of the Russian Federation) is implanting a 'build, own and operate' model for four NPPs (a total of 4.8 GW(e)) to be constructed in Akkuyu, Turkey (see also the discussion of mechanisms to reduce market risks above).

* ECAs are sovereign or quasi-sovereign entities designed to promote the exports of a country.

In addition to the financing models outlined in Table 2, the latest report of the Intergovernmental Committee of Experts on Sustainable Development Financing (ICESDF) emphasizes the need to internalize externalities and mainstream environmental sustainability when mobilizing domestic public financing [57]. Policy measures such as cap and trade systems and carbon taxes seek to curb GHG emissions by raising the price of emissions and internalizing externalities. Such incentives could also support nuclear investments. Nonetheless, carbon markets remain relatively small, covering only 7% of the world's emissions. Furthermore, the impact of current carbon prices on the returns of low carbon investments is not sufficient to fill the gap between the private and social returns of such projects. The ICESDF report also suggests considering other governmental policies such as subsidizing R&D of clean technologies, tax incentives and feed-in tariffs as well as the inclusion of environmental accounting into national GDP assessments. It is important that, in changing the investment patterns, such public policies support a level playing field for all low carbon sources.

International public finance complements and facilitates national efforts on sustainable development. The future role of development banks in the financing of NPPs is currently unclear. Although they have financed past projects, development banks are not at present financing nuclear plants, but could potentially play a role in assisting developing countries interested in nuclear energy [52]. With a view to financing global sustainable development, the ICESDF report suggests further exploration of innovative mechanisms in the international community. International financial institutions, including the World Bank and other development banks, and specialized mechanisms, such as the Global Environmental Facility, the Climate Investment Fund and the Green Climate Fund, have the potential to increase the mobilization and deployment of finance for sustainable development.

In search of such an enabling environment for financing sustainable development, nuclear arguably merits treatment on an equal footing with other low carbon technologies and inclusion in the intergovernmental discussions and negotiations for the post-2015 development agenda on financing sustainable development.

3.5. ENERGY SUPPLY SECURITY

Energy security is a high priority of all societies. It includes a set of concerns such as the vulnerability of primary fuel supplies to physical interruptions, possible unanticipated movements in the price of primary or secondary energy forms and the reliability of the supply of energy to end users [58]. Attaining reliable and resilient (besides affordable and sustainable) modern energy services is another fundamental pillar of SDG 7 on Energy (see Figs 1 and 3).

Nuclear energy is well placed with regard to several dimensions of energy security illustrated in Fig. 18. (Resource exhaustion has been dealt with in Section 3.1 and is not revisited here.)

Concerning price stability, a key factor is that the operating costs of nuclear energy are a small part of the overall unit cost of electricity generation; by far the largest cost component is the upfront construction cost. The share of uranium in the generating cost structure of nuclear power is very small (7–10%), which makes total generating costs predictable and stable in the long run. Even a tenfold increase in the price of uranium would only increase the total cost of nuclear power by 18–36%. In contrast, for gas fuelled combined cycle gas turbines (CCGT) with a fuel cost share of around 70%, a mere doubling of natural gas prices translates into an 80% cost escalation [38]. Policy resilience is another attribute that reduces the exposure of energy sources to the risk of cost increases

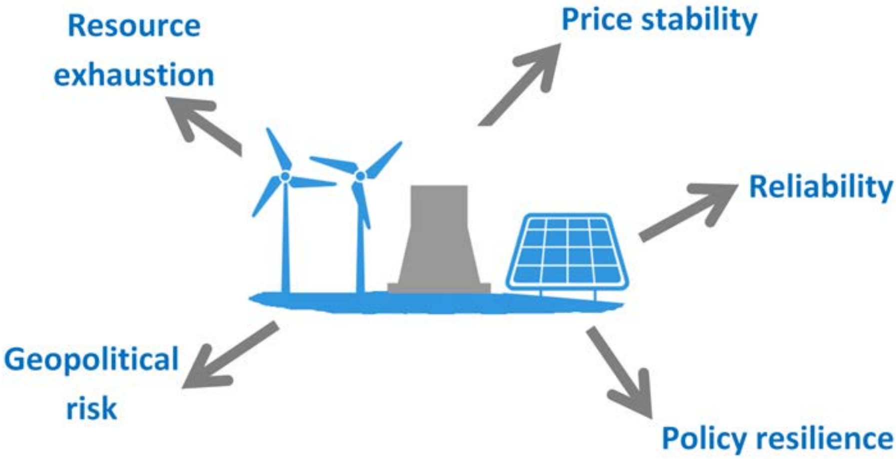

FIG. 18. Main dimensions of energy security.

and fluctuations resulting from international initiatives to levy a cost on GHG emissions. There is a widespread agreement among economists that only a global carbon price (through the establishment of a tax or an emission trading system) can constrain countries to reduce GHG emissions [59]. Nuclear based electricity production is carbon free during operations. This provides nuclear energy with enormous resilience against any changes in the global carbon policy [58].

As far as reliability is concerned, nuclear power is an established and reliable way of generating electricity. In normal operating conditions, given sufficient fuel supply, around 80% of the nuclear capacity can be assumed to be available to help meet peak demand for electricity. However, no power plant generates electricity 100% of the time. There are periods when NPPs need to be shut down for refuelling and maintenance or need to operate at reduced levels. Most of these shutdowns are planned, and can therefore be foreseen and adapted to times of lower demand. Unplanned shutdowns can also occur when the plant is forced to shut down either automatically or manually by the plant operator taking the decision as a result of a suspected fault in the plant. Such shutdowns are measured by the unplanned capability loss factor (UCLF) which is the percentage of maximum energy generation that a plant is not capable of supplying to the electrical grid because of unplanned energy losses (shutdowns, outage extensions or load reductions due to unavailability) (Fig. 19). As such, it is a suitable metric primarily for non-intermittent resources. Intermittent resources (e.g. wind) can fail to supply energy to a grid at times of high demand for one significant reason other than either (a) those underlying the UCLF, or (b) planned outages — namely the unavailability of the natural 'fuel' (wind or sunlight of sufficient

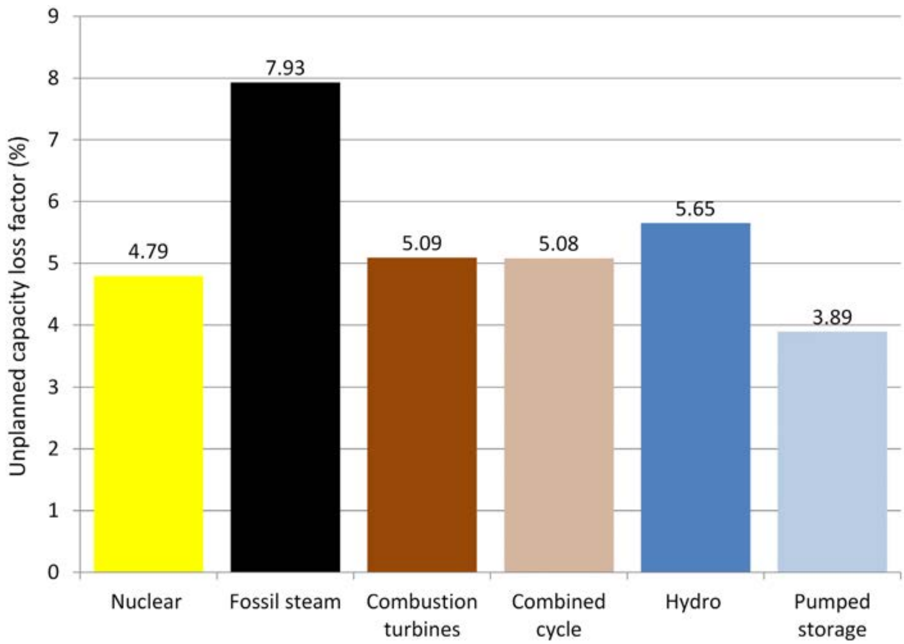

FIG. 19. Unplanned capacity loss factors by generating technology, 2005–2009 annual averages. Source: Based on Ref. [60]. Note: Nuclear is worldwide data; all others are North American data.

quality). As shown in Fig. 19, the UCLF of nuclear compares favourably with the performance of its alternatives.

Geopolitical risks arise when energy supply systems of a jurisdiction are deemed vulnerable to disruptions from outside their borders. In particular, the physical disruption of energy imports may be a particular concern for jurisdictions that lack domestic energy resources. One approach to mitigating such risks is to maintain a diverse domestic energy portfolio. Since the oil shocks in the 1970s, nuclear energy has been seen as a hedging instrument to decrease the risks associated with the dependency of OECD countries on imported fossil fuels.

The main drivers of nuclear energy in the diversification of energy supply include a globally even distribution of reserves (Fig. 20), lower level of risks associated with transportation and the possibility of accumulating significant stockpiles. Owing to the geographic variety of both uranium-rich and uranium producing countries and their sociopolitical stability, it is very unlikely that sudden changes in key supply countries would cause disruptions in global supplies of uranium. In addition, the small volume of nuclear fuel required to run a reactor makes it easier to establish strategic fuel inventories at a low cost. This is an important advantage in comparison with fossil fuels. For example, the

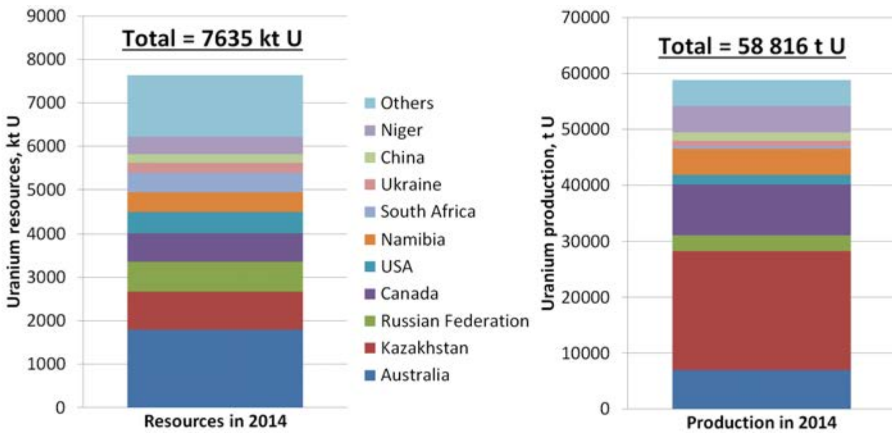

FIG. 20. Reported uranium resources and production in 2014. Source: Based on Ref. [33].

IEA requires its Member Countries to keep crude oil reserves equal to 90 days of the previous year's imports, at considerable cost. Furthermore, owing to the lower physical amounts of uranium needed for power generation compared with other fossil fuels, its transport is quicker and safer and can take various shipment routes, thus reducing significantly the risk of transport interruptions, avoiding risks associated with pipelines and limited transport corridors (e.g. recent tensions in the Strait of Hormuz).

Recent developments regarding the establishment of a reserve of fuel grade uranium (i.e. low enriched uranium (LEU)) owned and managed by the IAEA intend to provide additional insurance against geopolitical risk for IAEA Member States. Should the supply of LEU to a Member State's NPP be disrupted, and should commercial markets, State–State arrangements and all other such means fail to restore this supply, the Member State may call upon the IAEA LEU bank to secure LEU supplies at the market price prevailing at the time of supply.

Overall, in the face of geopolitical supply risks, whether due to import dependency, resource exhaustion or changes in carbon policy, nuclear energy is favourably positioned thanks to the widespread distribution of uranium resources, the limited transportation and logistics risks, the modest impacts of uranium price swings and the resilience to carbon policy shifts.

3.6. OTHER ECONOMIC CONSIDERATIONS

Engaging on a sustainable development path and transforming energy systems entails far reaching economy-wide impacts and can only be achieved with a holistic view of energy consumption patterns and the anticipation of the evolution of global energy markets while bringing development and global environmental sustainability together. This transformation affects the behaviour of all economic agents, from households to public administrations and private companies. Ambitious policy incentives need to be designed and implemented effectively to support the technological transition, translating into significant adjustments of market prices of energy as well as non-energy goods and services.

Establishing a more sustainable and climate resilient energy supply infrastructure is expected to result in higher energy prices. NPPs and their low operating costs can push the most expensive power technologies out of the merit order and therefore contribute to the mitigation of rising electricity prices. Supplementary policy measures to incentivize energy conservation remain vital to avoid a further rise in electricity prices, to alleviate future growth in electricity consumption and associated investments to produce energy. Improving the overall efficiency of power supply, supporting the adoption of efficient electrical appliances and demand side management tools also contribute to cutting energy bills and eventually stimulate the whole economy [61].

Adequate energy pricing is thus necessary to support the cost effective replacement or enhancement of ageing fossil fuel based power infrastructure with efficient, low carbon alternatives that are often more capital intensive. Electricity markets need to be designed to ensure the timely construction and maintenance of reliable power supply capacities. Applied electricity tariffs are needed to raise sufficient revenues for power utilities to recover their investment expenditures. The issue of the under-recovery of costs is prominent in poorer countries and hinders the development and financing of energy infrastructure [62].

The introduction or reinforcement of predictable carbon pricing schemes can also act as a mechanism for stabilizing end use energy prices in the mid to long term. About 40 countries and more than 20 cities, federal states and provinces have now implemented or are considering the introduction of a carbon pricing scheme to bring down GHG emissions. According to the World Bank [63] the initiatives currently in operation are valued at almost US $50 billion.

As developing or emerging countries often support the wasteful production and use of fossil fuels through subsidies, energy — predominantly electricity — is often underpriced. Getting energy prices right by removing these market distortions and misallocation of resources would assist governments in their fiscal consolidation efforts and would allow for further investments in critical areas such as education and public health. The International Monetary Fund recognizes that subsidies are particularly detrimental to fiscal sustainability and urges governments to take the opportunity provided by current low oil prices to implement reforms of existing subsidies and energy taxes to foster a smooth transition and alleviate impacts on end users before prices return to higher levels [64]. Some public funding could then be redirected to foster the deployment of low carbon energy, particularly substituting for coal and natural gas fired power generation and biomass burnt in cooking stoves in Africa and South Asia.

In 2013, nearly US $550 billion of public money was spent worldwide on direct fossil fuel subsidies that mostly benefited the wealthy, who use more energy than the poor [61]. Global post-tax energy subsidies even reach US $4.2 trillion (5.8% of the global GDP in 2011) if the environmental damage from energy consumption is factored in [65]. More than 20 countries have recently taken steps to cut subsidies to energy consumption, including Angola, Côte d'Ivoire, Egypt, India, Indonesia and Malaysia. Subsidies to fossil fuel resource extraction and energy production (e.g. through access to subsidized inputs, preferential tax treatment and direct budget transfers) are generally much smaller than consumer subsidies.

Tailored solutions to smooth transition in pricing regimes need to be identified in accordance with each country's circumstances, and public involvement is to be encouraged. A sustainable and socially acceptable reform of energy prices also accounts for its distributional impacts, particularly in developing countries, where heterogeneity in household disposable income and energy spending is very stark [61, 66]. Some caution is necessary during the phase of reduction or elimination of subsidies in order to avoid harming the poorest segments of the population disproportionately because higher energy costs reduce the affordability of fulfilling basic energy needs for households and harm the competitiveness of service providers and the manufacturing sector. To prevent an extra burden on the poor and on small firms, some redistribution mechanisms could therefore be put in place. According to the OECD, tackling inequality through tax and transfer policies can also be an engine of sustainable growth, provided that these policies are well designed and forcefully implemented [67].

4. THE ENVIRONMENTAL DIMENSION

4.1. CLIMATE CHANGE IMPACTS

Climate change is considered the most consequential sustainability problem because it triggers a virtually irreversible transformation of the earth's climate system. This transformation is likely to increasingly affect future generations by jeopardizing food and water supplies, leading to ocean acidification[15], loss of sea ice, longer, more intense heat waves and other extreme weather events. The earth's climate system is warming owing to increasing concentrations of GHGs, especially CO_2 emissions, resulting mainly from fossil fuel burnt in the energy sector. The urgency to combat climate change and its impacts is specified in the dedicated SDG 13 on Climate Action (see Figs 1 and 3). Furthermore, the Paris Agreement, signed in December 2015, marked a major milestone in concerted efforts to fight climate change [53]. It confirmed the target of limiting the increase in the global average temperature to well below 2°C above pre-industrial levels in order to reduce the potentially severe risks of climate change. In order to ratchet up actions in step with increasing mitigation ambitions, each party to UNFCCC is invited to communicate a Nationally Determined Contribution every five years starting in 2023. Nuclear power and other low carbon technologies will be fundamental in putting the world on this ambitious mitigation pathway.

