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Research Article

# Determination of optimum insulation thickness in submarines

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## ABSTRACT

One of the most effective ways to save energy for cooling and heating applications is thermal insulation. Because of this, determining the ideal insulation thickness is a popular topic for publications. The purpose of this study is to determine the appropriate insulation thickness needed for a submarine's external construction while it is cruising in various locations. Since seawater makes up a submarine's external environment, situations involving five distinct seawater temperatures from around the globe have been studied. There are five of them: the Mediterranean, Marmara, Aegean, Black Sea, and Sakhalin, which is in the North Pacific Ocean and has the coldest seawater on earth. By using the idea of degree-days, the annual cooling and heating needs of submarines in various regions have been computed. Based on life cycle cost analysis, optimization has been accomplished. In the beginning, the results of a study published in the literature supported the calculation methods utilized. The use of insulation materials such as rock wool, glass wool, polyurethane, expanded polystyrene, fiberglass, and foam glass, as well as fuel oil to run the generator, has been taken into account in a number of calculations, including the best insulation thickness, annual savings value, annual energy cost, and payback period. The findings indicate that depending on seawater temperatures and insulation materials, the ideal insulation thicknesses range between 2 and 12 cm, energy savings between 8.5% and 90%, and payback periods between 1.1 and 10 years.

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## INTRODUCTION

Fossil fuels account for more than 60% of the world's energy, which contributes to global warming. In order to protect the future and leave cleaner air for future generations, countries should lessen their adverse effects by restricting their consumption of fossil fuels with required rules on the use of insulating materials. Because of this, using insulating materials is becoming increasingly important. Heat loss is decreased with the use of insulation materials, which means

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the required energy lessens with insulation. The amount of fossil fuels consumed and greenhouse gas emissions that contribute to wintertime global warming are decreased as a result of the energy savings made. Additionally, it's anticipated that refrigerants—which contribute to the ozone layer's depletion—will be used less frequently in air conditioners throughout the summer.

Since the world population is growing rapidly, there are less available energy supplies, which lead to increased energy usage. The necessity of thermal insulation cannot be overstated in order to minimize the amount of energy needed to heat and cool living spaces. Various types of thermal insulation materials are needed for many home and industrial systems. For instance, the four main categories of thermal insulation products currently on the market are inorganic, organic, mixed, and innovative materials made in a variety of ways, such as rigid, porous, natural shape, and reflecting structure [1]. 60% of the market is made up of inorganic materials (such as glass wool and rock wool), while 27% is made up of organic materials. Due to their low heat conductivity and low cost, traditional thermal insulation materials including polyurethane, poly-isocyanurate, extruded polystyrene, and expanded polystyrene are preferred in many buildings and thermal energy storage systems [2]. The relevant studies in the literature are outlined in chronological sequence below. The studied in the literature are focused on structures and buildings, and for the best of authors' knowledge the current study is the first attempt that identifies the ideal insulation thickness for submarines.

Based on life cycle cost analysis, Comakli K. and Yüksel B. [3] determined the ideal thickness of insulation materials used in buildings for Turkey's coldest cities, Erzurum, Erzincan, and Kars (LCCA). According to the studies, the ideal insulation thickness, annual gain, and payback periods for Erzurum, Kars, and Erzincan were 0.1048 m, 12.1378 $/m^2$, 1.457 years, 0.10737 m, 12.7207 $/m^2$, and 1.446 years, respectively, and 0.0852 m, 7.9924 $/m^2$, 1,576 years. Using the life cycle cost analysis method again, Bolattürk A. [4] chose 16 different cities from four distinct climatic areas in Turkey and determined the ideal insulation thickness for buildings. The impact of various energy sources on the insulation thickness was examined using solely polystyrene as the insulation material and coal, natural gas, gasoline, liquefied petroleum gas (LPG), and electricity as the energy source. According to the estimates, depending on the city and fuel type, the ideal insulating thickness was between 2 and 17 cm, and the payback period ranges between 1.3 and 4.5 years. The environmental consequences of the ideal insulation thickness on outside walls for Denizli, Turkey, were examined by Dombayci O. A. [5]. The thermal insulation of buildings during the heating season is said to be crucial for lesser energy use and lowering emissions. The calculations employed expanded polystyrene as the insulating material and coal as the fuel source. It has been found that using the right amount of insulation reduces energy use by 46.6% and $CO_2$ and $SO_2$ emissions by 41.53%. The goal of Ekici B. B. et al. [6] was to determine the ideal insulation thicknesses for various wall types, including those commonly utilized in Turkish building construction, such as stone, brick, and concrete. The best option for each of the four regions—Antalya (first region), Istanbul (second region), Elazig (third region), and Kayseri (fourth region), as assessed by the Turkish Thermal Insulation Standard (TS 825), were picked. Calculations were made for insulation thicknesses, energy savings, and payback times. As insulation materials, glass fiber, expanded polystyrene, and polyurethane were chosen. Five distinct fuels were used in the calculations: coal, LPG, electricity, fuel oil, and natural gas. The findings revealed that the ideal insulation thickness varies from 0.2 to 18.6 cm, and energy savings range from 0.038 to 250.415 dollars per square foot. The payback times ranged from 0.714 to 9.104 years depending on the city, wall type, insulation material, and fuel cost. Wati E. et al.'s [7] goal was to optimize the insulation layer thicknesses on a building's outside walls for a tropical location based on the amount of shadow. The insulation used was expanded polystyrene, and it was expected that the construction site's shade level ranged from 0% to 97% with an increase of 25% or 2%. For south, north, and east/west oriented walls, it was found that as the amount of shadow rose, the ideal insulation thickness fell by an average of 0.035 cm, 0.029 cm, and 0.036 cm per percent of solar radiation blocked. Based on the shadow level and wall orientation, the results showed that energy savings ranged from \$46.89/$m^2$ to \$101.29/$m^2$ and payback times ranged from 3.56 years to 4.97 years. Different approaches were utilized by Açikkalp E. and Kandemir S. Y. [8] to establish the ideal insulating thickness for structures. They have calculated using the environmental approach method, the economic approach method, and the environmental and economic approach methods, which are taken into consideration jointly, in accordance with the meteorological conditions in Bilecik. These calculations revealed that the ideal insulation thicknesses for glass wool were 0.185 m, 0.140 m, 0.467 m and rock wool, were 0.176 m, 0.133 m, and 0.227 m. In order to calculate by taking into account all climatic zones in Iran, Rosti B. et al. [9] performed a study to identify the ideal insulation thickness, payback period, and energy savings for exterior walls of buildings in eight different distinct. When the optimal value determined by the life cycle cost analysis calculations was compared to the optimal values determined for other countries, it was discovered that Iran's optimum insulating thickness value was substantially lower. This was attributed to the nation's economic structure and the relatively inexpensive cost of energy consumed. As a result, they emphasized the importance of the economic opportunities of the countries when determining the ideal insulating thickness.

