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Original Article

Nuclear power utilization as a future alternative energy on icebreakers

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A B S T R A C T

Diversified fuel types such as methanol, hydrogen, liquefied natural gas, ammonia, biofuels, have been come to fore in consideration of the limitations, regulations, environmental perception and efficient use of resources on maritime sector. NE is described as a substantial alternative energy source on the marine vessels in the sense of de-carbonization and fuel efficiency activities carried out by IMO. Although NPVs have been constructed for the merchant, navy and supply fields over the years, their numbers are few and working ranges are quite limited. NE generation techniques, reactor types, safety and security issues in case of any leakage or radiation pollution are analyzed and comparisons are performed between fossil-based fueled and NP based on icebreakers. The comparison are conducted on the basis of dimensions, resistances and operational competences by the VIKOR. NP icebreakers operated in recent years occupy a notable position in the ranking, although fossil fueled ones are most prevalent. Consequently, refueling period and emissions are the principal benefits of NPVs. Nevertheless, the use of such systems on marine vessels especially for merchant ships may come to the fore when all concerns in terms of safety, security and society are resolved since the slightest mistake can have irreversible consequences.

1. Introduction

The use of nuclear-powered (NP) will increase once safety concerns are sufficiently addressed, considering the future restriction of fossil-based fuels in transportation particularly in the maritime sector [1,2]. Maritime transport, which constitutes a substantial part of world transportation, should evolve towards the elimination of greenhouse gases; air and water pollutants [3]. Therefore, a lot of work is being performed on reactors in the maritime field, and this situation also creates a worthy infrastructure for land facilities to be installed in the future. Moreover, the first application was used for submarines in 1955 [4,5].

Regulations on radioactive material, which is reviewed and updated according to developing technologies, for the Safe Transport of Radioactive Material which was published by the International Atomic Energy Agency (IAEA) in 1961. Moreover, Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code), which is in a quality that completes the regulations put forward by the IAEA on radioactive materials, was introduced by the International Maritime Organization (IMO). The main purpose is to ensure the safety of the package, regardless of the mode of transport. In this way, the radiation effect that may occur in people, property and the environment is minimized by IAEA. Likewise, the purpose of the INF code title changed as "International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes onboard Ships" that underlines the issues of loss of stability, fire outbreak and structural deterioration that occurred in carrying radioactive material, as well as in case of any damage of marine vessels [6]. NPVs are a prime technologically ready option in meeting the IMO's 2030 and 2050 targets, especially in terms of decarbonization [5].

Nuclear-powered vessels (NPVs) especially on merchant type are also considered as alternatives, in addition to the environmental economic benefits of renewable energies, biofuels that produced biologically from manure and waste of animals and food by anaerobic digestion and some fossil-based fuels such as natural gas [3,7]. Widespread use of nuclear systems can begin and become a notable competitor compared to classical power plants when the reliability and maintainability of nuclear power plants (NPPs) are ensured in terms of safety provided in Generation III for security, cost and efficiency especially in coastal and offshore regions applications [5,8,9]. A nuclear machine converts the heat energy obtained from fission atoms of radioactive materials such as uranium,

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into mechanical energy for turning the propeller [10]. The nuclear propulsion systems (NPSs) has been successful especially on military ships and icebreakers [3]. Nuclear systems are still not in a noteworthy position in the energy market, notwithstanding that the small NPPs which are one of the land-based NPPs that have significant advantages compared to conventional energy production systems in hard-to-reach areas [11]. Nuclear reactors use uranium, plutonium, thorium and mixed fuel (MOX) that contain both of them [12].

1.1. Naval nuclear-powered vessel

Nuclear reactors are an ideal power generator that provides a propulsion system for military ships [13]. Until this time, NP propulsions have been used for naval purposes such as aircraft carriers and submarines that ensure the secrecy of navy and submarines [1,14,15]. Even though, an increasing interest have occurred in NP navies in other countries, United States of America (USA), United Kingdom, France, Russia, China, and India have NP navies [16]. One of the fundamental outputs for long-term projects in the maritime field is de-carbonization [3]. The use of nuclear reactors in Mobile Nuclear Power Plants (MNPPs) provide benefits both in eliminating harmful emissions released into the atmosphere and cargo capacity. Many autonomous tools and optimum numbers of expert personnel should be kept in NPVs that operated with MNPPs in an attempt to gain maximum productivity from the point of security, safety and health [9].