As three quarters of global GHG emissions are energy related, the use of energy technologies that emit small amounts of CO_2 per unit of energy service is crucial to meet the needs of populations growing in size and affluence (especially in developing countries and in those that are least developed). Nuclear power is among the energy sources and technologies available today that could help meet this demand for growth in a climate friendly way. On a life cycle basis, nuclear power emits only a few grams of GHGs: a median value of 14.9 g CO_2-eq/kW·h with an interquartile range of 5.6–19.7 g CO_2-eq/kW·h was estimated based on more than 200 individual estimates (for light water reactors) published in the literature. The bulk of nuclear related GHG emissions stems from cement production, material production and component manufacturing in the construction phase, but emissions are also affected by the carbon intensity of the electricity supply and enrichment technology in the uranium enrichment phase [38]. Life cycle emissions from the nuclear power chain are comparable with the best renewable energy chains and several orders of magnitude lower than fossil fuel chains, as illustrated in Fig. 21. Even by adding CCS, the life cycle emissions of fossil fuel fired power plants remain relatively high — at about 190 g CO_2-eq/kW·h for coal and about 130 g CO_2-eq/kW·h for gas — owing to the loss of efficiency arising from additional energy requirements to capture CO_2 (known as the energy penalty).

[15] Some CO_2 gets absorbed by the oceans, eventually changing their acidity, which can have dramatic impacts on some organisms and cause knock-on effects throughout the food chain. Minimizing and addressing the impacts on marine life is specified in SDG 14 on Life Below Water.

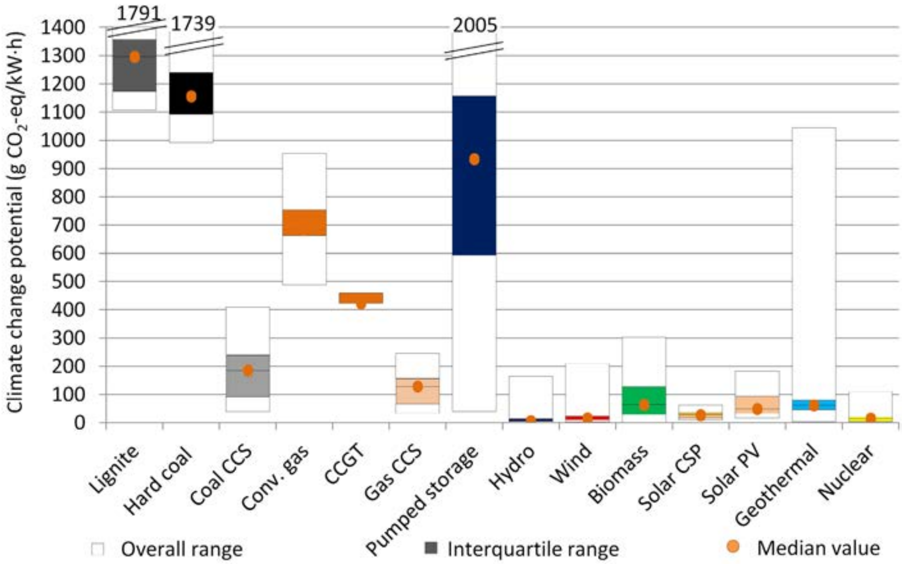

FIG. 21. Life cycle GHG emissions from electricity generation. Data source: Ref. [68]. Note: The interquartile range includes half of the calculations around the median of the overall range; CCS — carbon dioxide capture and storage; CCGT — combined cycle gas turbine; CSP — concentrating solar power; PV — photovoltaic.

Low carbon technologies have prevented significant amounts of GHG emissions over the past decades. It is estimated that in the period 1970–2012, the combined electricity generation from NPPs, hydropower and other renewables avoided the emission of over 157 gigatonnes (Gt) CO_2 relative to the emissions if that electricity had been supplied by coal, oil or natural gas fired generation. The contribution of nuclear power alone was 64.5 Gt of avoided CO_2 emissions.[16] Increasing shares of nuclear power in domestic electricity mixes contributed to the reduction of electricity related CO_2 intensity in countries such as Belgium, Germany, the Republic of Korea and the UK (see Ref. [69]).

In 2014, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) Working Group III [70] confirmed the significant potential of nuclear power in decarbonizing the global economy and, in

[16] This approach might underestimate the emissions avoided by nuclear power because, in the historical context of the 1970s, most of the nuclear capacity expansion occurred with the specific aim of reducing dependence on imported oil and gas, and therefore coal would have likely been the predominant non-nuclear alternative at that time.

particular, the power sector. In scenarios consistent with the objectives of the Paris Agreement (2°C target), nuclear generation capacity is projected to increase more than twofold (from 383 GW in 2015 to 930 GW in 2050). In addition to the stringency of climate policy, the mitigation potential of nuclear power will be influenced by the growth in energy demand and the share of that demand met by electricity. Furthermore, the market share of nuclear power will also depend on the technological development of other cost effective low carbon energy sources (such as wind, solar and geothermal) and, in particular, of CCS based technologies for which current costs and performances remain uncertain [70] (Fig. 22). The most favourable conditions for nuclear power expansion combine high levels of energy demand driven by economic growth and a rapid transition away from fossil fuel based technologies without CCS (see also Ref. [69]). However, the degree of nuclear power expansion in future electricity mixes could be moderated by the faster adoption of energy savings measures whose potential for climate change mitigation is considerable.

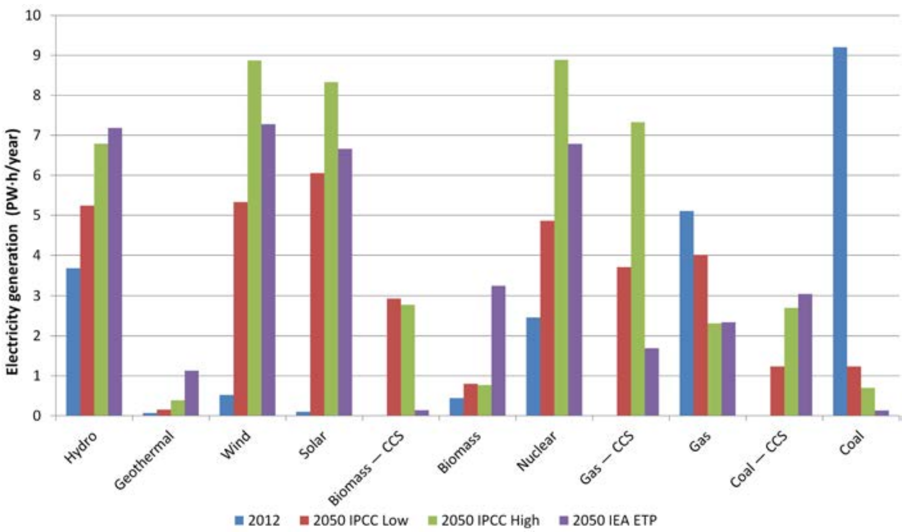

FIG. 22. Deployment of low carbon technologies for electricity generation in 2012 and 2050 in the IPCC 2°C scenarios with low and high energy demand and in the IEA ETP 2°C scenario. Source: Based on Ref. [30] and figure 7.11 in Ref. [70]. Note: 'IPCC Low' (resp. 'IPCC High') refers to median estimates of deployment with the growth in final energy demand in 2050 being less (resp. more) than 20% of the demand in 2010; CCS — carbon dioxide capture and storage.

The deployment of nuclear power can also decrease the aggregate global economic costs of reaching stringent mitigation targets [70]. It is predicted that the total discounted policy costs would increase by 18% to 23% in the stringent mitigation 2°C scenarios when global nuclear capacity is aggressively phased out relative to cases where nuclear power remains in the fuel mix [71]. In addition, more economic benefits of nuclear energy could be realized if non-power applications of nuclear energy (e.g. for hydrogen production, nuclear desalination and district heating) were also considered [72]. For example, in the transport sector, the principal mitigation options are: (1) reducing transport volumes; (2) reducing energy consumption through modal shift, e. g. from road to rail; (3) improving fuel efficiency; (4) using biofuels; (5) electricity; and (6) hydrogen. The extent of decarbonization of the power sector via the deployment of nuclear and renewable energy will play a key role in determining the mitigation contribution of options (2), (5) and (6). Plug-in hybrid electric vehicles can reduce CO_2 emissions by 66% relative to internal combustion engines if fuelled by carbon free electricity.

The deployment of hydrogen powered fuel cell vehicles could also moderate fossil fuel consumption and its associated GHG emissions. Nuclear energy can play a major role in hydrogen production for direct use by energy consumers either by thermochemical water splitting or via electrolysis. Thermochemical water splitting (heat and water combined yield hydrogen and oxygen) is a highly efficient and more economical process than electrolysis of water with electricity. However, its large scale development remains a technological challenge because of the required temperatures (750–1000°C). These high temperatures are compatible with the operation of certain reactor designs. Excess nuclear power beyond that required for hydrogen production could supply baseload electricity.

Nuclear power can contribute effectively to the mitigation of GHG emissions. Its potential to decarbonize the power sector and provide energy for alternative usage will depend on the national circumstances: the level of economic development of a country; the availability of cheap domestic fossil resources; the potential for using renewable energy; access to finance; and climate policies and standards being already in place or proposed, for instance in the future Nationally Determined Contributions under the Paris Agreement.

4.2. IMPACTS ON ECOSYSTEMS

Biodiversity and terrestrial ecosystems are essential for providing ecosystem services and benefits to society. Their preservation is specified in the post-2015 development agenda in SDG 15 on Life on Land (see Figs 1 and 3). The two main environmental disturbances — acidification and eutrophication — originate primarily from anthropogenic emissions of SO_2, NO_x and NH_3. Most of the SO_2 and NO_x is emitted into the atmosphere from fossil fuel combustion during the operation of power plants and industrial facilities, residential heating systems and in the commercial and service sectors. As well as its low GHG emissions, the use of nuclear power emits virtually no air pollutants that cause harm to ecosystems.

Acidification is the buildup of acid chemicals that give rise to acid rain, snow, fog and mist in wet climate areas, resulting in ecosystem impairment of varying degree, depending upon the nature of the affected ecosystems and on the acidity of the water, chemistry and buffering capacity of the soils involved as well as on the types of fish and other living beings that rely on the water. In dry climates, acid chemicals are incorporated into dust and smoke and then deposited on the ground, buildings and trees. These dry deposited gases and particles can be washed off by rainstorms, leading to increased runoff of more acidic mixture. Effects of acid deposition are widespread and appear in a number of ways, including acidification of freshwater systems resulting in the loss of fisheries, impoverishment of soils, damage to forests and vegetation, corrosion of buildings, cultural monuments and materials. Sulphate and nitrate transport across national borders also contributes to the occurrence of haze, strongly limiting visibility and reducing sunlight, and possibly changing the atmospheric and surface temperatures as well as the hydrological cycle [73]. Furthermore, human-made gaseous sulphur and nitrogen emissions are precursors to the formation of PM2.5, with detrimental impacts on human health (see Section 5.1).

An analysis of the up to date life cycle inventories in the Ecoinvent database (a life cycle inventory database) [74] shows that coal technologies present the highest acidification potential, whereas nuclear power is among the power generating technologies with the lowest acidification potential per unit of energy produced, as shown in Fig. 23. The underlying calculations take into account already implemented technical solutions to reduce emissions from energy technologies with high acidification potential, while any further reductions can be achieved at costs varying significantly across countries. Novel technologies such as fossil fuel based technologies with CCS (not shown in Fig. 23) are estimated to slightly increase the acidification potential compared with the corresponding technologies without CCS, mainly owing to increased demand for fuel and its associated transportation, but also due to mono-ethanolamine production and the disposal associated with the process of carbon dioxide capture [75].

Eutrophication results from increased concentration of chemical nutrients, thereby enriching the surface water bodies and soils, leading to abnormal biomass productivity. Eutrophication causes excessive growth of plants such as algae, resulting in severe impairments in water quality and reductions in animal populations. Emissions of ammonia, nitrates, NO_x and phosphorous to air and water all have an impact on eutrophication. Two of the most acute and commonly

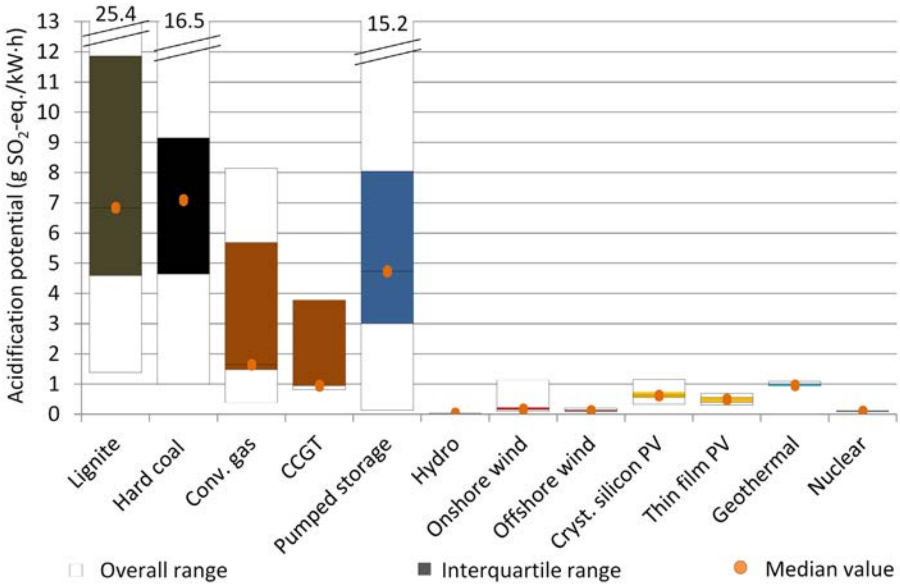

FIG. 23. Acidification potential of emissions from selected electricity generating technologies. Source: Based on Ref. [75]. Note: The interquartile range includes half of the calculations around the median of the overall range; CCGT — combined cycle gas turbine; PV — photovoltaic.

recognized symptoms of eutrophication are harmful algal blooms and hypoxia associated with limited oxygen replenishment from surface waters and leading to fish death. A harmful algal bloom, which occurred near Hong Kong in 1998, wiped out 90% of the entire stock of Hong Kong's fish farms and resulted in an estimated economic loss of US $40 million [76]. From region to region, there are significant variations in the relative importance of nutrient sources. Agricultural sources (commercial fertilizers and animal manure) are typically the primary sources of nutrient pollution in the waterways of the EU and the USA, whereas urban wastewater is often a primary source of nutrients in coastal waterways in Asia, Africa and South America. Fossil fuel combustion represents approximately one fifth of the contribution of synthetic nitrogen fertilizers. Nevertheless, in the Baltic Sea, atmospheric deposition, primarily from burning fossil fuels, accounts for as much as 25% of nitrogen inputs.

In the life cycle assessment framework, the eutrophication potential of NPPs is estimated to be very low; only run-of-river and reservoirs (alpine, non-alpine and tropical) show a slightly lower eutrophication potential (Fig. 24). The main sources of eutrophication from fossil based technologies originate from coal mining and transport, power plant waste treatment and NO_x emissions from

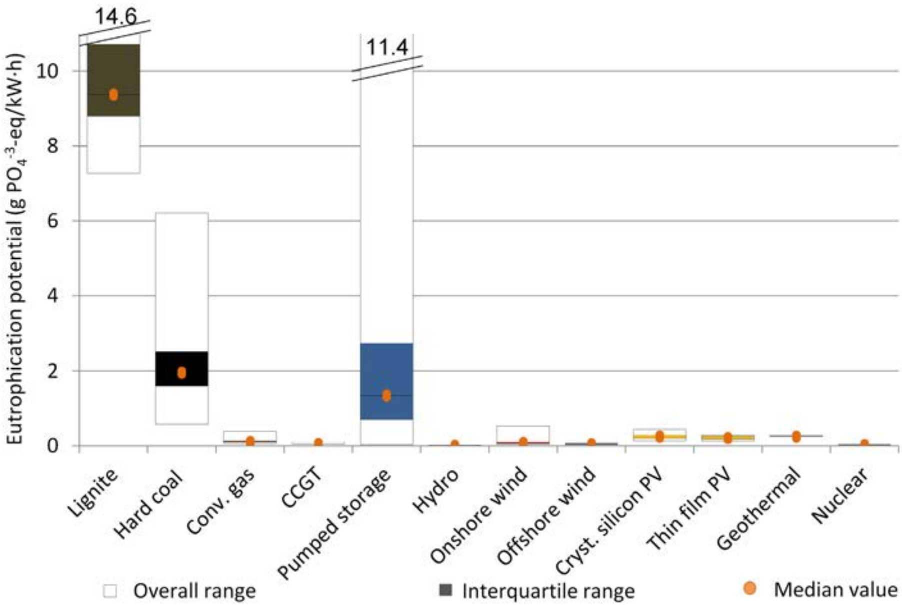

FIG. 24. Eutrophication potential of emissions from selected electricity generating technologies. Source: Based on Ref. [74]. Note: The interquartile range includes half of the calculations around the median of the overall range; CCGT — combined cycle gas turbine; PV — photovoltaic.

power generation. Similarly to the acidification potential, the eutrophication potential of CCS based technologies (not shown in Fig. 24) is found to double in comparison to power plants without CCS [75]. In general, the impacts of nuclear power on air pollution and ecosystems is very limited. The low acidification and eutrophication potentials of nuclear power can therefore contribute to the preservation of the integrity of natural habitats and can help avoid damages to human-made structures.