Thermal insulation helps to save energy by reducing fuel consumption, which lowers $CO_2$ emissions and lowers the cost of construction and maintenance of the buildings. Additionally, the insulation stops formation of the potentially dangerous substances like mold and fungus. Due to the rising relevance of thermal comfort conditions and the diminishing energy resources, thermal insulation is becoming more and more crucial on a daily basis. A study on the thermal insulation of maritime vehicles has not been included in the literature when the studies on thermal insulation are evaluated. All of the studies have concentrated on the thermal insulation of buildings. This study's goal is to address the ideal insulation configuration for a submarine, which is essential for all climate conditions and throughout the annual thermal fluctuations of the deep water conditions.

Submarines are marine vehicles with an incredible technological infrastructure that can move under water and on it [10]. They were originally designed to explore the bottom of the sea, to investigate living life. Later, it gained importance in the military field and the safety of the seas in wars. Submarines navigate invisibly under the sea for months. For this reason, in order to ensure the internal air balance for the people inside and also to prevent excessive energy use, the exteriors of submarines should be in the appropriate insulation material types and thicknesses according to the region where they will cruise.

The best insulation thickness for pipes, buildings, and other structures has been the subject of numerous studies in the literature. However, a similar study hasn't been conducted on submarines. This study aims to fill this gap. The optimal insulation thickness, annual gain amount, annual insulated energy cost, and payback periods for submarines were estimated for this purpose after the calculation methodology was validated using the findings of the studies available in the literature.

## MATERIALS AND METHODS

### Climatic Features

Life cycle cost analysis is used to evaluate design alternatives – property cost – all economic decisions after the evaluation of design alternatives for the determination of the optimum design – all or component of a building can be applied to any building. The critical aspect of the LCCA is the determination of the evaluation period during which the building or its parts are expected to continue to operate [11]. The Degree Days (DD) approach is one of the most popular ways to determine how much energy is needed to meet a space's heating and cooling needs. A "degree day method" is a unit of measure for recording how hot or how cold it is over a 24-hour period. Calculations are made separately for the heating degree days and the cooling degree days. The average temperature values to be used in the calculations can be daily, weekly or monthly depending on the time period of the calculation to be made. For example, heating degree days applied to calculate the need for heating on any day of the week is determined by finding the average temperature for that day, and then comparing the average temperature with a base value of 24 °C for heating. If the average temperature is lower than the base value, it is concluded that there is as much heating need as the difference. The base temperature is 18 °C for cooling degree day. So all calculation steps are the same with heating degree days but at the end the comparison should be with 18 °C. If the average temperature is lower than the base value, there is no need for cooling, if it is high, it is understood that the need for cooling is as much as the difference. In this study CD is used for Cooling Days and HD is for Heating Days. In order to determine the DD value, a certain equilibrium temperature is used, $T_b$. The temperature at which the heat sources inside the structure (people, lighting, solar radiation, etc.) and the heat losses from the structure are equal is referred to as equilibrium temperature. As a result, the estimation of the DD value is influenced by a variety of elements, including the structural characteristics of the structure (wall type, insulation status, air leaks, and solar radiation status), meteorological circumstances, and the individual preferences of the users [12]. $T_b$ was determined in this study to be 18 °C for summer conditions and 24 °C for winter conditions, respectively [13].

$$\mathrm{HD} = \sum_{\mathrm{day}}(\mathrm{T_b} - \mathrm{T_m}) \qquad (\mathrm{T_m} > \mathrm{T_b}) \tag{1}$$

where $T_m$ is the average outdoor temperature. If $T_m < T_b$ then $HD = 0$.

$$\mathrm{CD} = \sum_{\mathrm{day}}(\mathrm{T_m} - \mathrm{T_b}) \qquad (\mathrm{T_m} > \mathrm{T_b}) \tag{2}$$

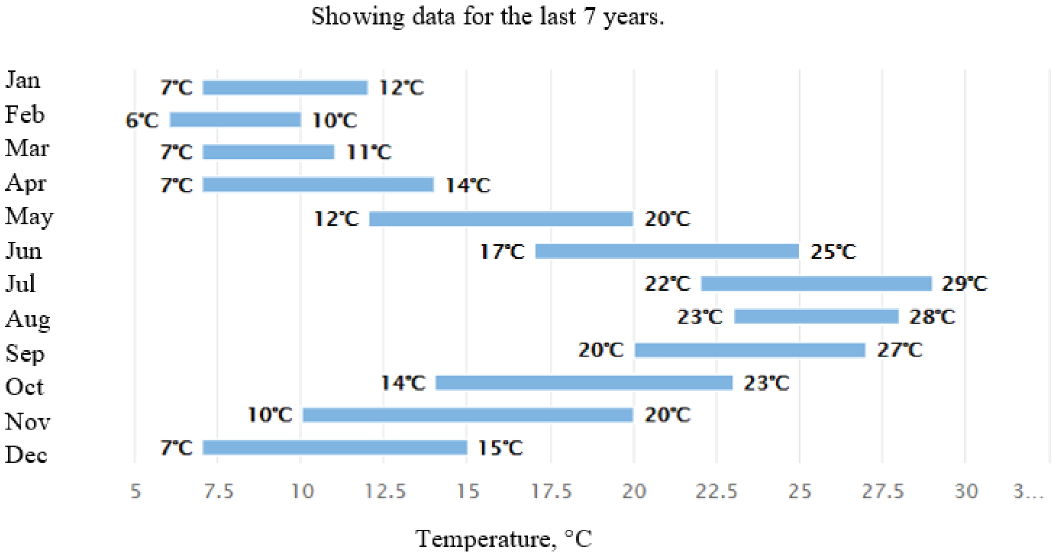
If $T_m < T_b$ then $CD = 0$.

Submarines should compute their average outside temperatures based on the seawater temperature of the area where they will be stationed. In this study, Figure 1 shows the average temperatures for the Marmara, Black Sea, Aegean, Mediterranean, and Pacific Oceans.

The table contains values for each month as intervals, and the computations use the average of these numbers. For instance, the computations used 9.5 °C as opposed to the numbers reported between 7 and 12 °C for January in the Marmara Region. Table 1 contains the HD and CD values for the regions used in the calculations. It should be noted that the Pacific Ocean's CD value was determined to be zero ($T_m < T_b$). This indicates that no insulation calculation because no cooling process is required. Thus only ideal insulation thickness value is needed, which is for the heating system.