NP propulsion is mostly preferred in submarines due to the necessity of operating without refueling and surfacing, at the same time these types of propulsion systems can be installed in military cruisers, aircraft carriers and other navies [1]. Approximately 40% of the USA Navy's combatant fleet is propelled by nuclear power. Furthermore, more than 50% of all military submarines and aircraft carriers are propelled the same systems [4].

Nuclear propulsion draws attention in the light of studies performed in Australia. One of the most vital advantages of nuclear propulsion systems is the elimination of periodic charging in the battery system and theoretically provides infinite sinking time that lets the possibility of continuous operation under the sea [4,17]. In this way, the state of being noticed by military ships at any moment was blocked since recharging batteries by require surfacing. Except for naval purposes, a few ships are propelled by nuclear-power for experimental purposes [2]. Applications of NPVs are mostly used on submarines. US Navy, Russian Navy and China have the number of submarines as 73,21 and 14 respectively. On the other hand, nuclear power also utilized on aircraft carriers and battle cruisers in some nations [5]. Small modular nuclear power reactor (SMR) has come to the fore, especially with safety benefits in recent years, notwithstanding, still various uncertainties have existed regarding this issue [17,18]. Besides, MNPPs constitute a prominent alternative for the maritime transportation, especially on container ships [9].

SMR are capable of 70 MW power output as performed on Suezmax Tanker Concept to ocean crossing operating [3]. Modular Helium Reactors each one provides 50 MW power output where compressors operated with water jet pumps and additional 50 MW gas turbine are used for NP propulsion system as design stage to monitor and analyse the efficiencies that can be achieved at every stage [19]. PWR type NPVs are useful in meeting new regulations on the maritime field [20]. PWR systems can provide power output ranging from 27 MW to 300 MW in a wide range [12]. PWR systems are generally used in maritime applications [5,21]. In addition to PWR, intermediate neutron flux beryllium sodium cooled reactor, experimental beryllium oxide reactor, super critical water reactor, organic moderated reactor experiment, lead-bismuth cooled fast reactors are the other type of reactor that can be used in the maritime field [4]. Russia developed water-cooled submarine reactors using lead-bismuth coolant on their constructed naval surface ships and ice breakers [21].

1.2. Types of reactor on nuclear energy

The fundamental types of fuels, which are uranium-zirconium, uranium-aluminum, and metal ceramic, used in nuclear reactor have high specific energy. This situation eliminates the refuelling process for a long time owing to developments in modern naval reactors where high burnable fuels used to get theoretically infinite range, operational times exceed 10 years without the need for any refueling by a high enrichment level of 93% in U235 that consists of 15% zirconium and 85% uranium [4,22]. In the world, 441 active NPPs were operated by the end of 2020. Technologies used in NP production, installed regions and the numbers of each reactor type are described in Table 1 [1].

Boiling Water Reactor (BWR), Fast Neutron Reactor (FNR), Gas-Cooled Reactor (GCR), Light Water-Cooled Graphite-Moderated Reactor (LWGR), Pressurized Heavy-Water Reactor (PHWR) and Pressurized Water Reactor (PWR) are the main types of NPPs. In BWR system water is boiled by reactor that use radioactive materials and generated steam is used on turbine to generate electric power as well as 20% of reactors around the world use this system. LWGR system light water coolant is used in pressure tubes that surrounded by the graphite moderator in the process of enrichment [5,23]. PHWR that applied in 10% of reactors worldwide also, deuterium oxide is used for both coolant and moderator [5,24]. Approximately 60% of nuclear reactors operated by PWR systems these are more beneficial in terms of noise compare to BWR systems [1,5]. GCR systems in which CO_2 and graphite act as the coolant and moderator on the nuclear systems respectively, are more beneficial in terms of operation and safety than water-cooled reactors. In addition, the efficiency of converting heat to electricity can reacht 50% by using advanced gas turbines, this rate is around 30% in water-cooled systems [5,25].

