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Carbon emissions and costs associated with subsidizing New York nuclear instead of replacing it with renewables

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ABSTRACT

We compare the cost of maintaining a proposed subsidy for New York's three upstate nuclear power plants with the cost of replacing the plants with renewable technologies from 2016 to 2050. Keeping nuclear operating with subsidy until 2050 is the most expensive option, costing $32.4 billion (2014 USD) over that period in the base business as usual case. The least expensive option is to shut down nuclear today and replace it with onshore wind, saving $7.9 billion. All analyzed renewable scenarios lead to 20.1 to 27.4 Mt CO_2 greater life-cycle emission reductions. In addition, re-investing the cost savings of the renewable scenarios into additional onshore wind increase CO_2 savings up to 32.5 Mt.

1. Introduction

In 2015 the state of New York (NY) committed to ambitious climate mitigation goals, aiming to reduce greenhouse gas emission by 40% by 2030 compared with 1990 levels (New York State Energy Plan, (New York State, 2017)). To accomplish this, NY plans to transition from its current electricity generation portfolio—which heavily relies on natural gas-fired systems (41% of total annual power generation) and nuclear power plants (32%) (US Energy Information Administration, 2017a)—to higher shares of electricity from renewable energy (RE) systems. More specifically, by 2030 50% of power generation must come from RE sources (photovoltaic, wind, hydro, and biomass). This is in line with a general trend where states start to aim for more ambitious renewable goals, e.g. through renewable portfolio standards (RPS). The state of California, for example, targets a RE share of 50% by 2030 (and is proposing 100% by 2045), Vermont 50% by 2040, Oregon 75% by 2032, and Hawaii 100% by 2045 (US Energy Information Administration, 2017b).

1.1. Nuclear power - a low carbon alternative to renewables?

Nuclear energy is often seen as a fundamental or bridging technology for future low-carbon systems (International Energy Agency, 2015a; Echavarri, 2013). While it is true that electricity production from nuclear energy is characterized by very low CO_2 emissions during the operation phase of the plant, its full life-cycle CO_2 emissions, including all up- and downstream processes, are typically much more CO_2 intensive. Additionally, several drawbacks of the technology exist, such as operational risks including potential reactor accidents as happened in Chernobyl and Fukushima, concerns in weapon proliferation, waste issues, ecological hazards from byproducts of uranium mining, construction costs of new reactors, and a divided public acceptance (IPCC, 2015; Beckham and Mathai, 2013). The key practical challenge throughout the history of nuclear power development has been the high construction cost, which has been increasing steadily during the last few decades (Davis, 2012). While the operating costs of nuclear plants are relatively lower, the construction costs are currently so high that it becomes difficult to make an economic argument for nuclear even before incorporating all life-cycle costs and aforementioned

Abbreviations: BAU, Business as usual; CAPEX, Capital expenditure; CF, Capacity factor; HCLB, High costs low benefits; LCHB, Low costs high benefits; LCOE, Levelized Cost of Electricity; Nuc, Nuclear power plant; NY, State of New York; O&M, Operation and maintenance costs; OPEX, Operating expenditure; PV, Photovoltaic; RE, Renewable energy; RPS, Renewable portfolio standard; SCC, Social costs of carbon; ZEC, Zero Emission Credit.

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external factors (Davis, 2012). Aside from having a very high capital expenditure cost (CAPEX), new nuclear plants are plagued by planning, permitting, and construction delays (Davis, 2012). In particular, the multi-year planning and construction phase bears the risk of technology lock-ins, where a change to more efficient technologies is almost impossible once investments are made (Beckham and Mathai, 2013). Other low-carbon technologies, including onshore wind and utility-scale solar photovoltaics, generally take much less time between planning and operation. Finally, nuclear power often is heavily subsidized, even to the extent that the overall subsidies actually exceed the value of the generated power (Koplow, 2011; Bradford, 2017).

Nevertheless, even after the severe impacts of the Fukushima accident, nuclear power generation is currently still the backbone of many energy systems, even though the worldwide annual electricity production of "modern" renewables (wind, photovoltaics) has exceeded that of nuclear power in recent years (and even surpasses electricity production from natural gas if hydropower > 50 MW is included) (Lovins et al., 2018). As of 2017, nuclear plants provided 10% (2,557 TWh) of the worldwide electricity generation (International Energy Agency, 2017), increasing its share by 3% compared with 2016. Still, worldwide additional nuclear capacity barely exceeded reductions due to shut-downs in 2017 (International Energy Agency, 2017).

1.2. Literature review

There are various studies that analyze the role of nuclear power as an alternative or complementary technology to renewables. Typically, these studies either focus on techno-economic aspects of nuclear-renewable hybrid solutions (Ruth et al., 2016; Suman, 2018), which combine nuclear reactors with RE systems and industrial processes in order to compensate for shortcomings in each technology, or on region-specific case studies, which analyze the role of nuclear power in decarbonization scenarios (Beckham and Mathai, 2013; Park et al., 2016; Dong et al., 2017, 2018; Strategen Consulting, 2017; Caldwell et al., 2016). We summarize and assess some of the recent literature on such case studies.

Park et al. (2016) study whether nuclear power is cost-effective relative to RE systems in Korea. The authors quantify the willingness to pay of private customers to replace nuclear and fossil power with renewables. This metric is also compared with the actual costs of building and operating renewable systems. While the study of Park et al. (2016) has much value, the analysis uses high cost data for renewables and low cost data for nuclear power from 2014 relative to, for example, Lazard (2014). In addition, the authors do not differentiate between different renewable technologies—such as residential and utility-scale Photovoltaic (PV) or wind power systems—but instead aggregate all renewable technologies and assign one cost per unit of electricity produced. When compared with more recent levelized costs of electricity (LCOE) data (e.g., Lazard (2017)) RE systems are less expensive relative to nuclear power than shown by Park et al. (2016).

Studies of China and India that analyze CO_2 mitigation strategies as well as the efficient use of energy (Tollefson, 2018) acknowledge the importance of RE compared with nuclear power as an alternative. Dong et al. (2018), (Dong et al., 2017), for example, highlight the importance of RE systems for CO_2 mitigation in China. The authors emphasize that, while nuclear can help to reduce CO_2 emissions, its potential contribution is significantly smaller than of RE systems. Moreover, the study concludes that RE systems will become gradually more important over time. Similarly, Beckham (Beckham and Mathai, 2013) argues that nuclear power cannot fulfill the promise of an unlimited energy resource in India and points out that it is impossible to incorporate all ancillary and social costs over the whole life-cycle of a nuclear power plant. Costs are therefore distorted and under-estimated. As the current electricity generation share of nuclear power in India is only around 2%, and the technology is typically associated with large opportunity costs that arise from the time lag between planning and operation of a nuclear plant relative to RE systems (Jacobson et al., 2017), Beckham (Beckham and Mathai, 2013) advises against the expansion of nuclear power in India.