### Wall Structure

The non- insulated submarine's structure, which will be used in the calculations, consists of an outer layer of 2 cm steel and an inner layer of 1 cm aluminum. In the calculations the value of the water has been considered because water has a higher heat transmission coefficient than air. The regions and corresponding HD and CD values are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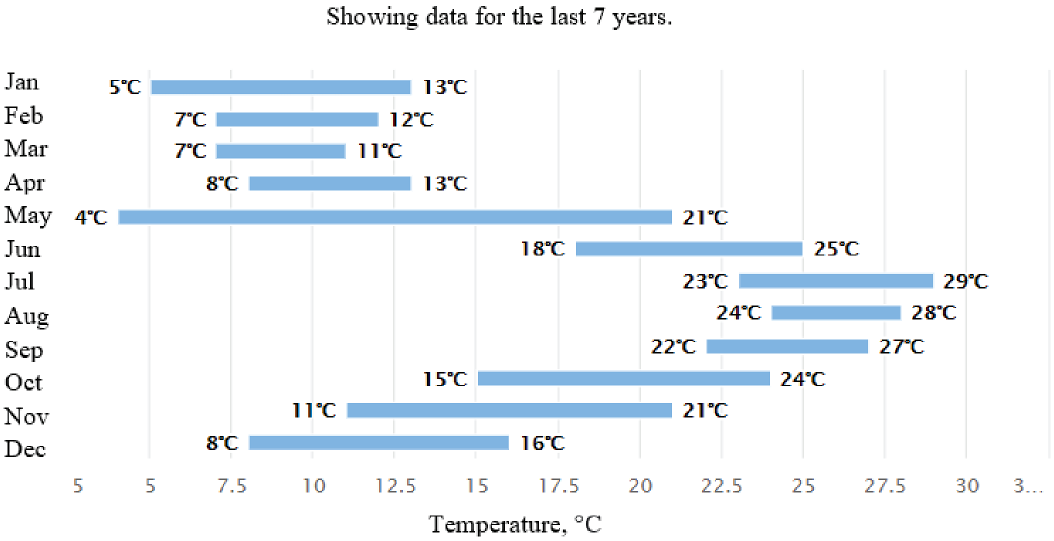
Temperature, °C

(a)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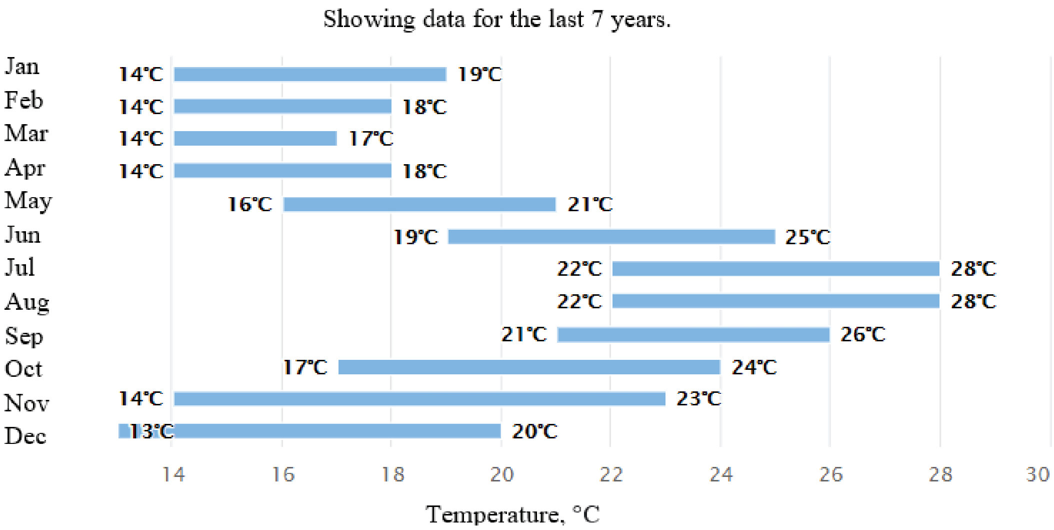
Temperature, °C

(b)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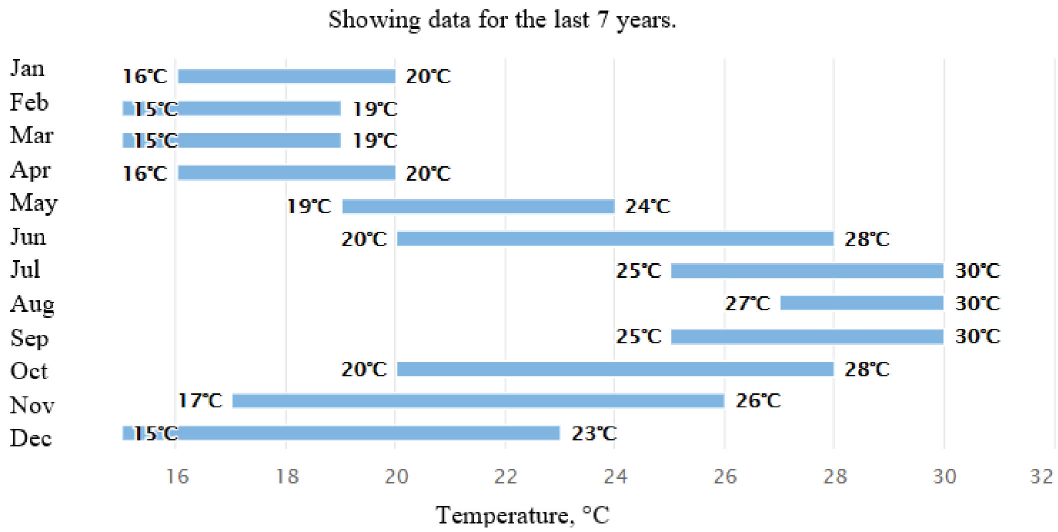
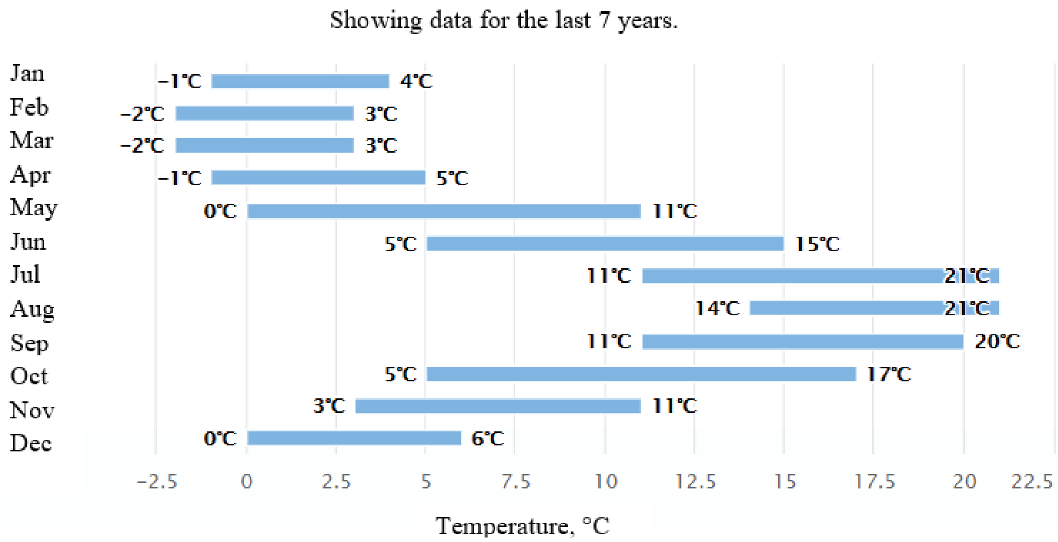
13℃ 20℃
14 16 18 20 22 24 26 28 30
Temperature, °C

(c)




(d)




(e)

**Figure 1.** Variation of annual average water temperature values by months, (a) Marmara, (b) Black Sea, (c) Aegean, (d) Mediterranean, (e) Pacific Ocean, [14]

listed in Table 1 and the submarine wall structure details are given in Table 2 [15].