In 2020, 6 reactors operated in France, USA, Russia and Sweden since 1970 were permanently closed. On the other hand, five reactors connected to the grid during 2020 in United Arab Emirates, Belarus, China, Russia. Vodo-Vodyanoi Energetichesky Reactor (VVER) is a type of PWR however the use of horizontal steam generators, hexagonal fuel equipment and high pressures provides differentiation. This type of reactor will be deployed in the Akkuyu NPP to be built in Turkey. In the case of full capacity operation, 90% of Istanbul's electricity or 10% of the entire Turkey per year will be met [1].

1.3. Prohibitions, suggestions, advantages and disadvantages of nuclear energy

Potential hazards from the use of nuclear fuel on marine vessels should have been eliminated by authorities such as port and flag states. Despite the high energy output, it can create devastating situations in terms of security. Thus, the field and port of

Table 1
Technologies used in NP production, installed regions and number of Nuclear Power Plant (NPP).

Regions/Types	BWR	FNR	GCR	LWGR	PHWR	PWR	TOTAL
Africa	–	–	–	–	–	2	2
Asia	21	–	–	–	24	95	140
E. Europe& Russia	–	2	–	12	–	40	54
N. America	33	–	–	–	19	63	115
S. America	–	–	–		3	2	5
W. & C. Europe	9	–	14	–	2	100	125
Total	63	2	14	12	48	302	441

installation must be determined clearly. Due to the possibility for large energy output from radioactive fuels, commercial NPV access to canals or ports may be limited or forbidden [26].

Reactor production, high investment and operating cost, maintenance, emergency response, difficult dismantling process and fuel disposal are remarkably compelling, comprehensive, costly and unpredictable compared to conventional propulsion marine vessels [9,19,26,27]. That's why sustainability and stability could not be achieved, in spite of that NPVs left a notable impact on maritime history [26]. Shipbuilders, ship-owners and ship operators have not fully accepted NP systems on merchant ships, despite the fact that low fuel cost, high speed and increased cargo capacity make nuclear ships optimistic [10]. Environmental perceptions and social concerns are the primary barriers on NPVs operation, throughout the entrance and mooring to the ports [26]. High vibrations and increased pitch and roll can result in extremely serious threats on the environment, people, and other things, when NPVs operating in bad weather conditions. In addition, accidents such as collision, grounding and sinking that can also occur even in good sea conditions can cause the leakage of radioactive material and meltdowns [5,10]. Nuclear power plant equipment and workers' clothing are exposed to radioactive pollution. Briefly, possible damage as a result of the spread of radioactivity to the environment is one of the biggest and most noteworthy obstacles to nuclear system [2,28] since the behavior of the reactor and the limits of harm are difficult to fully pinpoint [5]. That's why, radiation shielding barrier, vibration reduction tools, collision and grounding preventive systems, energy, cooling equipment should be installed on NPVs to minimize or completely eliminate the leakage [3,12].

In contrast to high energy, the construction of new NPVs brings nuclear waste. Therefore, disposal processes need to be accelerated and improved since disposal of old nuclear wastes still continues [2]. Service supply, port acceptance procedure of countries, lack of trained personnel are tremendous challenges on using in maritime industry [10]. Moreover, NPVs have the potential to invade the lands of thousands of people [2]. The other challenging point is finding an insurance company that will cover the damages in any adverse situation [10]. Nevertheless, NPVs can operate for a long time with high-speed that increases the transportation of products compared to conventional propulsion system ships [10,22,26]. NPV is operated more due to the small and constant volume of the fuel type that indirectly affects the cargo capacity and amount of weight [10,19,22]. Nuclear merchant ships can be operated for 2–5 years without refueling, which provides an almost endless range [10,22]. The fuel cost also is not affected by the fluctuations in the fuel price, especially in upward moves [10]. On the other hand, more tonnage carrying capacity and the state of being economical in the operation of large-sized merchant vessels described as a good option any vessel especially on merchant ships [5,19,20].

