Multi-Criteria Decision Making using TOPSIS Method for Battery Type Selection in Hybrid Propulsion System

Murat Bayraktar[a], Mustafa Nuran[b]

In the maritime sector, many improvements are performed on ship propulsion system. The hybrid propulsion system (HPS) is one of the innovations in the marine sector, considering International Maritime Organization (IMO) energy efficiency measures. The main objectives of the HPS are reduction in fuel consumption, maintenance costs, and minimization of the emissions of gases that harm the environment. The IMO International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI "Prevention of Air Pollution from Ships" determines nitrogen oxide, sulfur oxide, and particulate matter limits emitted from marine vessels. These limitations will be met with the HPS to be established on marine vessels. Batteries, an Energy Storage System (ESS), are used to drive electric motors, part of the HPS equipment. In this study, battery types are evaluated in terms of their chemical properties, capacities, volumes, weights, energies, specific energies, costs, and life cycle by TOPSIS method and the most suitable battery for the HPS is selected. According to the results, the highest rank (0.643127638) for the HPS is obtained from lithium iron phosphate (LFB) battery that has 200 Ah capacity, 30.55-liter volume, 27.7 kg weight, 92.42 Wh/kg energy density, 987 \$/kWh cost, and 400~13,000 life cycle. This study will be a good source for researchers and maritime sector stakeholders, whose studies regard Energy Storage Systems, especially batteries on the HPS in marine vessels.

KEY WORDS
~ Hybrid propulsion system
~ Battery
~ Marine vessels
~ Energy efficiency
~ TOPSIS
~ Marine engineering

a. Zonguldak Bülent Ecevit University, Maritime Faculty, Zonguldak, Turkey
e-mail: bayraktarmurat@beun.edu.tr
b. Dokuz Eylül University, Maritime Faculty, Izmir, Turkey
e-mail: mustafa.nuran@deu.edu.tr

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1. INTRODUCTION

In conventional propulsion systems, both two-stroke and four-stroke diesel engines patented by Rudolf Diesel (Woodyard, 2009) are widely used in the maritime industry. Two-stroke machines using petroleum-based fuels are generally used for ocean going vessel (Wankhede, 2016). The construction of oil tankers is an important issue as the demand for oil is still rising. Most technical demands, efficiency of operation and shortening of construction period, are met with designs to be made using existing ship data. A power estimation curve is created according to the DWT values, and this allows designer to make an easy choice (Pham et al., 2020). Two-stroke machines have a higher power-to-weight ratio. Due to this aspect, it becomes a profitable option especially for trade and cargo ships (Alturki, 2017). Although electricity is at a very important point in human life and in the operation of industrial establishments, it is even more significant that electricity production is obtained from renewable energy sources (Nguyen and Hoang, 2020). Electric propulsion systems perform reliable and efficient operations, especially in meeting international regulations on greenhouse gas emissions, reducing operational costs. In the HPS, conventional internal combustion engines work in combination with the electric motor using alternative energy sources such as battery power, solar, wind etc. (Nguyen et al., 2020). The power required for the ship's operation is met by a combination of different mechanical and electrical power sources in the HPS. In this way, the ship operates at optimum performance by transferring the right amount of power and torque to the propellers (MAN, 2014; ABB, 2021; Yaskawa Company, 2015; Wartsila, 2017; Wartsila, 2018).

It is significant to determine the ratio of electrical power to mechanical power obtained from the main engine. The electrical power output range should meet the important part of ship operations; otherwise, the installation may fail to meet its purposes. Therefore, the electrical/mechanical power balance forms the basis of efficiency output in the HPS (ABB, 2021). The HPS in marine vessels can be operated for different modes such as Power Take-Off (PTO), Boost Power Take-In (PTI), Power Take Home (PTH), PTO / PTI and Electrical Cross-Connection Mode. In addition, the HPS predicted that will have advantage on tugboats, ferries, merchant and also offshore construction serving vessels (MAN, 2014; Yaskawa Company, 2015; Wartsila 2017; Wartsila2018; Pham and Hoang, 2020).