In this study glass wool, rock wool, polyurethane, expanded polystyrene, glass fiber, and glass foam are used as insulation materials and the Table 3 [16] provides information on the cost and thermal conductivity values of insulating materials.

Total heat transfer coefficient U for a typical wall with an insulating layer,

**Table 1.** The number of days of heating and cooling degrees by region

| Region | HD | CD |
|---|---|---|
| Marmara | 1410 | 345 |
| Aegean | 285 | 345 |
| Mediterranean | 60 | 795 |
| Black Sea | 1410 | 450 |
| Pacific Ocean | 3780 | 0 |

**Table 2.** Details of submarine wall structure

| Material | Thickness x (cm) | Thermal conductivity k (W/m.K) |
|---|---|---|
| Steel | 2 | 0,78 |
| Vacuum | 1 | 0,65 |
| Steel | 1,5 | 0,78 |
| Aluminum | 1 | 117 |

**Table 3.** Specifications of insulating materials

| Insulation Material | k (W/mK) | Price ($/m³) |
|---|---|---|
| Expanded Polystyrene | 0,038 | 154,6 |
| Polyurethane | 0,028 | 346,1 |
| Rock wool | 0,04 | 132 |
| Glass wool | 0,032 | 102 |
| Glass fiber | 0,042 | 75 |
| Glass Foam | 0,036 | 710 |

$$U = \frac{1}{R_i + R_w + R_{insulation} + R_o} \quad (3)$$

Here, $R_i$ and $R_0$ are the heat transfer resistances for indoor and outdoor environments, $R_w$ is the total thermal resistance of non-insulated wall materials, and $R_{insulation}$ is the thermal resistance of the insulation layer.

$$R_{insulation} = \frac{x}{k} \quad (4)$$

where $x$ and $k$ are the thickness and thermal conductivity of the insulation material, respectively. If the sum of the remaining resistances in Eq.3, excluding the insulation resistance, is expressed as $R_{w,t}$, the total heat transfer coefficient U can be written as follows.

$$U = \frac{1}{R_{w,t} + R_{insulation}} \quad (5)$$

According to TS 825, the $R_i$ value is taken as 0.13 m²K/W. Since the external environment of submarines is water, the heat transfer resistance calculation of the external environment is found as follows [17].

$$h = 10886{,}8 + 61{,}2888 \, . \, T_m \quad (6)$$

$$R_o = {}^{1}\!/_{h} \quad (7)$$

The total thermal resistance of the non-insulated wall is calculated as follows.

$$R_{w,t} = R_i + \frac{x_1}{k1} + \frac{x2}{k2} + \frac{x3}{k3} + \frac{x4}{k4} + R_O \quad (8)$$

The outside temperature (sea water) on this particular day is $T_m$. All months and the examined regions, the Marmara, Aegean, Mediterranean, Black Sea, and Pacific Ocean, were used in the $R_0$ calculation. The averages are obtained from the table below and computations are made using just one value because the results were quite small and closely spaced. Table 4 displays the computation of the external environment's heat transfer resistance for all areas and months. Table 4 includes six months values for Black Sea region, other calculations can be perform with same process for all region and months. Table 5 accounts for the mean values from Table 4 for all region and 12 months.

### Heating Load for The Wall

#### Annual energy requirements

$$\text{Annual energy requirement for heating} = \frac{86400 \ HD \ U}{\eta} \quad (9)$$

here η is the efficiency of the heating system.

$$\text{Annual energy requirement for cooling} = \frac{86400 \ CD \ U}{COP} \quad (10)$$

here COP is the coefficient of performance of the cooling system.

**Table 4.** Average convective heat transfer coefficient considered for calculation procedure

| Region | $R_O$ ve $R_{w,t}$ (m²K/W) |
|---|---|
| Black Sea | 0,000084 |
| Marmara | 0,000084 |
| Mediterranean | 0,000082 |
| Aegean | 0,000083 |
| Pacific Ocean | 0,000088 |
| $R_o$ | 0,0000842 |
| $R_{w,t}$ | 0,1904 |

**Table 3.** 6 months external surface thermal resistances ($R_o$) for Black Sea region

| Black Sea | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Jan | T | 9 | Feb | T | 9,5 | March | T | 9 |
| | h | 11438,4 | | h | 11469,04 | | h | 11438,4 |
| | $R_o$ | 0,0000874 | | $R_o$ | 0,0000872 | | $R_o$ | 0,0000874 |
| Apr | T | 10,5 | May | T | 13 | June | T | 22,5 |
| | h | 11530,33 | | h | 11683,55 | | h | 12265,8 |
| | $R_o$ | 0,0000867 | | $R_o$ | 0,0000856 | | $R_o$ | 0,0000815 |

### Annual energy consumption

$$\text{Annual energy consumption for heating}=\frac{86400\ \text{HD}}{\left(R_{w,t}+\frac{x}{k}\right)\text{LHV}\ \eta} \quad (11)$$

Here, $x/k$ expression is the thickness and heat transmission coefficient values of the insulation to be used in the building. LHV refers to the lower calorific value of the fuel, and LHV is usually expressed in units of J/kg, J.m$^3$ or J/kWh, depending on the type of fuel.

$$\text{Annual energy consumption for cooling}=\frac{86400\ \text{CD}}{\left(R_{w,t}+\frac{x}{k}\right)\text{COP}} \quad (12)$$

### Calculation of the Optimum Insulation Thickness

### Annual energy cost

Annual heating cost in insulated condition for heating

$$=\frac{86400\ \text{HD}\ C_{fuel}\ \text{PWF}}{\left(R_{w,t}+\frac{x}{k}\right)\text{LHV}\ \eta} \quad (13)$$

Here, $C_{fuel}$ is the fuel cost, which can be expressed in units of \$/kg, \$/m$^3$ or \$/kWh, depending on the fuel type. PWF is the present value factor.

