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Investigating Long-Term Commitments to Replace Electricity Generation with SMRs and Estimates of Climate Change Impact Costs Using a Modified VENSIM Dynamic Integrated Climate Economy (DICE) Model

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Abstract: During the last few years, nuclear energy has received great attention due to the increase in climate change awareness. According to the Paris agreement, global temperature is to be kept below 2 °C and preferably below 1.5 °C by 2050. This approach has been substantially confirmed in the recent COP 26 in Glasgow. This research investigates the effects of integrating SMR nuclear power plants (small modular reactors) into the Nordhaus Dynamic Integrated Climate Economy (DICE) model for reducing the CO_2 emissions in the atmosphere by substituting all existing fossil-fueled power plants (FPPP). The software is based on the VENSIM dynamic systems modeling platform. Simulations were carried out from the year 2019 to 2100 using 10-year increments. Several scenarios were thus simulated replacing roughly 70,000 FPPPs operating at this time in the world. Simulations indicate a CO_2 reduction of approximately 12.63% relative to the initial conditions used and using 87,830 SMR core units of 80 MWe electric each to meet such demand. The DICE model further predicts the cost of climate damage impacting the upper ocean and atmospheric temperatures, and the deep ocean temperature as USD 1.515 trillion (US Dollar; (US) trillion = 1,000,000,000,000 (1×10^{12})) by the end of this century. From a modified section of the model, a cost of USD 1.073 trillion is predicted as the toll on human health costs. This is thus equal to a USD 2.59 trillion loss in the economy.

Keywords: climate change damage; modified VENSIM DICE model; small modular reactors; solar and wind power costs

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1. Introduction

During the 19th and early 20th centuries, the emerging second industrial revolution developed large-scale manufacturing operations, which significantly raised the energy demand due to their intensive energy applications [1]. To expand the economic growth (GDP) and achieve this production system's requirements in numerous countries, fossil fuels (FFs) were mainly used: this has led to the emission of great amounts of greenhouse gases (GHG) and to climate change [2]. GHG gases (or greenhouse gases) cause the greenhouse effect, trapping more energy than they can reflect out [3]. By-products of FF combustion are many different environmental air pollutants such as carbon dioxide emissions (CO_2), methane (CH_4), nitrous oxide (N_2O), and solid particulates, which increase the greenhouse effect and global warming [4]. GHG emissions have a very unfavorable impact on sustainability [5]. Therefore, the intergovernmental Panel on Climate Change (IPCC)'s 5th Assessment Report (AR5) confirmed that GHGs, specifically CO_2 emissions, are the cause of global warming [6]. Some climate scientists believe that the safe upper limit of CO_2 in the atmosphere should be 350 parts per million (ppm). Current levels are well above this value, having passed 400 ppm and reaching close to 418 ppm in 2021 [7]. The Paris agreement on climate change approved during COP21 (2015 Paris Climate Conference) emphasizes keeping the global atmospheric temperature below 2 degrees Celsius and preferably below 1.5 Celsius by 2050 [8]. With the expansion of energy demand and rapid growth, to lower the level of GHG emission, replacement of the FFs with zero net (lower or zero CO_2) emissions energy sources have been proposed for electricity production sector such as renewable energies (hydropower, solar, wind, biomass, tides, biofuels and geothermal) as well as nuclear energy (NE).

With the help of integrated assessment models (IAMs), possible climate change scenarios (and not necessarily predictions) can be estimated and proposed to policymakers [9]. IAM models are extensively used by climatologists and researchers due to their simple approach and flexibility [10]. Integrated assessment models (IAMs) are scientific models that link multiple sectors such as society, economics, and climate change, and integrate them into one single framework. Integrated assessment models are divided into two models [11]: the process-based IAM is able to quantify future development scenarios such as IMAGE, MESSAGEix, AIM/GCE, and the cost–benefit IAM, which is able to integrate the cost of climate change and climate mitigation to estimate the total cost of climate change [11] such as DICE, FUND, and PAGE.

In this work, the DICE model (Dynamic Integrated Climate-Economy model) is used. The DICE model is an integrated assessment model (IAM) originally developed at Yale University by W. D. Nordhaus to simulate climate change based on available economic and environmental data to slow global warming [12]. For this research, an SMR nuclear power plant model was designed and integrated into the original Nordhaus DICE model using the VENSIM dynamic modeling and simulation software platform. A graphic user interface (GUI) allows VENSIM easy access to all elements of the simulation algorithm as well as to integrate other algebraic models.

In the newly introduced SMR nuclear power plant sub-model, all operating fossil fuels power plants are substituted by small modular reactors; this includes coal power plants (CPP), natural gas power plants (NGPP), and petroleum power plants (PPP). Thus, the continuous accumulation of CO_2 in the atmosphere can be mitigated. DICE macroeconomic models allow for analyzing the return on investment, as well as the costs of such operation including the very heavy cost due to climate change, "loss of opportunity", and human health related. Manufacturing historical data for renewable energy sources such as solar and wind power are also studied to extrapolate the tendency or range of operations to be required by the nuclear industry to match up possible demands of future SMRs.

2. Climate Change and Greenhouse Gas Emissions

Climate change refers to the average long-term changes (such as rainfall, temperature, snow, or wind) in many regions on Earth [13]. Global climate change describes long-term changes in the average condition of the entire planet [13]. This change is seen via short-term weather extremes [14]. Both human activities and natural factors contribute significantly to climate change [15]. Natural factors refer to changes in the solar energy intensity, fluctuations in the Earth's orbit, terrestrial volcanic activity, the circulating currents of the ocean and atmosphere, and the naturally occurring concentration of GHGs [13,16]. Human factors refer to emissions from burning fossil fuels, cutting off forested lands, and developing farms, cities, and roads. All these activities emit GHG gases into the atmosphere [15]. The primary human activity that has a paramount role in climate change is producing GHG emissions by combusting fossil fuels, mainly but not exclusively to generate electricity and heat [15,17].

Greenhouse gases (GHGs) are gases in the atmosphere that are highly efficient in trapping heat within the atmosphere defined as the greenhouse effect; they absorb outgoing solar and infrared radiation and can cause the global temperature to rise over time [18]. GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (CFCs, etc.) [18]. Some concentration of these GHGs may be required to maintain life on Earth since they trap heat in the atmosphere that sustains the Earth's thermal regulation. NASA, however, reports that CO_2 emissions by human activities are more than 100 times larger than naturally produced sources such as volcanic activity. One might argue that the real impact of accumulated levels of GHGs in the atmosphere will not be known until several decades later in the future [19]. This fact brings us to the point where if we wait to observe the real effect, it may be too late to reverse the effect of high quantities of GHGs in the atmosphere. Consequently, it is vital to predict and control CO_2 emissions as early and accurately as possible.