NPVs described as a leading potential to create competition against fast-ships operated along the Atlantic Ocean and also can be operated as merchant vessel on rush ordering for ocean transition to minimize risks such as political, safety and security except for military purposes [19,26]. NP can be confident one when major accident prevention is fully insured and also can be acceptable to the public that still thinks that nuclear power is unsafe and creates high costs [5,20]. The authority must take precaution on passengers, crew and environment even the smallest amount of leakage occurred [10]. Reactors should be placed in the mid-ship section of the ship especially on tankers and bulk carriers since this section is least affected by six degrees of freedom and minimum deformation or leakage occurs in mid-ship section in case of stern and the bow side accidents. Despite all these positive aspects of the mid-section that reduces the longitudinal strength Furthermore, the vibration occurred by the propeller revolution is highest at the stern side where the ship's propeller installed [12].

The decrease in the reserves of fossil based fuels that bring NPPs into the forefront in the sense of the maritime sector [2]. The sector stakeholders should perform together to cover the costs and gain experience on nuclear systems. The media plays a critical role in the utilized of nuclear systems, as well as their internalization by the public [20].

2. VIKOR method and application on icebreakers' performance

VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), one of the Multi-Criteria Decision Making methods (MCDM) introduced by Opricovic in 1998, is applied on this paper. Specifically for this study, VIKOR is performed to compare fossil fueled marine vessels and NPVs in terms of the dimension, resistance and operational competence. Nevertheless numerous research are performed by VIKOR at the stage of resolution of uncertainties in the maritime sector such as selection of the most appropriate planned maintenance method, energy source, emission factors. Thanks to this analysis, especially one of the multi-criteria decision-making problems that are hatching cover design to minimize water tightness and external wear in maritime transport are performed [29]. Propulsion system common faults in diesel engines and auxiliary systems have been identified and most grand ones are highlighted among them by VIKOR [30]. Moreover, MCDM is utilized to determine most suitable tug boat by VIKOR [31]. VIKOR method is applied to find the best method to prevent pollutants originating from marine vessels. Prohibitions on the use of heavy fuel oil fuels and remote monitoring of low sulphur fuel usage are the main ones in preventing emissions in terms of international regulations [32]. VIKOR also utilized for solar energy, which is one of the renewable energy sources and has many applications in the maritime field, installation area [33].

Different reactor and ship types were analyzed based on certain parameters such as power, volume and efficiency. The installation of High-Temperature Gas-Cooled Reactor (HTGR) is designed to apply on container feeder and also analyzed on submarines in terms of specified parameters [34,35]. Moreover, concept designs of NP tankers and high-speed cargo ships are analyzed to highlight the state of the application in different types of this energy on merchant vessels [3,19]. In this paper, detailed information about ships is acquired from sector reports, maritime companies, internationally accepted providers of ship tracking and maritime intelligence in order for the analysis to be carried out efficiently. In the light of literature review and potential applicability of nuclear energy (NE), ice breakers, which are NP and fossil fueled, are compared. Deadweight, gross tones, length, breath, speed and ice breaking capability, reactor type, reactor power of acting, decommissioned and future icebreakers powered by nuclear reactor are investigated Table 2 to perform comparing.

The power output of NP icebreakers, which have been started to be built in recent years, is higher than constructed in previous years. The developments performed on the reactor are the biggest proof of this situation. RITM-200 type reactor is used in LK-60 series icebreakers recently and also this reactor also installed on land and offshore power plant. RITM-200 has superiority over OK-900 A, which is frequently performed in past applications, in terms of the operation time, equipment life, volume and amount of power [38]. The substantial results acquired from the RITM-200 enable the installation of RITM-400 and RITM-200B in future projects. Increased power output leads to a change in the obtained speed values in the same direction. Although significant changes aren't observed in the sense of ice break thickness that is approximately 2 m at certain speeds around 2 knots, small changes are performed in

Table 2
Technical specification of NPVs [1,5,36,37].

