Nuclear Engineering and Technology 53 (2021) 1658–1663

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

# The Pahlev Reliability Index: A measurement for the resilience of power generation technologies versus climate change

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ARTICLE INFO

*Article history:*
Received 31 July 2020
Received in revised form
14 October 2020
Accepted 20 October 2020
Available online 28 October 2020

*Keywords:*
P-index
Power generation
Exergy analysis
Power system planning
Climate change impacts
Reliability index

ABSTRACT

Research on climate change and global warming on the power generation systems are rapidly increasing because of the Importance of the sustainable energy supply, thus the electricity supply since its growing share, in the end, uses energy supply. However, some researchers conducted this field, but many research gaps are not mentioned and filled in this field's literature since the lack of general statements and the quantitative models and formulation of the issue. In this research, an exergy-based model is implemented to model a set of six power generation technologies (combined cycle, gas turbine, nuclear plant, solar PV, and wind turbine) and use this model to simulate each technology's responses to climate change impacts. Finally, using these responses to define and calculate a formulation for the relationship between the system's energy performance in different environmental situations and a dimensionless index to quantize each power technology's reliability against the climate change impacts called the Pahlev reliability index (P-index) of the power technology. The results have shown that solar and nuclear technologies are the most, and wind turbines are the least reliable power generation technologies.


## 1. Introduction

Clean energy is key to low carbon and a greener future, Which can help us avoid the 2-degree celsius threshold as the climate goal. Today the share of the renewables in the end-use energy is 19% (2017), and it must be more than 65% by 2050 to meet the environmental goals of the COP21 meeting in 2015 [1]. On the other hand, to meet this goal, the share of the renewables in the power generation must reach 86% from 25% (2017) by 2050 [2]. The impacts of the environment and climate change are among the challenges that the power sector and the electricity generating technologies face. These impacts and the effects of climate change are highly effective in the energy sectors [3]. The studies on the power sector's vulnerability in terms of security and reliability of the energy show that the power sector is gravely dependent on its surrounding environment and its condition [4]. This effect is not limited to generation, but also it can affect the transmission sector and the other sections of the power industry [1]. The power sector's Importance is not deniable because of the growing share of the electricity in the end-use energy supply. The power sector is venerable to climate change. Among the power technologies, renewables depend on climate parameters such as ambient temperature, precipitation, irradiation, and wind speed [4,5]. The existing studies on climate change and power technologies can be reordered and categorized into two categories [2]. Most of the literature available in this field is a general overview of the climate change effect on the energy sector, and they are qualitative studies mostly based on regional assumptions. The second set of previous research conducted in this field focuses on a single technology and mathematical modeling of the climate change effect on the energy generation and supply-side [3]. Uncertainty and the limitations of the previous literature in this field have shown the Importance of a comprehensive quantitative model to address all of the leading power production technologies and a technology base model, not a regional model with a generalization uncertainty [4]. Ref. 5 studied the effect of climate change on power generation in Australia.

In this study, the authors implemented a parametric study on the efficiency and performance of the power sector and its impacts on the region's economic status. Ref. 3 studied the impact of climate change on the energy and the power market and the share of each technology in the energy portfolio. In this study, the author insists on the regional differences and the variant situations and potentials of the power sector's venerability toward climate change. In this

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https://doi.org/10.1016/j.net.2020.10.013
1738-5733/

research, thermal power plants are also mentioned as sources that are not being affected by climate change. Ref. 6 studies the literature on climate change impact as review research and states that the wind, solar, and thermal power are globally affected by climate change because of the global warming phenomenon. However, the biomass and hydropower are more region-dependent, and a worldwide generalized formulation may not be concluded. There are other researches like Ref. 6, which are regionally based and are more general qualitative suggestions for the future. In this field, the research gap is to generalize the effect of the climate change on the power sector on a global scale and also the lack of a quantitative methodology to formulate and describe this impact to project the reliability of each power generating technology and also an index to choose the most reliable and less venerable one as a long-term energy supply source [4–6].