The energy sector is the largest sector in GHG emissions at 73.2%, followed by agricultural and forestry, at 18.4%, as reported by World Resource Institute in 2020 [20]. Global carbon emitted by burning fossil fuels has significantly increased since 1900 [12]. The largest share of GHG emissions is generating electricity coming from fossil fuels, accounting for 61.3%; of this percentage; the distribution attributed are: coal 35.1%, gas 23.4%, and oil 2.8%, while nuclear, solar, wind, and hydro have the smallest share in GHG contribution [21]. The burning of fossil fuels produces around 21.3 billion tons of CO_2 per year [22]. It is predicted that natural processes can only absorb half of this amount, and thus the accumulation of CO_2 contributes to the rise in Earth's surface temperature [22].

3. Small Modular Reactors (SMR)

Small modular reactors (SMRs) are the newest generation of nuclear fission reactors with components and systems that can be fabricated in the factory and then transported in modules to construction sites. SMRs are smaller than current large conventional reactors both in size and power, which is according to IAEA [23] between 3 MWe and 300 MWe. While reasons for this range can be presented, this range is generally arbitrary.

SMRs' advantages consist of modularity, smaller financial risk, load following design, simplified factory production and assembly, and deployability for off-grid applications. In remote locations where trained workers and a higher cost of shipping are the main concern, SMRs represent an ideal solution. They are also flexible in providing electricity and heat based on demand. The feature of compact design and passive or inherent safety in many SMRs promote safety-in-design and limit the on-site refueling (if any), while the possibility for remotely monitored operations significantly reduces on-site staffing. With the introduction to the energy generation market of SMRs, the need for flexible power generation for a wider range of users and applications can be fulfilled, and financial and safety barriers of the conventional nuclear reactors can potentially be overcome [24,25].

Various reactor concepts have been proposed in SMR designs such as water-cooled reactors, high-temperature gas-cooled reactors, liquid metal, sodium, and gas-cooled reactors with fast neutron spectrum, molten salt reactors, and most recently microreactors. IAEA has published a 2020 update of the advanced reactors information system (ARIS) booklet [23]. Concluding the regulatory review and/or construction within a country with regulatory approval is assumed to be the completion of the SMR design and engineering processes. So far, only the American NuScale, Russian, Chinese and Argentinian concepts have passed regulatory approval or are under construction. Many designs will not finish the regulatory review or finish in time and be ready for operation by 2030.

During COP26, Rolls Royce announced an estimate of the first-of-a-kind to nth-of-a-kind-cost reduction with multiple-unit orders. In 2019, Rolls Royce stated that they can deliver the PWRs at a price of about USD 2.3 billion each once factory production begins after the first five units (470 MWe each) have been built [26].

4. Dynamic Integrated Climate-Economy Model (DICE)

The Dynamic Integrated Climate-Economy (DICE) is able, through integrated macroeconomic models, to assess the global impact of climate change, putting in evidence the major economic forces taking place in such contest.

DICE is a global model that uses data from all major countries to evaluate the global aggregate. Algebraic equations describing macro-econometric correlations are used; being a macro-economic model, typical issues connected to micro-economics such as labor economics, and the relationship between demand and supply or cost of production are not evaluated. The DICE model also does not include societal choices, local decisions, allocation of resources, or aspects of supply chain issues. A series of economics, CO_2 production, and CO_2 impact equations have been captured to quantify the climate change impact on economic output. A Cobb–Douglas production function is considered to calculate the global economic output using physical capital, labor and energy as inputs [27,28]. Variables in DICE are expressed in simple algebraic equations in terms of each other. The major limitations of DICE in climate change-related research studies are the time-based independency of its variables [28].

Energy production in this model comes from carbon-based fuels such as coal and natural ages, and non-carbon-based technologies such as solar, geothermal energy, and nuclear power [29]. Labor is determined by the global population and grows over time. Labor and total factor of productivity grow exogenously over time and it is proportional to the global population [28]. An initial value of labor and capital are used in the model. Capital accumulation is calculated by the individual consumption rates of each region [29]. Consumption includes food, shelter, amenities, and services. This model assumes that the CO_2 intensity of economic production and cost of emission reduction decline exogenously over time, which causes a loss in the output according to Hicks-neutral climate change damage function.

DICE algorithms do not use sets of econometric partial differential equations or integro-differential equations. Consequently, the cost of reducing emissions for a given period is unrelated to the previously determined pathway nor future prospects can be impacted in any way. This temporal independence can be seen as a Markovian process and considered a limitation in climate change research studies as pointed out by [30]. However, this limitation and its possible solutions are beyond the scope described in this research paper.

In DICE, the atmospheric concentration of CO_2 is considered a "natural capital". Given its influence over the global average surface temperature, this produces a negative effect on the total economic output. For this reason, DICE can be considered an ideal tool able to provide stakeholders and decision-makers a perfect view of costs and benefits and so advocate for proper balanced economic decisions when dealing with CO_2 emissions. Color-coded sections of the entire DICE model are shown in Figure 1. Within the VENSIM developer window, the algebraic relationships used appear underneath the graphical user interface.

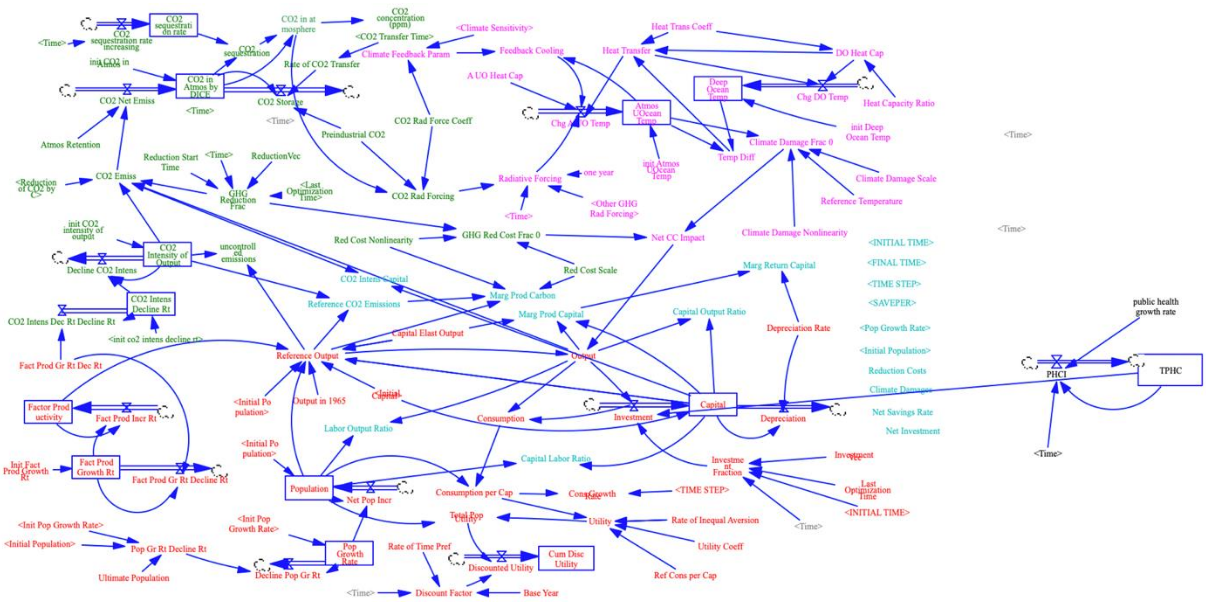

Figure 1. Schematic of DICE model as applied in VENSIM.