$$\text{Annual heating cost without insulation}=\frac{86400\ \text{HD}\ C_{fuel}\ \text{PWF}}{(R_{w,t})\ \text{LHV}\ \eta} \quad (14)$$

Annual cooling cost in the insulated condition for cooling

$$=\frac{86400\ \text{CD}\ C_{fuel}\ \text{PWF}}{\left(R_{w,t}+\frac{x}{k}\right)\text{COP}\ (3{,}6\text{x}10^6)} \quad (15)$$

$$\text{Annual cooling cost in uninsulated condition}=\frac{86400\ \text{CD}\ C_{fuel}\ \text{PWF}}{(R_{w,t})\ \text{COP}\ (3{,}6\text{x}10^6)} \quad (16)$$

### Total annual cost

Total annual cost for heating in the insulated condition

$$=\frac{86400\ \text{HD}\ C_{fuel}\ \text{PWF}}{\left(R_{w,t}+\frac{x}{k}\right)\text{LHV}\ \eta}+C_{insulation}.x \quad (17)$$

$C_{insulation}$ is the price of the insulation material and its unit is \$/m$^3$, and $x$ is the optimum insulation thickness found in the calculations.

Total annual cost in the insulated condition for cooling

$$=\frac{86400\ \text{CD}\ C_{fuel}\ \text{PWF}}{\left(R_{w,t}+\frac{x}{k}\right)\text{COP}\ (3{,}6\text{x}10^6)}+C_{insulation}.x \quad (18)$$

### Amount of annual earnings

Annual earnings for heating

$$=\frac{86400\ \text{HD}\ C_{fuel}\ \text{PWF}}{(R_{w,t})\text{LHV}\ \eta}-\left(\frac{86400\ \text{HD}\ C_{fuel}\ \text{PWF}}{(R_{w,t}+\frac{x}{k})}+C_{insulation}.x\right) \quad (19)$$

Annual earnings for cooling

$$=\frac{86400\ \text{CD}\ C_{fuel}\ \text{PWF}}{(R_{w,t})\ \text{COP}\ (3{,}6\text{x}10^6)}-\left(\frac{86400\ \text{CD}\ C_{fuel}\ \text{PWF}}{\left(R_{w,t}+\frac{x}{k}\right)\text{COP}\ (3{,}6\text{x}10^6)}+C_{insulation}.x\right) \quad (20)$$

### Payback period

$$\text{Pay back}=\frac{\text{Energy Cost in the Isolated Case}}{\text{Annual Earnings}} \quad (21)$$

### Optimum insulation thickness

The insulation thickness (x) value, which minimizes the costs, gives the most appropriate insulation thickness ($x_{opt}$).

$$\text{For the heating } x_{opt}=293.94\sqrt{\frac{\text{HD}\ C_{fuel}\ k\ \text{PWF}}{\text{LHV}\ C_{insulation}\ \eta}}-k.R_{w,t} \quad (22)$$

$$\text{For the cooling } x_{opt}=293.94\sqrt{\frac{\text{CD}\ C_{fuel}\ k\ \text{PWF}}{C_{insulation}\ \text{COP}\ (3{,}6\text{x}10^6)}}-k.R_{w,t} \quad (23)$$

### PWF Calculation

The overall cost of heating over the submarine's useful life is calculated using the life cycle cost analysis utilized in this study. By multiplying the overall heating cost by the present value factor throughout the course of the N-year lifespan, the whole cost is converted to present value. The following formula is used to determine the PWF value, which includes the interest rate "i" and the inflation rate "g" [4].

$$\text{If } i>g \text{ then } r=\frac{i-g}{1+g} \quad (24)$$

$$\text{If } i<g \text{ then } r=\frac{g-i}{1+i} \quad (25)$$

$$\text{PWF}=\frac{(1+r)^N-1}{r\,(1+r)^N} \quad (26)$$

Here N is assumed to be 10 years.

$$\text{If } i=g \text{ then PWF}=\frac{N}{1+i} \quad (27)$$

Table 6 [18–19] displays the PWF value as estimates using inflation and interest rates. Diesel engines are the submarine's primary power source. Diesel engines power the electric motor, charge the batteries, and keep the submarine in contact with the surface while they are running. The characteristics of the fuel of diesel engines are listed in Table 7 [20] and COP=2.5 for the cooling system.

**Table 5.** Calculation of PWF

| N | 10 |
|---|---|
| Inflation | % 12 |
| Interest rate | % 20 |
| PWF | 6,98 |

**Table 6.** Fuel characteristics

| Fuel | Price (\$/kg) | LHV | η (%) | COP |
|---|---|---|---|---|
| Diesel | 0,754 | 40483000 | 0,8 | 2,5 |

**Verification of the Accounting Methodology**

The study of Bollaturk et al. [4] is chosen as the benchmark work from the literature. The same model from the literature was taken into consideration in order to verify the findings before applying it to a submarine that is intended to operate in diverse seas. The average difference between the data from the literature and the calculations used in this study, it was determined, was less than 0.05%.

## RESULTS AND DISCUSSIONS

In this study, numerous insulation materials for submarines traveling in areas including the Marmara, Black Sea, Aegean, Mediterranean, and Pacific Ocean were examined in order to determine the ideal insulation thickness. The DD technique was used to compute the total yearly energy consumption, and life cycle cost analysis was applied to determine the ideal insulation thickness. Heating and cooling requirements are met using diesel fuel. The previous section contains the formulas and parameters needed to do the computations.

Table 8 lists the results of calculations made using different insulating materials during the heating season in each region. The thickness of this insulation material was not specified because the calculations for the glass foam

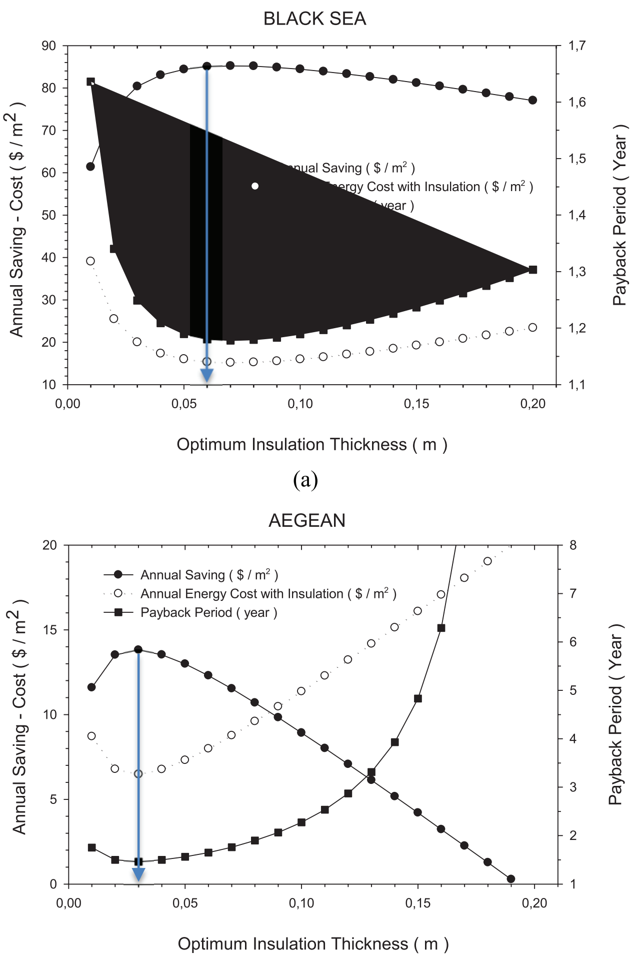
**Table 8.** Optimum insulation thickness, annual savings and payback periods of different regions during the heating period for (a) glass wool, (b) rock wool, (c) polyurethane, (d) expanded polystyrene, (e) glass fiber, (f) glass foam