In this research, these research gaps are filled with an exergy-climate change model to relate and formulate the global warming to the energy performance or the exergy efficiency of the power generating technologies and introduction of a new index to describe quantitative reliability each power source toward the climate change impacts. The main aims of this paper are modeling power generating technologies, studying climate change impacts on these models, using the results of this analysis to estimate the vulnerability of each technology to climate change effects, using the estimated quantities of vulnerability to define a reliability index for each power generating technology, and prioritizing main power generating technologies in the term of their reliability toward climate change impacts.

## 2. Methods and materials

This analysis considers the exergy (useful Energy performances) of each leading power-generating technologies. The energy model is conducted for all the technologies mentioned in the research: the Nuclear power plant, gas turbine, combined cycle of Rankine-Bryton, Solar photovoltaic, and wind turbines considering the first and second thermodynamics laws. However, there are some differences in the modeling of the climate change effect and the exergy model of the renewables and the conventional power technologies; these differences, the emission footprint of the conventional power technologies, are addressed in the combustion methods. And, for the renewables, the Carbon life cycle analysis is implemented [6]. Global warming data shows that climate change became a severe issue that must be addressed. Moreover, the emissions are severely increasing the climate change effects throughout the globe. In the results section, the effect of the emissions on the power plants is being studied. As a fact, GHGs increase the ambient air temperature, which causes a decrease in the exergy efficiency of the electricity generating units. The mentioned fact illustrates that the GHG emission is a severe problem for the efficiency and exergy destruction in the power plants [3,7]. The correlation of the exergy efficiency and the ambient temperature is investigated in linear regression and forecasting this effect toward IPCC scenarios for the next half-century by 2050. Moreover, the correlation index of climate change increased temperature, and the exergy efficiency is considered the reliability factor of each power technology [8]. The most important driving factor of the climate change effect is considered exergy efficiency [2]. The Pearson parameter estimates the quality of the relationship between two variables of the model, which are the exergy efficiency, and climate change increased in the mean temperature. This model's correlation parameter is varied between [-1,+1], and the zero means no linear relationship. The parameter is estimated as follows [3]:

$$PRI_{PCC} \frac{\sum_{i=1}^{n}\left(ExE_i - \overline{ExE_.}\right)\left(T_i - \overline{T_.}\right)}{\sqrt{\sum_{i=1}^{n}\left(ExE_i - \overline{ExE}\right)^2}\sqrt{\sum_{i=1}^{n}\left(T_i - \overline{T_.}\right)^2}} \quad (1)$$

The equation mentioned above (eq. (1)) is the statistical derivation of the pearson formula. Data ($ExE_i$, $ExE_{k,\,i}$) is used in eq. (1) to estimate the relationship intensity or coefficient between the power sector and climate change [9]. Where ExEi is the data i from Exergy efficiency set and $ExE_{k,i}$ is the data i of the component k, where the k is (k: Combined cycle, Nuclear cycle, Gas turbine, Photovoltaic, Windpower), PRI is the Pahlev reliability index, and T stands for ambient temperature [10,11]. In this paper, the climate change effect on each power technology's energy performance mentioned before is described using the formulations introduced as the Pahlev reliability index and Energy performance-climate change model (see Fig. 1). Pahlev reliability index shows the dependency of the performance of the power technology on climate change effects. This index is calculated using the correlation index of the exergy and temperature increase caused by climate change since 1900. The energy performance-climate change model (EPCCM) shows the quantity dependency of the power technology's performance to the climate change effects. This model is calculated using the linear regression index of the Exergy and Cumulative temperature increase caused by climate change since 1900.

## 3. Results and discussion

This paper's mathematical and technical goals have been satisfied and discussed in the sections' methodology and results. The P-index for the reliability of the power technologies against climate change impacts is the first quantitative index introduced in this field, and there is no other reference to be compared. The quantitative results should be compared with other qualitative findings of the literature in this field. Elements and aspects of the energy systems which are affected by the climate change (i.e., average climatic conditions, the variability of conditions, and the frequency of the period and intensity of the extreme climate and weather phenomenons) are mentioned before, and the mean result of the specified factors are being presented in the article body.