In the PTO mode, the main engine provides the propulsion system by turning the propeller through the gearbox and provides electrical energy needed on board ship, together with the generators or main engine meeting the energy needs of the entire ship and serving as a power plant (MAN, 2014). Operating in this mode provides more efficient operational outputs instead of running additional generators to generate the electrical energy needed on ships (ABB, 2021).

In the Boost PTI mode, the electric motor and the main engine are combined to meet the load power demands of the ship's propulsion system. Generators both provide energy for the electric motor and provide the electricity requirement on the ship. Such systems are very suitable for ships that demand high power in a small period of their operation, especially for port tugboats. In this way, gains are obtained from the installation cost and fuel consumption of large-size machines. However, a larger energy storage systems are required for operation of the electric motor in poor design (MAN, 2014; Xiao et al., 2016; Dedes et al., 2012; Kwasieckyj, 2013; Yaskawa Company, 2015; ABB, 2021).

In the PTH mode, the main engine of the vessel does not operate and the propulsion system is provided by the electric motor (Xiao et al., 2016; Dedes et al., 2012; Kwasieckyj, 2013; ABB, 2021). This mode is particularly effective in meeting low power demands, entering and leaving ports, and emission control areas (ECAs). Thanks to this mode, the vessel will release SOX, NOX gases to the region at a minimum level and prevent noise pollution (Yaskawa Company, 2015; ABB, 2021). In addition, this mode is highly efficient if operations are performed at low speeds or without load (ABB, 2021). In the PTO/PTI mode maximum efficiency is achieved on both the propeller and the engine, also exhaust emissions are minimized (MAN, 2014).

In Electrical Cross-Connection Mode, one of the engines provides the sustainability of the propulsion system like the PTH mode and also meets the ship's electricity needed, like the PTO mode (MAN, 2014). Energy storage systems such as batteries can be used with frequency converters for electrical and the HPS. Efficient operations will be provided with the improvements to be achieved in the energy storage systems (ABB, 2021).

Electrical energy plays an important role in people's daily lives and this energy is used in mechanical energy conversion, heating and lighting. In batteries, energy is stored in chemical compounds, and in case of any discharge, a chemical reaction occurs, so energy is produced by drawing electric current at a certain voltage from the battery (Kiehne, 2003).

The batteries consist of five main components: anode and cathode electrodes, separators, electrolyte, negative and positive terminals, and case (Link et al., 2015; Dhameja, 2001). Battery cells are electrically connected in parallel and in series and form the battery pack that provides power to electronic drive systems (Dhameja, 2001). Batteries provide the opportunity to be operated in many fields, such as in electronic devices, space exploration, maritime sector and land vehicles (David & Thomas, 2001). The selection of the cells is of great importance for the efficiency of electric vehicles since the voltage and resistance of the cells depend on the chemical properties of the elements (Link et al., 2015).

In the selection of battery type, the electrochemical systems, voltage, amount of current drawn, operating temperature range, operational life, physical requirements, such as size, shape, weight, shelf life, charging efficiency, resistance to environmental conditions, such as vibration, pressure, humidity, safety and reliability degree, also maintenance service quality, purchasing and operating costs are quite noteworthy. Secondary (rechargeable) batteries are used in hybrid and electric vehicles (David & Thomas, 2001).

Most batteries are lead-acid, lithium-ion, nickel-cadmium, nickel-metal hydride, nickel-zinc, sodium sulfur and sodium / nickel-chloride. Lead-acid batteries were introduced in 1859 by the French chemist Gaston Plante (Enos, 2015). These batteries operate in wide temperature ranges: -650C to +650C in the storage and discharge state, -400C to +650C in the charging state; also they do not cause harmful chemical reactions during energy generation (David & Thomas, 2001; Crompton, 2000).

Although their energy density and specific density are low, their environmental friendliness, very reliable performance in variable temperature ranges, and low cost make these types of batteries stand out (David & Thomas, 2001).

