Energy Strategy Reviews 1 (2013) 296–301

Contents lists available at SciVerse ScienceDirect

Energy Strategy Reviews

journal homepage: www.ees.elsevier.com/esr

REPORT REVIEW

The role of nuclear power in mitigating emissions from electricity generation

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ARTICLE INFO

Article history:
Received 3 September 2012
Received in revised form
11 December 2012
Accepted 16 December 2012
Available online 20 January 2013

Keywords:
Power production
Nuclear energy
Life cycle analysis
Greenhouse gases
Carbon dioxide
Climate change mitigation
Particulate matter

ABSTRACT

This article presents an updated overview of recent literature on the role of nuclear power in mitigating greenhouse gas (GHG) and particulate matter (PM) emissions from electricity generation. Emission intensities are strongly dependent on the country of operation and type of technology used in each category of power production options, but robust observations can be made with regards to the average emission intensity of each main alternative. The majority of emissions from nuclear energy is associated with parts of its overall life cycle other than the operation of nuclear power plants. Technological progress in especially uranium enrichment has recently yielded energy intensity reductions that have significantly lowered the GHG footprint of nuclear power, which at present amounts to 5–17 gCO_2eq/kWh. As a result, average GHG emissions are today around two orders of magnitude lower for nuclear energy than for conventional coal-based power production. This article also addresses the feasibility of potential deployment scenarios for nuclear power and their implications in terms of global GHG emissions mitigation.

1. Introduction

Whether nuclear power can contribute to establishing sustainable development has been a subject of analysis for many years (see e.g. Ref. [2,7]). Arguments can be made that certain aspects of nuclear energy are in support of environmental sustainability, while some of its other features are at clear loggerheads with sustainable development. Many energy analysts would argue that despite its multiple drawbacks, among which especially the production of long-lived radioactive waste, the risks of reactor accidents with pervasive environmental and health consequences, and the diversion of nuclear materials and technologies for military or terrorist purposes, nuclear energy can in principle play a role in mitigating global climate change. The reason is that the operation of nuclear power plants does not generate emissions of GHGs, plus nuclear energy is expandable, at least from a technical point of view. One may question the climate-neutrality of nuclear energy, however, by considering that parts of the complete nuclear energy chain or entire fuel cycle involve emissions of CO_2. The main purpose of this article is to test the claimed carbon-free nature of nuclear energy through an updated overview of the recent literature dedicated to this subject. A comparison is made between life-cycle GHG emissions from different types of electricity generating technologies, including nuclear energy. It is also addressed what scenarios are plausible for nuclear energy's future contribution to global GHG emissions reduction. To complement this assessment, a concise summary is presented of the extent to which nuclear energy could help avoiding the health impacts associated with several power production options, such as related to PM emissions.

2. LCA for nuclear power

Recently two overviews have been published of studies on the GHG emission intensity of nuclear energy, by respectively [20,26]. This paper builds on, and adds to, their work in at least three major respects. First, given that several years have passed since their publication, the present paper has profited from the opportunity to consult more literature than could be included in the reference lists investigated for these two review articles. Second, while the present review follows the selection criteria of Ref. [20] that studies (a) must be relatively recent (in our case not published prior to the year 2000), (b) ought to be accessible (hence

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2211-467X/$ – see front matter
http://dx.doi.org/10.1016/j.esr.2012.12.008

should be in the public domain and thus be verifiable, plus preferably in English), and (c) should include primary calculations (hence not rely on secondary sources and thus merely involve findings obtained and reported before), the current overview adds an important extra requirement, namely that studies (d) should have appeared in the peer-reviewed literature. This extra criterion yields a risk that high-quality work is left out because it was never published in an international scientific journal, but it adds a (in our opinion desirable) check that enhances the probability (while not entirely ascertaining) that the work is of an acceptable level and satisfies academic standards, and has benefited from suggestions and corrections from independent experts. Third, the present paper represents a necessary update of these two publications, since nuclear energy has undergone sizeable change over the past few years and will continue to do so over the next several years, in particular with regards to those aspects of the total power production chain relevant for life cycle analysis (LCA). For this article we have chosen to report on the situation as applicable today, rather than corresponding to the past decade as considered in Ref. [20,26].