| REGION | | BALCKSEA - MARMARA | AEGEAN | MEDITERRENIAN | PACIFIC OCEAN |
|---|---|---|---|---|---|
| (a) | | | | | |
| Glass wool | Optimum insulation thickness (m) | 0,071 | 0,029 | 0,001 | 0,12 |
| | Annual earnings ($/m$^2$) | 85,21 | 13,81 | 1,63 | 243,89 |
| | Annual earnings (%) | 84,88 | 68,06 | 38,26 | 90,62 |
| | Payback period (year) | 1,18 | 1,47 | 2,61 | 1,1 |
| (b) | | | | | |
| Rock wool | Optimum insulation thickness (m) | 0,068 | 0,027 | 0,008 | 0,12 |
| | Annual earnings ($/m$^2$) | 81,3 | 12,26 | 1,13 | 237,24 |
| | Annual earnings (%) | 80,99 | 60,44 | 26,51 | 88,15 |
| | Payback period (year) | 1,23 | 1,65 | 3,77 | 1,13 |
| (c) | | | | | |
| Polyurethane | Optimum insulation thickness (m) | 0,034 | 0,013 | 0,003 | 0,06 |
| | Annual earnings ($/m$^2$) | 75,01 | 9,9 | 0,5 | 226,41 |
| | Annual earnings (%) | 74,72 | 48,78 | 11,75 | 84,12 |
| | Payback period (year) | 1,34 | 2,05 | 8,51 | 1,19 |
| (d) | | | | | |
| Expand. polystyrene | Optimum insulation thickness (m) | 0,061 | 0,024 | 0,007 | 0,11 |
| | Annual earnings ($/m$^2$) | 80,31 | 11,88 | 1,02 | 235,55 |
| | Annual earnings (%) | 80 | 58,55 | 23,84 | 87,52 |
| | Payback period (year) | 1,25 | 1,71 | 4,19 | 1,14 |
| (e) | | | | | |
| Glass fiber | Optimum insulation thickness (m) | 0,095 | 0,039 | 0,014 | 0,16 |
| | Annual earnings ($/m$^2$) | 85,47 | 13,91 | 1,67 | 244,32 |
| | Annual earnings (%) | 85,14 | 68,57 | 39,1 | 90,78 |
| | Payback period (year) | 1,17 | 1,46 | 2,56 | 1,1 |
| (f) | | | | | |
| Glass Foam | Optimum insulation thickness (m) | 0,025 | 0,007 | - | 0,045 |
| | Annual earnings ($/m$^2$) | 61,05 | 5,28 | - | 201,61 |
| | Annual earnings (%) | 60,81 | 26,03 | - | 74,91 |
| | Payback period (year) | 1,65 | 3,84 | - | 1,33 |

insulation in the Mediterranean Region could not determine the acceptable yearly revenues.

Figure 2(a) shows that at 0.071 m, the ideal insulation thickness for the Black Sea Region, the yearly gain amount is largest, the annual insulated energy cost is smallest, and the recovery period is shortest. Values deviate from the optimal point in a negative way. The significance of calculating the ideal insulation thickness in terms of savings is made abundantly evident by this circumstance. The ideal insulation thickness for the Aegean region is determined to be 0.012 m in Figure 2 (b), and the annual income amount is determined to be 9.89 $/m^2$. On the other side, it was discovered that the Black Sea, which is a colder region due to climatic circumstances, required an insulating thickness that was roughly 6 times more than that of the Aegean Sea.

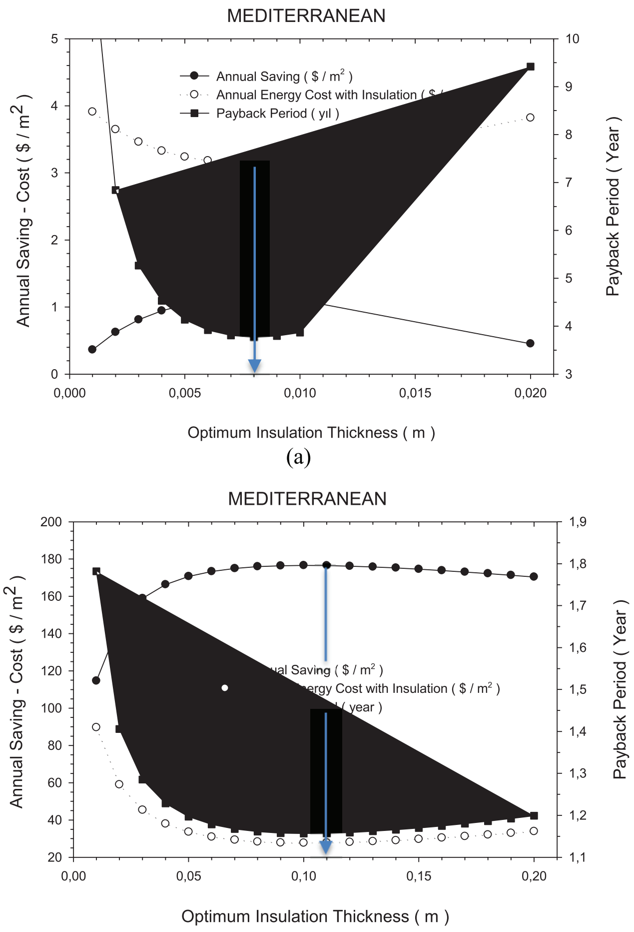
The results for the Mediterranean Region are shown in Figure 3 (a) for the heating phase and (b) for the cooling period. Even in the winter, the southern region's climate is pleasant in comparison to other places. The ideal insulation thickness increases from 0.008 m during the heating season to 0.1 m during the cooling season. In calculations for insulation that solely take heating conditions into account, the payback period is four years. On the other hand, the cooling period is reduced to 1.2 years as a result of calculations that took annual earnings into account.