As a result of deterioration of the active substance in the positive plates, formations such as shedding, sedimentation, and loss of adhesion occur in the battery. Short circuit formations in the battery system caused evaporation or gasification, causing water loss in the cells as the time progressed (Enos, 2015). Lithium-ion batteries for the first commercial applications were produced by Sony company in 1991. In this way, light, small, rechargeable and very powerful storage systems were created for mobile phones, computers and cameras (Bresser et al., 2015; Kiehne, 2003) In the lithium-ion battery types, LiCoO2, LiNiO2, LiMn2O4 and LiFePO4 are used as positive electrodes; also graphite or copper is used on the negative electrode side (Kiehne, 2003; Huang et al., 2018). Lithium-ion batteries do not require maintenance since they consist of sealed cells; they also have fast charging and discharging feature, long shelf life, and life cycles. Moreover, they can operate in wide temperature ranges and high energy efficiency, density and specific energy values (David & Thomas, 2001).

In order to minimize CO_2 emissions in the automotive sector, the use of lithium-ion battery technology comes forth in hybrid and electric vehicles. The main objectives expected from the battery technology are long driving distance, low weight, long life cycle, and reliability during operation (Perner & Vetter, 2015). Today, most electric vehicles use lithium-ion batteries (Cano et al., 2018). Toyota, one of the electric vehicle manufacturers, uses lithium-ion batteries in some models (Toyota, 2020). The battery loses its chemical properties and deteriorates at high temperatures, also when overcharged and crushed, which causes capacity loss and thermal leakage (David & Thomas, 2001). Serious amounts of lithium-ion batteries are needed, considering electric vehicles coming forth, so that recycling systems should be installed on lithium-ion batteries in order to prevent the increase of environmental pollution and waste of raw material resources (Huang et al., 2018). Nickel-cadmium batteries have a very robust structure as a mechanical part, and are suitable for operation at low temperatures; also, the operating life is quite long. The battery system is suitable for very low temperature applications, such as -60°C. These batteries pollute the soil, water, and air as a result of burning or leaving them in waste collection areas. Therefore, restrictions or prohibitions are imposed on the use of this type of batteries in various regions. To minimize environmental concerns, nickel-cadmium batteries that have completed the life cycle must be collected from the consumer and this creates additional costs (Huang & Du, 2015; Crompton, 2000; Assefi et al., 2018). Considering all these reasons, it becomes very difficult to compete with other battery types that have a share in the (Huang & Du, 2015; Crompton, 2000). Despite environmental concerns arising from its chemical structure, nickel-cadmium batteries are very effective from the point of high performance values, durability, low maintenance cost, and long life cycle (Huang & Du, 2015).

Nickel-metal hydrid batteries come to an important point for electric vehicles (David & Thomas, 2001). This type of battery is used in electric vehicles produced by automobile companies in the late 20th and early 21st centuries (Huang & Du, 2015). Ni-MH batteries are used in Toyota RAV4 “Flame” model (Toyota, 2020). Nickel-metal hydrid batteries do not contain flammable chemicals, can be operated at -30°C to -75°C temperatures and the cell structure is not complicated, so these situations highlight their use (Huang & Du, 2015). Recycling processes are applied to nickel, manganese, zinc, cobalt, and other elements that are produced as a result of the batteries completing their life cycle (Innocenzi et al., 2017). Historically, the beginning of production of nickel-zinc batteries patented by Michaelowski in Russia goes back to 1901. Although this type of battery was developed by the Irish scientist Drumm in 1930, its usage area is very low due to its short life cycle (Coates & Charkey, 2002; Kiehne, 2003). High-speed charging capacity, environmentally friendly energy source, abundant raw materials used in the system, and low maintenance costs highlight this battery type.

Sodium sulfur and sodium / nickel-chloride must be operated at 270°C to 350°C in order to ensure sufficient ionic conduction (Braithwaite & Auxer, 1995). Material strength, cost and safety problems arise since the batteries are operated at high temperatures and must be minimized to realize efficient operations (Lu & Yang, 2014). In addition to these batteries, the other ones have different chemical components such as zinc–bromine and metal/air batteries are used in various industries. Comparison of battery types is performed according to operating temperature range, life cycle, power and energy density, efficiency and cost. This comparison is detailed in Table 1.

Table 1.
Comparison of energy density, efficiency, cost, life cycle, and operating temperature range according to battery types (Hasankhani et al., 2014; Coates & Charkey, 2002; David & Thomas, 2001; Butler et al., 2001; Marongiu et al., 2010; Nikolaidis & Poullikkas, 2018; Konur, 2016; Amazon, 2020; Stevens et al., 1996; Lu et al., 2011; Kazempour et al., 2009).