The goal of LCA is to calculate the environmental impacts or, in particular, the emissions of substances such as GHGs, over all steps needed ("from cradle to grave") to fabricate a product or deliver a service, electricity in our case. Several types of LCA exist that can be categorized in essentially two main classes. Process-chain analysis (PCA) is performed on the basis of all components and materials – and their associated environmental footprint – used in the production process. Input-output analysis (IOA) investigates the economic sectors responsible for the various manufacturing activities of the production process. For the overview presented in this article no distinction is made between these two complementary methods: outcomes are included from both methodologies in the findings reported below. All results are expressed in terms of emissions per kWh of electricity produced. For instance, results for calculations of GHG emissions are presented in gCO_2eq/kWh. The unit gCO_2eq indicates that different GHG species are aggregated and expressed in terms of their global warming potential in CO_2 equivalents (based on a time frame of 100 years). Radiation exposure effects are measured in mSv/yr.

The life cycle chain for nuclear power is inspected from the front-end stage (including the mining, milling, conversion and enrichment of uranium as well as the fabrication of fuel rods), to the operation of power plants (including maintenance), and the back-end of the nuclear fuel cycle (involving short- and long-term deposition of nuclear waste and decommissioning of the nuclear reactor and power plant site). The highest environmental impact in the past resulted from GHG emissions associated with the enrichment of uranium, because it used to be a particularly energy intensive phase of the nuclear fuel cycle. If the electricity used for enrichment activity derived from fossil based power plants, the corresponding GHG emissions were typically high. At present, approximately two fifth of all uranium enrichment activity of around 50 million SWU/yr is undertaken through gas diffusion technology. The remaining three fifth is fulfilled by centrifuge technology. Gas diffusion was the first enrichment method employed on a large scale by the five nuclear weapons states to produce highly enriched uranium for the construction of nuclear bombs, and was subsequently used for the production of low enriched uranium as fuel for nuclear reactors. Because it is one to two orders of magnitude more energy intensive than centrifuge technology, the last two large gas diffusion plants, in the US and France respectively, are currently being replaced by centrifuge enrichment plants. It is expected that over the next few years world-wide the vast majority of uranium will be enriched through centrifuge technology. Around 2015 no large gas diffusion plant may be in operation anymore. If all currently planned capacity is realized, before the end of the decade 70–80 million SWU/yr may be in operation based entirely on centrifuge technology ([24]). This paper's scope pertains the situation today and in the near future, hence we assume that gas diffusion plays only a moderate role.

We suppose that for our short-term perspective (typically until 2020) both the open and closed nuclear fuel cycles continue to co-exist.[1] Whereas in the longer run either of these options may dominate, it is likely that for the foreseeable future some countries will carry on reprocessing and recycling spent fuel, while others will abandon this practice or continue refraining from it. Both fuel cycle alternatives are therefore part of the results reported below. Furthermore, for the next decades light water reactors (LWRs) will continue to dominate nuclear energy capacity world-wide, so this study does not focus on the emission intensities of future more advanced technologies such as Generation-IV reactors.

[1] The distinction between these two main options in the nuclear industry relies on whether spent fuel is considered waste to be disposed of (as in the open cycle) or reprocessed to be used as fuel in nuclear reactors (as in the closed cycle). The main benefits of the latter are waste volume reduction and resource base increase, while major drawbacks are costs and sensitivity for diversion of plutonium for military or terrorist purposes.

3. GHG emissions

Fig. 1 shows LCA results for GHG emissions of several main power production options. The normal distributions are drawn on the basis of literature review data gathered by Weisser [26] (2007, Fig. 5), such that Weisser's reported min–max ranges correspond to approximately 95% confidence levels in the Gaussians of Fig. 1. As meaningful as their means are the depicted uncertainty ranges of these distributions, because for each option the GHG emission intensity strongly varies with the country or technology under consideration, or even the type and completeness of the LCA method applied. Since for nuclear energy, hydropower and wind energy the reported GHG emission intensities have similar central values and comparable uncertainty ranges, and likewise for photovoltaics (PV) and biomass based electricity generation, these two sets of options are each represented by one Gaussian probability density function. This simplification facilitates their depiction in one graph. Most striking in Fig. 1 is that electricity generation from nuclear energy and renewables is characterized by much lower GHG intensities than the use of fossil fuels in conventional power stations (note the logarithmic scale of the x-axis). Natural gas fired power plants are significantly less GHG-intensive than coal fueled plants, typically by about a factor of two. Nuclear energy and hydro- or wind power have comparable GHG intensities, while these three options have typically a lower GHG footprint than their PV or biomass counterparts. For PV technologies the majority of emissions arise during the manufacturing of the module, with other significant GHG releases from the construction of the balance-of-plant and inverter, while operation and end-of-life activities involve very limited GHG emissions. For biomass based power production the vast majority of emissions arise at the stage of fuel production from biomass crops: the stage of electricity generation itself through the combustion of biofuels (wood-based in the case of Fig. 5) is supposed to be carbon-neutral. Not observable (but pointed out in Ref. [26]) is that the upper limit of the GHG intensity for biomass exceeds that for PV as a result of the large diversity in combustion efficiencies and biofuel feed types. Note that going from left to right in Fig. 1 implies larger uncertainty spreads due to the increasing abundance of technology and/or fuel types.