Despite these findings, global installations of new nuclear plants are usually delayed or slowed down (International Energy Agency, 2015b). In addition, the Fukushima accident initialized the phase out of nuclear in some countries, such as Belgium, Germany, and Switzerland. Mathai (2013) describes the policy reactions to Fukushima as a "a pause, nod, shrug policy".

1.3. Nuclear power in New York

NY operates four nuclear power plants at the moment. Recently, the state proposed to subsidize the three upstate nuclear plants Fitzpatrick, Nine Mile Point Unit 1, and Ginna through Zero Emissions Credits (ZEC) to keep them operating rather than investing into new RE capacities (New York State, 2016). This approach was assumed to save costs while relying on a low carbon technology, very much in line with the idea that existing nuclear power as a bridge technology to low carbon scenarios (International Energy Agency, 2015a; Echavarri, 2013). Whether this is the case has already been investigated in several studies for other power plants and sites, e.g. for Diablo Canyon (Caldwell et al., 2016)—the last nuclear plant in California operated by Pacific Gas & Electric—and Indian Point north of New York City (Strategen Consulting, 2017). The former study concludes that replacing the twin reactors of Diablo Canyon with renewables and energy efficiency measures can save up to $5 billion, compared with extending the life-time. The latter finds that $315 million over five years can be saved if Indian Point is replaced with a combination of wind and solar power, electricity storage, and increased energy efficiency.

We evaluate the NY proposal by comparing the nuclear subsidy scenario with several alternative renewable scenarios with regard to cost and life-cycle CO_2 emissions.

The remainder of this paper is structured as follows. Section 2 describes the methodology and the analyzed scenarios. Section 3 presents the results in terms of mitigation costs and CO_2 emissions savings, including a sensitivity analysis of the main drivers. Section 4 summarizes conclusions.

2. Methodology and data

We compare costs based on fixed annuities of the investments and operating expenditures (OPEX). The latter are comprised of fuel costs and variable operating and maintenance (O&M) costs. Fixed O&M costs are included as a share of the CAPEX. All cost assumptions are time-dependent and can change over the observation period (e.g. due to learning effects or resource scarcity that increase fuel prices). Throughout the scenarios, a discount rate of 4.5% and an amortization period of 20 years are assumed. Sensitivity tests are run to test the effects of 3% and 6% discount rates.

Emissions are considered per kWh of produced electricity (kWh_{el}), including emissions that occur over the complete life-cycle of a technology (*cradle to grave*). We use the following values (based on Sovacool (2008), Lenzen (2008) and updated values from Jacobson (2009); nuclear: 66 g-CO_2/kWh_{el}, onshore wind: 10 g-CO_2/kWh_{el}, PV (no difference between utility-scale and rooftop): 30 g-CO_2/kWh_{el}.

The summed installed capacity of Fitzpatrick, Nine Mile Point Unit 1, and Ginna is 2.1 GW (US Energy Information Administration, 2015), providing 16,330 GWh of electricity per year (which equals ~11% of NY's overall electricity demand as of 2015 (US Energy Information Administration, 2017a). In our scenarios, replacing these plants with 100% RE systems would require either

i. 7.5 GW of onshore wind capacity
ii. 3.7 GW of onshore wind capacity and 4.4 GW of utility-scale PV capacity
iii. A combination of 3.7 GW onshore wind, 2.2 GW of utility-scale PV, and 2.7 GW of rooftop PV

As such, in this study, we examine the following scenarios:

Scenario 1 ("business as usual" or "BAU"): All three upstate nuclear plants keep operating from 2016 until 2050. Their annual electricity generation of 16,330 GWh is assumed to stay constant during that period. To ensure comparability, any alternative scenario[1] is assumed to provide the same electric energy annually. The proposed nuclear subsidy, which runs until 2028, is assumed to continue thereafter until 2050 at the rate of the last year of the subsidy in 2028.

Scenario 2 ("Nuc until 2028"): Nuclear is assumed to stay open until the end of 2028, when the currently proposed subsidy runs out and is then replaced by onshore wind. The installed capacity of wind turbines needed to provide 16,330 GWh/yr with a capacity factor[2] (CF) in New York of 0.25 (average CF 2013 (windAction, 2014)) is 7.5 GW. The investment in the wind turbines starts in 2025 as the construction and planning time for wind farms has to be considered.

Scenario 3 ("Wind"): Nuclear closes as soon as possible (end of 2020) and is replaced by onshore wind. It is assumed that electricity generation from wind power starts in 2021 due to construction and planning times required, while the investment begins in 2017. In that case, the nuclear subsidy continues until the end of 2020.

Scenario 4 ("Wind/PV"): Nuclear closes as soon as possible (end of 2020) and is replaced by wind, utility-scale PV, and residential rooftop PV (investment starts in 2017, first operating year is 2021). Capacity factors of utility-scale PV and rooftop PV are 0.21 and 0.17, respectively, and based on the 2015 mean values of the lower and upper CF range of NREL's ATB Cost and Performance Summary (National Renewable Energy Laboratory, 2016). 50% of the overall electricity generation (16,330 GWh/yr) is provided by onshore wind (8,165 GWh/yr at 3.7 GW); utility-scale PV and rooftop PV provide 25% each, resulting in a required installed capacities of 2.2 GW and 2.7 GW, respectively.

Scenario 5 ("Wind/PV utility"): Nuclear is replaced by a combination of onshore wind (8,170 GWh/yr at 3.7 GW) and utility-scale PV (8,170 GWh/yr at 4.4 GW). Wind and PV generation start in 2021. The nuclear subsidy ends at the end of 2020, as with the other cases.

Scenario 6 ("Nuc moderate CF"): This scenario assumes that the 2015 CF of the three nuclear power plants averaged between 2016 and 2050 (0.91) decreases to 0.85. The rationale is that older nuclear plants require greater maintenance and higher penetration levels of renewable systems imply less utilization of nuclear power. As a consequence, the electric power generation from nuclear declines from 16,330 GWh/yr to 15,316 GWh/yr. In order to be comparable with the other scenarios (i.e. having the same annual electricity generation of 16,330 GWh/yr), the reduction in nuclear generation (1,013 GWh/yr) is made up for by a mix of additional onshore wind, utility-scale PV, and rooftop PV (231 MW, 138 MW, 170 MW, respectively).