Battery Types	Energy Density (Wh/kg)	Efficiency (%)	$/kW	Life Cycle	Operating Temperature Range (oC)
Lead Acid	25-50	50-90	150-600	200-2000	-15/45
Ni/Cd	35-75	60-90	280-1900	1,500-3,000	-40/70
Ni/Zn	50-100	~70	~3,000-6,000	~500	-40/50
NiMH	50-79	50-80	270-700	1,200-1,800	-40/70
Lithium Ion	100-425	80-100	125-4,000	3,000-10,000	-30/60
Lithium Iron Phosphate (LFP)	75-200	75-80	270-1200	1,600-5,000	-30/60
Zn/Br	65-85	68-75	700-2500	2,000-3,500	0/40
Metal (Zn etc.) Air	450-650	~50	100-250 (Zn/Air)	100-300	-20/50
NaS	120-240	70-92	1,000-2,250	1,500-5,000	275-360
NaNiCl	125	70	150-300	1,000	250-350

According to the values obtained in Table 1, the specific energy density of the lead-acid battery ranges from 25 to 50 Wh/kg, its efficiency from 50 % to 90 %, and also cost varies between 150 and 600 $/kW. The highest energy density per unit weight is obtained from lithium, sodium and metal / air based batteries. The energy efficiency of this type of batteries varies between 50 % and 92 % depending on the battery type. Evaluating in the way of life cycle, lithium-based batteries have the highest value. The robust structure of lead acid batteries comes into prominence between -15oC and 45oC operating temperature. The battery types with most disadvantages in the sense of cost are Ni/Zn and lithium-ion and their costs per unit power are 3,000-6,000 $/kW and 125-4,000 $/kW respectively. Moreover, Zn/Br and Ni/Cd type batteries are 700-2,500 $/kW and 280-1,900 $/kW respectively. Lead Acid, NiMH, Zn / Air and NaNiCl type batteries bring the lowest costs. Environmental and electrical conditions affect battery design and power generation from the battery. There is no single type of battery that performs optimally in all operating conditions. It is necessary to get maximum benefit from the selected battery, taking into account the operating conditions. In order to increase efficiency, different battery types are still being researched and the existing ones are still being developed (David & Thomas, 2001). The aim of this article is to select the most beneficial batteries in terms of capacity, weight, volume, energy, cost per unit energy and life cycle. In this context, the batteries in the market were researched; the technical properties of the suitable ones were obtained and analyzed by TOPSIS.

2. METHODOLOGY

In the HPS, batteries are used to drive the electric motor, meeting the high power requirements of the main engine, also providing the propulsion system at low load. Furthermore, batteries can be used to meet the energy demands of the electrical devices used. Technical and dimensional characteristics of 10 models of batteries, i.e. LFB, Lead Acid, Enhanced Flooded Battery (EFB) and Absorbed Glass Mat (AGM) with different capacities were obtained from the manufacturers to apply the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. In this method, calculations were made on numerical values by using objective rather than subjective decisions. By assigning different weights to the variables, results were obtained according to the desired importance points. The capacities (Ah), volumes (l), weights (kg), specific energies, costs, and life cycles of these battery types are described in detail in Table 2.

Table 2.
Capacities, volumes, weights, specific energies, costs and life cycles of batteries used for HPS (Banshee, 2021; Relion, 2021; Dakota Lithium, 2021; B. B. Battery, 2021; Yuasa, 2021; Odyssey, 2021; Amperetime, 2021; Victron Energy, 2021; Battery Megastore, 2021; Outbackmarine, 2021; Inutec, 2021).