Ship No	1	2	3	4	5	6	7
Name	Lenin	Yamal Sibir/Arktika Rossija/Sovetskiy	Taymyr Vaygach	50 Let Pobedy	Arktika/Sibir Ural/Yakuti Chukotka (LK-60)	Project 10510 (LK-120)	Project 10570 (LK-40)
Commissioned	• 1959/1970	• 1992 • 1977/1974 • 1985/1989	• 1989 • 1990	• 2007	• 2020/2021 O 2022/2024 o 2026	o 2026	o In Future
Decommissioned	• 1989	• Active • 1992/2008 • 2013/2014	• Active	• Active	• Active o In Future	o In Future	o In Future
Length (m)	134	148	152	160	173	209	152
Beam (m)	27.60	30	28.9	30	34	50	31
Deadweight (t)	3073	2750	3550	3505	7146	–	–
Gross Tonnage	11620	20646	20791	23439	33327	–	–
Displacement T.	16000	23500	20790	25800	33540	69700	20700
Speed [knots]	18	20.6	16.5	20.4	22	22	>20
Propulsion P. [kW]	34000	49000	32500	54000	60000	120000	40000
Reactor Type	OK-150*3 OK-900/A*2	OK-900A*2	KLT-40 M	OK-900A*2	2*RITM-200	2*RITM-400	RITM-200B
Reactor Power [MWt]	3*90 2*159 2*171	2*171	171	2*171	2*175	2*315	209
Ice break thickness [m]/Speed [knots]	2/2	2/2	1.77/2	2/2	2.8/2	–	–
• Decommissioned		• Active			o In Future		

terms of dimensions on ice breakers. Taimyr and Vaygach are quite significant since these are the first icebreakers constructed outside of Russia. The list of fossil-based fuel-powered icebreakers is described from the point of decommissioned date, dimensional properties, deadweight, gross-tonnage, displacement tonnes, speed and power in Table 3.

Oden is the first non-nuclear-powered icebreaker at the North Pole in 1991 [42]. Antarcticaborg and Arcticaborg icebreaker can be operated in shallow waters thanks to its low draft value which is approximately 2.9 m. Moreover these ships are also used for different purposes such as firefighting, rescue operations and anchor handling etc. [40]. Moreover, MPSV Botnica also have multi-functional properties such as support/offshore services [46]. Aurora Australisha has an endurance capacity as 25000 nautical miles (nm) and 90 days. Thanks to technological advances, RSV Nuyina handle operations in high sea state and wind conditions, these are (strong gale) and 12 (hurricane) according to Beauport scale respectively, also during varying air temperatures −30 °C–45 °C [43]. The design of the ship SCF Sakhalin, which was decommissioned in 2005 for arctic operations, was used on the Vitus Bering and Aleksey Chirikov construction are optimized for ice condition and open water [40].

First of all, the index of f_j^* and f_j^- are specified in formula (1) according to whether the variables are positive or negative respectively to calculate VIKOR index.

$$\begin{cases} f_j^* = \max_i f_{ij} \\ f_j^- = \min_i f_{ij} \end{cases} ; i=1,\dots,m\; j=1,\dots,n \;\&\; \begin{cases} f_j^* = \min_i f_{ij} \\ f_j^- = \max_i f_{ij} \end{cases} ; i = 1,\dots,m\; j=1,\dots,n \tag{1}$$

Secondly, the index of S and R are acquired in formula (2) respectively by using f_j^* and f_j^- values to calculate The VIKOR Index.

Table 3
Fossil-based fuel powered icebreakers [5,39–45].

Ship No	8	9	10	11	12	13	14
Name	Aurora Australis	Oden	MPSV Botnica	Antarcticaborg Arcticaborg	Vitus Bering Aleksey Chirikov SCF Sakhalin	Gennadiy Nevelskoy Stepan Makarov Fedor Ushakov Yevgeny Primakov	RSV Nuyina
Decommissioned	1990	1991	1998	1998 1998	2012 2013 2005	2017/2017 2017/2018	2021
Length (m)	94.9	107.75	97.3	65.1	99.9	104.2/99.90 104.40/99.74	160.3
Beam (m)	20.3	31.2	24.3	16.4	21.7	21.23/25.60 21/21.23	25.6
Deadweight (t)	3911	4906	2890	650	4715.20 4748.70 4297.50	3259/3879.40 3824.4/3670.40	8250
Gross Tonnage	6574	9605	6370	1453	7487 7487 6882.00	8362/8365 8597.00/8626.00	22862
Displacement T.	23500	13000	18260	33540	69700	20700	25500
Speed [knots]	16	16	10	13	15.7	16	16
M. Engine (Propulsion) P. [kW]	(10000)	(18000)	15000 (10000)	(3200)	18000 (13000)	21000 (13000)	30200 (26600)
Ice break thickness [m] and speed [knots]	1.23/2.5	1.9/3	0.8/8 1.2 Max.	0.6/3	1.5/3	1.5/3 2.1 Max.	1.65/3

Table 4
Descriptions of positive and negative attributes.