Fig. 1 summarizes the temporal sequence of investments and power generation until 2050.

3. Results

3.1. Cost savings

Fig. 2 shows the overall system costs and life-cycle CO_2 emissions for each scenario, separated into CAPEX, OPEX, and nuclear subsidies. Section 3.2 compares CO_2 emissions for the case where the costs depicted in Fig. 2 are instead invested in additional wind capacity.

Scenario 1 ("BAU"): The overall costs between 2016 and 2050 are $32.4 billion (in 2014 USD), mainly consisting of subsidies for nuclear power. For the first 12 years, nuclear receives a subsidy that increases annually and caps at $805 million in 2028, summing to $7.6 billion between 2016 and 2028. In this scenario, we assume that the subsidy continues at $805 million/yr for the remaining 22 years past 2028 until 2050, totaling an additional $17.7 billion from 2028 to 2050 or $25.3 billion ($7.6 + 17.7 billion) over the entire 34 years from 2016 to 2050. Operating costs, mainly fuel costs, are around $7.0 billion (22% of the total costs) during this period. The total life-cycle CO_2 emissions are the highest among all scenarios, resulting in 37 Mt CO_2 until 2050.

Scenario 2 ("Nuc until 2028"): The overall costs are $31 billion. Around 66% ($20.6 billion) are CAPEX of the newly installed wind turbines, while 25% of the cost ($7.7 billion) is a subsidy to the nuclear power plants, which operate until 2028. OPEX account for only 9% ($2.7 billion). Although the costs do not differ substantially from the BAU costs, this scenario saves 20 Mt of CO_2 emissions until 2050 compared with BAU.

Scenario 3 ("Wind"): This scenario has the lowest overall system cost ($24.5 billion) and CO_2 emissions (9 Mt CO_2). Most of the cost reduction is achieved by avoiding the subsidy for nuclear power. Some subsidies ($2.1 billion), however, continue during the period between planning and initial investment (2017) and operation (beginning of 2021) of the wind farms. The biggest cost component is CAPEX for the new onshore wind capacities. OPEX are insignificant and consist of fixed operating and maintenance costs (variable operating costs for renewable systems are assumed to be zero).

Scenario 4 ("Wind/PV"): This scenario is only slightly less expensive than BAU, resulting in system costs of $31.6 billion, saving around $0.8 billion. The additional cost, compared with scenario 3 ("Wind"), arises due to the lower capacity factor and higher cost of PV (utility + rooftop) versus onshore wind in New York. The scenario reduces CO_2 emissions by 23 Mt compared with BAU. As for scenario 3, the initial years after the investment into renewable capacities, nuclear power plants still need to be kept online for the duration of the construction time.

Scenario 5 ("Wind/PV utility"): The second least-costly scenario results in system costs of $25.8 billion, reducing overall costs by $6.6 billion and CO_2 emissions by 23 Mt compared with BAU. When compared with scenario 4 ("Wind/PV"), where 25% of the electricity is provided by rooftop PV, the lower CAPEX and higher CF of utility-scale PV leads to lower overall system costs. The total CO_2 emissions are identical, as the same lifecycle emissions per kWh for utility-scale and rooftop PV were assumed (see Section 2).

Scenario 6: Assuming a lower CF of nuclear power plants, while renewable technologies compensate the difference in power generation is slightly more expensive the Scenario 1 (+$1.2 billion). However, due to renewable generation, around 1.4 Mt of CO_2 can be mitigated compared to Scenario 1.

[1] Except in Scenario 6 where a decrease of the capacity factor of nuclear implies a change in annual electric energy generation.

[2] The capacity factor describes the utilization of a generation technology. It is defined as the actual energy generated divided by the maximum possible energy generated during the year.