The abiotic resource depletion potential (ARDP) is another category in life cycle assessment measuring the impacts of different energy technologies on the environment. More specifically, it is a broader concept to characterize resource depletion encompassing the depletion of natural resources: fossil fuels (discussed in Section 3.1) as well as minerals such as iron, nickel and copper ores, for example. The ARDP considers all resources that will be used and required in a life cycle of a technology, not just fossil fuel resources, and is therefore an important indicator in the comparative assessment of energy systems. The ARDP is estimated for each extraction of minerals and fossil fuels by taking the ratio production/(ultimate reserve)^2 divided by the ratio production/(ultimate reserve)^2

for the reference resource (Antimony, Sb) and then multiplying the ratios with the quantity of the resources used and aggregating them. The reference unit for abiotic resource depletion is kilograms of Sb equivalent (kg Sb-eq). The indicator refers to the commercially available reserves. Because of the depletion of fossil fuels, the ARDP is obviously greatest in the life cycle of coal and natural gas, as shown in Fig. 25. However, some renewable energy sources (solar and geothermal) also display non-negligible ARDPs. This is owing to the higher metal requirements of the renewables relative to their electrical output [77]. Nuclear, wind and hydropower are among the technologies with the lowest ARDPs.

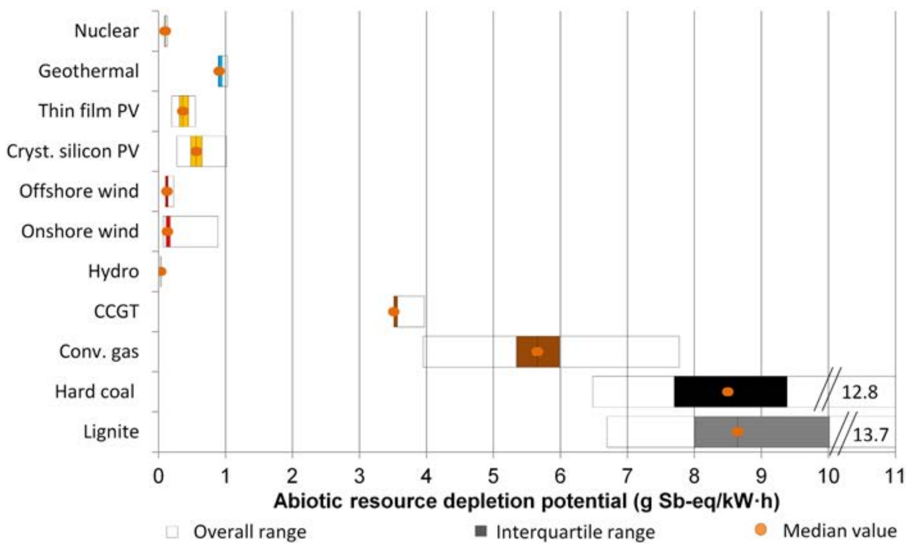

FIG. 25. ARDP of selected electricity generation technologies. Source: Based on Ref. [74]. Note: The interquartile range includes half of the calculations around the median of the overall range; CCGT — combined cycle gas turbine; PV — photovoltaic.

4.3. WASTE GENERATION

Waste generation is a key sustainability issue as it relates to the use of resources and the proper management of waste in order to avoid long lasting impacts for humans and the environment. Substantial reduction and environmentally sound management of waste is specified in SDG 12 on Responsible Consumption and Production (see Figs 1 and 3).

The quantity of fuel used to produce a given amount of energy — the energy density — plays a vital role in determining the magnitude of such impacts as it influences the fuel extraction activities, transport requirements and the quantities of environmental releases and waste. The high energy density of nuclear fuel relative to other alternatives for producing electricity is therefore an advantageous physical characteristic. The energy density of selected fuels are:

— 1 kg coal = 8.2 kW·h;
— 1 m^3 gas = 1.1 kg coal-eq = 9.0 kW·h;
— 1 kg oil = 1.4 kg coal-eq = 12.0 kW·h;
— 1 kg uranium = 2.7 million kg coal-eq = 50 000 kW·h.

Coupled with the nature of the conditions under which nuclear waste is generated, nuclear energy results in relatively low waste volumes that are subject to strictly controlled disposal, thereby following the so-called confinement strategy for waste management rather than the dispersion strategy[17] (e.g. CO_2 emissions into the atmosphere).

It is instructive to place the global production of radioactive waste in the context of overall global waste production. Worldwide, 8–10 billion tonnes of waste are currently generated annually; this excludes mining and mineral extraction wastes, which are usually not counted as waste. Of this, around 400 megatonnes (Mt) is hazardous waste and less than 0.5 Mt is radioactive waste. Moreover, the small overall volume of radioactive waste is generated by a relatively small number of easily identifiable generators (such as NPPs and nuclear fuel facilities); this small number facilitates the management, packing, transport and disposal of waste in compliance with strict regulation and careful control.

In order to maintain the efficiency of the reactor, NPP operators remove and replace spent uranium fuel every 18–24 months. It has to be either reprocessed or disposed of as radioactive waste. Around 2–3% of this radioactive waste — termed high level waste (HLW) — presents particular challenges due to its radiotoxicity and long half-life. The remaining 97–98%, representing only 8% of radioactivity, can be broadly categorized into low level waste (LLW) and intermediate level waste (ILW). LLW and ILW arise mainly from routine facility maintenance and operations. LLW can be contaminated clothing such as protective shoe covers, floor sweepings, paper and plastic. ILW can be, for

[17] Confinement is defined as a barrier surrounding the main parts of a facility containing radioactive materials that is designed to prevent or mitigate the uncontrolled release of radioactive material to the environment.

example, reactor water treatment residues and filters used for purifying the reactor's cooling water. The radioactivity of such forms of waste ranges from just above natural background level to more elevated radioactivity in certain cases, notably for components removed from inside the NPP reactor vessel. Disposal options that are considered highly suitable for LLW and ILW include engineered surface facilities and intermediate depth facilities, respectively. In contrast to HLW, disposal of LLW and ILW is already being implemented in several countries. On a volumetric basis, around four fifths of all the radioactive waste produced since the inception of the nuclear industry has already been sent for safe and controlled disposal.

The nuclear community generally agrees that the safety and isolation of the disposed HLW from the environment can be assured in stable geological formations combined with multiple engineered barriers. For example, continental shield rocks have proven their geological stability, as well as their favourable geochemical conditions and limited water movement, over hundreds of millions of years. Several planned repositories in various countries have been assessed with regard to potential radiation leakage for a period of up to ten million years. These studies showed that owing to the "efficiency of the technical (waste encapsulation, casks, repository engineering) and natural barriers (host rock)", the released doses are limited to "at most one tenth of a percent of the exposure to background natural radioactivity" (Ref. [38] p. 154).

Over the last two decades, there have been major advances towards the first operating disposal facility for HLW. As of April 2014, all vertical shafts of the underground spent nuclear fuel repository Onkalo in Finland had been drilled to the planned depth of about 450 m. After the initial period of ensuring the suitability of the underground rock facility, final disposal via the access tunnel and other underground structures is planned to begin in 2022. In Sweden, in March 2011, the Swedish Nuclear Fuel and Waste Management Company (SKB) has applied for the licences needed for a final spent fuel disposal facility. In July 2016, the French National Assembly passed a law on the procedures for the deep geologic repository project [78]. According to the National Agency for Radioactive Management (Andra), these parliamentary requirements will be included in the licence application, which will be submitted in 2018 [78]. All these examples show that the implementation of geological repositories spans decades owing to the long processes of characterizing, analysing and selecting sites involving high level scientific, political and public participation.

Non-radioactive waste also stems from nuclear power generation, but this is not limited to the nuclear energy industry. Other energy industry supply chains also generate various non-radioactive wastes. In some cases, this waste is disposed of in landfills, whereas in the case of waste containing toxic and hazardous elements, a special handling, treatment and/or disposal is required. If not managed appropriately, this waste can cause harm to the environment and to human health.[18] Globally, fossil fuels, in particular coal and lignite, which are used for electricity generation, produce the largest amount of solid waste per unit of energy output (Table 3). Nevertheless, consistent data for the comparative evaluation of solid waste streams from different electricity generating technologies is scarce. Radioactive waste from NPPs is the most documented waste stream; all other categorization of waste toxicity has received little attention. Bulk waste, hazardous waste, slag and ashes are reported as cumulative or single figures although their characteristics and management requirements are entirely different [85, 86].

TABLE 3. SOLID WASTE QUANTITIES OF SELECTED ELECTRICITY GENERATION TECHNOLOGIES
(Based on Refs [74, 79–84])

Solid waste from operational processes (g/kW·h)	Hard coal ash	84
	Lignite ash	172
	Oil ash	0.8
	Natural gas sweetening	4.7
	Nuclear non-radioactive — hazardous[a]	0.022
	Nuclear non-radioactive — other[a]	4.2
	Nuclear radioactive waste[a]	0.2
	of which HLW/spent fuel	0.004

[18] Millions of tonnes of coal combustion residues are regularly disposed of in landfills or in surface impoundments, which may lead to breakthroughs such as the breakthrough of a 72 acre coal waste impoundment near Inez, Kentucky, in October 2000, or to coal ash spills such as the massive spill at the Tennessee Valley Authority's Kingston facility in 2008. The latter spill flooded more than 300 acres of land, harming ecosystems and damaging homes and property.

TABLE 3. SOLID WASTE QUANTITIES OF SELECTED ELECTRICITY GENERATION TECHNOLOGIES (cont.)

Solid waste from upstream and downstream processes (g/kW·h)	Mining coal	3000
	Nuclear non-radioactive — hazardous[b]	0.01
	Nuclear non-radioactive — other[b]	0.97
	Wind — hazardous waste[c]	0.0485
	Hydro (reservoir, run-of-river)	310
	PV — heavy metals[d]	1.1E-05–3.3E-05

[a] Operational or core processes for nuclear comprise the operation, the interim storage of spent fuel, the treatment of low level radioactive waste with subsequent interim storage as well as the disposal of radioactive waste in deep geological repositories.

[b] Upstream processes for nuclear include uranium mining, conversion, enrichment, reprocessing, blending and fuel assembly.

[c] Hazardous waste mainly stems from the disposal of electronic components as these have been classified as hazardous waste; it is also produced in the surface treatment of the tower Section by both metallization and sand blasting.

[d] A range of heavy metals (cadmium, arsenic, chromium, lead, mercury and nickel) for the manufacturing of three types of solar photovoltaic systems: multicrystalline silicon, monocrystalline silicon and thin film cadmium telluride.

In most countries, waste from coal power generation is not yet classified as hazardous despite its heavy metal content[19] [61, 87]. Coal combustion residuals (CCRs) include fly ash, bottom ash, boiler slag and flue gas desulphurized gypsum. CCRs typically contain a broad range of heavy metals such as lead, mercury, arsenic, cadmium and nickel and acid gases such as hydrochloric and hydrofluoric acids. In countries with intensive exploitation of coal for electricity generation, waste from coal fired power stations is responsible for as much as 25% of the total waste produced [88]. CCS equipped power plants are expected to further increase the volume of waste generated to produce the same amount of electricity, owing to the energy penalty which is estimated to augment the demand

[19] For example, a new set of regulations in the USA, the Mercury and Air Toxics Standards, which are expected to come into force by 2016, could lead to the closure of more than 20 GW(e) of coal fired capacity. The new regulation is intended to reduce the emissions of hazardous air pollutants such as mercury and acid gases from coal and oil fired power plants.

for coal by 25–40%; this coal will need to be mined, transported, processed and combusted [89]. In addition, in contrast to spent nuclear fuel that can be stored safely and inexpensively for decades until the disposal facility becomes operational, immediate disposal of CO_2 is necessary for CCS based technologies, thereby imposing a real time constraint [90].

Manufacturing solar PV cells also generates toxic wastes of varying quantities depending on the technology and manufacturing process used and the PV conversion efficiency [80]. Disposal of most of these wastes is still unregulated, although total quantities of end-of-life PV panels might amount to millions of tonnes in the near to medium term future, given the sharp increase in PV capacity foreseen. If not disposed of properly, end-of-life PV panels might directly threaten humans and the environment by lead and cadmium leaching [91]. The burning of municipal solid waste containing potentially harmful material also produces waste constituents that may migrate into groundwater supplies if not contained safely. Therefore, the hazardous or non-hazardous nature of wastes ought to be determined ex ante to arrange appropriate management and disposal. Incineration of wastes is regarded as an important source of mercury emissions into the atmosphere. However, the information available on these emissions is very incomplete.

Some power generating technologies allow for partial recycling of the wastes produced. Recycling provides an opportunity to limit environmental and health impacts while adding value to resource use. Residues from coal fired power plants provide high potential for recycling. The ashes are widely used as construction material while the residues from flue gas cleaning (gypsum) can be used in the production of gypsum products. It is estimated that approximately 43% (54 Mt/year) of CCRs are reused in the USA, around 88% in Europe (53 Mt/year) and 26% in Canada (1.9 Mt/year). However, some concerns remain over the fate of mercury and other metals when CCRs are spread on land surfaces (e.g. in mine reclamation, highway construction, soil amendments, agriculture, and concrete and cement production) or are used as a raw material that will be eventually disposed of (e.g. the disposal of wallboard in unlined landfills). In particular, the impact of advanced mercury emissions control technologies (e.g. activated carbon injection) on some potentially beneficial uses of CCR is uncertain. For example, the presence of increased concentration of mercury or high carbon content may reduce the suitability of CCRs for use in some applications (e.g. carbon content can limit fly ash use in Portland cement concrete) [92].

A number of treatment and recycling processes are under development for PV panels. The most common ones relate to recycling semiconductor material and glass [91]. The European Directive on Waste Electrical and Electronic Equipment [93] makes it compulsory for manufacturers to take back and recycle at least 85% of their PV modules free of charge. Nevertheless, the financing mechanism, which is a crucial element for the sustainability of any waste management scheme to ensure the availability of the necessary financial resources at the end of the modules' life, remains unclear in many countries.

Spent nuclear fuel (which is not a waste until declared as such) can be, and routinely is, recycled in some countries[20] via reprocessing to recover and reuse its fissile content [77] to reduce the need for uranium ore and to mitigate the associated environmental burdens while simultaneously reducing the volumes of HLW. New methods (e.g. partitioning and transmutation) are emerging to convert long lived radioactive waste components to shorter half-life species. Another alternative to address long term HLW related concerns is the introduction of fully closed fuel cycles using FRs and continuously recycling all actinides until they fission so that only nearly actinide-free reprocessing wastes would go to final disposal, as discussed in Section 4.3.1.

A unique feature in the economics of waste management in nuclear energy concerns the possible partial financing of radioactive waste disposal by electricity sale revenues. By contrast, the management of hazardous waste from other energy producing technologies is generally carried out on a commercial basis with immediate payment for the service received and is thus more exposed to market swings. Representative costs remain difficult to establish since fees vary greatly according to waste types and treatment options [77].

4.3.1. Waste characteristics of selected nuclear fuel cycles

In order to examine the impacts on waste, the IAEA developed several nuclear energy system scenarios on the basis of experience and estimates from countries pursuing FR development programmes (China, France, India, Japan, the Republic of Korea and the Russian Federation). Two 'steady state' scenarios (both with a constant power capacity of 60 GW(e) and about 400 TW·h electricity output per year during the 21st century) have been selected: the currently dominant thermal OTFC and the future fully closed nuclear fuel cycle (CNFC) with fast reactors. Selected results of the study are displayed in Table 4.

[20] As of 2009, China, France, India, Japan, the Netherlands, the Russian Federation and the UK reprocessed most of their spent fuel.

Owing to their higher operating temperatures in comparison with current water cooled reactors, FRs have higher thermal efficiency and produce less HLW per unit of electricity in the CNFC system. This is also true in the case of all advanced high temperature power reactors regardless of whether they have open or closed fuel cycles. Moreover, in comparison with open or OTFC, the FR system, where all actinides are recycled (CNFC), reduces the amount of transuranic elements (Pu, Am, Cm) for final disposal by a factor of about 200. These elements account for the bulk of long lived radiotoxicity in HLW in a final waste depository. Furthermore, recycling all plutonium and minor actinides in CNFC systems reduces significantly the radiotoxicity of radioactive waste to be disposed of. The level of radiotoxicity in the HLW equivalent to natural uranium ore is reached in several hundred thousand years in the OTFC system, whereas only a few centuries are needed for the CNFC system. Despite the longevity of the radiotoxicity of transuranic elements in a final waste depository, it is important to note that these elements do not migrate, therefore they have a small or non-existent potential to impact the environment.