(a)

(b)

**Figure 2.** The results of the glass wool insulation material during the heating period for (a) Black Sea, (b) Aegean.




(a)

(b)

**Figure 3.** Results of rock wool insulation material for Mediterranean Region, (a) Heating, (b) Cooling.

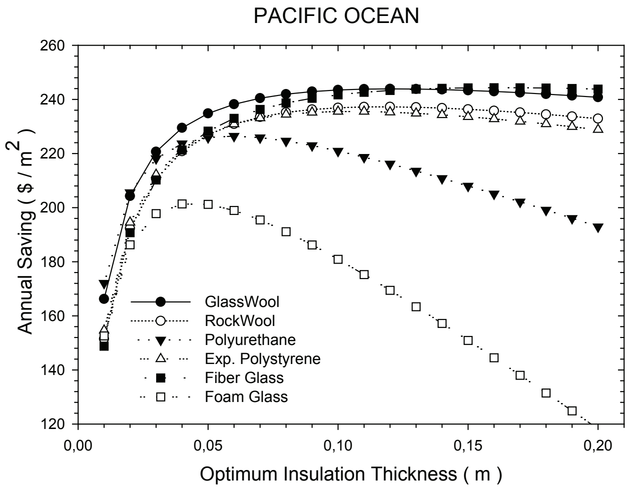



**Figure 4.** The amount of annual earnings for the Pacific Ocean region during the heating period ($/m$^2$).

Figure 4 displays the annual gains during the Pacific Ocean Region's heating season according to the thicknesses of various insulation materials. The ideal insulation thickness and annual benefits are thus 0.12 m, 243.89 \$/m$^2$, and 85.87%, respectively, when the values for glass wool are checked. For example, the ideal insulation thickness and annual gains for rock wool are 0.11 m, 237.24 \$/m$^2$, and 82.22%; for polyurethane, they are 0.059 m, 226.4 \$/m$^2$, and 76.33%; and for polystyrene, they are 0.105 m, and for expanded polystyrene, they are 0.105 m, respectively. \$235.54/m$^2$ and 81.29%, 0.16m, 244.32 \$/m$^2$ and 86.11%, and 0.045m, \$201.64/m$^2$ and 63.17% are the prices for glass fiber, respectively. Since the Pacific Ocean's sea temperatures are very low, insulating materials with strong heat conduction resistance can be used to stop the transferred heat. Calculations reveal that when enough opposition is offered, the annual income amount is actually rather substantial. Since the temperature of the Pacific Ocean is very low, no further cooling is required. It can be concluded that while choosing the insulation it is essential to perform the aforementioned analysis. It is observed that applying insulation while just taking the cooling case into account might be inappropriate.

Figure 5 displays the annual revenues for the Marmara Region according to the thicknesses of various insulation materials throughout the heating season. The ideal insulation thickness and annual gain, then, are 0.071 m, 84.88%, and 85.21 \$/m$^2$, respectively, when the values for glass wool are checked. For example, the ideal insulation thickness and annual gain for rock wool are 0.069 m, 80.99% and 81.3 \$/m$^2$, respectively. For polyurethane, this value is 0.034 m, 74.72% and 75.01 \$/m$^2$, for expanded polystyrene, it is 0.061 m, 80 and 80.3 \$/m$^2$, for glass fiber, it is 0.095 m, 85.13% and 85.4 \$/m$^2$, and for glass foam.

Figure 6 displays the annual insulated energy cost amounts for the Mediterranean Region according to the insulation thicknesses of various insulation materials. The ideal insulation thickness and annual insulated energy cost are therefore 0.104 m and 21.91 \$/m$^2$, respectively, when the values for glass wool are checked. The ideal insulation thickness and annual insulated energy cost for rock wool are 0.1 m and 27.66 \$/m$^2$, respectively. For polyurethane, it is 0.05 m and 36.98 \$/m$^2$, expanded polystyrene is 0.09 m and 29.11 m, glass fiber is 0.14 m and 21.54 \$/m$^2$, and foam glass is 0.038 m and 58.19 \$/m$^2$.

The payback period shows how long it will take for this application's investment to earn back its money. Calculations for the cost of insulating materials include the crucial word, payback period. Accordingly, the average payback period for the best insulation thicknesses was discovered to be

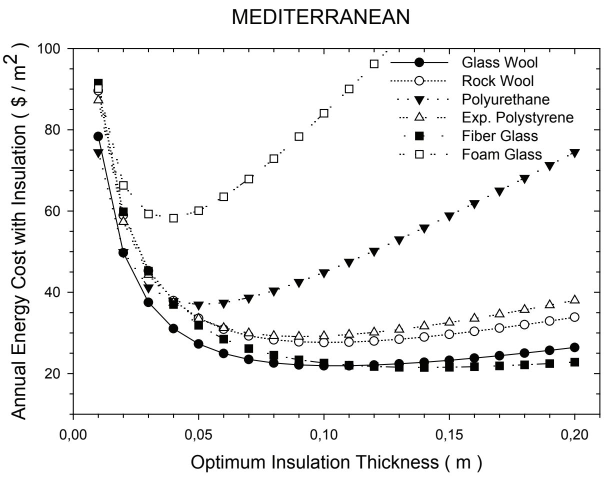



**Figure 6.** During the cooling period, the annual amount of insulated energy costs of the Mediterranean region (\$/m$^2$).