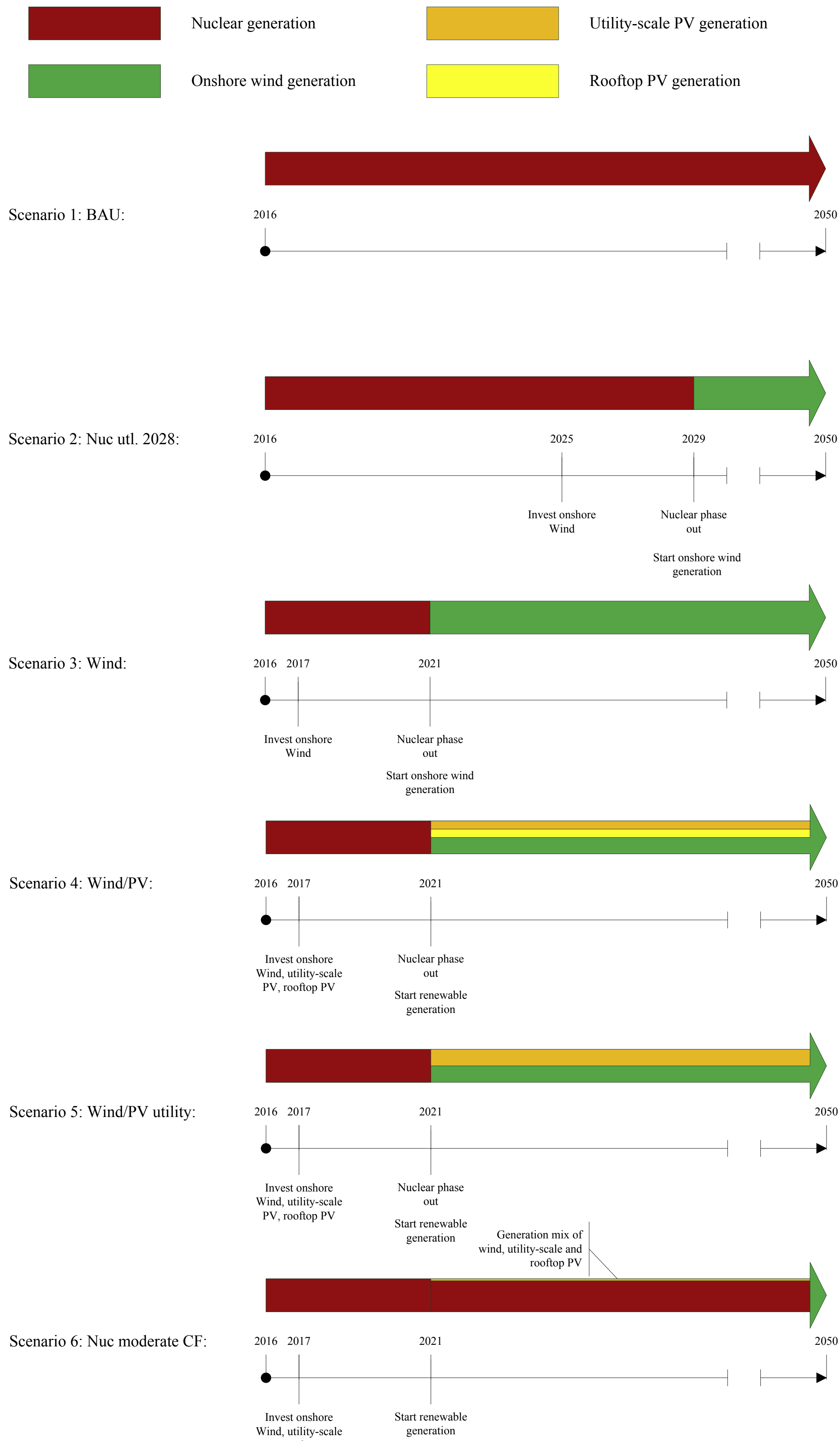

Fig. 1. Timeline of investment and power generation in each scenario.

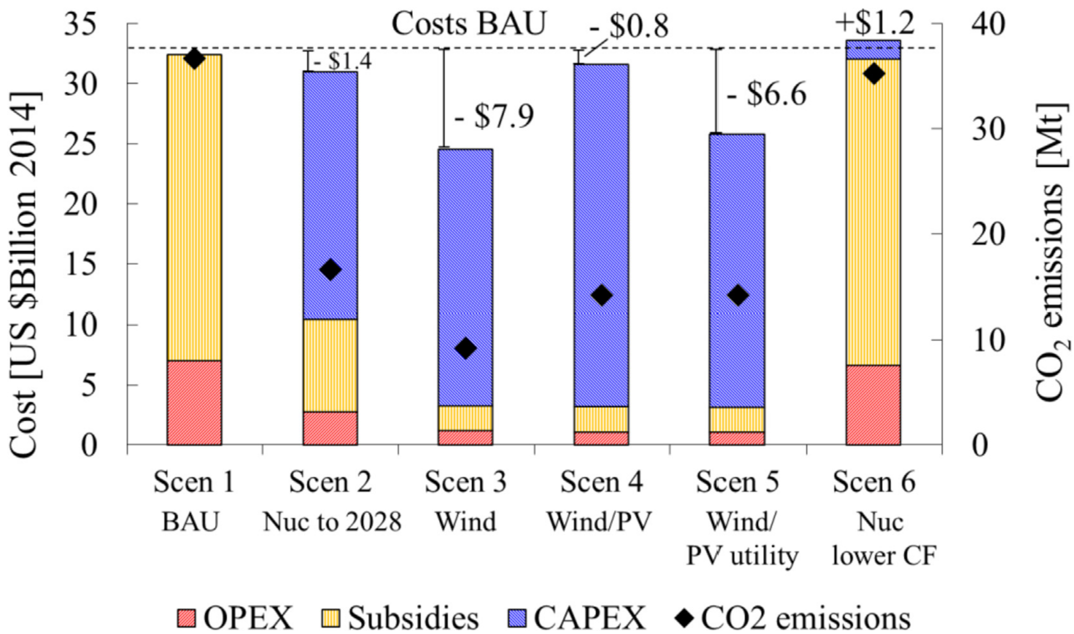

Fig. 2. Comparison of all costs (primary ordinate) and CO_2 emissions (secondary ordinate) for each scenario. Operating costs (OPEX) include fuel costs as well as fixed and variable O&M costs. Subsidies refer to Zero Emission Credits (ZEC) for nuclear power plants. All exact values can be found in Table A.2. in the Appendix.

3.2. CO_2 savings

Results indicate that all renewable energy scenarios lead to system costs savings. Subsequently, we analyze how CO_2 emissions are affected if these cost savings are invested into additional wind power capacities after 2050. It is assumed that the additional RE capacities substitute grid electricity with a specific CO_2 factor of 535 g-CO_2/kWh$_{el}$ (Brander et al., 2011). Fig. 3 illustrates the CO_2 savings in all scenarios compared with BAU with and without re-investing into onshore wind capacity. CO_2 emissions w/o re-investing are identical to the values shown in Fig. 2.

Fig. 3 shows that re-investing the cost savings into onshore wind can save up to 5.1 Mt of additional CO_2 emissions (compared with the scenarios without re-investment). There are no differences in CO_2 mitigation in Scenario 6 since the scenario does not result in any cost savings that can be re-invested (see Table 1).

3.3. Sensitivity analysis

The robustness of the results is tested against variations in the assumed discount rates and different CF's for each of the five main scenarios. Variations in the CF for wind and PV foster a change in the required installed capacities of these technologies (as we require that PV and wind must always provide the same annual electric energy as nuclear, i.e. 16,330 GWh/yr). Table 2 provides the assumptions.

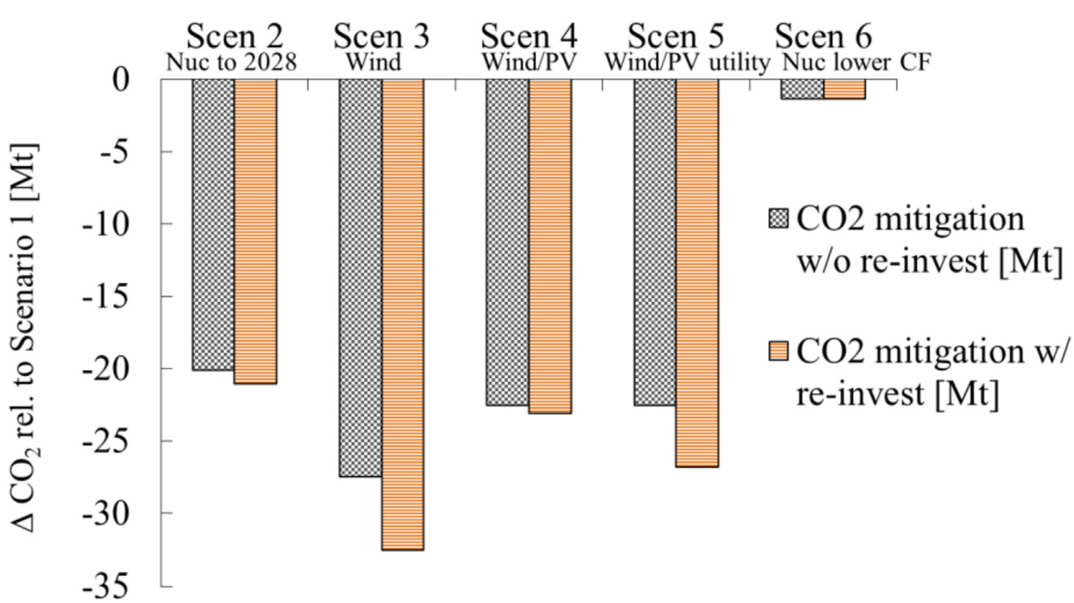

Fig. 3. Comparison of CO_2 emission mitigation compared with BAU for each scenario with and without re-investing of the cost savings into additional onshore wind capacity.