The pink section represents the climate, the green area represents carbon or emission production, the black section is public health, the blue is indices, and the red portion represents the economy.

Tables 1–4 highlight the major inputs and outputs of the color-coded macroeconomic areas as illustrated in Figure 1. Further variables can be taken from the existing VENSIM DICE model literature [31].

Table 1. Major inputs and outputs of section highlighted in green representing the carbon or emission production.

Major Inputs	Major Outputs
• Time • Reduction of CO_2 by target year (which is the output of the modified part of DICE model) • Initial CO_2 in atmosphere • Factor productivity growth rate decline rate	• CO_2 rad coefficient • CO_2 rad forcing • GHG reduction cost fraction

Table 2. Major inputs and outputs of section highlighted in pink representing the climate.

Major Inputs	Major Outputs
• Time • GHG reduction cost fraction • Upper ocean heat cap • Deep Ocean heat cap • Initial atmosphere upper ocean temperature • Initial atmosphere Deep Ocean temperature • Climate sensitivity • Climate damage scale • Reference temperature	• Net climate change impact • Temperature difference

Table 3. Major inputs and outputs of section highlighted in red representing the economy.

Major Inputs	Major Outputs
• Time • Investment • Population • Growth rate • Utility coefficient	• Factor productivity growth rate decline rate • Reference output • Consumption • Capital output ratio • Depreciation rate • Economy output

Table 4. Major inputs and outputs of section highlighted in black representing the public health.

Major Inputs	Major Outputs
• Time • Public health damage growth rate • Initial public health damage cost	• Public health damage cost

In this research, four major climate change output variables are considered: CO_2 concentration in the atmosphere, atmospheric and ocean average temperatures, and cost estimates of climate damage according to the DICE original model definition.

Furthermore, the impact of climate change on human health is added to the original model given its significance and predicted impact.

CO_2 concentration in the atmosphere is predicted in the original DICE model. However, this section was modified by H. Shen [31] to express the atmospheric CO_2 concentration level in parts per million (ppm) as this measure is widely being used nowadays.

The atmospheric CO_2 concentration was calibrated by Shen by introducing "CO_2 sequestration" to the model.

Concentrations of CO_2 from the year 1992 to 2011 calculated using the original DICE model were compared for calibration with the actual level of CO_2 concentration provided by the Mauna Loa Observatory in Hawaii. CO_2 sequestration was then adjusted to produce a difference of no more than 3% with available data [31].

In this research, to study the impact of replacing FFPP with nuclear power plants for the reduction of CO_2 emissions, a nuclear sub-model of DICE proposed by H. Shen has been used [31]. In the nuclear sub-model, to replace the existing FFPP units with SMR units, a ratio needs to be calculated: this is the average power produced by one SMR unit compared to the targeted fossil fuel unit. In this study, an SMR unit (core) of 80 MWe (gross) has been considered as a reference. This generically represents a US iPWR SMR, design certified and candidate for construction [32].

The assumption in this sub-model is to fully replace the FFPPs with SMRs to reduce GHG emissions and consequently verify the reduction or mitigation of CO_2 emissions. This is due to the fact that the amount of GHGs produced by an NPP is significantly less than that of an FFPP [21]. The modified DICE model can calculate the reduction of GHGs emissions based on different construction rates and then feed this information into the Nordhaus portion of the DICE model to predict the total amount of CO_2 emissions after a period of time, the total amount of CO_2 in the atmosphere, atmospheric and ocean temperature increases and other factors. The proposed nuclear power plant sub-model is shown in Figure 2.

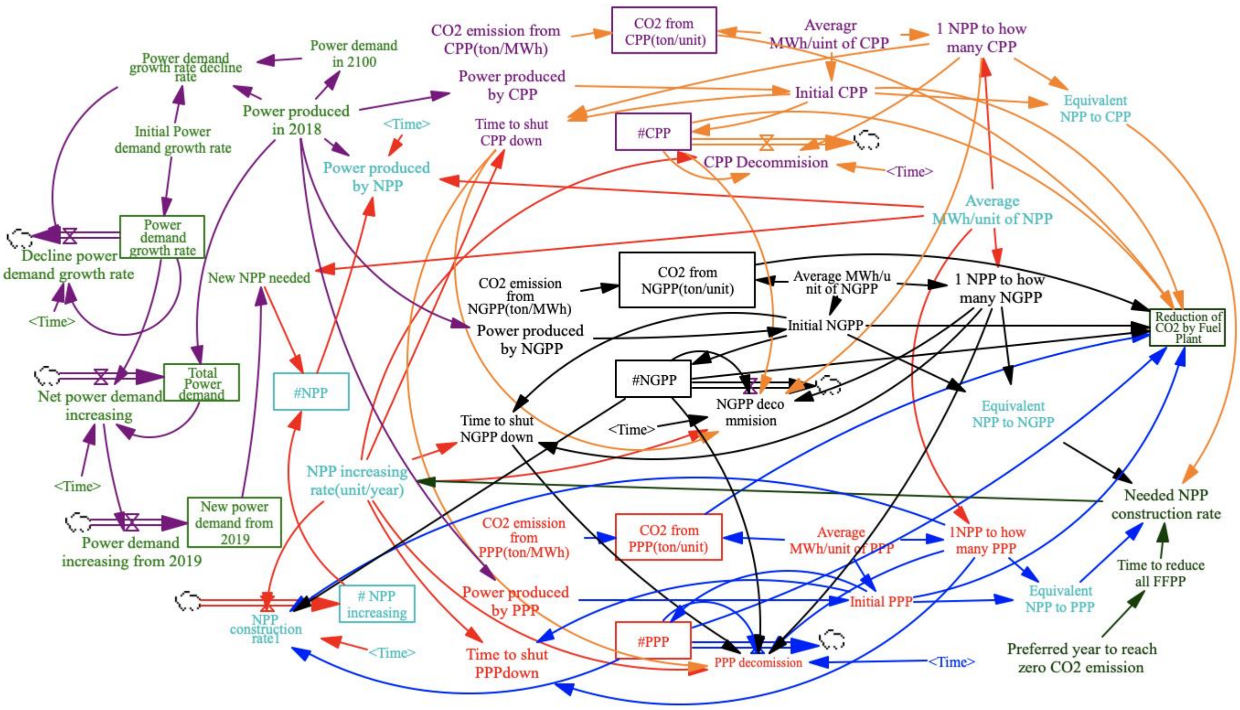

Figure 2. Schematic of NPP DICE sub-model as applied in VENSIM.