TABLE 4. WASTE CHARACTERISTICS OF SELECTED NUCLEAR FUEL CYCLES
(Based on Ref. [94])

	OTFC	CNFC
Plutonium, americium and curium for waste disposal (kg/TW·h)	27.9	0.15
Time for radiotoxicity to reach the level of uranium ore	Several hundred thousand years	Several centuries

4.4. WATER USE IMPACTS

Nearly all socioeconomic activities and ecosystem functions depend on water. Continuing current practices with regard to water use will lead to an increasing gap between unsustainable global supply and demand for water withdrawal. Proper management of freshwater resources and equitable share of its benefits is essential for sustainable development [95]. The post-2015 development agenda tackles the issues related to water scarcity and water pollution in the dedicated SDG 6 on Clean Water and Sanitation (see Figs 1 and 3). Water resources are, to a large extent, used locally for multiple and competing purposes, including electricity generation that requires large volumes of water. In the USA and the EU, over 40% of total water abstractions serve as cooling water for power stations.

Studies on water use for electricity generation commonly stress the relevance of the life cycle approach that distinguishes between and accounts for upstream and operational water uses. Upstream use refers to water used, for example, for the fabrication of generating devices and stations. Operational use refers to water used during power plant operation, typically for cooling purposes in thermoelectric plants. A distinction is made between the amount of water withdrawn (i.e. removed from the ground or diverted from a surface water source) for use and the amount of water consumed (i.e. evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment) and not returned to its source. A large volume of the withdrawn water is typically returned to its source and is thus available for subsequent usage, albeit with altered heat and/or oxygen content characteristics.

A recent life cycle assessment of water use by different power generation technologies in the USA [96] highlights the sensitivity of water use factors (measured in litres per MW·h (L/MW·h)) for thermoelectric plants (fossil and nuclear) to the nature of the cooling system employed[21] (Fig. 26). Typically, open cycle (once-through) cooling systems withdraw 10 to 100 times more water per unit of electricity generated than closed cycle cooling systems (cooling towers and ponds), although most of the water is returned to a receiving body. In contrast, closed cooling systems require less withdrawn water, but consume (evaporate) at least twice as much water as open cooling systems [97]. Based on two key assumptions (see below), the study suggests that, when measured over the entire life cycle, water withdrawals are of the order of 4168 L/MW·h for NPPs with cooling tower technology, compared with 3804 L/MW·h (respectively 958 L/MW·h) for coal fired (respectively CCGT) power plants. Water usage doubles in fossil fuel power plants equipped with CCS. With the exception of biomass, less water withdrawal is needed for renewable based electricity: PV systems require 1900 L/MW·h, wind farms use 230 L/MW·h and only 50 L/MW·h is used for hydropower. However, the study does not take into account backup generation capacity, which is required when output from renewables is variable. The study also stresses the assumption under which water used during the upstream phase (i.e. during the production and fabrication stages of the equipment for renewable technologies) is not treated as withdrawal. When this assumption is removed, the total life cycle water withdrawal for wind

[21] The issue of water scarcity is region dependant and water use is often inefficient in areas where it is abundant. Consequently, samples of water withdrawal factors from water abundant areas are of less relevance as compared to areas where water is scarce.

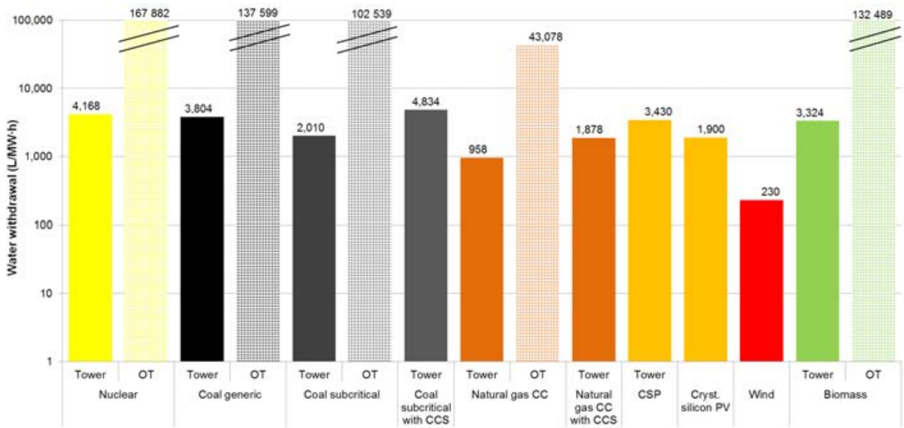

FIG. 26. Life cycle water withdrawal factors for selected electricity generating technologies in the USA (L/MW·h). Source: Based on Refs [96, 97]. Note: OT — once-through cooling system; Tower — cooling tower technology; CCS — carbon dioxide capture and storage; CC — combined cycle; CSP — concentrated solar power; PV — photovoltaic.

and PV technologies increases dramatically (to levels more than two orders of magnitude higher) (see Fig. 4 in Ref. [91]).

As an important user of water, the power sector is also highly vulnerable to changes in water availability, especially those that may result from potential climate change impacts, e.g. heat and droughts [98, 99]. Globally, 44% of the operational nuclear reactors are situated on the coast. These NPPs use seawater for cooling and are thus immune to such risks. Potential changes in ocean temperatures are not deemed radical enough to affect cooling capacity or trigger regulations related to heat discharges. Because high withdrawal and discharge rates impact oceans only moderately, reactors using seawater for cooling typically opt for cheaper once-through systems compared to closed cycle cooling systems. As such, the advantage of low water consumption of closed cycle cooling systems cannot justify their adoption for such sites [100].

Inland NPPs (56% of all operational reactors) are more vulnerable to heat and drought events. Older plants tend to use once-through cooling systems, whereas more recently built NPPs use closed cycle cooling systems in response to high water withdrawal and stringent regulations on water discharges. Closed cycle cooling systems reduce water withdrawals but come at the expense of increased water consumption that may benefit an abundant water body but may raise issues in areas with regular water shortages. In places where the minimization of water consumption is a critical priority, dry cooling may be the preferred option in spite of its costs, both in energy and economic terms [100]. Other water saving cooling technologies include: (a) the use of alternative water sources such as wastewater, (b) the increased effectiveness of cooling towers through greater intensity of water usage and (c) the recovery of evaporated water [101].

There is also scope for using water more sustainably in non-electric applications of nuclear energy, in particular in desalination. Desalination of seawater and brackish water can help overcome existing freshwater scarcity, avoid regional and territorial conflicts and provide water to support sustainable development. After four decades of experience in water desalination, desalinized seawater is considered a reliable and abundant source of drinking water [102] as evidenced by the rapid expansion of contracted seawater desalination projects. The contracted capacity of seawater desalination plants worldwide has been increasing steadily since 1965 and reached a total capacity of 78.4 million cubic metres per day (m^3/d) in 2013 [103]. The viability and reliability of seawater desalination using nuclear energy has been demonstrated successfully with nearly 200 reactor-years of operating experience accumulated worldwide [104]. Two nuclear desalination plants operate currently in India: a 6300 m^3/d nuclear desalination demonstration plant coupled with a power station and a low temperature, first of a kind desalination plant coupled with a research reactor. In June 2010, China started operating its first seawater desalination system associated with an NPP, with a freshwater production capacity of 10 080 m^3/d. In Japan, several desalination facilities linked to power reactors exist, each providing 1000–3000 m^3/d of drinking water, which is used for the reactors' own cooling requirements.

Most desalination plants today use fossil fuels as their primary energy source. The combustion of fossil fuels for desalination purposes produces large amounts of GHGs and other toxic emissions. Conservative estimates in the Mediterranean region indicate that the production of 10 million m^3/d of water from seawater desalination using fossil fuels would release 200 Mt CO_2/year, 200 000 t SO_2/year, 60 000 t NO_x/year and 16 000 t volatile organic compounds per year [105]. The use of nuclear or renewable energy for desalination would avoid such emissions. With low discount rates, nuclear desalination proves to be the most economic option and presents a smaller risk profile than fossil fuelled desalination. With higher discount rates, nuclear desalination remains a lower cost option in 80% of the cases, depending on fossil fuel prices [104]. This probability reaches 90% if a carbon penalty is applied. Nuclear desalination faces several challenges, including the need for a suitable infrastructure and skilled human resources, its capital intensive process and its need for public acceptance. Looking to the future, depleting resources, the uncertainty of fossil fuel prices and environmental concerns are likely to lead to the favouring of nuclear desalination.

4.5. LAND USE IMPACTS

Land use intensity of energy resources is an important dimension of sustainable development. Sustainable natural resource and land use practices form part of SDG 8 on Decent Work and Economic Growth, SDG 12 on Responsible Consumption and Production and SDG 15 on Life on Land (see Figs 1 and 3).

The existing literature reporting life cycle estimates for land use by energy technologies identifies various metrics and methodologies to describe the variety of uses of and impacts on land [106, 107]. Recent methods for quantifying land use include evaluating the direct and indirect life cycle use [108], total area (i.e. land associated with the complete project) and direct area impacted (i.e. land disturbed owing to physical infrastructure development) [109], percentage effective land use [110], temporary and permanent land area requirements [111], and land footprint (m^2 per capita) [112]. Despite sparse evidence, nuclear based electricity appears to be one of the technologies with the smallest land use footprints. However, the management of HLW requires the maintenance of future disposal sites that may increase the land intensity of nuclear facilities [108].

Life cycle assessment generally distinguishes between two classes of land use: transformation (land use change, m^2) and occupation (land use, m^2year) [113] per unit of capacity and/or electricity produced. Transformation refers to the total land area that needs to be converted from current use, a process often called land use change. Occupation, on the other hand, also incorporates the duration for which the converted area will be unavailable for other uses, including the time required for land restoration [114]. Most life cycle impact assessment methods consist of analysing land use impacts through the lens of biodiversity degradation [113]. Occupation impact is generally also considered, taking into account the time evolution of land degradation. In the case of mining related activities for conventional fuel cycles, the land occupation factor is particularly sensitive to the time frame of land restoration. For example, constructing a PV plant is significantly less harmful to land quality than coal mining [108]. Local circumstances are also important factors for land degradation. The local impact of NPP construction on land use is generally limited, even in countries importing large amounts of uranium ore such as France, Japan and the USA.

Figure 27 shows the life cycle estimates for land use for various electricity generating sources drawn from the Ecoinvent database [74]. The database provides estimations of total land use for each energy chain that corresponds to the sum of the different land types according to their transformation from the near natural state to one of the following states: dump, industrial, traffic area, reservoir and transformed ocean based area. The data also include active land restoration endeavours and the period of time during which the land is being used.

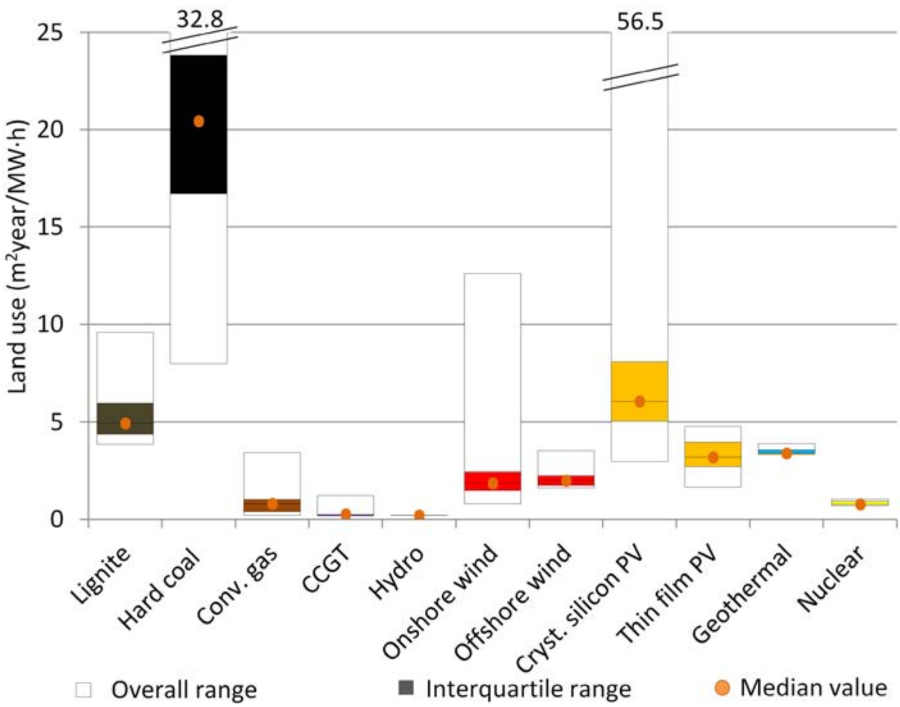

FIG. 27. Life cycle estimates of land use for selected electricity generating technologies. Source: Based on Ref. [74]. Note: The interquartile range includes half of the calculations around the median of the overall range; CCGT — combined cycle gas turbine; PV — photovoltaic.

The land footprint of nuclear facilities is among the lowest according to the data for the 55 light water reactors reported in the Ecoinvent database. Only CCGTs and hydroelectric plants (except those with pumped storage) are found to have a smaller median footprint (0.26 and 0.2 m^{2}year/MW·h, respectively) than nuclear (0.78 m^{2}year/MW·h) among the technologies considered.[22] In the nuclear fuel cycle, power plants account for the largest fraction of total land use (40%) whereas mining and fuel disposal make up smaller shares (25% and 24%, respectively) [108]. The high density of nuclear fuel and the low volumes of generated waste partially compensate for the long lasting impact on land use of radioactive waste disposal.

[22] These measurements remain sensitive to the definition of land use. Fthenakis and Kim [108] find even lower estimates of surface areas transformed by NPPs (0.12 m^2/MW·h in the USA). However, their metrics only refer to the process of land alteration relative to a reference state, while the Ecoinvent data factor in the full duration of land alteration.

By contrast, hard coal based electricity generation leaves the highest land use footprint per unit of generated electricity over the full lifetime of plant operation (median estimates of 20.4 m^2year/MW·h). The coal fuel cycle is mainly affected by the type of mining involved (open pit or underground), the restoration time, the land area dedicated to the power plant itself as well as the land used for conveying coal from mines. Because of the high ash content, coal waste disposal largely impacts the land use footprint of coal fired power stations [115]. In addition, only a partial restoration of land that has been dedicated to coal mining is generally possible. For instance, forest may be transformed into industrial or residential areas after the mining ends [108]. It can also be noted that the median value of land use for hard coal is five times higher than that for lignite. Among the factors explaining the difference is the fact that lignite power plants are built in the proximity of the mining site, while hard coal is often transported long distances, and storage facilities are required for large quantities of coal.

The land use footprint of hydropower depends on the size and type of the power plant as well as the topography of the site. Run-of-river plants, accounting for the majority of the Ecoinvent records, tend to have very low life cycle land use; hence the modest estimate for hydropower in Fig. 27. The footprint can be much larger if land needs to be flooded for a reservoir, especially in alpine conditions. Logically, dams with larger capacity reduce their land use footprint per unit of electricity generated.

Land use requirements for most renewable energy sources are highest during the operational stage. When examined on a full life cycle basis, a unit of electricity generated by most renewable energy sources (wind, PV, geothermal, bioenergy) is more land intensive than nuclear power, although these land use requirements exhibit a large variability. In the case of wind, wave and ocean/tidal energy, some spacing is needed between units, sometimes to the detriment of people living in surrounding neighbourhoods, to reduce the effect of turbulence and energy dissipation. With land use requirements ranging from 3 m^2year/MW·h to as high as 57 m^2year/MW·h, crystalline silicon PV panels, the dominant solar PV technology currently on the market, are at a considerable disadvantage relative to other power generation options[23] [109]. Local insolation and assumptions made on solar cell efficiency explain the variability in figures. Turney and Fthenakis [106] argue that the land use intensity of solar PV becomes somewhat smaller with the increasing age of the power plant, which is explained by the faster recovery time of the land transformed. However, the efficiency

[23] The statistical range for 72% of installed and under construction utility scale PV and CSP capacities in the USA has been found to be narrower: 11–22 m^2year/MW·h.

losses of PV cells relative to their nominal values (i.e. their performance ratio) would equally tend to increase with the age of the power plant. These losses are usually caused by the ageing of the electrical components, atmospheric dust deposition, non-optimal orientation and other indirect factors that are not taken into account by the nominal power rating of PV modules [116].

Future energy systems involving rising shares of renewables will often be accompanied by additional land requirements associated with the establishment and upgrade of distribution and supply networks, although to different degrees, depending on the technologies used [117]. Roof-mounted solar PV panels and solar thermal installations do not entail land use. The land occupied by wind, wave and ocean/tidal technologies can also be considered partial since other activities, including farming, fishing and recreation activities, can be conducted in parallel. By contrast, fossil fuel, NPPs and central PV and CSP technologies do not allow for parallel activity on power generation sites.

Existing data and evidence suggest that every unit of nuclear based electricity requires only a limited land surface in comparison with other power generation technologies. There is scope for methodological improvements towards a more thorough comparative assessment of the land use requirements for power generation, in particular, by factoring in the properties and conditions of the land required (e.g. arable land or brownfields[24], close or remote to centres of demand), the nature of land use (exclusive or allowing for multiple use) as well as the duration and reversibility of the transformation (former land use/cover, reclamation times) [117].