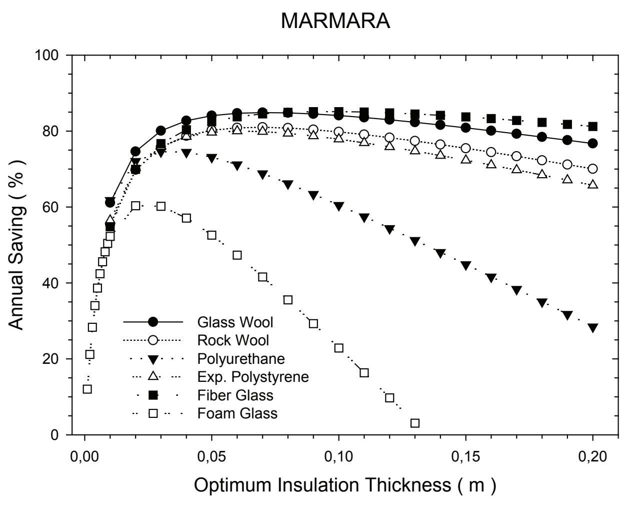



**Figure 5.** Heating period, the amount of annual earnings for the Marmara Region (%).

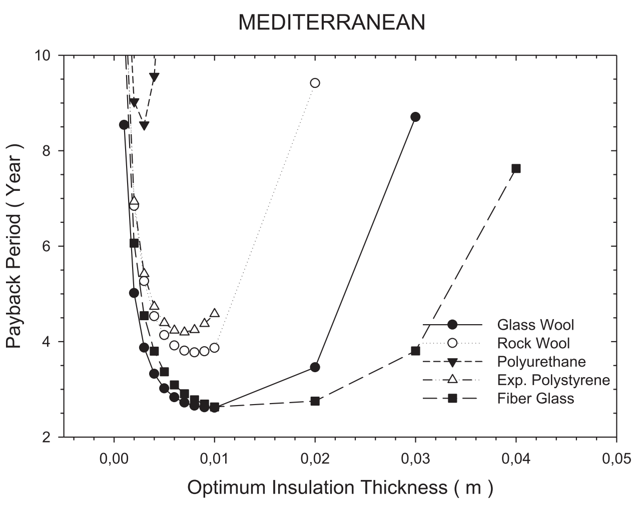



**Figure 7.** During the heating period, payback periods for the Mediterranean Region (year).

between 1.5 and 4 years as a result of calculations done for various insulation materials during the heating season. In addition, the average payback period was determined to be between 1.25 and 2 years using the cooling duration calculations. In other words, it has been determined that compared to the heating phase, the costs associated with cooling will pay for themselves more quickly. This is evidence of the significance and necessity of insulation in cold climates.

Figure 7 displays the payback times based on the insulation thicknesses of various insulation materials used throughout the Mediterranean Region's heating season. The ideal insulation thickness and payback period, then, are 0.01 m and 2.61 years, respectively, when the values for glass wool are analyzed. The ideal insulation thickness and payback period for rock wool are 0.008 meters and 3.77 years, respectively. For polyurethane, they are 0.028 meters and 8.51 years, expanded polystyrene is 0.069 meters and 4.19 years, and glass fiber is 0.013 meters and 2.56 years. It has been determined from the calculations that the glass foam material is not an insulating material suitable for the Mediterranean Region's climate. There is less need for heating in the Aegean and particularly the Mediterranean regions due to the high sea temperatures. As a result, compared to other regions, the investment's recovery period is longer. Additionally, since the procedures carried out in accordance with the Number of Cooling Days resulted in the same number of cooling days being needed for the Marmara and Aegean regions (CD=345), the outcomes in these two regions are also the same.

Figure 8 displays the payback times based on the insulation thicknesses of various insulation materials used during the Aegean Region's cooling phase. The ideal insulation thickness and payback period, then, are 0.067 m and 1.19 years, respectively, when the values for glass wool are checked. To clarify for other insulation materials: For rock wool, the ideal insulation thickness and payback period are 0.064 m and 1.25 years, respectively. For polyurethane, 0.032 m and 1.37 years, expanded polystyrene is 0.057 m and 1.27 years, glass fiber is 0.089 m and 1.19 years, and glass foam is 0.022 m and 1.71 years.

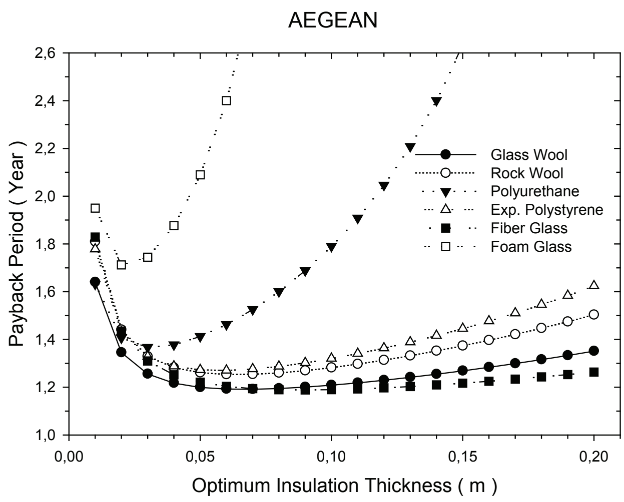



**Figure 8.** During the cooling period, payback periods for the Aegean Region (year).

## CONCLUSIONS

Submarines operate fully submerged to the seas and oceans and globally, the water temperatures vary from region to region, which needs to be considered in the designing stages of the submarines. In this study, calculations were done for the deployment of submarines in the Sakhalin/Pacific Ocean Location, the world's coldest region, reflecting the most challenging conditions, and additionally the Black Sea, Mediterranean, Marmara, and Aegean regions are also investigated. Rock wool, glass wool, expanded polystyrene, polyurethane foam, glass fiber, and glass foam are some of the materials that have been used as insulation materials.

According to the presented analysis, glass wool, glass fiber, rock wool, expanded polystyrene, polyurethane, and glass foam are the insulating materials that offer the greatest cost savings across all regions. The ideal insulation thickness, annual gain, and payback duration for the heating period, when using glass wool as the best insulating material, are 0.12 m, \$243.89/m$^2$, and 1.10 years, respectively, for the Pacific Ocean, which has the most challenging climate conditions.

The results show that the use of insulation material reduces heat loss from the environment under conditions of low outdoor temperature. As a result, there are improvements in both annual earnings and payback times. With the help of this study, it has once again been shown how crucial insulation is for maximizing the use of energy resources, lowering emissions' harmful effects on the environment, cutting expenses, and creating comfortable and affordable living spaces.

## NOMENCLATURE

| | |
|---|---|
| $C_{fuel}$ | Fuel price, \$/kg |
| $C_{insulation}$ | Insulation price, \$/m$^3$ |
| g | Inflation rate, % |
| h | Heat transfer coefficient, W/m$^2$K |
| i | Interest rate, % |
| k | Thermal conductivity, W/mK |
| N | Annual service life, year |
| $R_i$ | Inner surface thermal resistance, m$^2$K/W |
| $R_o$ | Outer surface thermal resistance, m$^2$K/W |
| $R_w$ | Non-Insulated wall thermal resistance, m$^2$K/W |
| $R_{w,t}$ | Thermal resistance without the insulation material. m$^2$K/W |
| $R_{insulation}$ | Insulation thermal resistance, m$^2$K/W |
| $S_d$ | Diffusion equivalent air layer thickness of the water vapor, m |

| | |
|---|---|
| $T_b$ | Balance temperature, °C |
| $T_m$ | Mean outdoor temperature, °C |
| U | Total heat transfer coefficient, W/m²K |
| η | Efficiency of the heating system, % |
| α | Sun absorbency of the outer surface of the wall |
| μ | Water vapor diffusion resistance coefficient |
| $\Sigma_{day}$ | Number of total days |
| x | Thickness of insulation material, m |
| $x_{opt.}$ | Optimum insulation thickness, m |
| CD | Number of cooling degree days |
| COP | Coefficient of performance |
| DD | Degree days |
| EPS | Expanded polystyrene foam |
| HD | Number of heating degree days |
| LCCA | Lifecycle cost analysis |
| LHV | Lower calorific value of fuel |
| LPG | Liquefied petroleum gas |
| PWF | Present value factor |
| XPS | Extruded polystyrene |

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

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