One of the main inputs in this model is time. The parameter, "target year to reach CO_2 emission" is introduced in this sub-model to represent different scenarios for reaching net-zero CO_2 emissions by entering different target years. The two major outputs for each scenario would be the total number of SMR units that need to be constructed per scenario as well as the cost impact to reach net-zero by 2100. Having different scenarios available allows policymakers and relevant stakeholders to assess the problem and take appropriate decisions by evaluating the costs and scales involved.

The historic and current quantity of NPPs and FFPPs in the world is added to the model. One of the assumptions in the model is an expected generation lifetime of an NPP is 60 years. This allows the model to consider NPP decommissioning after 60 years, from the constructed year and replace it with a new one. In the model, to meet the original power output, the amount of constructed NPPs will need to be maintained.

The next part of the model is the replacement part of FFPPs by NPPs applying a construction ratio. Three types of FFPPs have been considered in this research: coal, natural gas, and petroleum. The logic used in the model is to start decommissioning the CPPs first since they are the largest producer of CO_2. Then, with all the CPPs decommissioned, the DICE model starts replacing the NGPPs, and after decommissioning all the NGPPs, finally, PPPs follow.

The average power for CPPs, NGPPs, and petroleum power plants is calculated by taking the average power output for all existing operating plants in the world for 10 years from 2001 to 2010 [33]. Furthermore, the power capacity for SMRs used in the model is the same for the newly added NPP.

To calculate the number of CPP units that will be decommissioned and replaced when an NPP unit is built, the model divides the average power (MWh/unit) of an NPP by the average power (MWh/unit) of CPP. Consequently, the model will calculate the amount of CO_2 emission eliminated by decommissioning of CPP units; then the calculated amount of reduced CO_2 is fed into the standard DICE model CO_2 emission variable. While this approach can be argued, it provides a pragmatic reference.

In this study, the climate damage impact on public health is added to the original DICE model as a sub-model to investigate the cost of postulated, consequential damage. The potential climate change damages are many such as in agriculture, sea-level rise, other market sectors, human health, nonmarket amenity impacts, human settlements and ecosystems, and catastrophes [34]. In this sub-model, a climate damage function for public health is added: this is missing from the standard DICE model. Using this modification, the cost of damage to human health as the economic lost opportunity is evaluated. Figure 3 shows the proposed sub-model for climate damage to public health. The macroscopic nature and limitations of the human health sub-model translate into DICE as a lost economic opportunity model.

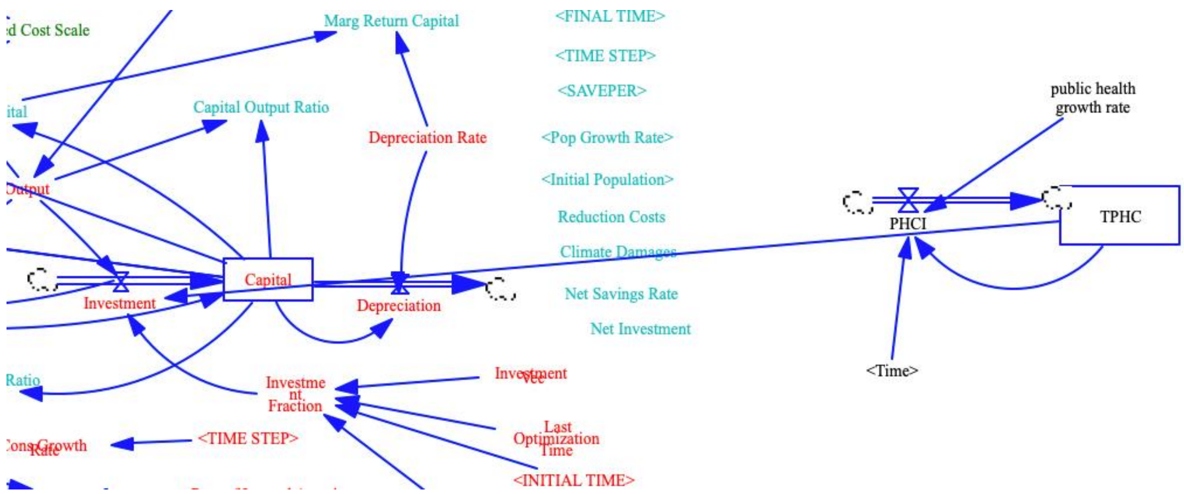

Figure 3. Schematic of climate damage and public health correlation as applied in VENSIM.

Climate change overall affects the social and environmental aspects of health (clean air, safe drinking water, sufficient food, and secure shelter) [33]. According to World Health Organization (WHO), between 2030 and 2050, climate change is anticipated to cause about

250,000 additional deaths per year, from malnutrition, malaria, diarrhea, and heat stress. The direct climate damage costs to health, (i.e., excluding costs in health-determining sectors such as agriculture, water, and sanitation), are projected to be around 2–4 billion/year USD by 2030. WHO indicated that reducing emissions of GHG can result in improved health, particularly through reduced air pollution [33]. NRDC report in 2021 [35] demonstrates that people in the USA are facing more than USD 820 billion in physical and mental health impacts from burning fossil fuels, and climate change-related events each year, mainly from air pollution. In the proposed health sub-model, USD 3 billion/year has been considered as the average yearly increase in economic opportunity lost starting from 2020, and USD 842.2 billion was captured as the initial value. The output of the health sub-model is fed to the gross investment to calculate the climate damage on per person health in dollar value.

5. Simulation and Results

The SMR nuclear sub-model and climate change impact on public health sub-model has been designed and successfully integrated into the original DICE model. Then, many scenarios were simulated by changing many of the available inputs.

All data used were provided by published references from IEA [36]. The first ten countries contributing most to CO_2 emissions were then considered, as follows: China, the USA, Japan, South Korea, Russia, European Union, Brazil, South Africa, Mexico, and Saudi Arabia. These countries all together generate over 66% of the total emissions [37].

Net-zero CO_2 emissions in the year 2100 have been studied and analyzed. For this scenario, the different construction rates of NPPs have been considered and tested. Table 5 shows in detail the proposed rates of SMR installation as well as data on decommissioning for the existing FFPPs.

Table 5. Construction rate for SMR units and decommissioning rate of FFPP units estimated for 2100 scenario.