4.6. OTHER ENVIRONMENTAL ASPECTS: A NEXUS APPROACH

The environmental considerations outlined in this section demonstrate that technology choice in the power sector has important implications for the types and magnitudes of environmental impacts incurred when producing electricity. Such choices therefore involve important trade-offs as all power generation technologies are associated with some form of environmental risk and impact. The scale of natural resource use and the release of emissions, effluent and solid waste to the natural environment also means that policy and strategy in the power sector have ramifications well beyond the sector itself. Power generation competes with other uses of resources such as land and water, and it is a major source of a range of pollutants. This opens up the possibility for detrimental impacts in other sectors and the likelihood that policies and strategies promoting

[24] Brownfield is land previously used for industrial or some other commercial purpose.

sustainable development in the power sector can compromise progress towards policy goals in other areas.

For instance, agriculture and the power sector are the largest users of water and the two sectors combined account for over 90% of total water withdrawals worldwide [118]. Increased water allocation for power generation could therefore impact the amount of water available for agriculture. It is therefore conceivable that policies to reduce carbon emissions from the power sector could adversely impact water and food security. As depicted in Fig. 26, low carbon electricity can be both water intensive (e.g. biomass and solar thermal) or water efficient (e.g. solar PV and wind), indicating that promoting low carbon electricity can be either consistent with or detrimental to water conservation goals depending on the technology choice. Similarly, 2.5–3.0% of harvested land is devoted to energy crops [119, 120] and the increasing use of bioenergy can displace food crops. Figure 27 demonstrates that some sources of low carbon electricity are land intensive (e.g. solar PV, wind) while others have a high power density in terms of land use (e.g. nuclear power). It follows that the impact of low carbon electricity may either increase or decrease commercial pressures on land.

Such considerations have led to the idea that for a more comprehensive assessment of sustainability in the power sector, it must be considered not only with respect to the specific sustainability goals of the sector itself, but also in the context of policy goals in other sectors [2, 6, 121–124]. These concerns are often referred to as the energy–water–food nexus, as the ‘food versus fuel’ dilemma or by similar terms. This integrated view highlights how the challenges of providing these resources and services in a sustainable, safe and affordable manner are not separate but are interlinked challenges that require coherent and cohesive strategies and policies. This interlinked nature of the sustainable development challenge is depicted in Fig. 1.

One approach to address such concerns is the Climate, Land, Energy and Water (CLEW) framework codeveloped by the IAEA and partners [125]. CLEW is a set of methodologies for the integrated assessment of resource systems. It was developed to provide a means to simultaneously address matters pertaining to energy, water and food security. This is done while considering the impacts of the utilization of these resources on the climate as well as how society’s ability to continue employing these resources could be impacted by climate change. A driving motivation is addressing issues pertaining to policy cohesion by exploring the cross-sectoral impacts of individual policies and measures. A CLEW analysis explores how policies and actions intended to promote sustainability have ramifications beyond the targeted sector of the economy. The primary concern is to ensure that efforts undertaken in pursuit of one policy goal do not inadvertently compromise progress towards attaining goals in other areas. Conversely, there may be instances where an action has multiple benefits across various areas. Identifying such trade-offs and synergies can provide additional insights into development policies and support the formulation of robust sustainable development strategies [6, 120, 126, 127].

5. THE SOCIAL DIMENSION

5.1. IMPACTS ON HUMAN HEALTH

The post-2015 development agenda includes the dedicated SDG 3 on Good Health and Well-being (see Figs 1 and 3). Health constitutes human capital in sustainable development as well as a desirable outcome in its own right [128]. Average population health levels and inequalities in health indicate how well a society is functioning. Improving health also leads to economic development that usually leads to further improvements in health. Among the biggest threats to human welfare is the unsustainable use of energy and the associated air pollution (indoor and outdoor) at the local and regional levels.

Apart from its low GHG emissions and other environmental benefits, the use of nuclear power generates lower human health impacts than fossil fuel fired power generation and comparable health impacts to those of renewable energy sources [51, 116, 129, 130]. Life cycle assessments commonly measure human health damages in terms of disability adjusted life years (DALYs) [131] — an indicator that combines information on quality of life and life expectancy. It refers to the number of healthy life years lost due to morbidity or premature mortality, summing up the years of life lost and the years of life spent disabled. It commonly represents an end point level in life cycle impact assessment methods linked quantitatively with the most common midpoint impact categories such as human toxicity, ionizing radiation, ozone layer depletion, particulate matter formation and photochemical oxidant formation. These methods are sensitive to the characterization factors describing steps from the emission of a substance to the potential impacts on health.

Figure 28 shows the contribution of future centralized electricity generating technologies to total human health damage expressed in nano-DALY (nDALY) per kW·h. Health damages reflect average European estimates projected for the year 2030 assuming an improvement in average electrical efficiencies of installed

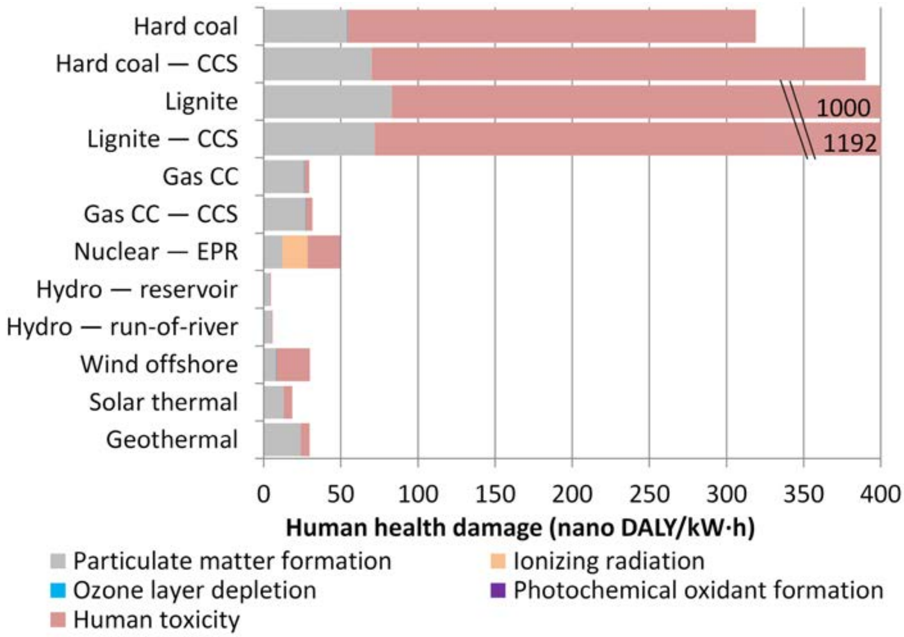

FIG. 28. Impacts of future centralized electricity generating technologies on human health. Source: Based on the hierarchist perspective of the Recipe life cycle impact assessment method[25] described in Ref. [129]. Note: CCS — carbon dioxide capture and storage; CC — combined cycle; EPR — European Pressurized Reactor.

power generation fleets from 36% to 46% for hard coal and from 50% to 62% for natural gas CCGT. More efficient power plants have a lower impact on human health. Nevertheless, despite sizeable improvements in efficiencies, the total health impacts of pulverized hard coal power plants are estimated to be on average 11 times larger than those of other technologies, with the exception of lignite fired power plants and hydropower. CCS equipped power plants exhibit higher health damage than technologies without CCS owing to their inherent energy penalty.

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[25] The recipe life cycle impact assessment method includes three perspectives: individualist (I), hierarchist (H) and egalitarian (E). The hierarchist perspective is based on the most common policy principles with regards to time frame; it is also the most frequently used and referenced perspective in the International Organization for Standardization standards on life cycle assessment. The individualist perspective is based on short term interests, whereas the egalitarian view is the most precautionary and uses the longest time frame.

Human toxicity and the formation of particulate matter are by far the most important contributors to health impacts related to electricity generation. Although all electricity generating technologies produce ionizing radiation at some stage of their life cycles, this impact is most prominent in the case of nuclear power. This issue is under continuous assessment by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR); the assessment focuses on the exposure of the public and workers to various sources of radiation. Apart from human-made sources of radiation from peaceful uses (e.g. nuclear power production and the medical use of radiation), these sources also include natural sources and enhanced sources of naturally occurring radioactive material (see below). Other health impacts due to photochemical oxidant formation and ozone depletion are found to be negligible for all technologies.

To characterize the health impact category in terms of human toxicity, an index is calculated to reflect the potential harm of a unit of a chemical released into the environment based on both the inherent toxicity of the compound and its potential dose [132]. The potential for human toxicity factors in all effects on human health, except respiratory effects caused by inorganics and the effects caused by ionizing radiation, ozone layer depletion and photochemical oxidation. Assessing the toxicological effects of a chemical emitted implies a cause–effect chain that links emissions to impacts through three steps: environmental persistence (fate), accumulation in the human food chain (exposure) and toxicity (effects) [133]. Nevertheless, this impact category is under continuous debate as to the reliability of models to calculate characterization factors for toxicological effects (route specific, scale specific, carcinogenic and non-carcinogenic) as well as to provide cumulative toxicological risks [134] and potential damage associated with a specified mass (kg) of a chemical emitted into the environment [135]. Owing to the difficulties of finding the most accurate characterization factors, human toxicity potential remains variable among different life cycle impact assessment methods, albeit consistently low for nuclear power.

The by-products in this impact category, mainly arsenic, sodium dichromate and hydrogen fluoride, are generated for the most part by coal power plants. These are chemicals that are potentially dangerous to human beings through inhalation, ingestion and even contact. Cancer potency is also a consideration [132]. The main part of human toxicity originates from upstream fuel supply chains (e.g. mining) and from the construction of renewable power capacities.

The impact category of particulate matter formation represents a complex mixture of extremely small particles. Particle pollution can be made up of a number of components, including acids (such as nitrates and sulphates), organic chemicals, metals and soil or dust particles [132]. Various life cycle impact assessment methods lead to very similar health impact estimates for this category. The World Health Organization (WHO) established strong links between both indoor and outdoor air pollution exposure and cardiovascular diseases, such as strokes and ischaemic heart disease, as well as between air pollution and cancer. Additionally, a multitude of respiratory diseases, including acute respiratory infections and chronic obstructive pulmonary diseases, are linked to air pollution. According to WHO estimates, around 7 million people died in 2012 as a result of outdoor and indoor air pollution exposure; this represents one in eight of total global deaths in that year [15]. Nearly 84% of these air pollution related deaths were experienced in low and middle income countries, in particular in the Western Pacific and south-east Asia regions [14]. In many cities in developing countries, the major sources of urban outdoor particulate matter pollution are transport and industrial emissions[26] [136] leading to the level of particulate matter often exceeding 70 micrograms per cubic metre (μg/m^3). Reducing it to 20 μg/m^3 (the air pollution concentration level recommended by WHO), air quality related deaths could be cut by around 15% [137].

NPPs emit virtually no air pollutants during their operation. On a life cycle basis, only hydropower and offshore wind technologies have lower health impacts than NPPs in the particulate matter formation category. A recent joint study by NASA's Goddard Institute for Space Studies and Columbia University's Earth Institute examined the historical and potential future role of nuclear power in preventing air pollution related mortality. The study estimated that nuclear power has prevented over 1.8 million air pollution related deaths globally that would have resulted from fossil fuel burning between 1971 and 2009. The study also included hypothetical scenarios in which the entire nuclear capacity projected by the IAEA in 2011 is phased out and progressively replaced by fossil fuels by 2050. The scenario based on the low IAEA nuclear capacity projection results in an increase of the number of premature deaths related to air pollution by 4.4 million, while in the high nuclear case the substituting fossil fuels cause seven million additional deaths. These projections confirm the benefits of maintaining and expanding the role of nuclear power in global energy supply [138, 139].

The impact category of ionizing radiation in life cycle assessment relates to the damage to human health that is linked to the emissions of radionuclides throughout the life cycle of particular energy chains. In general, a two stage approach is followed. First, fate and exposure models are used to assess the transport, dispersion and deposition of radionuclides and to derive values for

[26] The following sectors were the most important sources of primary PM10 emissions in 2011 in European countries: commercial, institutional and households (combustion related emissions from sources such as heating) (35%), industrial processes (29%), energy production and distribution, and energy use in industry (14%), road transport (11%) and agriculture (8%).

actual human absorption expressed in milligrays (mGy). Second, an effect (dose–effect relationship) and damage (DALYs) analysis is performed.

Epidemiological findings from exposed populations (e.g. survivors of the Hiroshima and Nagasaki bombings and their children, survivors of accidental irradiations in industrial or medical environments and uranium miners) show a statistically significant relationship between high radiation dose and health effects; risk estimates for many types of cancer at doses of 50–100 millisievert (mSv) for solid cancers, at about 200 mSv for leukaemia in adults and at about 100 mSv for thyroid cancers in children. Below these doses, a statistically significant dose–effect relationship could be neither demonstrated nor rejected owing to difficulties in measuring health effects from low dose ionizing radiation. Given the large number of cancers normally occurring in the population and the relatively small incremental effect due to the exposure to low doses, a very large statistical sample would be needed to measure a dose–effect relationship [140]. To overcome these complexities, epidemiological findings at medium and high exposure are generally extrapolated to low doses using a linear no threshold (LNT) relation (also employed in the Recipe and in other life cycle impact assessment models). The validity of the LNT method is therefore questionable in itself. For example, in case of a possible nuclear accident, the LNT method might overestimate the human health impacts from ionizing radiation because low dose exposure is the most relevant for professional and public exposures. According to the International Commission on Radiological Protection (ICRP), the LNT assumption should be used for radioprotection purposes only and not for the risk assessment of potential health effects on a large population at low and very low doses[27] [141]. Furthermore, UNSCEAR recommends not multiplying "very low doses by large numbers of individuals to estimate numbers of radiation induced health effects in a population exposed to incremental doses at levels equivalent to or lower than natural background levels" (Ref. [142] p. 10).

Current average effective doses to the global public from major nuclear accidents and military tests are very low[28] (Table 5). Doses received by people will keep on diminishing along with decaying radionuclides. Nevertheless, in major nuclear accidents, the surface activity concentration of radionuclides in the environment close to the accident sites can be severe and can remain so for years or decades. It is estimated that inhabitants of the contaminated areas due to

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[27] For example, many studies have used the notion of collective dose, obtained by adding the individual doses of all individuals exposed, to predict long term health effects of the accident at the Chernobyl NPP.

[28] Effective dose, expressed in Sievert, takes into account the impact of different types of radiation and their effects on the specific organs exposed by using appropriate weighting factors.

the Chernobyl accident have received an average dose of 9 mSv during the first 20 years of exposure [143] in decreasing increments over the years. Nonetheless, in 1986, the average dose to more than 300 000 recovery workers was nearly 150 mSv. Two workers died in the immediate aftermath and 134 suffered acute radiation syndrome, which proved fatal for 28 of them. Among the people who were children and adolescents at the time of the accident in affected areas of the former Soviet Union, more than 6000 cases of thyroid cancer have been reported (15 cases proved fatal up to 2005) that were principally attributed to contaminated fresh milk containing the short lived radionuclide iodine-131. Among the persons exposed to the highest radiation doses in 1986 and 1987, there are reports [144] of an increased incidence of leukaemia and cataracts. However, to date there is no other consistent evidence of other radiation related health effects.

TABLE 5. AVEARGE RADIATION EXPOSURE TO PUBLIC AND WORKERS
(Based on Ref. [143])

Average global public exposures [a] (mSv)			
Natural	*2.4*	*Artificial*	*0.65*
Food	0.29	Nuclear power plants	0.0002
Cosmic	0.39	Chernobyl accident	0.002
Soil	0.48	Weapon fallout	0.005
Radon	1.3	Nuclear medicine	0.03
		Radiology	0.62
Global radiological exposure of workers (mSv) (2000)			
Natural	*2.9*	*Artificial*	*0.5*
Aircrew	3	Medical uses	0.5
Coal mining[a]	2.4	Nuclear industry	1
Other mining	3	Other industries	0.3
Miscellaneous	4.8	Miscellaneous	0.1

TABLE 5. AVEARGE RADIATION EXPOSURE TO PUBLIC AND WORKERS (cont.)

Average effective dose per person in the USA (2007) (mSv)	
Natural	3.1
Total medical exposure	*3*
Interventional radiology	0.4
Diagnostic radiology	0.3
Nuclear medicine	0.8
CT scans	1.5
All others	0.14

[a] *Uranium mining is included in the category 'nuclear industry'.*

In Fukushima Prefecture, the doses to the general public, both those incurred during the first year following the accident and those estimated for the lifetime of the affected people, are generally low or very low. For adults, UNSCEAR estimates the average lifetime dose to be of the order of 10 mSv or less, and the first year doses to be one third to one half of that [145]. No radiation related death or acute diseases have been observed among the workers or among the general public. Furthermore, no discernible increase in the incidence of radiation related health effects is expected among exposed members of the public or their descendants.

Besides human-made ionizing radiation, radioactive nuclei are naturally present in the form of cosmic rays from outer space and natural terrestrial radionuclides existing in the earth's soil and in building materials such as granite and marble. The level of exposure to cosmic rays depends primarily on latitude and altitude. Exposure also arises from the intake of radionuclides in the earth's soil by inhalation (mainly radon) and ingestion (in the form of food and drinking water). The global average natural exposure to naturally occurring sources of radiation is 2.4 mSv and ranges from 1 to 13 mSv [145].