All results shown in Fig. 1 are based on calculations published between 2000 and 2006. Hence the underlying data are close to a decade old, or more. About half of the results originate from non-peer-reviewed publications, and for nuclear energy several numbers correspond to a heavy reliance on

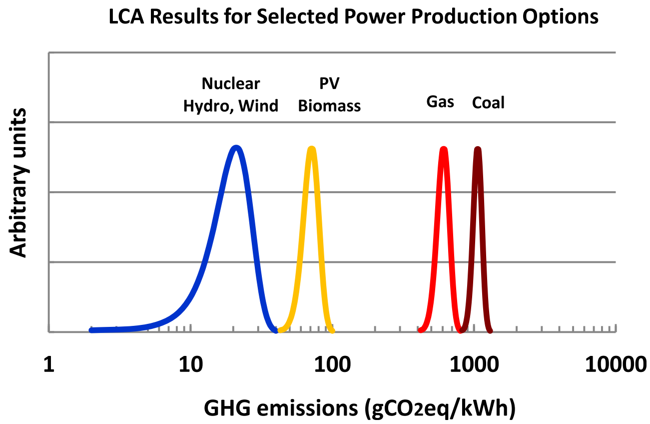

Fig. 1. Life cycle analysis results for greenhouse gas emissions of several power production options. Normal distributions based on data from Ref. [26].

energy-intensive gas diffusion technology for uranium enrichment. For nuclear power the present paper therefore provides an update, based on the aforementioned four main selection criteria. The opportunity is taken to extend the review of Ref. [26] with more results reported during the past decade, in order to obtain a better overall balance of LCA-based GHG emission intensity calculations. Table 1 lists the articles we consulted that appeared in the peer-reviewed literature. The quoted figures are LCA outcomes for nuclear power based on predominantly centrifuge enrichment and represent a mix between open and closed fuel cycles.

This list of 8 articles (co-authored by 20 experts) describe a total of 12 different studies. It expands previous overviews and differs significantly not only from the list assembled by Weisser [26], but also from the review by Sovacool [20], given our more stringent selection criteria. In particular, 4 of the 8 publications reviewed by Weisser [26] were omitted on the grounds that they did not constitute peer-reviewed literature (while the remaining 4 papers passed all criteria). Several references were added that were included in the work of Sovacool [20], but only a subset of the 19 studies he selected were retained in our collection for the present review, because a number of papers were published without prior expert checks. Also omitted was the paper by Rashad and Hammad [18], because it did not involve primary research, while Dones et al. [3] was added, since it reported the results of original calculations, contrary to what was claimed by Sovacool [20].

A recent publication by Pearce [17] was dismissed on the grounds that it presents no new GHG emission intensity calculations, but relies on a secondary source instead. The few authentic calculations it presents on the energy requirements of uranium extraction from ore are of no consequence for our review, as they are based on out-dated non-peer-reviewed literature, include no progress for either extraction or enrichment technology, embody no improvement in the carbon intensity of power production (and thus involve no increase in e.g. the share of renewables or natural gas), stipulate ungrounded energy payback times for power plant construction, and – last-but-not-least – imply unrealistic expansion rates for nuclear energy (10%/yr, so that a capacity of close to 20,000 GWe is installed in 2050, in comparison to around 350 GWe today).[2]