Target Year	Construction Rate of SMR Units (Unit/Year)	Decommissioning Rate of CPP Units (Unit/Year)	Decommissioning Rate of NGPP Units (Unit/Year)	Decommissioning Rate of PPP Units (Unit/Year)
2100	625	161	1113	8470

The table clearly shows that by 2100, as many as 87,830 nuclear SMR units (cores) will be required to replace all of the FFPPs now in service and to meet rising power demand due to growth in population and in developing countries. The quantity of SMR units required to replace all of the world's FFPPs, in order to achieve net-zero emissions by the year 2100 is shown in Figure 4.

From 2019, an increase in the number of SMR units can be seen in Figure 5. The blue curve depicts the number of SMR units in 2030 when all FFPPs are decommissioned. This estimate is fairly unrealistic since, in 11 years from 2019, 4604 SMR units (cores) per year will need to be constructed to replace all the FFPP units globally. The supply chain, time, cost, and resources will not be able to accommodate the replacement in the examined time frame. However, it is important to evaluate the scale of the effort that will be needed by the manufacturing industry to match at least some of the requirements for the longer-term scenarios. Furthermore, replacement of SMR with more expensive, larger nuclear reactors is certainly possible in some regions.

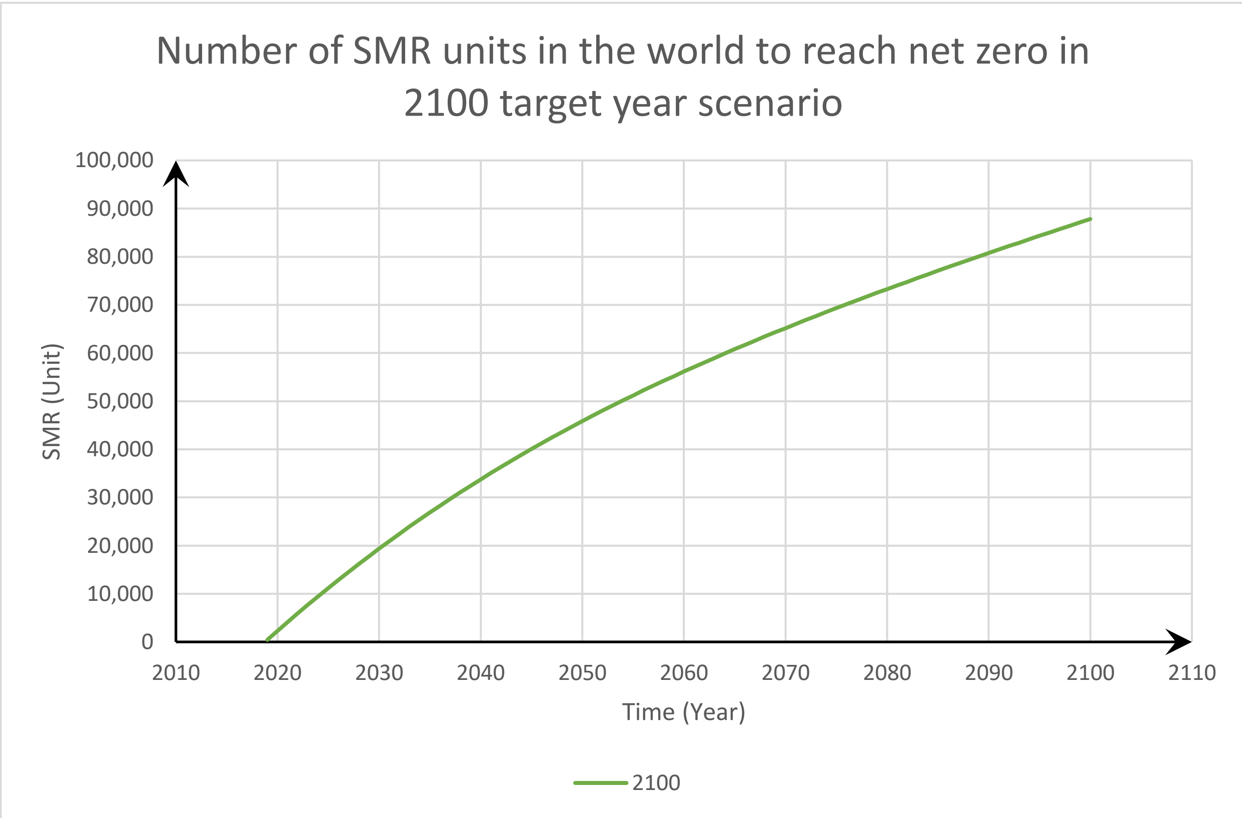

Figure 4. Number of SMR units to reach net-zero in 2100 target year scenario globally.

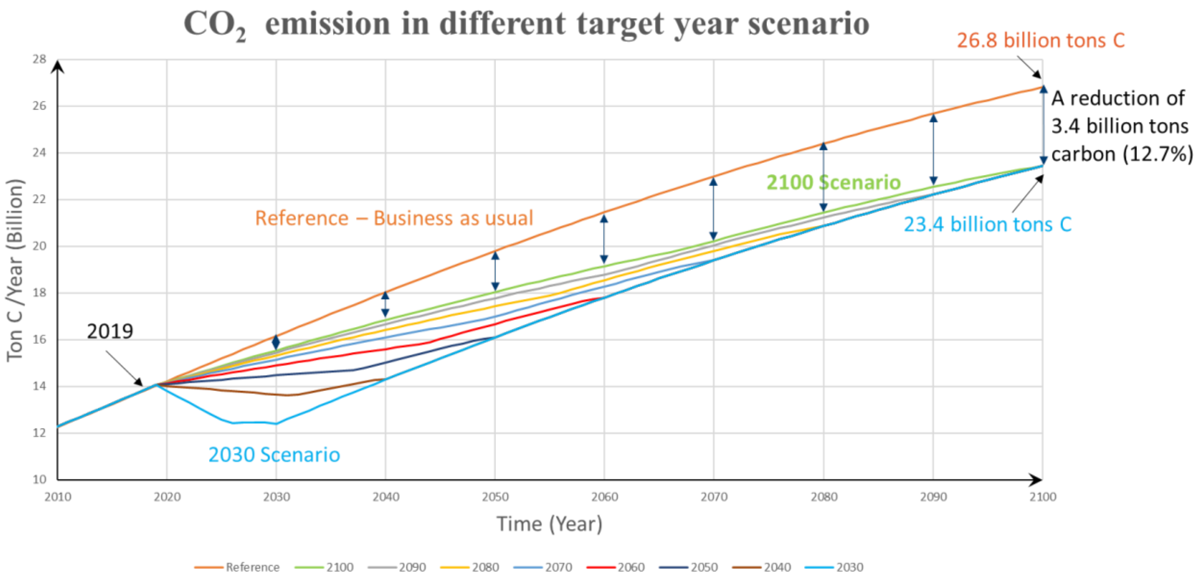

Figure 5. CO_2 emission in different target year scenario.