In summary, total human health damage from nuclear power remains relatively low and comparable to the damage caused by most renewable energy sources and natural gas CCGT plants. In this sense, nuclear power can contribute to the mitigation of human toxicity and air pollution effects.

5.2. EMPLOYMENT

The cost, reliability and ease of access to energy services are also factors in creating conditions for jobs, production and decent work. Improving the economic well-being of citizens is a key priority of sustainable development as reflected in SDG 8 on Decent Work and Economic Growth (see Figs 1 and 3). A nuclear project creates many long term jobs in operations, contracting and the supply chain. Nevertheless, employment and other macroeconomic impacts of nuclear power have received less attention, in contrast to the large volume of literature dealing with the issues of financing and waste management [146]. Furthermore, there are substantially more employment estimates for renewable energy sources than there are for fossil fuels and nuclear technologies. These estimates tend to vary within and across energy technologies owing to differences in assumptions and methods [147–149].

Energy related jobs are usually categorized into direct, indirect and induced jobs. Direct jobs are associated with producing and delivering energy products to final consumers. Indirect employment includes the number of people employed in sectors supplying the energy project with goods and services (e.g. the production of steel in the manufacturing of a wind turbine). Induced effects are generated through spending associated with direct and indirect employment (e.g. the spending of salaries). Indirect and induced jobs are estimated to account for what is termed the macroeconomic multiplier effect of increasing demand [147]. Due to the difficulties in their estimation, these types of jobs are reported less frequently than direct jobs. Nevertheless, studies estimating indirect and induced jobs generally agree that these often outnumber the creation of direct jobs. For example, in the USA, every job directly created by an NPP new build induces the creation of four additional indirect jobs in the rest of the economy [150]. The French example indicates that the nuclear industry in France generates 125 000 direct jobs and 410 000 jobs in total [151].

To compare employment estimates across technologies, Table 6 provides total (direct, indirect and induced) jobs for two job function groupings: (1) construction, installation and manufacturing (CIM) and (2) operations and maintenance (O&M), for five electricity generating technologies per effective capacity[29] of each project. The results in Table 6 show that solar PV, nuclear and geothermal projects create the most jobs in both the CIM and O&M categories of

[29] The effective capacity is calculated by multiplying the capacity factor of a given plant by the nameplate capacity of the same plant. For example, a 1400 MW nuclear power plant with a capacity factor of around 90% would have an effective capacity of 1260 MW(average) (MW(a)).

TABLE 6. CIM JOB-YEARS AND O&M JOBS NORMALIZED PER EFFECTIVE CAPACITY OF ENERGY TECHNOLOGIES
(Based on Ref. [147])

Technology	Effective capacity, MW(a)[a] (peak capacity, MW(p)[b] × capacity factor)	Total CIM (jobs-years/MW(a))	Distribution CIM (%) (direct/indirect/induced)	Total O&M (jobs/MW(a))	Distribution O&M (%) (direct/indirect/induced)	Total (jobs/MW(a))
Solar PV	15 (75 × 0.2)	157.8	(29/51/20)	3.27	(71/2/27)	9.57
Nuclear	1260 (1400 × 0.9)	42.5	(31/28/42)	1.28	(56/9/35)	2.34
Geothermal	143 (159 × 0.9)	31.9	(27/52/21)	0.99	(49/17/34)	1.79
Wind	26 (75 × 0.35)	6.0	(29/48/24)	0.69	(25/42/33)	0.93
Coal	716 (895 × 0.8)	8.3	(55/27/18)	0.36	(29/44/27)	0.57
CCGT	510 (600 × 0.85)	2.6	(30/35/35)	0.07	(31/26/43)	0.14

[a] MW(a) — MW(average capacity).
[b] MW(p) — MW(nameplate capacity).

employment. CCGT projects are estimated to create the least number of CIM and O&M jobs per unit of effective capacity.

Job creation, however, ought not to be considered in one sector in isolation when assessing employment impacts. It is also very important to factor in the corresponding resource requirements in the national economy and to appraise trade-offs with alternative usage of these resources in improving welfare by other means. A recent study estimated that reducing emissions in the power sector in the USA by 10% by using renewable energy might lead to an increase in the overall (economy-wide) unemployment rate by about 0.1–0.3%, though some sectors are likely to experience a decrease [152]. In general, there appears to be no conclusive results in the employment literature on either net creation or net destruction of jobs throughout national economies.

One factor influencing economy-wide employment assessment is the potential electricity price impact on consumers and businesses. In general, rising electricity prices are expected to have a negative impact throughout the national economy: a decline in consumption and eventually in jobs in all sectors producing goods and services. To get an insight into such impacts, a rather simplistic way (because intertemporal effects are ignored) is to compare energy technologies on the basis of the money spent on establishing effective capacity and on CIM jobs created.[30] Table 7 shows that while a solar PV project is estimated to create the most CIM jobs/MW(a), the effective capacity per MW is expected to cost several times that of any of the other representative projects. Compared to renewable sources, fossil fuel based and nuclear electricity generation is generally cheaper in terms of money spent per effective megawatt of capacity, suggesting a positive impact on jobs as a result of competitive advantage for domestic business and more money for consumers.

A more comprehensive analysis of employment would also appraise factors related to the quality of jobs created that could be measured by income, education levels or training. The energy sector generally requires a highly skilled workforce and hinges upon a wide range of competences. This is all the more true in the case of the nuclear industry, which brings together a wide spectrum of scientific and industrial disciplines and where meeting the most stringent safety standards is critical. Highly skilled and trained people are required to staff NPPs and the entire supply chain, including regulatory authorities, with the support of a large and global community of scientists and researchers. In general, skills development is an important dimension of job quality [153] resulting in higher

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[30] A more comprehensive estimate would also include O&M jobs for which fuel costs (for nuclear, coal and natural gas plants) would need to be accounted for. Given the small share of fuel costs in the nuclear cost structure, the impact on the cost per MW(a) would likely to be minor.

TABLE 7. COST OF ENERGY TECHNOLOGY PER CIM JOB AND PER EFFECTIVE CAPACITY
(Based on Ref. [147])

Technology	Overnight cost (US $1000)	US $1000/ MW(a)[a]	CIM jobs (jobs/ MW(a))	Lifetime (years)	US $1000/ CIM (job-year)
CCGT	400 000	784	0.07	40	299
Coal	2 240 000	3128	0.21	40	379
Nuclear	4 900 000	3889	1.06	40	92
Wind	1 925 000	5500	0.24	20	917
Geothermal	911 000	6366	0.80	40	199
Solar PV	325 000	21 667	6.30	20	137

[a] MW(a) — MW(average).

income, better health and career progression, and leading indirectly to higher general satisfaction with working life [154]. The average level of knowledge and training required by workers employed in every industrial energy branch can be used to assess work quality issues, although this type of indicator is difficult to derive and relies largely on expert judgments.

Recent tendencies in OECD countries have shown that the labour intensity of power generation is diminishing, favouring fewer but more qualified professionals [155]. The shift in staffing strategy is partly associated with the deregulation of electricity markets that encourages operators to reduce costs by outsourcing tasks requiring lower skills and by cutting down budgets for training [156] while optimized designs and increasing automation are favoured. However, training requirements in the nuclear industry remain relatively immune to changes in markets or overall economic conditions because of two factors. First, the nuclear industry is highly regulated and often has stringent training requirements, especially for safety related positions. Second, given the importance of safety for the nuclear industry, the highest levels of qualification are required in comparison with other industries (that may undertake actions only after a drop in performance becomes visible) so as to anticipate and avoid incidents and achieve the highest performance levels while ensuring top quality control.

As such, nuclear power can enhance a country's human capital, as it requires highly educated and trained personnel. Engaging in nuclear power implies a long term human capital investment, with potential driving effects on economic growth, via increased productivity within and beyond the electricity sector. The resulting enhanced human capital in the nuclear sector and related industries increases labour productivity and has dynamic spillover effects on related industries. These effects were particularly pronounced in the Republic of Korea [157]. Following growing demand for nuclear energy and isotope techniques, the Government of the Republic of Korea currently envisages increasing national industrial participation and gradually replacing imports as a source of both isotopes and related machinery and equipment. Over the past decades, the growth of these industries was exponential: as of 2003, almost 160 000 radiological technologists were licensed and nearly 26 000 radiation workers were employed in the nuclear industry handling radioisotopes [157].

Increasingly, concern is raised over the skills gap between the available workers and those needed by a growing nuclear industry. Engineers and skilled workers who were just starting their careers in the 1980s (the time of major nuclear expansion) are already approaching retirement age. This inevitably raises concerns about the ability of the nuclear industry to adequately face the energy challenges ahead with a sufficiently prepared workforce. Nonetheless, experience shows that during the period of fast nuclear expansion (after the oil crisis in the 1970s), the industry also lacked the necessary workforce but managed to train it quickly. Another wave of nuclear constructions would stimulate the activity of nuclear businesses and would incentivize the training of additional human resources. To support the upcoming development of the nuclear programme in the UK, the National Skills Academy for Nuclear has launched the UK Nuclear Education, Skills and Training Directory, showcasing the excellence in education and skills for nuclear provision offered by learning institutions and providers across the UK. In addition, the government unveiled its intention to open a new elite college funded jointly with the nuclear industry that would provide high level technical skills training for the nuclear power sector.

Although additional training may be needed for new workers without previous nuclear construction experience, the construction equipment and methods used for many of the NPP structures, systems and components are fairly similar to those used for other large industrial projects such as conventional power plants, refineries and chemical plants. About 30% of the total NPP investment cost is typically related to civil construction and erection on the site, including site excavation, the construction of utilities and support infrastructure, system installation comprising mechanical and electrical components, and other elements. Advantage can therefore be taken of the experience of local companies specializing in the construction of ports, complex buildings and hydro projects. In the case of mass construction, NPPs will likely be standardized, which, coupled with expected design simplification, will ideally make the preparation of workers and engineers faster and easier [157].

In conclusion, investments in a capital intensive project such as an NPP tend to spill over to other sectors in the economy such as construction, manufacturing and services, thus creating new employment and contributing to economic growth.

Finally, energy related jobs can also be characterized in the light of exposure to risks or hazards. The comparative assessment of accident risks is a pivotal aspect of any comprehensive evaluation of energy and sustainability. Accidents can be triggered by natural hazards, technological failures and human errors. A recent study on severe accidents in alternative energy chains makes use of extensive historical experience (the period from 1970 to 2008) for fossil chains and hydropower, a simplified probabilistic safety assessment for nuclear power, and a combination of available data, modelling and expert judgement for new renewable sources [158] (Fig. 29). The study concludes that in the fossil fuel chains, coal involves the highest fatality rates, whereas the natural gas supply chain is the least dangerous. Among large centralized technologies, modern nuclear and OECD hydropower plants exhibit the lowest fatality rates whereas dam failures in non-OECD countries have led to numerous casualties [159]. All other renewable technologies exhibit distinctly lower fatality rates than fossil

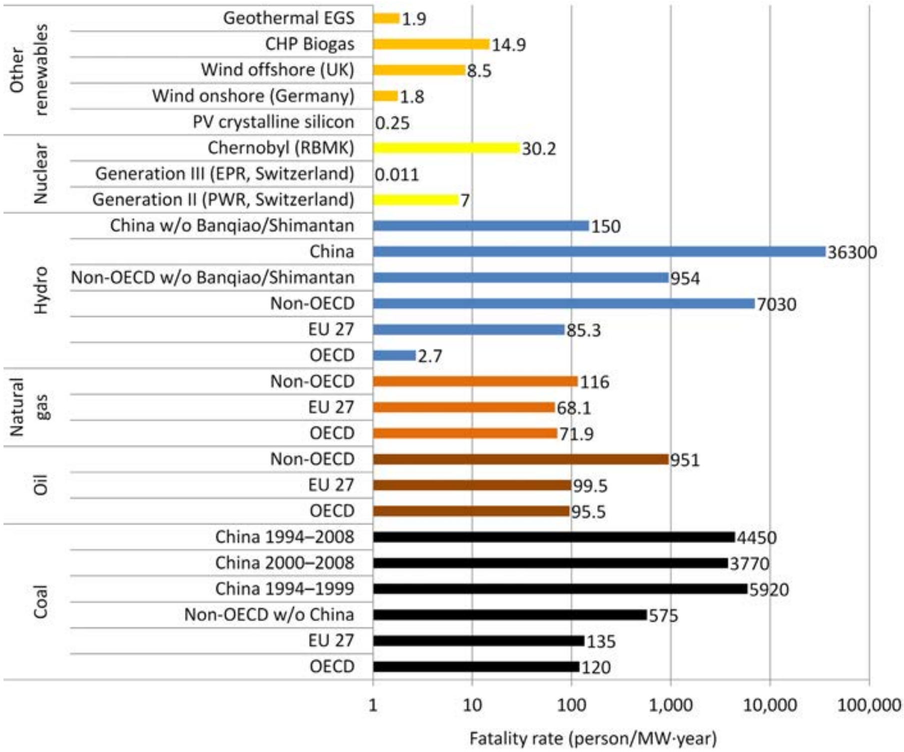

FIG. 29. Fatality rates in alternative energy chains. Source: Based on Ref. [159]. Note: EGS — enhanced geothermal systems; CHP — combined heat and power; PV — photovoltaic; RBMK — boiling water cooled graphite moderated pressure tube type reactor; EPR — European Pressurized Reactor; PWR — pressurized water reactor; Banqiao/Shimantan — the dam failure resulted in 26 000 fatalities in China in 1975.

chains and are in line with hydro and nuclear power indices in highly developed countries.

5.3. OTHER SOCIAL IMPACTS

Additional social impacts need to be considered when designing more sustainable energy systems. The problem of forced displacement and resettlement poses major social risks [160]. Among all energy infrastructure, the construction of large hydroelectric dams has caused the largest migrations in history. According to the World Commission on Dams, between 40 and 80 million people worldwide have been displaced by the construction of dams [161]. This is partially due to the enormous scale of many dam projects: China's Danjiangkou Dam displaced 383 000 people, while the Three Gorges Dam project forced the relocation of more than 1.2 million people. At least 5% of development induced displacement is caused by mining activities, in particular by open pit mining associated with the extraction of diamond, copper and coal [160]. A conservative estimate suggests that in India the development of coal mining displaced 2–2.5 million people between 1950 and 1990 [162].

Widespread social, economic and environmental changes stem from development induced displacement. These changes follow well identified patterns that may differ in severity according to the type of project or industry responsible for the displacement. According to a commonly used model to explain these patterns — the Impoverishment Risk and Rehabilitation Model [163] — supported by large academic consensus, population displacement generally results in the impoverishment of a majority of resettlers. The most visible risks, such as the loss of land and other potential impoverishment risks, threaten sustainability [164]. These other risks include joblessness, homelessness, marginalization, food insecurity, loss of common lands and resources, increased health risks, social disarticulation, loss of civil and human rights and disruption of formal education activities [162]. Evidence of this 'new poverty' is repeatedly reported in involuntary displacements throughout the world [165]. After the displacement induced by six infrastructure projects in the State of Orissa in eastern India, landlessness increased in all six areas, reaching up to five times its pre-displacement rates [162]. Similarly, about 56% of women were unemployed prior to the displacement, a figure which subsequently rose to 84% after the displacement. Forced relocation also increases the exposure of the poorest people to illnesses, including more severe psychological traumas and diseases (e.g. from unsafe water supply and sewage systems) [163]. High mortality rates immediately following involuntary resettlement from the reservoir areas of the Kariba dam in Zimbabwe and the Aswan High dam in Egypt are other examples [161]. Furthermore, empirical studies show that in many households, owing to drops in income and living standards, children never return to school and instead are drafted into the labour market at an early age [164]. Resettlement of populations is also intrinsically linked to the issue of land use rights of indigenous people and associated with complex resettlement and compensation issues. At a Chilean dam, for example, compensation was given only to those whose homes ended up under water although a range of other poor indigenous people along the shorelines were also encouraged to leave their land to make way for planned shoreline tourism developments [162]. Nevertheless, compensation by itself generally falls short of adequately restoring and improving the income levels and livelihood standards of resettlers; rather, it is a means to help ensure a sustainable outcome.

The largest displacements associated with the nuclear industry are related to evacuations following accidents. Although severe nuclear accidents are rare, three major ones have occurred: at Three Mile Island (1979), Chernobyl (1986) and the Fukushima Daiichi NPP (2011). In the aftermath of the Three Mile Island NPP accident, pregnant women and preschool children who lived within 5 miles (8 km) (later extended to 20 miles (32 km)) were advised to leave for precautionary reasons. Over 140 000 people in total fled the area, but most of them returned home within three weeks. Within the first two days after the Chernobyl accident, 115 000 local people were evacuated from the town of Pripyat and the surrounding settlements. Subsequently, a further 220 000 people were resettled [144]. In the aftermath of the Fukushima Daiichi accident, an estimated 160 000 people were evacuated [166]. Accident related evacuations have had a significant impact on societal sustainability through the loss of physical assets such as homes, cultural sites or income earning assets, but also non-physical assets such as social structures, networks and ties. In addition to the health effects of radiation exposure discussed in Section 5.1, adverse effects on mental health — post-traumatic stress disorders and other mood and anxiety disorders — were reported after the Fukushima and Chernobyl NPP accidents [167].