Table 1
Assumptions and results with respect to CO_2 emissions if cost savings are re-invested into additional wind capacity.

Scenario	Savings [$ billion]	Add. wind cap. [GW][a]	Generation of add. caps [GWh/yr][b]	CO_2 mitig. w/re-invest [Mt]	CO_2 mitig. w/o re-invest [Mt]	Add.CO_2 mitig.[Mt]
BAU	–	–	–	–	–	–
Nuc until 2028	1.4	0.8	1,776	20.1	19.2	0.9
Wind	7.9	4.4	9,710	27.4	22.3	5.1
Wind/PV	0.8	0.5	1,036	22.5	22.0	0.5
Wind/PV utility	6.6	3.7	8,105	22.5	18.3	4.3
Nuc moderate CF	–	–	–	1.4	1.4	–

[a] Assuming an onshore wind CF of 0.25 in 2050.
[b] Assuming a CAPEX for onshore wind of $1787/kW based on (Lazard, 2017).

Table 2
Overview of the sensitivity cases and their main assumptions.

Sub-scenario	Discount rate [%]		Capacity factor [-]		
Reference	4.5	(Jacobson et al., 2015), scen. HCLB	Wind:	0.25	Average CF 2013 (windAction, 2014)
			Utility PV:	0.21	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
			Rooftop PV:	0.17	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
CF low[a]	4.5	(Jacobson et al., 2015), scen. HCLB	Wind:	0.22	Scenario LCHB (Jacobson et al., 2015)
			Utility PV:	0.18	Scenario LCHB (Jacobson et al., 2015)
			Rooftop PV:	0.14	Scenario LCHB (Jacobson et al., 2015)
CF high[b]	4.5	(Jacobson et al., 2015), scen. HCLB	Wind:	0.33	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
			Utility PV:	0.21	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
			Rooftop PV:	0.18	Own assumption
Discount low	3.0	Own assumption	Wind:	0.25	Average CF 2013 (windAction, 2014)
			Utility PV:	0.21	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
			Rooftop PV:	0.17	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
Discount high	6.0	Own assumption	Wind:	0.25	Average CF 2013 (windAction, 2014)
			Utility PV:	0.21	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)
			Rooftop PV:	0.17	Mean 2015 of CF Range (National Renewable Energy Laboratory, 2016)

[a] Due to the lower CF, the following capacities are needed (assuming 16,330 GWh/yr); wind: 8.4 GW, PV utility: 10.4 GW, PV rooftop: 13.3 GW.
[b] Due to the higher CF, the following capacities are needed (assuming 16,330 GWh/yr); wind: 5.6 GW, PV utility: 8.9 GW, PV rooftop: 10.4 GW.

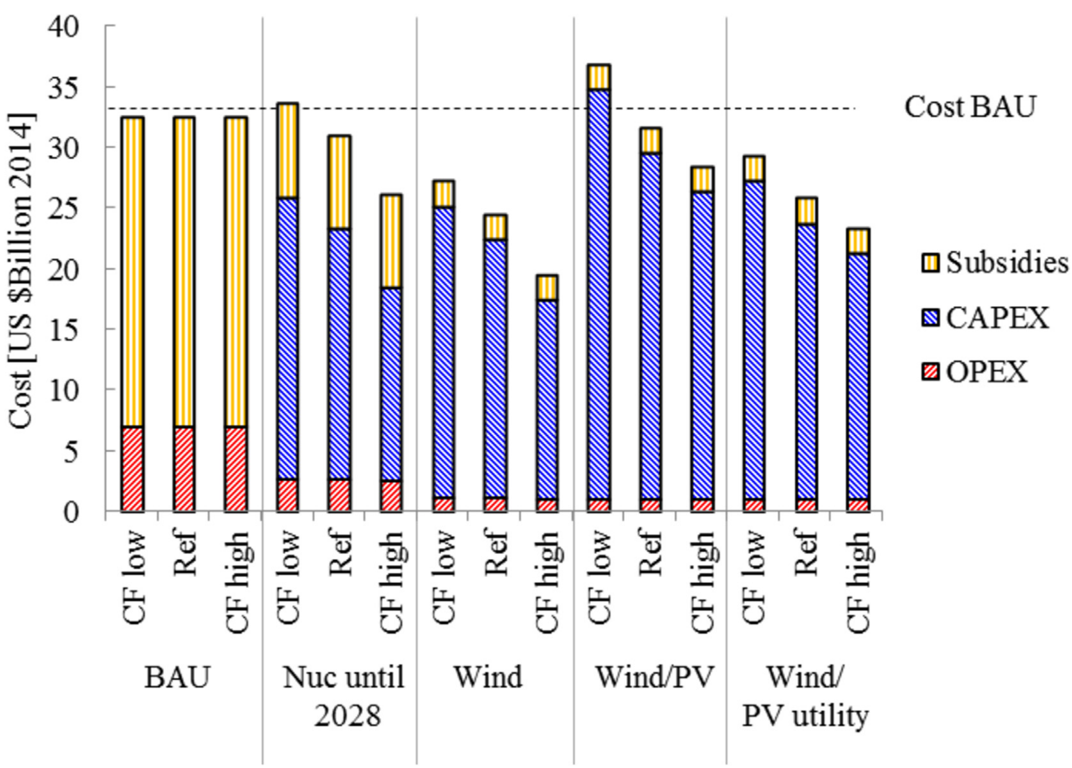

Fig. 4. Comparison of the system costs of the four main scenarios with different capacity factors (CF) for wind and PV systems.

Fig. 4 illustrates the influence of the different CF assumptions on overall costs.

Fig. 5 depicts the influence of the different discount rate assumptions on the overall costs.