### 3.1. Nuclear and thermal power plant

The Bushehr nuclear power plant (NPP) in Iran, built with Russian technology, has been operational since 2011. It is the first civilian nuclear energy generating facility in the Middle East. The Bushehr NPP, owned by the Islamist Republic of Iran through its nuclear division, Atomic Energy Organization of Iran (AEOI), is currently operated with a single 915 MW reactor unit. The unit was temporarily brought offline for fuel change and overhaul in April 2020, and it was refueled and reconnected to the grid for the first time by the Iranian technicians without Russian help in June 2020. Busher-1 produced 5,865 GWh of electricity in 2019, compared to 6,300 GWh in 2018. The Bushehr nuclear power station is being expanded by two more Russian reactors of 1,057 MW capacity each. The construction works for the Bushehr NPP expansion were started in October 2017, while the main construction of the Bushehr-2 reactor unit was started in September 2019. The effect of climate change and global warming on the Bushehr power plant's overall exergy efficiency is done from 1900 to 2020 and represented in Fig. 2(a) below, considering 1900 as the reference year for the climate change temperature difference. Fig. 2 shows that the more outside temperature causes more exergy destruction and less exergy efficiency. Exergy destruction caused by the less efficient

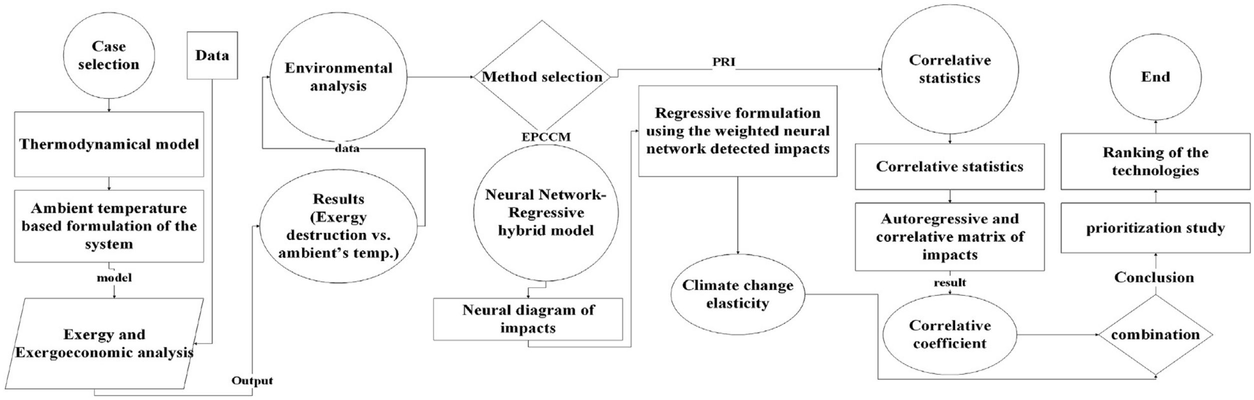


**Fig. 1. -** The algorithm of the methodology and modeling process.

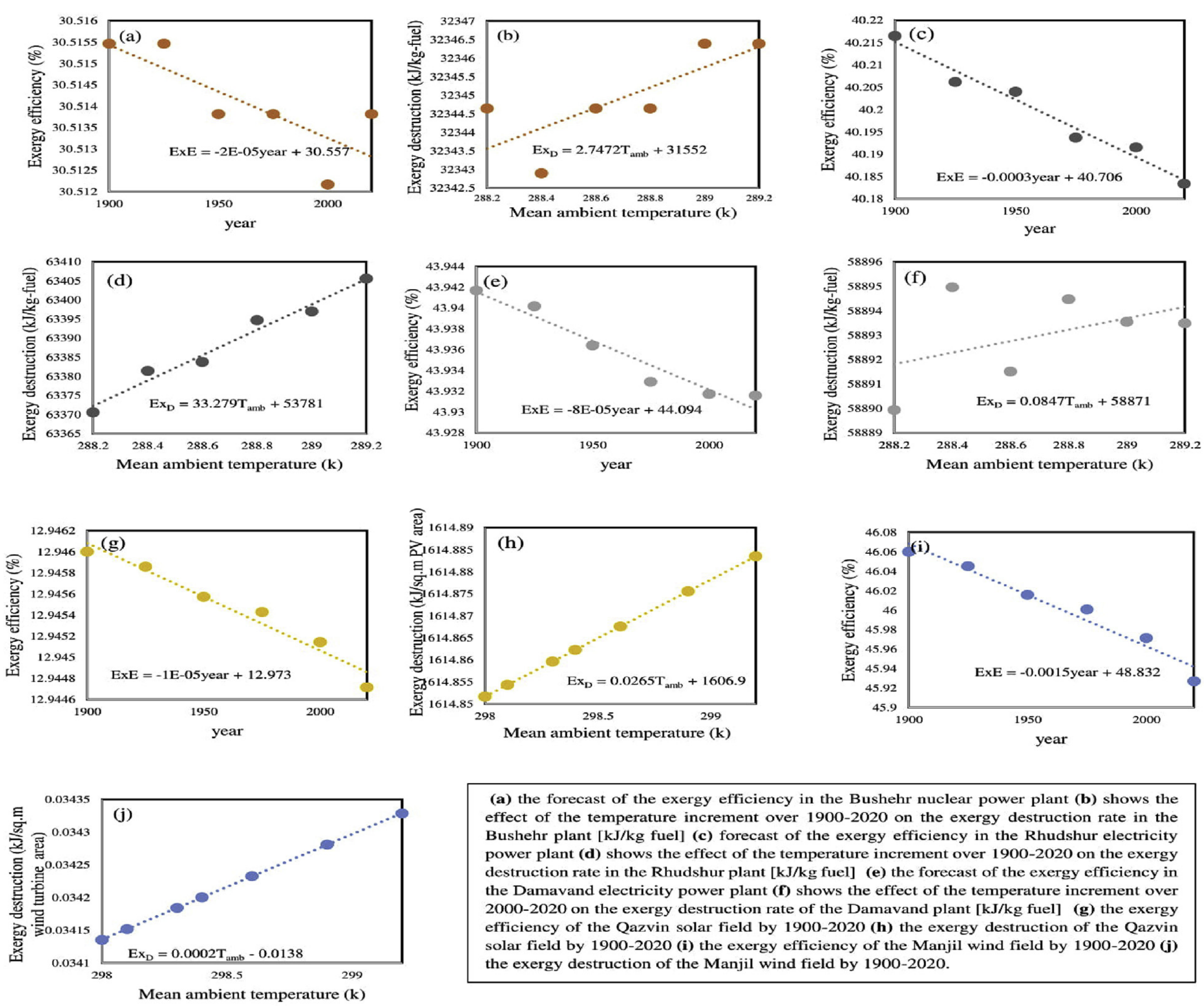


**Fig. 2. -** Results of the EPCCM and PRI analysis for the different power technologies.

performance because of climate change and global warming is presented in Fig. 2(b). Fig. 2(b) shows that the same size, power generation utility is much less efficient in 2020 than in 1900. This diagram clearly illustrates the damage of climate change and the global warming issue to the power sector, causing more exergy destruction and more emissions in the electricity utilities because more fuel is needed to produce the same amount of electricity compared to the last decades.