Fig. 2 depicts the outcomes of LCA calculations for the GHG emission intensity of nuclear power from the 12 studies reported in the 8 publications listed in Table 1. These independent findings are in remarkable agreement, and consistently imply a central value for the GHG emission intensity of nuclear energy of around 10 gCO2eq/kWh, within an uncertainty range of 5–17 gCO2eq/kWh. This range is broadly consistent with the one reported by Weisser [26], while its upper bound is several times lower than the mean value quoted in Ref. [20]. As indicated by the dots and error bars in Fig. 2, some studies merely report central values, while others describe ranges of outcomes. The error margins around a subset of data points derive from sensitivity analyses, or from the authors having investigated, for example, different reactor types (e.g. PWRs or BWRs) or fuel cycles (open or closed). The variability across these studies is the result of (a combination of) such effects. Part of the depicted variations between different studies may be due to the type of LCA performed (PCA or IOA) or the specific features, assumptions and/or completeness of the adopted tool or methodology. Differences occur as a result of varying assumptions with regards to the nature of the electricity mix (required e.g. to run an enrichment plant), or the lifetime of the nuclear power plant. National or regional variations may result from differences in adopted policies, for instance with respect to the decarbonization of the energy carriers used in the multiple stages of the nuclear fuel cycle (such as mining), or differences in policies regarding nuclear energy itself. As can be seen from Table 1, there is a fairly good distribution among analyzed regions, varying from the USA to Europe and East Asia. Tokimatsu et al. [22] explicitly distinguish between several nuclear energy policy cases. The results reported in Table 1 and Fig. 2 include in principle all GHG emissions, but CO_2 proves to largely dominate. Historic figures for nuclear power's emissions intensity and its breakdown in GHG species can differ substantially from numbers reflecting today's situation, for example when coal was used to fire power

Table 1
Publications in the peer-reviewed literature with original LCA calculations for the GHG emission intensity of nuclear energy (centrifuge enrichment, open and closed fuel cycles).

References	Journal	Results (gCO_2eq/kWh)	Region/Country/Case (numbers in brackets refer to *x*-axis Fig. 2)
[3]	Encyclopedia of energy	6–11	France/Germany (1)
[5]	International journal of life cycle assessment	5	Europe – near future (2)
		5–12	Europe – today (3)
		8–11	Western Europe (4)
[4]	International journal of global energy issues	9	China (5)
		5–6	Switzerland (6)
[6]	Energy policy	12	USA/Europe/Japan (7)
[11]	Energy	10–11	Japan (8)
[22]	Energy policy	10–13	Japan – LWR case (9)
		5–13	Japan – promotion (10)
[25]	Applied energy	6–7–8	Netherlands/Belgium (France) (11)
[27]	Fusion engineering and design	8–15–17	USA (12)

N.B. The ranges indicated in studies 11 and 12 refer to the lower, central and upper values of the performed uncertainty analysis.

[2] This high growth scenario assumes nuclear energy's multiple challenges are resolved. Pearce [17] consequently makes faulty conclusions regarding the availability of high concentration uranium ore in 2050.

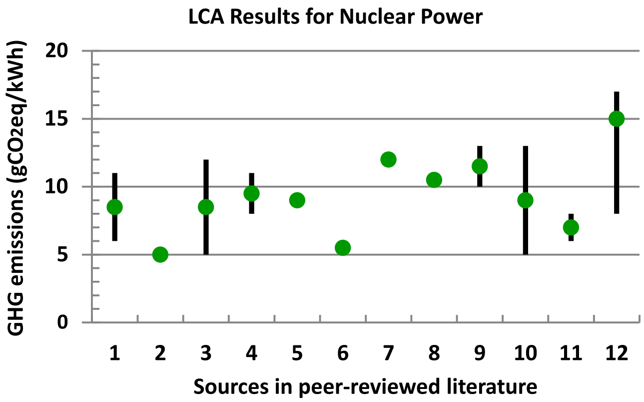

Fig. 2. Life cycle analysis results for greenhouse gas emissions of nuclear power according to 12 peer-reviewed studies. Numbers on the *x*-axis refer to references listed in Table 1.

plants whose electricity was used for gas diffusion enrichment: methane emissions from coal mining could then constitute a non-negligible contribution to the overall level of GHG emissions of the complete nuclear fuel cycle.