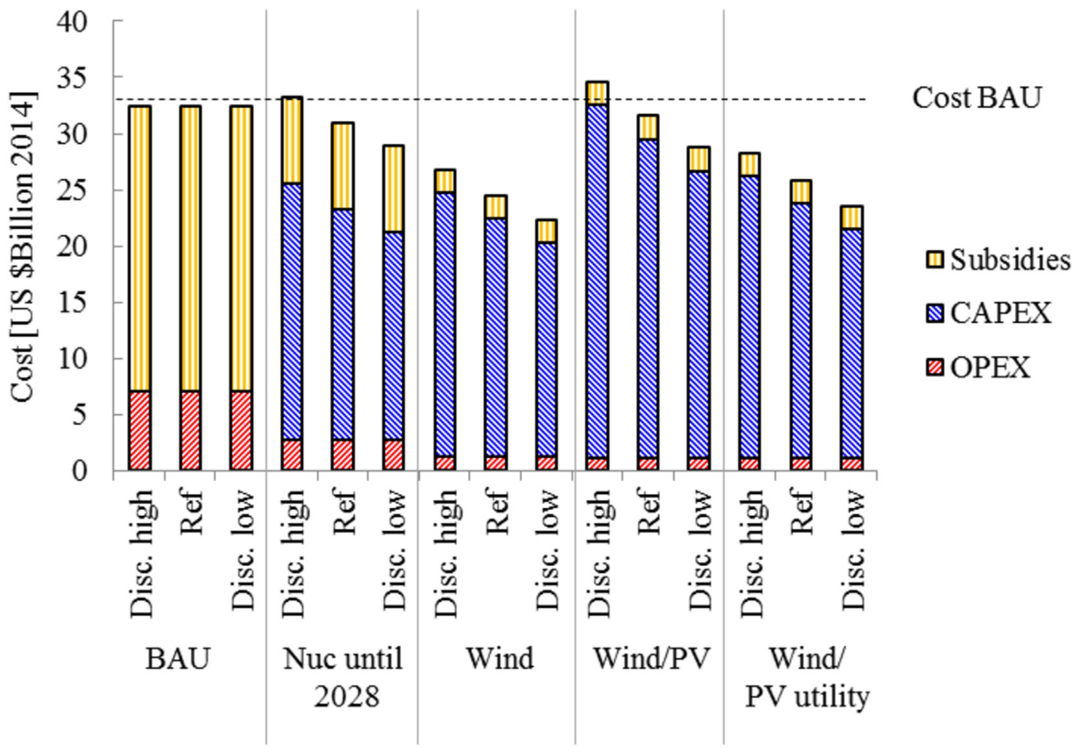

Fig. 5. Comparison of the system costs of the four main scenarios with different discount rates (Disc.) for wind and PV systems.

Figs. 4 and 5 support the key result that most of the renewable scenarios are less costly than the BAU scenario. Only for very low CF's or a high discount rate, scenarios 2 ("Nuc until 2028") and 4 ("Wind/PV") are slightly more expensive than BAU. Yet, scenario 3 ("Wind") and 5 ("Wind/PV utility") are always less expensive than BAU.

4. Conclusions

This paper compared the cost of maintaining a proposed subsidy for three New York nuclear power plants (Fitzpatrick, Nine Mile Point Unit 1, and Ginna) with the cost of replacing the plants with renewable technologies between 2016 and 2050 (business as usual case). Results indicate that keeping nuclear operating with subsidy until 2050 is the most expensive option, resulting in $32.4 billion (business as usual) in cumulative costs in 2014 USD. If the nuclear plants stay online until 2028 and are then replaced by wind and solar, the overall costs decline to $31.0 billion. The most favorable scenario is to shut down nuclear today and replace it with onshore wind capacities, saving $7.9 billion compared with the business as usual case. Substituting nuclear with a combination of wind and utility-scale photovoltaics saves $6.6 billion between 2016 and 2050. A mix of wind, utility-scale, and rooftop photovoltaics saves $0.8 billion. Substituting nuclear with a combination of wind and utility-scale photovoltaics would save $6.6 billion. A mix of wind, utility-scale, and rooftop photovoltaics saves $0.8 billion.

The four renewable scenarios lead to 20.1 to 27.4 Mt CO_2 greater life-cycle emission reductions between 2016 and 2050 compared with the nuclear scenarios. In addition, re-investing the cost savings of the renewable scenarios into additional wind capacity increases CO_2 savings by up to 32.5 Mt.

In sum, in all cases examined, subsidizing the three upstate nuclear reactors to stay open increases both CO_2 emissions and costs relative to the renewable scenarios. A sensitivity analysis supports the robustness of the results against changes in the assumed discount rate as well as in the capacity factors for wind and PV systems.

All renewable scenarios may be even more cost beneficial than depicted in this analysis for the following reasons:

i. It is assumed here that the investments in nuclear power plants are fully depreciated
ii. We use rather high CF's for nuclear power (0.91 and 0.85 in Scenario 6). However, it is likely that the CF of nuclear will decrease even more with increasing penetration of renewable generation
iii. All three nuclear power plants are rather old (Nine Mile: 1969, Fitzpatrick: 1976, Ginna: 1970) and require additional maintenance, replacement, or retrofit at some point. These additional costs are not included in the present analysis

In conclusion, our findings are in line with other research, such as the work of Lovins (2017a) and Bradford (2017). Both agree that nuclear power is often uneconomical without subsidies. Moreover, both authors conclude that, like with our calculation, nuclear typically saves less CO_2 emissions than shutting these plants down and reinvesting the funds in renewables. In other words, electricity from renewables reduces carbon emissions much faster and more efficient than nuclear power does (Lovins et al., 2018).

4.1. Implications for theory and practice

There are several implications that can be derived from our case study that affect theory and practice. First, nuclear power is associated with severe opportunity costs in comparison with renewables due to nuclear's direct energy costs and its relatively long period between planning and operation. This result is supported by the literature (IPCC, 2015; Jacobson et al., 2017; Jacobson, 2009;

Jacobson and Delucchi, 2011; Lazard, 2016; Cooper, 2016). Moreover, the technology bears financial risks, as over the long lifetime of a nuclear power plant, other technologies can become more cost-efficient (technology lock-in). This implication is supported by the present analysis and others (Davis, 2012).

Second, one must consider the dwindling social acceptance of nuclear power in recent years (Tsujikawa et al., 2016; Siegrist and Visschers, 2013; Siegrist et al., 2014; Sun et al., 2016). A publication by Visschers and Siegrist (2013) studied the acceptance of nuclear power in Switzerland before and after the Fukushima accident. In their conclusion, the authors summarize that the acceptance and perceptions of nuclear power as well as its trust were more negative after the accident. While social acceptance is an issue of renewable systems as well—particularly associated with NIMBY ("not in my backyard")—some studies point out that this effect is by no means the main barrier against renewable energy deployment (Wolsink, 2000).

Finally, the installation of renewable energy systems can have significant positive effects on direct and indirect job creation when compared with business as usual scenarios. Such effects are unaccounted for in this analysis and therefore might further improve the value of investing in renewables instead of nuclear (Jacobson et al., 2017; Jacobson et al., 2015; Jacobson et al., 2018).