Roodshour Power Plant is located in the 43 km of Tehran-Saveh freeway, Zarandieh city, Parandak, Markazi province. Roodshour Power Plant is Iran's first private power plant built based on Iranian experts' capabilities and experiences, in line with Article 44 of the

Constitution and government development plans with the Ministry of Energy's support. The power control system is DCS-Teleperm XP type, and according to the systems installed in the control room, all accessories and all units of the power plant can be controlled and monitored. Each unit has a local command room with full capability to operate the unit. The operation team includes one engineer, one controlling expert in the control room, and one local operator who also operates a 400 kV substation and gas station. The first phase of the plant has a rated capacity of 792 MW, and the second and third phases of the plant will have a capacity of 548 and 822 MW, respectively. The primary fuel is natural gas, and the backup fuel is diesel, which is switched automatically from gas to diesel and vice versa. The effect of climate change and global warming on the overall exergy efficiency of Rhudshur power plant is estimated from 1900 to 2020 and represented in Fig. 2(c) below, considering 1900 as the reference year for the climate change temperature difference. Fig. 2(c) shows that the more ambient temperature causes more exergy destruction and less exergy efficiency, and the conventional electricity sectors are causing their own less efficient performance. Exergy destruction caused by less efficient performance is because of climate change and global warming, presented in Fig. 2(d). Fig. 2(d) shows that the same size, power generation utility is much less efficient in 2020 than in 1900. This diagram clearly illustrates the damage of climate change and the global warming issue to the power sector, causing more exergy destruction and more pollutant electricity utilities because more fuel is needed to produce the same amount of electricity compared to the last decades.

Damavand Combined Cycle Power Plant (45 km - Khavaran Road and 35 km - Tehran-Mashhad Road) is a combined-cycle power plant with a 2868 MW capacity, which includes a 12 unit 159-MW V94.2 gas turbine set and 6 unit 160 MW steam turbine set. The average power output is 2366 MW, 2532 MW in winter, and 2172 MW in summer. Fig. 2(e) shows that the more ambient temperature causes more exergy destruction and less exergy efficiency, and the conventional electricity sectors are causing their own less efficient performance by their massive amount of carbon emission. The less efficient performance causes exergy destruction because of climate change and global warming, presented in Fig. 2(f). Fig. 2(f) shows that the same size, power generation utility is much less efficient in 2020 than in 1900. This diagram clearly illustrates the damage of climate change and global warming to the power sector, causing more exergy destruction and more pollutant electricity utilities because more fuel is needed to produce the same amount of electricity compared to the last decades.

Ref. 18, Ref. 19, Ref. 20, and Ref. 21 states that the thermal power plants are greatly affected by climate change impacts. In these papers, some quantitative amounts are being estimated, and they state that thermal power plants lose 0.3–0.7% of their energy performance per degree of the mean global temperature change. The results of this paper also show that a similar amount of the exergy and energy efficiencies decrease per each one-degree global mean temperature rise (0.465% for combined cycle, 0.332% for the Nuclear cycle, and 0.732% for the gas turbine power plants) [18–21]. Also, there will be more thermal power plants' issues in the severe climate change stages. Reduced water resources for cooling systems are expected for the coming decades, causing load reduction or shutdown of the power plants [22]. For example, for each 3-degree increase in the mean yearly temperature in the German power plants, up to 36% load reduction and constant shutdowns in the thermal power plants [23]. While some regions are projected and invested in the thermal power plants to supply their ever-growing electricity demand, it is expected that the mean capacity of the global thermal power plants will decrease 5–8% by 2100, which confirms the findings of this paper [21,24–28].

### 3.2. Solar energy field

In this section, the renewable portfolio is considered and modeled. The 4E analysis can be considered for the renewables, but because of the type of energy conversions in the mentioned technologies, exergy and energy efficiencies are almost equal. Moreover, for the environmental effect of the renewables, the life cycle analysis is considered, and for the economic approach, the economic feasibility methods are being implemented. The Qazvin solar field is a photovoltaic solar field designed and established by the MAPNA CO., and the cooperation is the owner of this 10 MW field. The exergoeconomic approach is not defined for renewable energy technologies because of the free source of energy they use. However, to investigate the economic and environmental footprint of those technologies, the feasibility methods and Life-cycle analysis are being used. The amount of life cycle emission or the overall emission per unit of power generated by the plant is calculated using equation (2) below to implement the LC approach for the power plants:

$$LCE = \sum GWP * \frac{Ef + Ec + Eo + Ed}{Q} \tag{2}$$

In equation (2), LCE stands for life cycle emission (kg/kWh), Ef for emissions of fuel used in the plant, Ec for manufacturing emissions, Eo for operation emissions, Ed for removal and end life emissions, GWP for Global warming potential of each greenhouse gas (for $CO_2 = 1$), and Q for Net power generated. The ambient temperature effect on the electronic components and the heat transfer efficiency has to be considered for the modeling of the climate change impact on the photovoltaic systems. Fig. 2(g) and (h) show the exergy efficiency variation from 1900 to 2020, and the exergy destruction rate caused by climate change.

Climate change foresight studies tend to agree that the cloud cover will be decreased, and the amount of the sunny days will be increased in the low-mid-latitude regions (i.e., Middle East and Southern Europe). As Ref. 16 states, this increase in the sunny days is a regional effect, and it cannot be generalized to the global scales, and also its positive impacts cannot completely Compensation the temperature rise performance reduction in the photovoltaic and other solar power conversion devices but significantly reduces it and this makes the solar power one of the best options for the future investments. These findings and statements confirm this paper's results, stating that the photovoltaic systems are the most reliable power technology against climate change impacts [16]. In some regional studies, the solar potential is projected to be increased by 2100 (the Middle East and Southern Europe). This increase is estimated by more than 10% in the year's cold seasons [17]. This fact notes that the electricity supply chain most is redesigned for an international scale to reduce the impacts of climate change on the economy and human society [24].

### 3.3. Wind field

Manjil, Hershel, seiyahpoosh, and Rudbar (shortly Manjil wind field) are wind farms located in Gilan, Iran. The total wind turbines installed in this project are Rudbar Wind Farm with 4 WTG units with a total capacity of 2.15 MW, Harzevil Wind Farm with 25 WTG units with a total capacity of 12.18 MW, Manjil Wind Farm with 52 WTG units with a total capacity of 27.47 MW and Seiyahpoosh Wind Plant with 69 WTG units with a total capacity of 45.54 MW in an entire field of 150 units with a total capacity of 87.34 MW. The ambient temperature effect on the electronic components can be ignored for the modeling of the climate change impact on the wind systems, but the air density's thermodynamic effect has to be

**Table 1**
The results of the climate change impact on the power technologies analysis (Pahlev's table) (for the IPCC baseline scenario).

| Technology | PRI | EPCCM formula | RMSE | SSE | MSA |
|---|---|---|---|---|---|
| *Nuclear plant* | −0.43 | −2.0E-05T + 30.557 | 0.92 | 0.87 | 0.85 |
| *Gas turbine* | −0.74 | −3.0E-04T + 40.706 | 0.90 | 0.86 | 0.84 |
| *Combined cycle* | −0.57 | −8.0E-05T + 44.094 | 0.95 | 0.91 | 0.89 |
| *Solar PV* | −0.31 | −1.0E-05T + 12.973 | 0.91 | 0.86 | 0.85 |
| *Wind turbine* | −0.92 | −1.5E-03T + 48.832 | 0.99 | 0.94 | 0.92 |

considered. Fig. 2(i) and (j) show the exergy efficiency variation from 1900 to 2020, and the exergy destruction rate caused by climate change [19].

A considerable lack of enough global scale studies is sensed in wind power, reviewing the previous research on climate change and the environmental impacts of the energy industry. Ref. [12] stated that the average wind speeds around Europe and North America would remain within ±15% of the current values by 2100, and they failed to conclude a general statement from the model developed in their paper. These limitations have been stated ±20% by Ref. [13] and even ±30% by Ref. [14]. As it was mentioned in this paper, the wind energy resources may not significantly be changed globally, and no change was detected in this paper, but the power generation in the wind turbines is also affected by the changes in the air density, which a small change in its amounts will have a significant impact on the power output. The temperature rise decreases the density, which causes the wind turbine's exergy rate to be reduced by the end of the century for more than 4% throughout the earth [15,16].