In contrast, the green curve of Figure 5 demonstrates the 2100 scenario in which all FFPPs units are to be decommissioned in a period of 80 years with an SMR construction rate of 625 units (cores) per year. This is an indirect statement that energy conservation is also needed in the immediate to long term; that energy "inequality" does exist. Owing to challenges in scale and construction rates, "demand" must be met by other scenarios and options.

Figure 5 indicates the CO_2 emission for each different target year scenario. From the result, the earlier the target year is, the least CO_2 will be emitted. The orange line (top line) in Figure 6 indicates the BAU (business as usual) scenario, the blue line depicts emissions of CO_2 if net-zero is achieved by 2030, and the green line demonstrates the CO_2 emissions if net-zero is set by 2100. As it can be observed from this figure, CO_2 emissions will drop starting from 2019 when applying all the different target year scenarios. The initial drop is fairly large since the CPPs, which are the largest contributors of CO_2,, are decommissioned first. Thus, the rate of decommissions decreases slightly when decommissioning of all the CPP units takes place. CO_2 emissions rise at the rate of the reference curve once the goal year has been reached (BAUS). As a result, the trends for each scenario converge, and the reference curve appears parallel. In this simulation, the difference in tones of CO_2 generated by FFPPs is the difference between the merged trend lines and the reference curve.

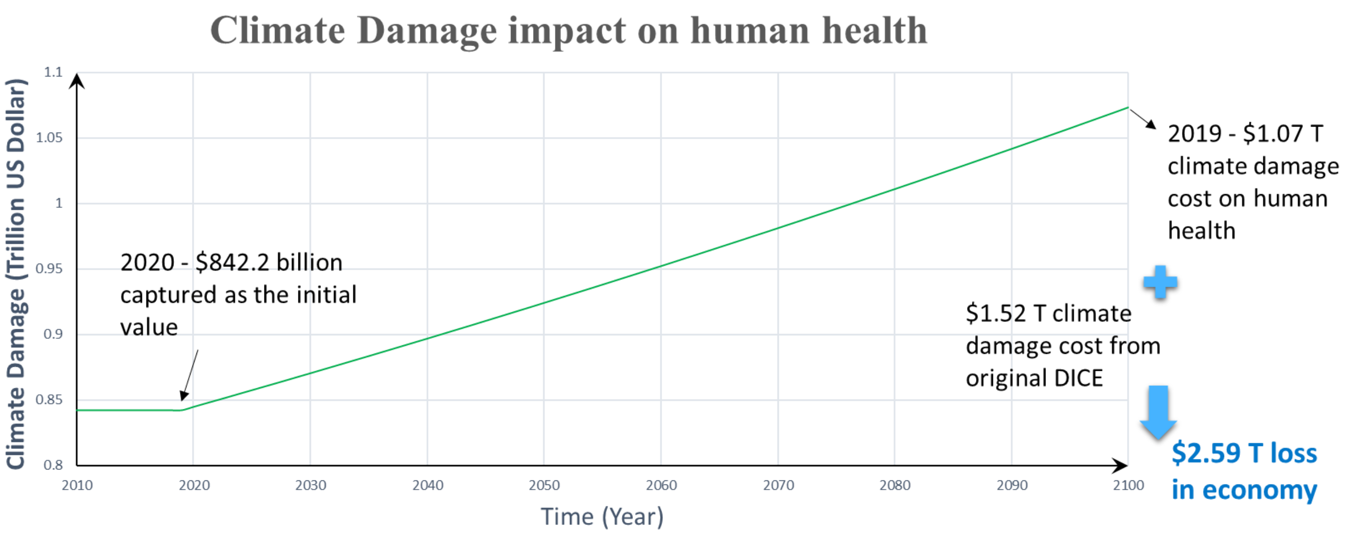

Figure 6. Climate damage impact on human health (trillion US dollar).

The replacement of all FFPPs with SMR units is anticipated to save 3.38 billion tons of CO_2 by 2100, according to simulation data. This is equivalent to 12.63 % of the total CO_2 in the atmosphere today. This calculation confirms that the usage of SMR units may significantly reduce yearly CO_2 emissions. Some CO_2 is actively absorbed by plants, seas, and other sources, so not all of it is accumulated.

Table 6 shows the economic loss associated with the climate damage impact in terms of the upper ocean, atmospheric temperature, and the deep ocean temperature, for different scenarios. The simulation data shows the prediction of saving USD 0.12 trillion to 0.23 trillion by the year 2100.

Figure 6 shows the costs associated with the climate damage impact on human health.

In this sub-model, from NRDC [35], USD 3 billion/year has been considered as the average increase per year on economic lost opportunity starting from 2020. Note that USD 842.2 billion are captured as the initial value for the health function. The simulations predict a USD 1.07 trillion climate damage cost on human health by the year 2100. The prediction of climate damage impact by the upper ocean and atmospheric temperature, and the deep ocean temperature from the original DICE is estimated to cost USD 1.515 trillion while the impact on human health cost is set at USD 1.073 trillion in 2100 if no action is taken; this is equal to a total of USD 2.59 trillion loss in the economy by the same year.

According to this analysis, the world will require as many as 87,830 nuclear SMR units by 2100 to replace all of the FFPPs now in service, as well as to fulfill rising electricity demand due to population increase. Of course, various scenarios may consist of larger nuclear and hydro plants, as well as wind and solar plants. If we consider the average price for 12 core SMR units to be USD 3 billion [38], USD 21.957 trillion is the average cost to install 87,830 SMR (~80 MWe) units for the 2100 scenario.

Table 6. Climate damage in different target year scenarios (trillion US dollars).

Target Year	Climate Damage in the Year 2100	Climate Damage Reduction in the Year 2100	Climate Damage Reduction in the Year 2100 (%)
2030	1.283	0.232	15.3%
2040	1.298	0.217	14.3%
2050	1.314	0.201	13.2%
2060	1.330	0.185	12.2%
2070	1.345	0.17	11.2%
2080	1.361	0.154	10.1%
2090	1.375	0.14	9.2%
2100	1.388	0.127	8.3%
Reference year	1.515	0	0

While the VENSIM DICE model is well known and tested, so are the limitations associated with macro-economic modeling and uncertainties that its models may generate. Thus, although the numbers here are given in (exact) significant digits, for the sake of discourse, the results are (at best) approximate, but in relative magnitude significant and relevant. As noted below, there is a clear need to derive a better, macroeconomic climate damage model able to address the uncertainties associated with relevant results.

6. Long-Term Scenario Manufacturing Trends

In this section, to investigate the large-scale deployment cost of SMRs, the possible manufacturing trend has been compared with the renewable technologies such as wind and solar to learn lessons that could decrease the deployment cost of SMRs. According to IEA, the cost of photovoltaic (PV) modules and wind turbines continuously decreased in recent years [39]. Wind turbines and photovoltaic (PV) modules were once in exactly the same situation as SMRs are today. Their challenges, successes, and failures have been extensively studied in the context of a wide-ranging transition to more sustainable energy production, distribution, and consumption. The case for the adoption of SMRs is now frequently positioned in the context of this transition.