Positive and negative attributes	Key Factor	Descriptions
Dimensional Measurement	• Construction cost • Operation cost and challenges	Providing the same operational efficiency with smaller vessels allows us to take the dimensional situation as negative.
Overcoming Ship Resistance	• Total Resistance Speed • Power	High power output on the propeller and ship speed are considered positive.
Operational Competence	• Ice thickness breaking capacity • Speed	The faster and thicker the ice breaks, the more efficient operations take place. Therefore it is evaluated as positive.

Table 5
Index of f_j^* and f_j^- for six variables.

Variables/Indexes	V_1	V_2	V_3	V_4	V_5	V_6
f_j^*	65.1	16.4	22	60000	2.8	8
f_j^-	173	34	10	3200	0.6	2

Table 6
$\boldsymbol{S_i}$, $\boldsymbol{R_i}$, $\boldsymbol{Q_i}$ and rank values.

No	S_i	R_i	Q_i and Rank Values			
			$\nu = 0.25$	$\nu = 0.5$	$\nu = 0.75$	$\nu = 1$
1	0.572	**0.167**	0.87(9)	0.73(9)	0.60(8)	0.46(6)
2	0.521	**0.167**	0.81(7)	0.62(7)	0.42(4)	**0.23(2)**
3	0.619	**0.167**	1.00(12)	1(12)	1.00(12)	1.00(12)
4	0.542	**0.167**	0.82(8)	0.64(8)	0.46(5)	**0.28(3)**
5	0.500	**0.167**	0.75(6)	0.5(4)	**0.25(1)**	**0.00(1)**
8	0.585	0.153	0.51(5)	0.52(5)	0.54(6)	0.55(7)
9	0.620	0.140	**0.23(3)**	**0.41(3)**	0.59(7)	0.78(10)
10	0.589	**0.167**	0.89(10)	0.79(10)	0.68(9)	0.58(8)
11	0.597	**0.167**	0.91(11)	0.81(11)	0.72(10)	0.63(9)
12	0.567	0.139	**0.11(2)**	**0.22(2)**	**0.32(3)**	0.43(5)
13	0.565	0.139	**0.10(1)**	**0.21(1)**	**0.31(2)**	0.42(4)
14	**0.642**	0.147	0.45(4)	0.61(6)	**0.76(1)**	0.92(11)

$$S_i = \sum_{j=1}^{n} w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)}; i = 1, \dots, m \ \& \ R_i = \max_j \left[w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right]; \ i = 1, \dots, m, j = 1, \dots, n \quad (2)$$

VIKOR index is calculated by formula 3 that uses the minimum and maximum values of S and R. In this way, ranking is performed according to VIKOR. The value of v that usually 0.5 is chosen, determines the strategic weight distribution between S and R [47].

$$\begin{cases} Q_i = \nu * \left[\left(S_i - S^*\right) / \left(S^- - S^*\right) \right] + \\ (1-\nu) * \left[\left(R_i - R^*\right) / \left(R^- - R^*\right) \right] \\ S^* = \min_i S_i, S^- = \max_i S_i, \\ R^* = \min_i R_i, R^- = \max_i R_i, \end{cases} \quad (3)$$

In the final stage, verification process condition takes place on the basis of formula (4) to select the most valid ranking. Furthermore, one of the S^* and R^- values that should correspond to the $Q(a')$. If the value of ν is greater than 0.5 that mean performed the analysis is accepted by the majority clearly. In the opposite case ($\nu <$ 0.5), it means that the majority is negative attitude [48].

$$Q(a'') - Q(a') > = dQ \ \& \ dQ = \frac{1}{(n-1)} \quad (4)$$

$Q(a')$ refers to the most efficient ship on the basis of the criteria specified according to the selected ν value and$Q(a'')$ also refers to second one.