### 3.4. Statistical results

All of the power generating technologies have an environmental effect. These effects are caused in every stage of the technology (manufacturing, O&M, and removal). Some of the technologies like conventional technologies have direct fuel combustion greenhouse gas emissions, but others like renewable technologies show this effect during the manufacturing or installment stage. Moreover, these effects are not Unidirectional but interactive ones and similarly climate change and environmental effects on the power sector and its operational process. This research is dedicated to climate change impact on the power sector. In this research, the interactive impact of climate change on the power sector has been studied by 1900–2050. They are considering Table 1 in which the result of the regression model for all of the studied technologies. Fig. 2 shows that although the thermal power plants have a more significant footprint in climate change and environmental issues, renewable energy technologies are higher affected by climate change impacts [14,15]. Renewable energies are highly connected to nature, and the reliability of these systems is highly dependent on the environmental condition.

Moreover, wind power is more affected by climate change. Moreover, in thermal power technologies, the gas turbine is highly sensitive to the ambient air temperature and global warming. In this case, using combined cycle technology helps to control this sensibility. Moreover, considering the carbon footprint of the power sector technologies, carbon emissions of the considered technologies affect climate change. Because of this effect, there is an interactive relation between the climate change and power sector, which its carbon emission rate determines its intensity. Considering the findings of this research, the impact of climate change on the power sector is undeniable, and there is a negative effect of climate change on power technologies [4,15]. To calculate and estimate each power technology's reliability toward the climate change in the term of a dimensionless index, which indicates the compatibility of each technology toward the others, the Pahlev index, defined in section 3.2, is implemented for each technology [24–28]. The indexing process results are illustrated in a table called Pahlev's table (Table 1 below).

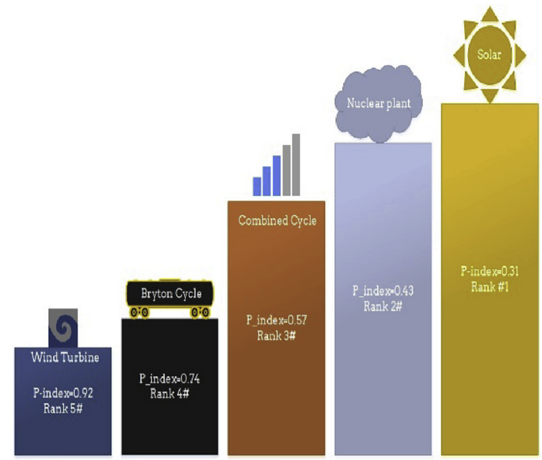


**Fig. 3.** – The reliability ranking of the power generating technologies.

The Pahlev correlation results show that the wind turbine is less reliable against the difficult climate change situations, and the photovoltaic is the most reliable technology for climate change mitigation. Fig. 3 below shows the ranking of the most reliable technologies toward climate change impacts.

## 4. Conclusion

In this paper, the exergy performance (Quality of energy) is being implemented to study the climate change effects on each energy technology (Solar PV, Wind turbine, Hydropower, Combined cycle power plant, Gas turbine, and Nuclear power plant). As the mathematical model states, the rise in ambient temperature and surroundings affects the exergy performance of the chosen power generation technologies. With quantitation of this impact, a global scale reliability index can be derived to use as a reference for the climate shifting status technology selection and feasibility studies. The statistical process is implemented using the correlative modeling, and the technologies rank and prioritized by their correlation coefficient (smaller absolute value means lesser integrated impact and higher reliable technology). Results show that photovoltaic technology is the most reliable power generation technology in climate change, and the wind and gas turbines are the least reliable technologies.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

The Author(s) announce that no funding used for this research in its conducting process, but we thank the Korean Nuclear Society for supporting the Open-access publish of this paper in the Nuclear Engineering and Technology Journal.

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