L. Boldon and his team analyzed the SMR total capital investment costs from the FOAK (first-of-a-kind) through NOAK (nth-of-a-kind) unit [40]. NOAK refers to the required number of units in which cost reductions limit the impact of the upfront licensing, design, and engineering costs [41]. Figure 7 shows the economy of scale curve and reduction factors for a 180 MWe multi-module SMR with a 0.51 scaling factor produced from L. Boldon's study.

As part of Canada's SMR roadmap, the upfront capital cost has been assumed to be lower as the supply chain develops from FOAK through NOAK [42].

C.A. Lloyd [43] estimated the overnight cost of construction (OCC) based on various levels of modularization (introducing DOM or degree of modularization) and has shown that modularized SMRs have the potential to achieve construction costs consistently lower than the current cost of larger nuclear projects due to both modularization and production learning. A.S. Agara and his team have applied analytical AHP and ranked the importance of different cost factors on the commercial success of the SMR from the perspective of different stakeholders, and they described SMR as more flexible for future applications [44].

Figure 8 illustrates serial production costs observed for nuclear propulsion reactors based on M.D. Carelli's study [45]. Similar to what was observed in the past for the factory fabrication of nuclear propulsion reactors, significant cost reductions occur with the first several units before leveling off [45,46] at a further unit production stage.

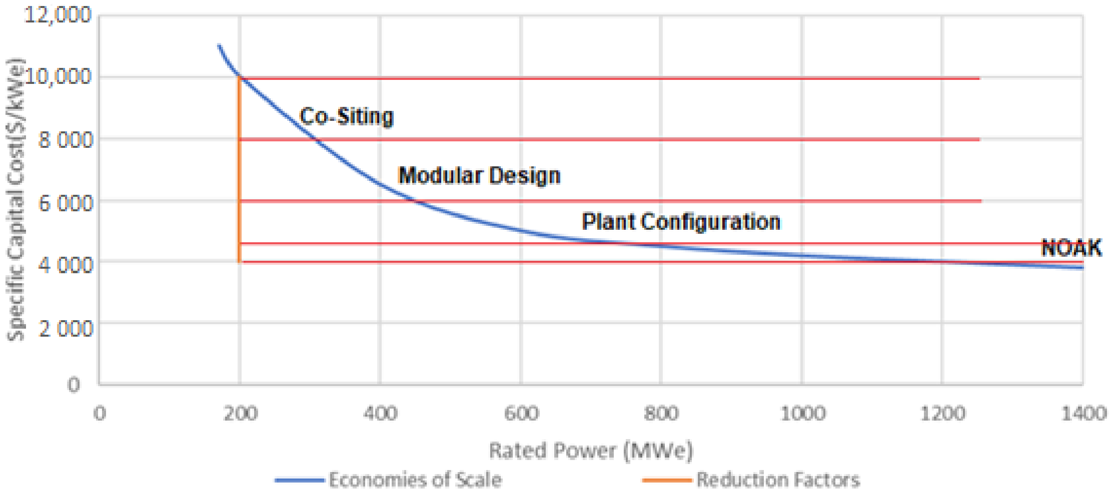

Figure 7. Economy of scale curve and reduction factors for a 180 MWe multi-module SMR with a 0.51 scaling factor. Own elaboration based on data from [40].

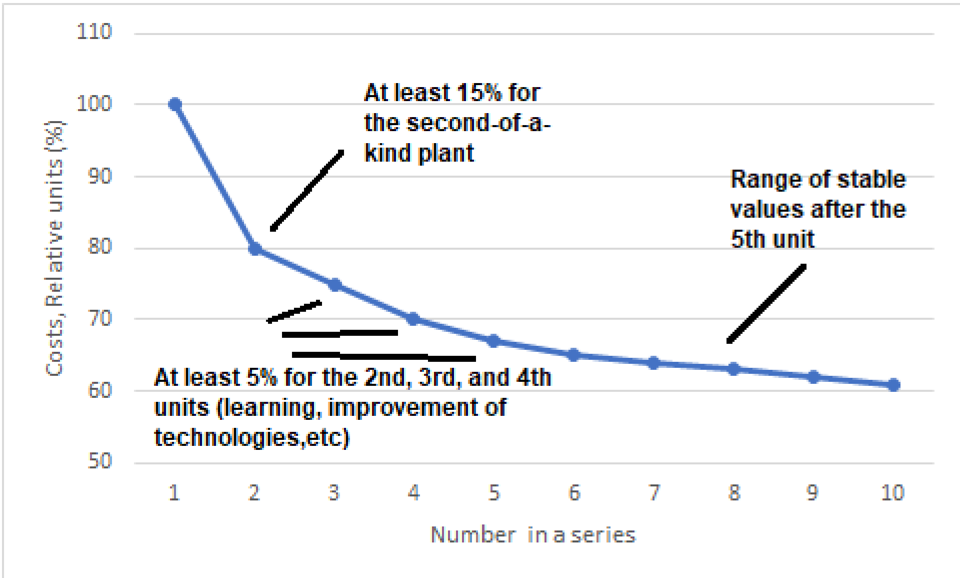

Figure 8. Serial production effects for nuclear propulsion reactors. Own elaboration based on data from [45].

Considering the above-mentioned trends, in this section, the capital cost of SMR has been compared with the historical trend taken from solar PV module and wind power manufacturing costs to verify the reduction in SMR price from the FOAK through NOAK unit [39,47,48].

In this study, the capital cost trend used for wind power is the installed wind power capital cost in the US [47], and the one used for solar is the capital cost for manufacturing the solar panel. According to S. Rehman and his team's study on PV power plant cost breakdown, RE equipment (solar panels) cost is 69.6% of the total cost, while the balance of plant cost is only 27.8% [49]. Therefore, with an additional 27.8% extra, the cost of solar panels can be considered in this study to give us a reference for the cost of a solar power plant.

In this work, the capital cost of 12 core SMR modules is considered USD 3 billion with an SMR unit (core) of 80 MWe (gross per core for a total of 960 MWe) used as reference.

This generically represents a US iPWR SMR, design certified and candidate for construction [32]. Other overnight capital cost estimates have been proposed such as the Rolls

Royce estimate announced during COP26 [50]: this is valued at USD 5 million per 1 MW after the NOAK condition is reached and it is almost 30% higher than the price that is considered in this study (USD 3.6 million per 1 MW). If the nominal operational hours per year of both nuclear reactors and renewable energy power plants (wind and solar) are taken into consideration, it is easy to verify that the corresponding LCOE is absolutely comparable and within the same magnitude.