An argument often raised against the deployment of renewable energy systems is their inherent variable electricity generation on the temporal time scale. To ensure the security of supply, critics claim that such systems would require large amounts of conventional storage or backup, resulting in a high overall system cost, or a breakthrough in bulk energy storage (Sinn, 2017). However, this is a typical misconception with renewable energy systems as, for example, shown by Zerrahn et al. (2018) and Lovins (2017b). The former shows how storage requirements in renewable energy scenarios for Germany are manageable and do not limit the expansion of wind and PV systems. Even at very high penetration rates of variable renewable energies (e.g. > 80%), the storage energy capacity is typically below 1% with regard to the annual energy demand. Lovins (2017b) extends this discussion by illustrating further analytic examples for the US, EU, China, and Denmark, where high shares of PV and wind can be achieved without major installations of bulk energy storage. Furthermore, Lovins (2017b) gives country-specific empirical examples where the deployment of variable renewable energies systems is functioning without massive storage requirements. A number of further studies has shown that reliable and stable systems are feasible at low cost, even with very high penetrations of renewables (Cebulla et al., 2017; Brown et al., 2018a; Jacobson et al., 2015, 2018).

The reasons why such systems work and the flexibility capacities are manageable are discussed subsequently. First, some smoothing effects can be achieved by a smart combination of wind and PV due to their different temporal generation patterns (Heide et al., 2010). Second, one must consider a combination of flexibility options and not only rely on large-scale, central electricity storage (Brown et al., 2018b; Scholz et al., 2017). Such flexibility can come from grid expansion—which enables balancing of generation and demand between different regions—demand side management, in particular in combination with new loads (electric heat pumps for heating and cooling, electric car charging, electric industrial processes, e-mobility), and supply-side flexibility (flexible power-plants, curtailment of wind or PV) (Haas et al., 2017; Lund et al., 2015). Moreover, sufficient flexibility in New York is also supported by an adequate amount of dispatchable generation and the ability of curtailments. Finally, the state agreed to a storage roadmap that includes 1.5 GW of capacity by 2025 (New York State, 2018).

Acknowledgments

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Appendix

Further assumptions

Projected fuel costs (see Figure A.1.) for uranium are based on (Jacobson, 2009). 2012 USD are converted to 2014 USD via a price deflator ratio for electricity costs of 1.031. To obtain from $/MMBtu to $/MWh a heat rate of 10.48 MMBtu/MWh is assumed.

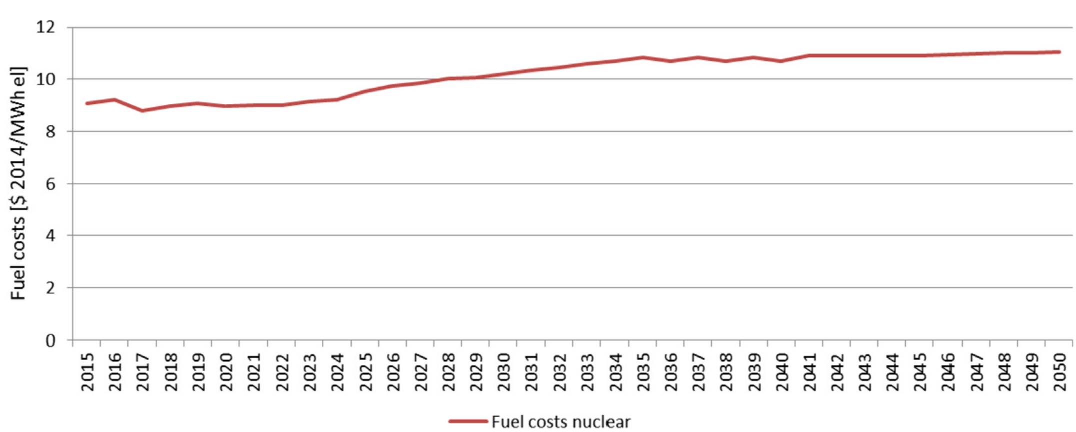

Fig. A.1. Fuel cost projections for nuclear power plants.

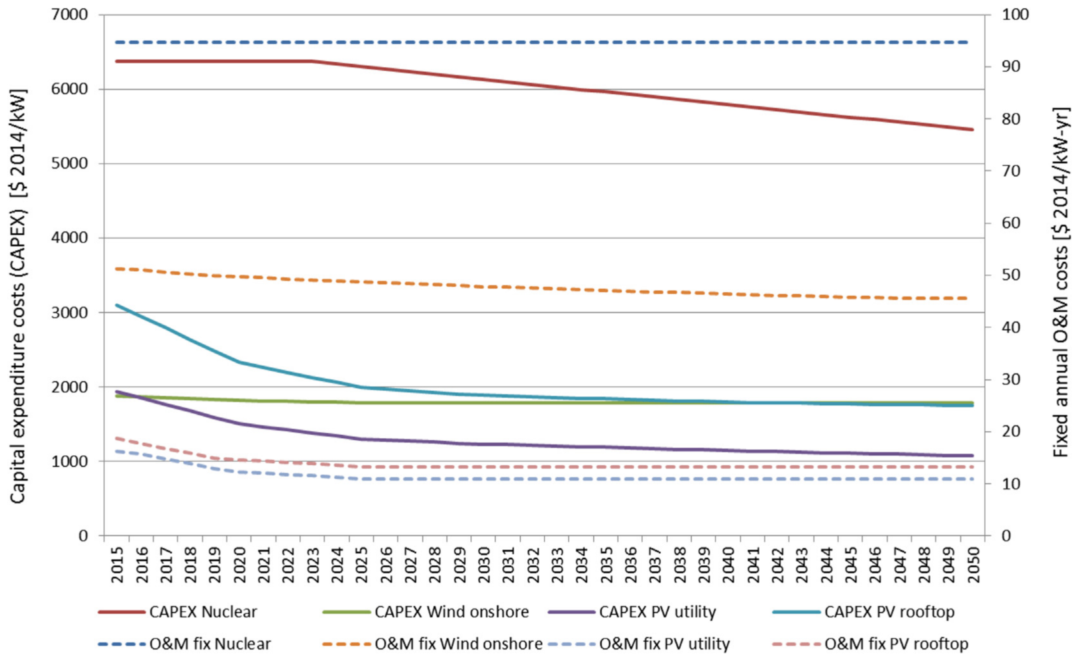

Fig. A.2. Cost projections of capital expenditure costs (CAPEX) on the primary ordinate and of the fixed annual operation and maintenance costs (O&M) on the secondary ordinate. Values are based on (National Renewable Energy Laboratory, 2016).