Battery No (BN)	Battery T.	Capacity (Ah)	Volume (l)	Weight (kg)	Energy (Wh)	Energy Density (Wh/kg)	Cost ($/ kWh)	Life Cycle	Applications
1	LFP	200	30.5448	27.7	2560	92.4187726	987.871094	4000~13000	Electric V.
2	LFP	100	12.4872	14.5	1280	88.2758621	702.34375	80 % DOD 2000	Solar Energy S.
3	SLA (AGM)	50	5.558355	16.5	600	36.3636364	295.316667	50 % DOD 700	Marine, Electric V.
4	EFB	100	11.73725	24	1200	50	137.9885	200	Caravans, motorhomes
5	LFP	300	40.40815	51	3840	75.2941176	867.28125	80 % DOD 2500	Off-grid solar and wind
6	LFP	100	12.5535746	10.97693	1280	116.608196	687.492188	100 % DOD 1200	RV Camper
7	AGM	74	17.925622	26.3	888	33.7642586	461.182432	650	Robotic Systems
8	LFP	300	26.8814299	31.29787	3840	122.692055	338.539063	4000+	RV, Solar
9	LFP	160	11.5637	20	2048	102.4	1062.56631	80 % DOD 2500	Off-grid solar and wind
10	LFP	330	19.59781	30	4224	140.8	1332.4929	80 % DOD 2500	Off-grid solar and wind

The analysis was performed on the basis of the mathematical formulas used in the TOPSIS method in order to choose the best battery for the HPS. Each parameter described in Table 2 is used as data in the analysis. Firstly, the normalization of the matrix formed as a result of Table 2 data.

$$x_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{1}$$

The weight values of each parameter were specified from 1 to 10, considering expert opinions of marine engineers. The weight values (w_j) and effects of each parameter are expressed in detail with their reasons in Table 3.

The weight values of each parameter are multiplied by the normalized matrix.

$$v_{ij} = x_{ij} \cdot w_j \tag{2}$$

By considering the matrix obtained by multiplying the weighted values with the normalized matrix, v^+,v^- is formed by reference to the best and worst values for each parameter in this matrix. Mathematical process is performed to calculate S_i^+, S_i^- values on the matrix to select the best and worst batteries to use for the HPS.

$$S_i^+ = [\textstyle\sum_{j=i}^{n} (v_{ij} - v_j^+)^2]^{0.5} \tag{3}$$

$$S_i^- = [\textstyle\sum^{n} (v_{ij} - v_j^-)^2]^{0.5} \tag{4}$$

Table 3.
The weight values and effects of each parameters.

Parameters	Effect	w_j
Capacity (Ah)	The high battery capacity reduces the number of batteries and minimizes the connection complexity to be used for HPS.	6
Volume (liter)	Volume increase due to the battery will create an area restriction on the marine vessel to be applied HPS.	6.9
Weight (kg)	The weight increase due to the battery increases the displacement tonnage. Therefore, the draft value of the ship increases and causes additional resistance.	5.9
Energy (Wh)	The high energy drawn from the batteries increases the applicability of HPS.	7.3
Cost ($/kWh)	The high cost of batteries creates a significant obstacle for ship owners to use the HPS system on their marine fleets.	8.6
Life Cycle	The long life cycle of the batteries increases the reliability and maintainability of the HPS systems.	7.7

The most appropriate battery is selected by using the S_i^+, S_i^- values obtained for each battery, and then performing the ranking of other batteries' "P_i" respectively.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{5}$$

The analysis was carried out based on the mathematical formula and the specified weight value. The detailed data are explained in the Results and Discussion section.

3. RESULTS AND DISCUSSION

In this section, the results of the analysis of battery types were examined and assessments were carried out. All the data required for the analysis were obtained from the catalog data of the batteries. Data were adapted to the framework required for the analysis, i.e. primarily, w_j, v_j^+, v_j^- values of capacity, volume, weight, energy, cost and life cycle were obtained for each battery, and the most prominent values are described in Table 4 with the battery number.

Table 4.
w_j,v_j^+ and v_j^- values obtained from battery analysis.

	w_j	v_j^+	v_j^-
Capacity (Ah)	0.141892	0.074742043 (BN 10)	0.011324552 (BN 3)
Volume (liter)	0.162162	0.013275739 (BN 3)	0.096512014 (BN 5)
Weight (kg)	0.138514	0.017535033 (BN 6)	0.081469652 (BN 5)
Energy (Wh)	0.172297	0.091010932 (BN 10)	0.012927689
(BN 3)			
Cost ($/kWh)	0.202703	0.023348174 (BN 7)	0.097363987
(BN 10)			
Life Cycle	0.182432	0.14562261 (BN 1)	0.003426414 (BN 4)