4. GHG emission reduction scenarios

Concerns over climate change, as well as air pollution and energy security, have increasingly dominated the energy policy agenda over the past decade – issues that nuclear energy could contribute to alleviate.[3] Yet even while these concerns stimulated considerable public discussion on energy technology futures and renewed political interest for nuclear power in many countries, they did not generate deployment that can be denominated 'nuclear renaissance', terminology used by some proponents of nuclear energy. The recent global construction rate of nuclear power plants, although with several GWe/yr during past years higher than a decade ago, still fell well short of the growth observed in the 1970s and 1980s with additions of 15–20 GWe/yr. If nuclear energy is to play a role in mitigating climate change, it would need to be expanded significantly, typically by at least a factor of three over the next 50 years (see e.g. Ref. [16,19]). Tavoni and van der Zwaan [21] find that for reaching a climate target of 550 ppmv atmospheric CO_2 concentration it could be economical to expand nuclear power by about a factor of three over the next half a century. Such an expansion would involve an average power plant construction rate close to 20 GWe/yr, hence similar to the level reached during the 1970–1980s, which should thus be possible from a techno-historical point of view. For an expansion over the coming half a century by a factor of three, however, large financial hurdles need to be overcome, not only because of current high commodity prices and correspondingly elevated upfront investment costs for power plant construction, but also since the recent banking and economic crises have reduced available budgets in both public and private sectors and have substantially limited capital borrowing opportunities. Apart from relatively unfavorable overall economics for nuclear power expansion in many countries at present, intrinsically long lead times and risks of delays for the construction of new nuclear power plants as well as legal, political and social uncertainties add to the obstacles experienced by the nuclear industry. An increase to a level of around 1000 GWe of nuclear capacity globally would generate challenges of untested proportions at a world scale, such as related to long-term radioactive waste storage and intra-state weapons-related proliferation of nuclear materials and technologies or their terrorist diversion. Even so, until early 2011, this growth could perhaps have been imaginable as upper limit of what may realistically be achievable ([23]).

After a first sea-change in public opinion following the Chernobyl accident in Ukraine in 1986, the accidents in the reactors and spent fuel cooling ponds of the Fukushima-Daiichi nuclear power plant in Japan in 2011 have generated a second land-slide in how people and governments view nuclear energy. As a result, a global increase of nuclear energy by a factor of three over the next 50 years is now unlikely. The previous Japanese government committed itself to abandon an earlier agreed expansion for the nation's nuclear power capacity, and was expected to formulate policy to eventually phase it out, but the country's newest leadership seems to prefer to continue reserving a long-term role for nuclear energy. The federal government in Germany has returned to its prior deal with the electricity sector, which implies it will phase out nuclear power over the course of the next 10 years. Switzerland will follow suit with a similar plan. In June 2011, in a second referendum on the subject since 1987, the Italian population expressed overwhelmingly their opinion that their country should not engage in the construction of nuclear reactors domestically. More countries in especially the developed world may pursue these examples. By contrast, several other countries remain for the moment firm in their desire to create or keep reserving a role for nuclear energy in national electricity generation, such as France and the US. Among these are notably China and India, as well as other countries in Southern and Eastern Asia. This category also includes states in Eastern Europe, such as Poland, and in the Middle East and Gulf region, like Egypt, Turkey and the United Arab Emirates. In other words, reactions to the Fukushima accident have been diverse and have generated different impacts across the planet. For an inspection of the different attitudes in two key countries in the industrialized world, Germany and the US, as well as a description of how to possibly prepare for a more uncertain future of nuclear power, see Ref. [8]. Whereas on aggregate nuclear power may still grow, albeit modestly, over the decades to come – a decline in some parts of the world being compensated by growth in other parts – a substantiated role for nuclear power in international efforts to mitigate global climate change seems now, unexpectedly, largely reduced.

Today an annual nuclear electricity generation of around 3000 TWh/yr contributes around 15% to global power production. Replacing all nuclear capacity by natural gas based power plants emitting 500 gCO_2eq/kWh, to reach the current nuclear electricity generation level, would add about 1.5 $GtCO_2$/yr of annual atmospheric CO_2 emissions. Likewise, substituting it with coal based power plants emitting 1000 gCO_2eq/kWh would contribute 3.0 $GtCO_2$/yr of additional emissions. Hence, with at present global CO_2 emissions of around 30 $GtCO_2$/yr, nuclear energy's climate mitigation contribution today amounts to approximately 5–10%, and is thus certainly non-negligible. One could in principle phase out nuclear energy as climate management option in favor of coal-based plants complemented with CCS technology. In an integrated assessment modeling

[3] While the benefits of nuclear energy in terms of the first two concerns may be evident (they constitute the subject of and hence are extensively described in this paper), its advantage in terms of ascertaining energy independence may appear less obvious: it lies in the fact that the energy density of uranium is very high in comparison to that of fossil fuels, the cost of nuclear power is little sensitive to uranium market price volatilities, and strategic reserves of uranium can easily be built from a broad set of providers throughout the world.

framework it was shown that the technical and economic improvements of CCS need to be large in order to render it cost-efficient enough for 'clean coal' to become the dominant alternative to nuclear power ([21]).