Furthermore, and notwithstanding the sustainability benefits of low carbon technologies discussed throughout this publication, the issues of public awareness and acceptance should not be overlooked (discussed in Section 5.4.2 for nuclear energy). The most common way of acquiring land for wind projects is the negotiation of leases or easements [168]. Certainly, this represents a major advantage over mining or dam projects that depend on formal expropriation. Nevertheless, numerous wind projects face public concerns regarding the visual impacts of wind turbines and their infrastructures — specifically, how they fit into the surrounding landscape. In North America and Europe, these impacts have emerged as critical socioeconomic impediments to the deployment of wind farms and their associated transmission lines. In Germany, the federal state governments of Bavaria and Hesse continue to campaign against the federal government's grid expansion plans to build high voltage lines connecting the windy north to the south [169]. The lines are described as essential to the success of the country's transition away from nuclear and coal power plants towards mostly renewable energies. However, the local political opposition remains unconvinced of the necessity for such lines and argue that they would be eyesores and blights on historic places or even health hazards [170]. In the USA, the development of offshore wind power has been hampered by opponents of the Cape Wind project in Massachusetts. Besides the visual aspects, legal challenges were raised by fisherman who argued that the massive wind plant would threaten their livelihood [171].

A variety of proximal nuisance effects are also associated with wind energy development, the most prominent of which is noise. Indeed, noise from wind turbines can be a problem especially for those living within close range owing to impacts characterized as both audible and subaudible sound (i.e. infrasound)[31] [172]. The conduct of a careful and thorough siting pre-assessment is considered an important step in improving local attitudes towards wind farms[32] [173]. Among the top concerns of communities considering solar power plants are the land requirements for centralized CSP and PV plants as well as perceptions regarding the visual impacts of and cooling water requirements for CSP plants. In addition, concerns over physical cultural resources have also been expressed: one of the reasons to mothball the proposed Rio Mesa Solar Electric Generating Station in Riverside County in the USA was the opposition of the native tribes, who argued that the power plant will affect and destroy their historic and cultural features. Overall, negative attitudes, such as nimbyism, are prevalent at the local level despite a commonly positive attitude towards wind and solar power in general [174].

Apart from these impacts on humans, wind farms and CSPs can also have negative effects on flora and fauna, particularly on birds and bats. At wind farms, birds and bats collide with spinning wind turbines (and also with meteorological towers with guy wires and power transmission lines). Multiple long term studies of bird mortality at various wind farm sites provide gloomy evidence — for example, over 1000 raptors (birds of prey) are killed each year ($2 \cdot MW^{-1} \cdot year^{-1}$) in turbine collisions at the Altamont Pass wind farm (580 MW) in California, including about 67 golden eagles and 188 red-tailed hawks along with over 2700 non-raptor species [175]. Moreover, because of very low reproductive rates, wind farms can become a local population sink for certain bat species, a situation in which mortality exceeds reproduction and the local population is maintained through influxes from adjacent areas [168]. The projected rapid scaling up of wind power development could lead to significant bat population declines over more extensive areas, assuming a continuation of the average estimated mortality of 12.8 bats $\cdot$ $MW^{-1} \cdot year^{-1}$ [176]. In the case of CSP plants, birds pass through the solar flux (intense radiant energy focused by mirrors on the power generating station) and encounter extreme heat before falling to the ground. They also

[31] Although sufficient supporting evidence is lacking, there are claims that subaudible sound, that is, below the nominal audible frequency range, may cause health effects.

[32] Concerns have also been raised that the visibility of wind power plants, turbine noise and shadow flicker (produced by rotating rotor blades) may cause negative impacts on residential property values at the local level.

collide with the blue sky reflecting mirrors, mistaking them for water. Moreover, a recent study in southern California suggest that a solar plant:

> "may act as a "**mega-trap**," attracting insects which in turn attract insect-eating birds, which are incapacitated by solar flux injury, thus attracting predators and creating an entire food chain vulnerable to injury and death" (Ref. [177] p. 2).

Without implementing specific measures, the projected expansion of solar and wind energy will likely intensify and worsen these biodiversity related impacts. As many countries rapidly scale up their wind and solar power development and as larger projects are considered, existing concerns may become more acute and new concerns may arise.

The aspects discussed in this section are relevant to low carbon technologies (hydro, nuclear, wind and solar). However, the scale and scope of the impacts remain heterogeneous. Nevertheless, they need to be adequately addressed if the sustainability benefits of these technologies are to be ensured.

5.4. CONSIDERATIONS RELATED TO NUCLEAR ENERGY

5.4.1. Intergenerational issues of radioactive waste disposal

The use of nuclear energy has repercussions beyond the life span of those currently living that raise concerns about intergenerational equity through the depletion of a non-renewable resource (uranium), and, more importantly, through the need to isolate radioactive waste from the biosphere for millennia. As argued in Section 3.1, uranium availability should not be a limiting factor for many future generations because economically recoverable uranium reserves remain abundant and are distributed widely around the planet. These reserves would be sufficient to fuel reactors for thousands of years with the introduction of fully closed fuel cycles using FRs. Although HLW makes up only 2%–3% of all waste generated by nuclear energy[33], spent fuel and HLW remain hazardous and have to be contained for long periods of time given the long half-life of many radionuclides and the current approaches to their treatment. Currently, the consensus in the nuclear community is that radioactive waste should be buried in geological repositories where safety is ensured by passive means and does not

[33] As an example, the spent fuel produced annually from NPPs operating globally would cover a space the size of a soccer field to a depth of 1.5 m.

rely on the use of active measures that would need to be taken after the closure of the facility. Key concerns from an intergenerational equity perspective include ensuring the safety and security of disposal facilities and ensuring that the funding necessary for their construction and operation is secured in a fair way, as defined below.

From a safety perspective, the nuclear energy sector has managed to store spent fuel safely for more than half a century. Nonetheless, there is currently no final disposal facility for the long lived HLW resulting from nuclear power generation. Several factors explain the postponement of implementing geological disposal, such as new technological developments (e.g. partitioning and transmutation[34] [178]) and pending decisions regarding fuel cycle options (open or closed). There are also advocates of reprocessing spent fuel (i.e. the extraction of the unused uranium and plutonium generated in the reactor) that reduces HLW by some 95% and decreases the demand for freshly mined uranium. However, the latest research indicates that substantial reductions in the reprocessing costs and significant uranium price increases are needed for the MO_X cycle to become competitive [39]. Although the MO_X alternative has a large present value for spent fuel management if two conditions are met, reprocessing does not eliminate the need for final disposal. Therefore, despite all these factors, there will always be waste that needs to be disposed of, although in potentially commensurate lower quantities and with shorter periods of hazardousness. Consequently, it is the responsibility of current generations to identify and develop sustainable, long term disposal solutions. Geological disposal matches these requirements and thus appears to be an appropriate candidate (see Section 4.3). From a security perspective, concerns around possible human intrusion into geological waste repositories are greatly reduced compared with those relating to surface storage, mainly because of the significant depths under the surface at which geological repositories will be located [179]. Furthermore, passive protection systems of repositories remove obligations from future generations to maintain the active surveillance required by the current waste stores on the surface.

From a funding perspective, financing arrangements for back end costs are usually designed to reflect both efficiency and ethical principles. The former is the 'polluter pays' principle, and the latter is the requirement that later generations should not be burdened with the responsibility for dealing with costs

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[34] Partitioning and transmutation form one of the key technologies for reducing the radiotoxicity and volume of the radioactive waste produced. Partitioning involves a series of physical and chemical separation processes, whereas during transmutation, one chemical element is converted into another by means of particle bombardment in a nuclear reactor or accelerator.

as a result of providing benefits for an earlier generation. Funding requirements aimed at meeting concerns over intergenerational equity are set out in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management that entered into force on 18 June 2001, and currently involves nearly 70 Contracting Parties. The Joint Convention is legally binding for its Contracting Parties and requires that they take appropriate steps to ensure that "adequate financial resources are available to support the safety of facilities for spent fuel and radioactive waste management during their operating lifetime and for decommissioning" (Ref. [180] article 22). Member States that signed the Joint Convention thus adopted the basic principle aimed at avoiding a burden on future generations and ensuring that adequate funds are available for the proper discharge of all financial obligations (future liabilities) related to spent fuel and radioactive waste management, including the development of a national policy establishing a mechanism for providing the resources and funds for their safe and long term management.

There is another interesting trade-off between generations regarding the retrievability of waste designed to give future generations an equal opportunity to benefit from the potential energy resources and economic value of radioactive waste [181]. Having the possibility of retrieving the waste preserves the option for future generations to make different decisions concerning the existing radioactive waste inventory. For example, it gives future generations the option to recycle material by reprocessing [179] but also to deal with any safety concerns that might be recognized only after waste emplacement [182]. However, a permanent arrangement to keep the repository open after emplacement operations are completed would clearly compromise long term safety. Therefore, retrievability as it is commonly understood implies a temporary measure based on the assumption that at some time in the future a decision will be taken to either retrieve the waste (for any purpose) or to close the repository. As such, retrievability involves costs and benefits that need to be considered during the design of the disposal site along with the ethical duty to protect people from exposure to hazardous waste [183].

5.4.2. Public perception

Irrespective of the sustainability benefits of nuclear power, its contribution to sustainable development might be severely constrained in the absence of public support. Nuclear energy involves complex technologies that may be beyond the understanding of lay people. Consequently, the associated risks tend be exaggerated, in particular where tailored information, openness and public involvement are absent.

The history of the general public's support or opposition to nuclear energy, as reflected in opinion polls, has tended to be cyclical over the past 35 years. Support weakens in the immediate aftermath of accidents (e.g. Three Mile Island, Chernobyl). Subsequently, as time passes without serious incidents, public acceptance of nuclear energy grows. There is some evidence that this pattern is indeed repeating itself in the wake of the Fukushima Daiichi accident, which occured in March 2011. Opposition to nuclear power increased in the immediate aftermath of the accident [184, 185]. However, according to a study released by the Ipsos Social Research Institute, "The impact on global opinion is variable between countries, and it does not appear to be lasting" (Ref. [186] p. 8).

Indeed, the social acceptance of risky technologies depends not only on scientific evaluations but also on perceived risks and benefits: the more people believe that a risky technology has positive rather than negative consequences, the more it will be accepted. For example, a correlation barely exists between the average fatality rates in the nuclear industry (seen in Fig. 29 in Section 5.2) and the subjective judgements of overestimating the probabilities of the seriousness of risks posed by this industry [187]. Furthermore, Eurobarometer survey studies show that many people do not differentiate between the risks associated with NPPs and the risks from radioactive waste disposal facilities [77]; they are perceived in a similar manner. This also indicates that perceived risks depend on a number of individual and societal risk factors other than objective probability of the risk of death. Psychological factors such as dread and unknown risks, moral aspects, fairness and trust all play an important role in supporting or opposing nuclear technologies (Fig. 30).

The factors most highly judged and perhaps the most relevant to the nuclear industry [189] are related to dread and unknown risk. Dread risk is synonymous with perceived lack of control, catastrophic potential, fatal consequences and the inequitable distribution of risks and benefits. The inextricable association of radioactive waste with nuclear power, the potential for a meltdown, nuclear weapons and security concerns such as proliferation fill the subject with dread fear of a nature that is rare for any other subject [190]. Unknown risk, commonly associated with radiation risk, is the perception of hazard as unobservable, unknown, new and delayed in manifesting harm [187]. In close relation to risk characteristics, affective aspects — hazards evoking feelings of dread — have been recently recognized to potentially play an important role in the perception of risk as it relates to large scale technologies [188, 189]. In general, subjects related to the nuclear industry remain strongly stigmatized. In particular, people are aware of past accidents and assume that similar events can occur in the future. As a result, they develop negative feelings of fear and anger and this leads to higher risk perception and lower acceptance.

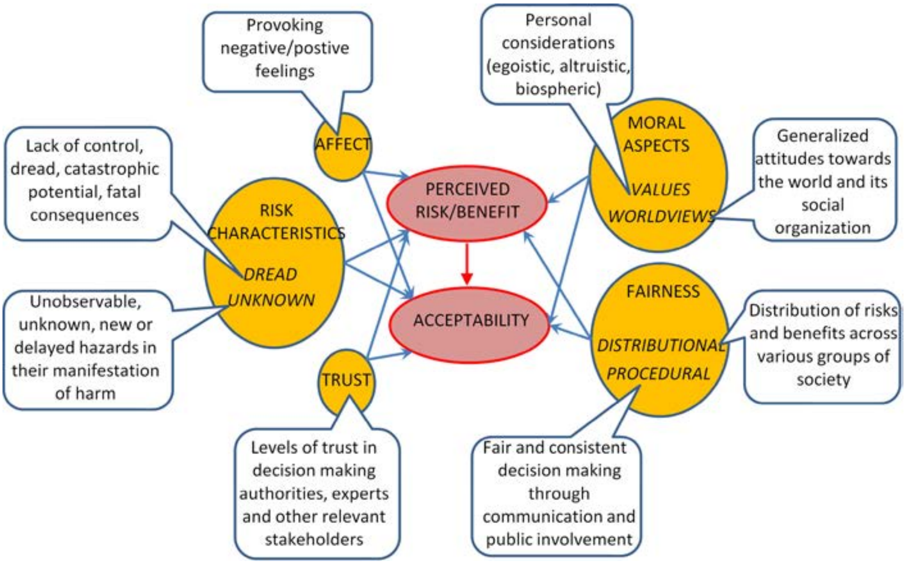

FIG. 30. The most important factors influencing public acceptance of nuclear energy. Source: Based on Ref. [188].

The weighting of risks and benefits of a large scale technology is also influenced by individual and generalized attitudes. A recent study [188] on the topic brings forwards at least three value orientations that are important in explaining the acceptability of the radioactive waste: economic (i.e. egoistic), community health and safety (i.e. altruistic) and environmental (i.e. biospheric). The general public might value the relatively cheap energy produced by nuclear power, but be concerned about the perceived risks for people, future generations and the environment. An alternative value orientation is that nuclear power is a low carbon energy source with significant potential to hamper climate change and reduce air pollution. The friction among value orientations is therefore present when weighing the risk and benefits of a new technology. Nonetheless, more research is needed to better understand the morally most acceptable choices people would consider, in particular when altruistic and/or biospheric considerations conflict.

As such, value orientations are closely related to the perceived distributional and procedural fairness: “what people perceive as ‘fair’ depends on what they value in life” (Ref. [188] p. 354). People who praise egoistic aspects will consider the construction of NPPs or the implementation of radioactive waste disposal to be fair when egoistic benefits (e.g. employment) outweigh the risks related to a new project. Similarly, a policy to implement the same project for people with strong altruistic values would be fair if social benefits (e.g. cheap energy) outweighed its risks. Again, more research is needed to allow fair distributional decision making, taking into account subjective risks to health, safety and the environment. In addition, the procedures to come to a decision should be perceived as fair and consistent towards all parties involved [191]. The lesson from attempts to identify sites for spent fuel/HLW facilities is that such efforts are more likely to succeed if and when they are based on transparent and participative processes designed to achieve informed consent from a host community. As noted by de Saillan,

> "many of the early, unsuccessful attempts at selecting disposal sites were the outcome of a closed, opaque decision-making process…the public often has not been given an opportunity to participate meaningfully in decisions on the disposal of nuclear waste…" (Ref. [192] p. 511−512).

Communication and public involvement are crucial for a fair and consistent decision making process. They also increase trust in local authorities, another factor relevant for explaining acceptability judgments [193]. A study in Sweden showed how extensive information programmes in four municipalities have positively changed the extent to which people accepted a local radioactive waste repository [194].

The relationships between psychological factors, perceived risks and benefits and acceptability are also affected by situational and group characteristics [188, 189]. If a new nuclear energy project is located far away from the host community, aspects related to distributional and procedural fairness may play a less prominent role because people would experience and perceive less individual risks or benefits from it. Furthermore, various studies indicate that lay people exhibit higher perceptions of risks involved with nuclear power compared to experts. Experts' numerical evaluation of risk is not related to dread; they see riskiness and expected annual mortality as synonymous whereas the general public uses a broader and more complex definition of the concept.

If public support for nuclear energy as a contributor to sustainable development is to be restored and/or maintained, policy makers might do well to understand the values and other factors that govern peoples' perceptions of nuclear power projects. Customized information needs to be provided to the public and decisions ought to be made in a fair manner by the relevant authorities.

5.4.3. Safety and non-proliferation

The sustainability of nuclear energy is also challenged by long standing public concerns about safety, security and proliferation. The overall trend towards higher safety in the nuclear industry observed for more than a decade as a result of long term and dedicated safety policies in Member States broke abruptly with the Fukushima Daiichi accident in March 2011. Although the accident did not cause fatalities and contamination was restricted to a small region in Japan, its consequences were global in terms of reviewing and improving nuclear safety. Near term measures and long term actions were initiated at national, regional and international levels to evaluate the vulnerabilities of NPPs to external hazards.