Evaluating Table 4, the highest weight value (wj) is the Cost with 0.202703 since cost is one of the most prominent factors in the maritime sector applications. No matter how efficient and reliable the developed system is, the excessive cost creates a major obstacle in practice. In the analysis, the Life Cycle is the second largest weight with 0.182432 because it is only applicable for the HPS when batteries provide high life cycle. Other weight values are 0.172297 (Energy), 0.162162 (Volume), 0.141892 (Capacity) and 0.138514 (Weight) respectively. Battery No. (BN) 10 has the highest v_j^+ values; these are 0.074742043 and 0.091010932 with regard to capacity and energy respectively. On the other hand, the lowest v_j^- values are in BN 3 with 0.011324552 and 0.012927689 in view of capacity and energy that are very low values compared to the highest one. Considering the smaller volume or weight the more effective, the highest one is BN 3 and BN 6 with 0.013275739 and 0.017535033 v_j^+ values respectively. BN 10, which has the highest value in the sense of capacity, has the lowest value in the way of cost. BN 5 has the worst volume and weight value that is 0.096512014 and 0.081469652. Moreover, BN 7 has the highest v_j^+ value in the sense of cost, i.e. 0.023348174. Lastly, evaluating in the sense of life cycle, BN 1 has the highest v_j^+ value, i.e. 0.14562261, while BN 4 has the lowest one with 0.003426414 value.

Table 5.
S_i^+, S_i^- and P_i values obtained from battery analysis.

No	S_i^+	S_i^-	P_i	Rank
1	0.089847778	0.161916682	0.643127638	1
2	0.144445308	0.102273787	0.414535352	6
3	0.167501831	0.123508925	0.42441361	5
4	0.16719842	0.10386226	0.383169776	8
5	0.150071818	0.108092753	0.418697082	7
6	0.161056697	0.097108032	0.376147556	9
7	0.167590816	0.100230444	0.374243791	10
8	0.116134231	0.120452851	0.509126915	2
9	0.130050306	0.105120784	0.446997052	4
10	0.134508305	0.123560812	0.47878961	3

The most suitable batteries for HPS are BN 1, 8 and 10, which have Pi values 0.643127638, 0.509126915, and 0.47878961 respectively, although these batteries do not have the best values in any parameter analysis. BN 1 is a lithium-iron-phosphate (LFB) battery that has 200 Ah capacity, 30.55 liter volume, 27.7 kg weight, 92.418 Wh/kg energy density, and 4,000~13,000 life cycle. Based on the results of the analysis on 10 batteries, the LFB batteries are the highest, followed by lead-acid, Enhanced Flooded Battery (EFB), and Absorbed Glass Mat (AGM).

4. CONCLUSION

The International Maritime Organization aims to increase the energy efficiency and reduce the amount of emissions from marine vessels. The installation of the HPS system on marine vessels comes forth for this purpose. Energy storage systems are used to drive the electric motors in the HPS system and to meet the existing energy needs on marine vessels. Batteries are one of the energy storage systems and in this study, they are analyzed by TOPSIS method. There are six parameters used in this method, including capacity, volume, weight, energy, cost, and life cycle. Based on these parameters, the LFP batteries are above the others. It is seen that those of the lithium-iron-phosphate type have high capacity and energy density, long life cycle, low weight and volume. On the contrary, the LFB batteries lose almost half of their capacity at low temperatures. Examining the technical data, costs per unit of energy are also higher than with other battery types. This study will be a good source for researchers and maritime sector stakeholders, whose studies are concentrated on energy storage systems, especially batteries.

CONFLICT OF 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.

NOMENCLATURE/ABBREVIATION

AGM	Absorbent Glass Mat
ECAs	Emission Control Areas
EFB	Enhanced Flooded Battery
ESSs	Energy Storage Systems
HPS	Hybrid Propulsion System
IMO	International Maritime Organization
LFB	Lithium Iron Phosphate
MARPOL	International Convention for the Prevention of Pollution from Ships
PTH	Power Take Home
PTI	Power Take in
PTO	Power Take Off
RV	Recreational Vehicles
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

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