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Review

Nuclear energy: Between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications

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A B S T R A C T

For decades, nuclear energy has been considered an important option for ensuring global energy security, and it has recently started being promoted as a solution for climate change mitigation. However, nuclear power remains highly controversial due to its associated risks – nuclear accidents and problematic radioactive waste management. This review aims to assess the viability of global nuclear energy economically (energy-wise), climatically and environmentally. To this end, the nuclear sector's energy- and climate-related advantages were explored alongside the downsides that mainly relate to radioactive pollution. Economically, it was found that nuclear energy is still an important power source in many countries around the world. Climatically, nuclear power is a low-carbon technology and can therefore be a viable option for the decarbonization of the world's major economies over the following decades, if coupled with other large-scale strategies such as renewable energies. These benefits are however outweighed by the radioactive danger associated to nuclear power plants, either in the context of the nuclear accidents that have already occurred or in that of the large amounts of long-lived nuclear waste that have been growing for decades and that represent a significant environmental and societal threat.

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Contents

1. Introduction

Nuclear energy is currently an important component of energy security and global economic development. It is one of the pillars of the world's energy needs, considering that in 2013 it covered 11% of global electricity, or 2477 TWh (terawatts hour) of the total 2013

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world energy production estimated at 23234 TWh (IEA, 2015). Nuclear power is therefore a viable power source given the increasing global energy demand, its high power supply capacity and the low fuel levels required for operation (Grandin et al., 2010).

Moreover, alongside renewable energy, nuclear energy is seen as a major opportunity for the decarbonization of global economies due to the fact that it is a low-carbon technology (NEA, 2015a). These technologies are essential, as today's society still largely (~80%) relies on fossil fuels, and fossil resources are projected to cover 50% of the total global energy supply up to 2050 (Don MacElroy, 2016). This large dominance of fossil fuels in the global energy sector has generated significant pressure onto the Earth's natural systems especially over the past five decades (1959–2010), during which it is estimated that 350 Gt C (gigatonnes or billion tonnes carbon) were released into the atmosphere (290 Gt C from fossil fuels and 60 Gt C from land use changes), of which 45% remained in the atmosphere (the other 55% was assimilated by the ocean and land areas), causing an accelerated climate warming (Ballantyne et al., 2012).

At present, more attention is being directed towards the relationship between nuclear energy and climate change (Verbruggen and Laes, 2015), considering that the climate system's perturbation is probably the most serious environmental problem in the world today (Rockström et al., 2009). Thus, it was suggested that this type of energy could be a major opportunity to improve some of these disturbances, by means of decarbonization and by stopping global warming at 2 °C above pre-industrial levels, which is the limit deemed necessary to ensure the stability of the Earth's biophysical systems (Fawcett et al., 2015). However, the condition for generating a clear effect on the decrease of atmospheric carbon is using the technology until 2050 in a mixed context, i.e. coupled with large-scale carbon capture and storage (CCS) and renewable technologies (NEA, 2015b). Therefore, even though a 17% increase in nuclear energy use is envisaged by 2050 (NEA, 2015b), without the simultaneous use of other viable strategies for eliminating atmospheric CO_2 emissions there can be no real chance of reducing global warming.

There is however a notable downside to nuclear energy – safety issues and the radioactive waste it generates. Even though it is known that nuclear power plants are safe systems, which have several built-in physical barriers conceived to prevent the escape of radioactive isotopes into the environment (Högberg, 2013), the past decades have shown that nuclear accidents can happen. Such instances include the well-known Chernobyl (1986) and Fukushima Daiichi (2011) events that released high amounts of radioactive isotopes into the environment, such as ^{137}Cs and ^{131}I (IAEA, 2012; UNSCEAR, 2008, 2013). Additionally, other risks can be associated to nuclear waste, which is highly radioactive and not easily storable safely and permanently. High-level radioactive waste is the most dangerous type, as it persists in the environment for up to one hundred thousand years (Horvath and Rachlew, 2016), which makes safe storage almost impossible.

Fortunately, nuclear waste management is rigorously regulated and controlled by the International Atomic Energy Agency – IAEA (and by other international organizations), the most important international entity that oversees nuclear activity globally (IAEA, 2006). In addition to the safety of radioactive waste storage facilities, this organization is also responsible for the cooperation between member states for nuclear development, and one of its primary roles is preventing the use of nuclear programs for military purposes (Prăvălie, 2014). Thus, IAEA was the main mechanism involved in the implementation of the 1968 Non-Proliferation Treaty, which was aimed at stemming the spread of military nuclear technology worldwide, except for five countries (United States, USSR/Russia, United Kingdom, France, and China) that were already nuclear powers at the time (Prăvălie, 2014).

This study aims to analyze the current state of global nuclear energy from three different angles – energetically, climatically and environmentally. This review paper, based on current relevant bibliographical sources and representative data, essentially aims to simultaneously assess the positive (energy security and support in fighting climate change) and negative (the risk of accidents and environment-related risks of spent nuclear fuel storage) effects of nuclear energy.

2. Past evolution of nuclear energy

The use of nuclear energy started in the early 50s, when the first nuclear reactor (a small unit called Experimental Breeder Reactor I) became operational at the Argonne National Laboratory in Idaho, United States. In the following years, the US, UK, Russia, France and Germany were the first to use nuclear technology commercially, and 20 other countries followed suit over the next decades (NEA, 2003). However, even though US president Dwight D. Eisenhower, in his famous “Atoms for Peace” UN speech, urged the international community as early as 1953 to cooperate in order to develop nuclear technology, atomic energy only underwent an ample international development phase almost 20 years later, in the early 70s (Fig. 1).

The most important global development stage in the history of nuclear energy therefore occurred roughly between 1970 and 1985, when the total number of nuclear reactors went from over 80 in 1970 to over 360 in 1985 (Fig. 1). While the number of operational nuclear reactors had an almost four-fold increase in this 15-year period, their installed power capacity had a much steeper 14-fold increase, i.e. from ~18000 MW in 1970–~250000 MW in 1985 (Fig. 1). This period corresponds to ~65% of atomic energy growth over six decades, when considering the increase in the number of nuclear reactors in 1970–1985 in relation to the entire analysed period 1955–2015.

The causes for the decrease in nuclear development after 1985 concern a series of events with global-scale effects, of which the most important are the increase of interest in oil after 1980 (as a result of price decreases) and especially the Chernobyl nuclear accident, which generated an obvious change in how countries worldwide viewed nuclear power (Albino et al., 2014). The effects of the 1986 nuclear disaster were so profound in both public and political spheres that, for instance, that same year Germany approved a resolution aimed at abandoning nuclear energy by the end of the decade, and the following year Italy completely shut down its nuclear energy program (Albino et al., 2014). In this context, Italy became the first country to go back to a “non-nuclear energy” status. Two other states followed its lead and abandoned their nuclear reactors in the following decades – Kazakhstan (1999) and Lithuania (2009) (Schneider et al., 2011).

However, several other states in Eastern Europe and Asia continued their nuclear energy projects after 1990, and went on to develop their nuclear capacity up to present day. Relevant such examples are Japan, South Korea, India, and China, which continued to build large fleets of nuclear reactors in the past two decades (Lovering et al., 2016). Nuclear energy technology therefore has kept on expanding up to present day globally (Fig. 1), and it is in fact going through a renaissance phase as a result of a notable rise in new power plant investments in developing economies, increases of fossil fuel prices and growing concern regarding climate change (Hedberg et al., 2010; Albino et al., 2014).

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