At the national level, a prompt reaction was taken by operators and national regulators to perform safety reassessments aiming at evaluating the design and safety aspects and the robustness of NPPs to withstand extreme events and to eventually introduce changes. In general, these targeted reviews have been based on new and existing safety studies and on engineering judgments to evaluate the behaviour of NPPs in a set of challenging situations [194]. At the regional level, the European Stress Test Programme organized by the European Nuclear Safety Regulators Group (ENSREG) is an example to mention. These comprehensive safety reviews or stress tests, which were successfully completed by April 2012, reassessed the adequacy of design basis accidents, but also evaluated beyond design basis situations, including extreme natural hazards and the consequent loss of safety functions or capabilities to cope with severe accidents [195].

At the international level, the IAEA convened the Ministerial Conference on Nuclear Safety in June 2011, as a result of which a worldwide Action Plan on Nuclear Safety (the Action Plan) [196] was adopted in September of that year. The key actions in the 12 key areas of the Action Plan are:

(1) Undertake assessment of the safety vulnerabilities of nuclear power plants in the light of lessons learned to date from the accident;
(2) Strengthen IAEA peer reviews in order to maximize the benefits to Member States;
(3) Strengthen emergency preparedness and response;
(4) Strengthen the effectiveness of national regulatory bodies;
(5) Strengthen the effectiveness of operating organizations with respect to nuclear safety;
(6) Review and strengthen IAEA Safety Standards and improve their implementation;
(7) Improve the effectiveness of the international legal framework;
(8) Facilitate the development of the infrastructure necessary for Member States embarking on a nuclear power programme;
(9) Strengthen and maintain capacity building;
(10) Ensure the on-going protection of people and the environment from ionizing radiation following a nuclear emergency;

(11) Enhance transparency and effectiveness of communication and improve dissemination of information;
(12) Effectively utilize research and development.

Although the Action Plan is still being implemented, significant progress, described in detail in the annual progress reports [197–199], has been achieved since its adoption, particularly in key areas such as assessments of the safety vulnerabilities of NPPs and the strengthening of the IAEA's peer review services. Missions and follow-up missions in the areas of the regulatory framework, operational safety, emergency preparedness and response and design safety were organized and conducted by the IAEA. An Expert Group was established to provide advice on strategies to strengthen and sustain sound international preparedness for nuclear and radiological emergencies. As part of the effort, national, regional and interregional training courses and workshops were organized and conducted by the IAEA. The IAEA Safety Standards were also reviewed with a focus on vitally important areas such as the design and operation of NPPs, protection of NPPs against severe accident(s) and emergency preparedness and response. The IAEA continued sharing lessons learned from the Fukushima Daiichi accident with the nuclear community through eight International Experts' Meetings (IEMs) and other topical conferences highly interlinked with the key areas of the Action Plan, and through the publication of full reports of these IEMs. In addition, as part of the effort to implement the Action Plan, the IAEA published a report on the Fukushima Daiichi accident [200]. The report presents an authoritative, factual and balanced assessment of the causes and consequences of the accident as well as the lessons learned. It is intended to serve as a key reference document for the knowledge base of existing and future generations.

As a result of all these actions, nuclear safety is improving throughout the world. Its operational safety remains high and improves steadily. The safety performance indicator — the number of unplanned shutdowns (scrams) per 7000 hours of operation — has decreased from 1.95 in 1990 to 0.61 in 2015 [201]. In addition, IAEA Director General Yukiya Amano recently stated that "While taking forward the lessons arising from Fukushima Daiichi, …it is time to start considering a broader approach to strengthening nuclear safety" [202]. He also stated that other safety aspects had to be considered, such as "decommissioning old facilities, extending the operating life of existing nuclear power plants, disposing of high-level radioactive waste, and developing innovative technologies" [202].

Furthermore, nuclear power must not only be safe and secure but must also be used solely for peaceful purposes. Unlike other energy forms, nuclear energy was first harnessed for weapons. The non-military applications of nuclear energy, such as civilian nuclear power generation, only followed afterwards.

The role of the IAEA, established in 1957, is to help States reconcile the dual nature of the atom so that nuclear energy could be put squarely in the service of peace and development. The IAEA Statute directed the Agency to "enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" and to ensure that its assistance "is not used to…further any military purpose" (Ref. [203] p. 5–6).

Over the course of several decades, the international community has put in place a number of international political and legal mechanisms to help stem the spread of nuclear weapons. They include the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) [204] regional nuclear-weapon-free-zone treaties, export control arrangements, nuclear security measures and also, importantly, the safeguards system of the IAEA. The purpose of the safeguards system is to provide credible assurances to the international community that nuclear material and other specified items are not diverted from peaceful nuclear activities and to deter proliferation by early detection.

States accept the application of technical safeguards measures through the conclusion of safeguards agreements. Over 170 States have safeguards agreements with the IAEA. Although there are various types of safeguards agreements, the majority of States have placed all of their nuclear material and activities under safeguards. Article III of the NPT requires each non-nuclear-weapon State to conclude an agreement with the Agency to enable the IAEA to verify the fulfilment of the State's obligation not to develop, manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices. Under such comprehensive safeguards agreements, a State commits to provide information on its nuclear material and activities, and to permit inspections.

Over time and in response to new challenges, the safeguards system has been strengthened. The IAEA's experience in the early 1990s in Iraq and in the Democratic People's Republic of Korea highlighted the limitations of safeguards implementation concentrating on declared nuclear material and safeguards conclusions drawn at the level of facilities. It showed that the IAEA needed to be much better equipped to detect undeclared nuclear material and activities. This led to important strengthening measures, including the adoption of the Model Additional Protocol, which provides the Agency with important supplementary tools that give broader access to information and locations. Some 110 States have brought such additional protocols into force to date.

The shift in focus of safeguards implementation from verification of declared nuclear material at declared facilities to understanding and assessing the consistency of information on a State's nuclear programme has resulted in a whole new way in which safeguards activities are planned and implemented, results are analysed, safeguards conclusions are drawn and follow-up activities are carried out. The framework for all this work is the so-called State-level concept that focuses on the State as a whole rather than solely on the nuclear material and particular facilities within that State.

The State-level concept requires States to be evaluated continually. The underlying basis is that a State's nuclear programme, whether past, present or future, will generally have detectable indicators. The State evaluation process integrates and assesses all information available to the IAEA about that State's nuclear activities and plans. Trained safeguards staff analyses the information provided by States, information derived from the Agency's in-field verification activities as well as information from open sources, such as satellite imagery. The analysis provides the basis on which the IAEA draws its safeguards conclusions and is also essential for planning and carrying out safeguards activities in the field and at headquarters. Safeguards implementation can, therefore, be described as information driven. By being responsive to changes, this ensures that the assurances provided to the international community remain credible and up to date.

The IAEA's verification activities are carried out by highly trained experts using advanced technology, equipment and infrastructure. The IAEA designs customized safeguards approaches for individual States and uses dedicated equipment for carrying out verification.

6. CONCLUSION

Identifying more sustainable ways to produce and use energy is at the heart of the post-2015 United Nations development strategy. The strategy's aim is to attain human well-being while safeguarding resources and capital (both human-made and natural) and providing global public goods (including environmental ones).

Existing energy systems face several major challenges that need to be addressed urgently and comprehensively. Access to clean and modern forms of energy needs to be extended to the 41% of the global population that currently relies on solid fuels and in general lacks reliable, affordable and low pollution energy sources.

At the same time, the rapidly increasing global demand for energy services needs to be met to support economic development while preventing dangerous climate change, adverse health effects and impacts on land, water and biodiversity. Furthermore, energy security needs to be ensured for all nations and regions.

Finally, given the long lifetimes of energy infrastructure and the possibilities of being locked into unsustainable technologies, current investments and financing policies need to be put into a long term perspective. Transforming the energy system is at the core of a dedicated SDG on energy of the new United Nations development agenda. In addition to complex socioeconomic impacts, risk, wastes and interactions with the environment are inherent to every energy technology. Therefore, a diversified mix of energy sources is needed to tackle global energy challenges. The role and compatibility of nuclear power with sustainable development objectives cannot be assessed in isolation but only in comparison with existing alternatives on a level playing field. The final choice of the energy mix in any given country will be a sovereign decision reflecting the country's situation and needs.

This publication reviewed the characteristics of nuclear power in comparison with alternative sources of electricity supply and in connection with the SDGs relating to economic, social and environmental pillars of sustainability. The findings summarized here and in Fig. 31 can also help the reader to reconsider widespread misconceptions regarding the development and operation of NPPs and their ability to contribute to more sustainable energy systems.

- Concerning the economic dimension of sustainable development:
  - Uranium (U) resource availability is vast and, when measured in terms of reserve–production ratio, it is far greater than oil or natural gas resource availability. The natural uranium ore deposits identified globally and used in OTFCs are sufficient to maintain current levels of nuclear power generation for more than a century, similar to the length of time for which coal based energy supply could be maintained with currently identified resources. The large scale deployment of FRs with closed fuel cycles would essentially remove the resource constraint altogether.
  - The direct comparison of levelized costs of electricity generation identifies nuclear power as one of the cheapest sources of baseload power generation worldwide, particularly when grid level system costs or health damage costs, which are both minimal for nuclear energy, are accounted for.
  - However, owing to the size and complexity of NPPs as well as the long lead times for their construction, the overnight investment costs of gas and coal fired power stations and of onshore and offshore wind farms are more favourable. Nonetheless, various financing mechanisms exist to alleviate the risks associated with nuclear projects and to allocate them to various stakeholders.

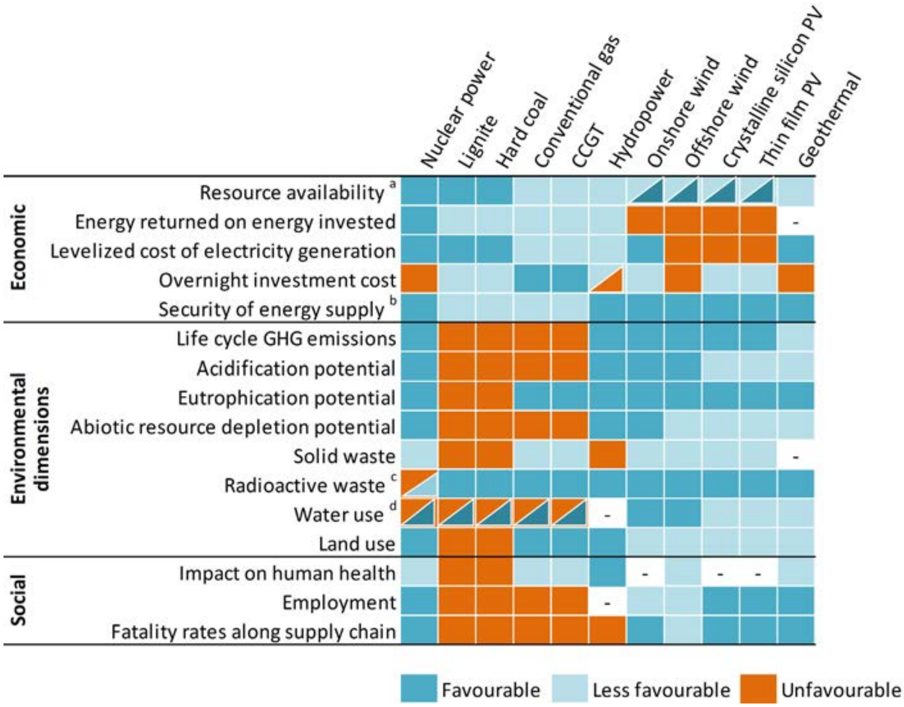

FIG. 31. Performance of nuclear power and its alternatives across a selection of sustainability indicators. Note: [a] Resources availability is sensitive to geographical location for solar and wind technologies; [b] Security of energy supply refers only to geopolitical supply risks. It does not take into account the backup needed for intermittent renewable energy sources, which, if provided by fossil fuels, might reduce their energy security benefits; [c] The closed fuel cycle in fast reactors largely reduces the volume and radiotoxicity of waste per unit of electricity generated; [d] An air cooling system eliminates water needs for cooling in thermoelectric power plants; Water consumption from concentrating solar power technologies (not in the figure) can be substantial; CCGT — combined cycle gas turbine; PV — photovoltaic; GHG — greenhouse gas.

  - As compared to its counterparts, nuclear technology remains less sensitive to policy changes such as the adoption of a stringent climate change policy, resource price instability or geopolitical risks.

— Regarding the environmental dimension of sustainable development:

  - On a life cycle basis, the comparison of GHG emissions demonstrates that NPPs are among the least carbon intensive power sources (less than 15 grams of carbon dioxide equivalent (g CO_2-eq) per kilowatt-hour (kW·h)). Increasing the share of nuclear energy in a country's energy mix is usually foreseen to achieve a decarbonized power system at the lowest cost.

- Operational NPPs and renewable power sources bring about sizeable environmental benefits in terms of reduced acidification, eutrophication and ARDPs, thereby preserving the integrity of natural habitats and avoiding damages to human-made structures, among other benefits.
- The generation of electricity also creates waste, the management of which remains a key environmental challenge. In the case of nuclear energy, the very high energy density of uranium results in relatively low volumes of radioactive and other wastes. Around four fifths of the total nuclear waste that has already been created has already been sent for safe and controlled disposal. The first depositories for high level radioactive waste are expected to begin operation within a decade. Spent nuclear fuel can also be partially recycled, while new methods are emerging to turn long lived radioactive waste into material with a shorter half-life.
- Life cycle water use by power generating technologies is another critical aspect of environmental sustainability, mainly because of the multiple and competing uses of water. Water requirements for NPPs equipped with once-through cooling systems can be substantial. But alternative cooling systems, such as hybrid systems with cooling towers, can bring water withdrawals down to levels comparable to those of alternative technologies. Future power plant designs and operations will also have to adapt to a changing climate, including droughts and flooding, so as to alleviate their vulnerability to such events.
- Land used for power generation, and the difficulty of restoring its original characteristics after the infrastructure is dismantled, is another determinant of energy system sustainability, particularly when the full life cycle of the plant is considered. Coal based electricity, with its associated mining and, to some degree, onshore wind generation and ground mounted solar PV usually involve significant land occupation. In contrast, a unit of nuclear based electricity requires only a limited land surface (median footprint of 0.78 square metre-year (m^2year) per megawatt-hour (MW·h)).

— Relating to the social dimension of sustainable development:

- A more sustainable energy system needs to be deployed with minimized impacts on human health. Nuclear and gas fired power stations encompass small levels of toxicity and allow for large reductions in particulate matter formation. Natural exposure to ionizing radiation, such as terrestrial or cosmic radiation, is several orders of magnitude higher than artificial, human-made radiation, especially the radiation stemming from the nuclear fuel cycle. Radioactive waste disposal emits insignificant doses.

- The transition to a more sustainable and, in particular, a low carbon economy is an opportunity to stimulate economic activity, enhance employment and improve the well-being of citizens. A nuclear power project creates many long term jobs in operations, contracting and in the supply chain. It also compares well with the alternatives in terms of money invested per effective megawatt of capacity. Furthermore, more skilled labour is necessary to design and operate complex nuclear technologies compared with other technologies, meaning that it has a higher potential to generate economic value during plant construction, operation and dismantling.
- The workforce is most exposed to risks of accidents and hazards in the fossil fuel and hydropower supply chains. In developed countries, the coal sector has much higher fatality rates than the oil and gas sectors. Risks are largely reduced in other sectors, including in nuclear energy and renewables, particularly in countries with long standing experience and large installed capacities.
- The specific sustainability concerns raised by nuclear power include the following:
    - First, the management of radioactive waste generated by NPPs involves multiple future generations. From an ethical point of view, it may be legitimate to leave future generations the option to retrieve waste and manage inventories differently. In the interim, the secured storage of spent fuel must be guaranteed. The funding necessary for the construction of future disposal sites and their monitoring is also of critical importance and needs to be addressed with fairness.
    - Second, attitudes towards nuclear energy tend to fluctuate appreciably and differ across countries, notably in the immediate aftermath of an accident. Risks associated with dread and the unknown, such as the perceived lack of control and the potential of catastrophic events with fatal consequences, often drive public opinion. Affective aspects also influence the weighting of risks and benefits. The public perception of the risks and merits of nuclear power, together with their acceptance, is of critical importance and necessitates dedicated, science based communication and public involvement.
    - Third, maintaining and deploying nuclear capacity worldwide requires the most stringent measures on safety and against proliferation of nuclear material and weapons. The peaceful and safe use of nuclear technologies is closely monitored and continuously verified by the IAEA and supported by its Action Plan on Nuclear Safety.

In the light of the wide range of indicators compiled in this publication and supporting these conclusions, nuclear power can be seen as a reliable source of power that can play a role in energy supply diversification and foster a more resilient sustainable power supply.

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