Briefly, three fundamental principles which are dimensional measurement (length and breaths), resistance (speed and power), operational competence (ice breaking thickness and speed) are utilized in the analysis. Weight distribution of each parameter obtained from ships is equal. Moreover, values of ν are selected as 0.25, 0.5, 0.75 and 1 respectively to calculate Q_i values.

3. Results and discussions

Indexes of f_j^* and f_j^- values are calculated based on positive and negative attributes. Overcoming ship resistance and operational competence are evaluated as positive attributes, on the other hand dimensional measurements are considered as negative attributes and also the reasons are detailed in Table 4.

Using data from Tables 2 and 3 excluding 2 future projects that contain 5 NP and 7 fossil-fuel powered icebreakers,f_j^* and f_j^- values obtained for 6 variables (V_1,V_2, ….,V_6) and described in Table 5.

Furthermore, The S_i, R_i and Q_i values are acquired from VIKOR analysis and the results comprehensively are expressed in Table 4 according to the number of icebreakers. Moreover, minimum values are underlined and maximum values are expressed in bold type in Table 6 on basis of index.

In term of index of S^* and S^- No. 14 have (0.642) and No.5 have (0.500) values respectively. Moreover, No. 1, 2, 3, 4, 5, 10 and 11 have the highest (0.167) R^*index value, otherwise No.12 and 13 (0.139) have lowest R^- index values. Rank of No.12 and 13 comes to the fore when the Q_i values are examined on the basis of different ν value. NPVs (No. 2, 4, 5) come into prominence when onlyν value is 1. On the other hand formula 4 based validation process is provided only at this stage.

Even if icebreakers powered by fossil fuels are superior in terms of Q_i, NP icebreakers have substantial advantages, particularly in terms of emissions and refueling. The ability to go for extended periods without refueling is made possible by NP icebreakers, particularly in arctic regions where it is challenging to do so. Additionally, the cooling process in the reactors is performed more easily due to the air temperature that is typically below zero degrees. In addition to these advantageous qualities, the reactor spill may have permanent consequences. Therefore, nuclear power has not become widely used especially on merchant ships despite the fact that it has been used on several ship types. Another critical matter is that problem people may be hesitant to work in nuclear power plants regarding radioactive contamination, safety and security problem. The problem can be minimized by professional individuals being trained in the operated area where necessary precautions have been taken. Moreover, maritime industries avoid the issue of operating NPVs since it is impossible to predict accident results that will affect people's health, safety, and the environment. On the other hand, ship owners and ship operators struggle with operating expenses like maintenance and installation charges. In addition to them, one of the biggest challenges in the case of an accident and end of life of the NPVs are reactor disposal process. The dynamic movements of marine vessels, weather and sea conditions are the other hindrances for NPVs. That's why, these kinds of power systems are favored in larger-sized ships especially for military purposes that are less affected by these effects. Submarines constitute the largest share in military-purpose ships because this energy makes it possible to stay underwater for a long time and to perform silent operas by keeping the level of secrecy at the maximum.

4. Conclusions

IMO is becoming more interested in alternative energy sources on both its present and future regulations in order to reduce emissions resulting from the usage of fossil fuels. NPVs meet these limitations without any modification. In this paper, a comparison is performed between NP and fossil-based fueled icebreakers by VIKOR in sense of dimensional measurement, ship resistance and operational competence in order to indicate the operational effects as well as emission benefits. Although icebreakers of both types have advantages over each other at certain points, fossil-based fueled icebreakers have a better rank value according to the analysis results. Nevertheless, nuclear-powered icebreakers that have been constructed recently and will be construct in future are impressively growing. Thanks to this, the exact comparison will become clearer in this field. This paper will be a significant resource for academics, industry professionals and maritime stakeholders who will study the history, types and reactors of NPVs. As a future study, it is aimed to carry out a comprehensive analysis in terms of environment, health and energy by the data acquired from newly constructed NPVs and their operations.

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.

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