5. PM and other emissions

Dones et al. [5] also perform extensive LCA for emissions of substances other than GHGs, including NO_x, SO_2 and PM, from power plants in Europe. The emissions of these by-products may have pervasive detrimental health and/or environmental effects. For example, Dones et al. [5] find that for nuclear power plants the fine PM ($PM_{2.5}$) emission intensity is about 5–7 mg/kWh, while for natural gas based power it is significantly higher, about 11–22 mg/kWh. In contrast, the combustion of oil for electricity generation emits at least one order (but possibly over two orders) of magnitude more PM than that of natural gas, while coal-fired power plants possess a PM emission intensity over four orders of magnitude higher than plants fueled with natural gas.[4] In the light of these figures, nuclear power's PM intensity is negligible. With integrated assessment models it has been calculated that optimal energy policy can reduce the number of premature deaths from air pollution by about 14,000 annually in Europe alone, and over 3 million per year globally, by lowering the chronic exposure to ambient PM ([1]). Nuclear energy can, along with other energy technologies, contribute to achieving mortality reduction by avoiding emissions of PM. It can do so not only in the power sector, but also in transportation if this sector switches to the use of e.g. (battery based) electric or (fuel cell based) hydrogen vehicles. There is increasing evidence that preferentially regulating certain types and sources of ambient fine PM – rather than the total mass of PM, as if all PM were equitoxic – is most effective to avert PM-related detrimental human health effects ([10,12,15]). In particular, public health will likely be better protected by reduction of various types of transportation emissions than by continued regulation of the total amount of fine PM ([9]). Whether nuclear power is used to generate electricity or produce hydrogen to fuel vehicles, in either way it could alleviate the impacts of some of the most harmful constituents (species) of airborne PM.

Nuclear energy is different from other power production options in that it generates (under normal operational circumstances) low levels of radioactive emissions to which power plant workers can be exposed. The radiation exposure the general public may possibly receive from nuclear power plants, as well as its potential health impact, is negligible in comparison to radiation and its effects from natural sources. The public receives typically several mSv/yr of natural background radiation, while one typical CT scan yields an exposure of around 10 mSv. At this radiation level there is no direct evidence for human health consequences. For workers in nuclear power plants, occupational radiation safety standards vary from 50 to 100 mSv/yr. Between 10 and 1000 mSv/yr, there are no early effects to human health of radiation exposure, but there is an increased incidence of certain cancers in exposed populations at the higher doses in this range.[5] Radiation doses from airborne effluents of older types of coal-fired power plants with high atmospheric releases of ash (containing traces of uranium and thorium) have been reported that may be higher than those from the operation of light-water nuclear reactors ([14]). Recently constructed coal-based power plants in some developing countries (such as China and India) often still have a relatively high ash content. For a recent overview of efforts to internalize external costs associated with various types of power production (including a broad spectrum of possible atmospheric effluents, such as GHG, PM and radioactive emissions), and an analysis of how accounting for the social costs of electricity generation can inform policy choices towards establishing sustainable development, see Ref. [13].

6. Concluding remarks

During the past decades significant progress has been made in reducing the GHG emission intensity of nuclear energy. Among the main drivers behind this improvement has been – and increasingly is– the use of more modern technology for uranium enrichment, an essential part of the nuclear fuel cycle. As a result of the ongoing replacement of gas diffusion by centrifuge enrichment technology, a process expected to be fully achieved in several years from now, the energy intensity and thus GHG emission intensity of nuclear energy is being reduced by factors, and in some cases even by an order of magnitude (when e.g. gas diffusion plants operating on electricity generated from coal based power plants are replaced by centrifuge enrichment plants running on solar, wind or hydropower). Further reductions in the GHG emissions intensity of nuclear power may be feasible by the use of laser enrichment technology, but it is unlikely that this technique will be commercially deployed on a large scale before the end of the decade and has thus not been accounted for in this study. Over the coming decades more progress is likely in reducing the CO_2 footprint of nuclear energy as the carbon intensity of the electricity portfolio declines. Today the GHG emission intensity of nuclear energy is low – surely in comparison to fossil fuel based technologies – and compares with that of most renewables, in particular hydropower and wind turbines. While some variation exists across different reactor types and fuel cycles, there seems no evidence in the current literature that the GHG emission intensity of nuclear power can be further decreased by switching to advanced technology such as thermal or fast Generation-IV reactors.

Acknowledgments

Alex Glaser, Ad Seebregts and Daniel Weisser are greatly acknowledged, as well as colleagues at the Earth Institute's Lenfest Center for Sustainable Energy at Columbia University, for useful comments to this paper and/or valuable input for the underlying work that was gratefully used when preparing this review. All remaining errors are those of the author only.

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