Based on the predicted SMR price, the annual cost of building a SMR power plant and the estimated total climate damage are then compared. The annual cost of SMR in the 2050 and 2100 scenarios are evaluated. It can be seen that if SMRs start to be operated from 2030, the annual cost to build SMRs in order to replace FFPPs and meet the increasing energy demand will be lower than the estimated total climate damage. New SMRs or nuclear power will be used to meet people's increasing demand for electricity. Comparing the 2050 to the 2100 scenario, the 2100 scenario forecasts a gradual transition (smoother) which society may expect. The results shown in Table 7 indicate that it will be worth using SMR/nuclear energy to combat global climate change as the annual cost due to climate change is comparable to the modeled cost to build SMRs. Further, the cost of SMR in both scenarios from Table 7 does not seem to be large when compared to the annual gross domestic product (GDP) of the world which is USD 84.747 trillion for the year 2020, and with world energy expenditures, which is more than 10% of the annual GDP (USD 8 trillion) [51].

Table 7. Total cost of SMR and climate change.

	2050 Scenario	2100 Scenario
Needed number of SMR cores before 2030	21,470	15,437
Cost before 2030 (billion USD)	5367	3859

In this model, the radioactive fuel supply is assumed steady state with almost no variation long the period of interest. Uranium is the raw material used to produce fuel for long-lived nuclear power facilities, necessary for the generation of significant amounts of low-carbon electricity and other uses, such as heat and hydrogen production, for decades to come [52].

According to the IAEA report, about 27 tons of uranium is required each year for a 1000 MWe pressurized water reactor [52]. Therefore, considering its use linearly, for an 80 MWe SMR core approximately 2.16 tons of material each is needed. Consequently, for the 2050 scenario, 21,470 SMR cores would consume almost 46,375.2 tons a year which will be approximately 3.7 million tons supply for the selected target year of 2100 in this study (80 years). Similarly, for the 2100 scenario with 15,437 SMR cores, the approximate uranium supply for the selected target year of 2100 would be 2.6 million tons.

According to the IAEA report, in addition to 6.1 million tons of uranium resources that were discovered, there is an estimate of 9 to 20 million tons that remain undiscovered [52]. In this contest, the supply of fuel (uranium) can then be considered substantially always available with relatively low changes in price, at least for the next 80 years.

7. Limitations of the Current Study

In this study, the proposed methodology might not be perfectly symmetrical on the total economic cost of climate damage since there are some limitations and large uncertainties associated with estimating the possible cost of elements such as climate damage's impact on human health, loss of portable water, loss of arctic glaciers and their cascading effect. Climate change cost as a "missed business opportunity" must be considered and evaluated by looking at the introduction of SMR at a large scale. Given the most recent analysis and studies done over uranium mines ores [52], it is quite realistic to imagine the duration of the basic nuclear fuel for at least 80 to 100 years, excluding the recently proven possibility of using MOX (mixed oxide) fuel. The use of plutonium would in fact extend that limit even further. Similar considerations could be carried out by exploiting the uranium contained in the oceans. As the climate change response requires staying within the parameters of the Paris agreement, there is much less time (15 to 30 years), so the focus is on the effective contribution SMRs can give starting from the late 2020s. In this contest, the supply of fuel (uranium) can then be considered substantially almost infinite.

Other possible costs associated with the use of SMR modules at a large scale, are the waste management cost, training personnel, and supply chain, which are beyond the scope of this study. A feedback loop (to be considered in the future) would help identify some of these elements. In addition, the problem of proliferation is not treated in this paper as undoubtedly, the new technologies being put in place, from artificial intelligence and cyber distant monitoring as well as perfectly sealed reactors will allow for some proliferation control.

Among the other possible limitations of this study, it is important to remember that while the DICE model is a very well-cited macroeconomic model, it does not incorporate all possible variables and phenomena taking place. DICE algebraic equations do not capture entirely a full dynamic temporal evaluation of parameters, as integral or derivative expressions are not considered. Uncertainty of data will be addressed in future work using a fuzzy logic approach.

8. Conclusions

Nuclear energy is receiving increased attention in the media as a means of low-to-zero carbon (GHGs) generating electricity sources. It is a potentially significant contributor to the current transition to low-carbon electricity generation. According to the Paris agreement, global temperature is to be kept below 2 °C and preferably below 1.5 °C by 2050. This goal was substantially confirmed in the recent COP 26 in Glasgow. This study uses the VENSIM dynamic systems simulation tool to modify the Nordhaus DICE macro-economic model, in order to evaluate the effect of replacing fossil-fueled power plants (FFPP) with SMR (small modular reactor) nuclear plants. This is with the aim of significantly reducing CO_2 emissions. Simulations were run in increments of ten years, from 2019 to 2100, with different global net-zero objectives in mind. Replacing the world's (over) 70,000 FFPPs would reduce CO_2 emissions by 12–13 percent, according to modeling studies (12.63%, exact) relative to the conditions attributed to 2020 (2019, exact), and 87,830 SMR core units (~80 MWe each) are needed to meet the forecast electricity demand. Larger reactors may reduce the SMRs required in some regions, as well as other means of electricity generation.

It is clear that there are multiple factors at play from the scenarios and options considered in the macro-economic models used in the DICE model. The relevant economic questions to address are how many units, and how much time will be needed to complete NPPs when connected to an existing electrical grid. It is clear that in the meantime, the regional to national, low carbon energy portfolio will need a linkage between baseload (nuclear, hydro) generation, fluctuating sources (wind, solar), and scaling of energy storage technologies. It is also clear that urgency means rapid change, and thus, socio-political reasons to maintain the BAU scenario will be counterproductive. In fact, this suggests an (international) aggressive transition to lower carbon (economy of scale) will be needed by 2030, as opposed to a longer-term transformation by 2050. An (aggressive) large transition now defines the rate of steady change to 2050. Otherwise, the transition to a lower carbon-emitting society, as well as the incurred damage, will increase such that change will become even more contentious.

The DICE macro-economic model thus predicts the cost of climate damage impacted by changes in the upper ocean, atmospheric temperature, and the deep ocean temperature as USD 1.515 trillion (US Dollar; (US) trillion = 1,000,000,000,000 (1×10^{12})) by the end of this century. These DICE parameters are seen as heuristic indicators of consequences that may ensue. By modifying a section of the model to estimate the high-level human health cost due to climate change, a cost of USD 1.1 (1.073, exact) trillion is predicted. Further, in terms of lost opportunity to the economy, this is estimated to equal USD 2.6 (2.59) trillion. The anticipated damage is more than 15–25% of the US budget and GDP (2016). While climate change damage is subject to anticipated debate, there are three large scenarios (other than BAU) as follows: (i) to pay for the economic damage as they occur, (ii) to anticipate the forecasted damage and take urgent preventative action immediately, and (iii) to take a hybrid approach—a combination of compensation and prevention. It is clear that a detailed, macro-climate change damage model is needed in order to reach a postulated consensus.

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