Variable operation and maintenance costs for renewable systems (wind onshore, PV utility-scale, PV rooftop) are assumed to be zero; for nuclear power plants $2/MWh were used (National Renewable Energy Laboratory, 2016). The projected fuel costs for nuclear power plants are based on (Jacobson, 2009).

Table A.1Cost assumptions of nuclear power subsidies.

Dates	Upper limit of ZEC [MWh/yr]	Adjusted social costs of carbon (SCC) [$/MWh]	Annual costs	Total costs
04/17–03/19	27,618,000	17.70	$488,838,600	$977,677,200
04/19–03/21	27,618,000	19.81	$547,112,580	$1,094,225,160
04/21–03/23	27,618,000	21.60	$596,548,800	$1,193,097,600
04/23–03/25	27,618,000	24.05	$664,212,900	$1,328,425,800
04/25–03/27	27,618,000	26.67	$736,572,060	$1,473,144,120
04/27–03/29	27,618,000	29.37	$811,140,660	$1,622,281,320
04/29–12/50	-[a]	–	$805,000,000	$17,710,000,000

a After 03/29 subsidies must continue at a minimum rate of $805 million/yr until 2050.

Detailed results

Table A.1
Cumulative costs in $ 2014 from 2016 to 2050 of each of the main scenarios disaggregating into the different technology options and cost components.

	Invest. costs [$]	Fuel costs [$]	$O\&M_{var}$ costs [$]	$O\&M_{fix}$ costs [$]	Subsidies [$]
Scenario 1	–	$5,800,742,600	$1,240,263,500	$189,426,844	$25,887,689,800
Nuclear	–	$5,800,742,600	$1,240,263,500	$189,426,844	$25,887,689,800
Scenario 2	$13,369,721,461	$1,954,374,400	$460,669,300	$528,268,319	$8,177,689,800
Nuclear	–	$1,954,374,400	$460,669,300	$180,921,966	$8,177,689,800
Wind	$13,369,721,461	–	–	$347,346,353	–
Scenario 3	$13,809,662,100	$737,626,100	$177,180,500	$514,261,211	$2,560,740,960
Nuclear	–	$737,626,100	$177,180,500	$162,365,867	$2,560,740,960
Wind	$13,809,662,100	–	–	$351,895,344	–
Scenario 4	$18,487,396,793	$737,626,100	$177,180,500	$399,710,432	$2,560,740,960
Nuclear	–	$737,626,100	$177,180,500	$162,365,867	$2,560,740,960
PV rooftop	$7,656,743,554	–	–	$36,787,825	–
PV utility	$3,925,822,190	–	–	$24,609,069	–
Wind	$6,904,831,050	–	–	$175,947,672	–

Table A.1 (*continued*)

	Invest. costs [$]	Fuel costs [$]	$O\&M_{var}$ costs [$]	$O\&M_{fix}$ costs [$]	Subsidies [$]
Scenario 5	$14,756,475,429	$737,626,100	$177,180,500	$366,831,950	$2,560,740,960
Nuclear	–	$737,626,100	$177,180,500	$162,365,867	$2,560,740,960
PV utility	$7,851,644,379	–	–	$49,218,137	–
Wind	$6,904,831,050	–	–	$155,247,946	–
Scenario 6	$998,801,435	$5,486,482,741	$1,174,279,572	$202,425,326	$25,887,689,800
Nuclear	–	$5,486,482,741	$1,174,279,572	$189,426,844	$25,887,689,800
PV rooftop	$315,126,655	–	–	$2,014,733	–
PV utility	$255,102,530	–	–	$1,347,747	–
Wind	$428,572,250	–	–	$9,636,001	–

References

Table A.2
Detailed costs (in 2014 USD) and CO_2 emissions for each main and sub-scenario. The CO_2 emissions for each sensitivity case do not differ since technology specific, annual electricity generation is identical.

Scenario	Sub-scenario	OPEX [$]	CAPEX [$]	Subsidies [$]	CO_2 emissions [Mt]
Scenario 1	Reference	$7,041,308,249	–	$25,398,851,200	37
Scenario 2	Reference	$2,745,682,445	$20,556,252,732	$7,688,851,200	17
Scenario 3	Reference	$1,212,882,137	$21,232,671,534	$2,071,902,360	9
Scenario 4	Reference	$1,098,331,358	$28,424,795,681	$2,071,902,360	14
Scenario 5	Reference	$1,065,452,876	$22,688,418,697	$2,071,902,360	14
Scenario 6	Reference	$6,674,062,944	$1,535,680,065	$25,398,851,200	35
Scenario 1	CF low	$7,053,485,584	–	$25,398,851,200	37
Scenario 2	CF low	$2,800,417,890	$23,141,494,039	$7,688,851,200	17
Scenario 3	CF low	$1,265,733,750	$23,902,982,130	$2,071,902,360	9
Scenario 4	CF low	$1,142,205,958	$33,636,046,688	$2,071,902,360	14
Scenario 5	CF low	$1,103,524,617	$26,204,920,322	$2,071,902,360	14
Scenario 1	CF high	$7041,308,249	–	$25,398,851,200	37
Scenario 2	CF high	$2,665,525,594	$15,812,502,102	$7,688,851,200	17
Scenario 3	CF high	$1,131,675,519	$16,332,824,257	$2,071,902,360	9
Scenario 4	CF high	$1,055,684,281	$25,320,848,796	$2,071,902,360	14
Scenario 5	CF high	$1,030,349,315	$20,238,495,058	$2,071,902,360	14
Scenario 1	Discount low	$7,041,308,249	–	$25,398,851,200	37
Scenario 2	Discount low	$2,745,682,445	$18,489,735,161	$7,688,851,200	17
Scenario 3	Discount low	$1,212,882,137	$19,098,153,663	$2,071,902,360	9
Scenario 4	Discount low	$1,098,331,358	$25,567,254,450	$2,071,902,360	14
Scenario 5	Discount low	$1,066,392,630	$20,407,554,741	$2,071,902,360	14
Scenario 1	Discount high	$7,041,308,249	–	$25,398,851,200	37
Scenario 2	Discount high	$2,745,682,445	$22,761,382,426	$7,688,851,200	17
Scenario 3	Discount high	$1,212,882,137	$23,510,362,662	$2,071,902,360	9
Scenario 4	Discount high	$1,098,331,358	$31,474,007,122	$2,071,902,360	14
Scenario 5	Discount high	$1,066,392,630	$25,122,272,105	$2,071,902,360	14

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