buildings

MDPI

Article

Optimal Insulation Assessment, Emission Analysis, and Correlation Formulation for Indian Region

Mehmet Ali Kallioğlu [1], Ahmet Yılmaz [2], Ashutosh Sharma [3], Ahmed Mohamed [4], Dan Dobrotă [5], Tabish Alam [6], Rohit Khargotra [7,*] and Tej Singh [8]

1 Faculty of Technology, Batman University, Batman 72100, Turkey
2 Computer Engineering Department of Engineering Faculty, Karamanoğlu Mehmetbey University, Karaman 70200, Turkey
3 Department of Mechanical Engineering, Dr B R Ambedkar National Institute of Technology, Jalandhar 144011, India
4 Structural Engineering and Construction Management Department, Future University in Egypt, Cairo 11835, Egypt
5 Faculty of Engineering, Department of Industrial Engineering and Management, Lucian Blaga University of Sibiu, 550024 Sibiu, Romania
6 CSIR-Central Building Research Institute, Roorkee 247667, India
7 Institute of Materials Engineering, Faculty of Engineering, University of Pannonia, 8200 Veszprem, Hungary
8 Savaria Institute of Technology, Faculty of Informatics, ELTE Eötvös Loránd University, 9700 Szombathely, Hungary
* Correspondence: rohitkhargotra@phd.mk.uni-pannon.hu

Abstract: The current study depicts the effects of different insulation materials and fuel types on the cooling and heating performance of buildings situated in hot and dry, warm and humid, composite, and cold climatic conditions in India. Ten different locations chosen from diverse climatic regions were selected, and various potential parameters for expanded polystyrene and extruded polystyrene insulation materials were evaluated. Potential parameters, such as optimal insulation thickness, annual savings, and payback period, were computed for cooling and heating requirements and were found in the ranges of 0.0428–0.891 m, 10.83–19.19 $/m^2, and 1.49–2.36 years for cooling, as well as 0.0063–0.1522 m, 0.29–55.92 $/m^2, and 0.95–6.52 years for heating, respectively. An emission analysis was also carried out for the estimation of greenhouse gas (GHG) emissions by the engagement of optimal insulation thickness for heating. The GHG emissions from natural gas, coal, and diesel by the employment of various insulating materials were found in the ranges of 5.39–11.28, 9.47–32.68, and 2.26–4.51 kg/m^2-year, respectively. A correlation formulation (power) for optimal insulation thickness was also carried out. For checking the preciseness of the developed mathematical models, statistical tools were utilized, and their obtained values in the satisfactory range signified the accurateness of the developed models.

Keywords: optimal insulation; environmental analysis; modeling; degree days; correlation

check for updates

Citation: Kallioğlu, M.A.; Yılmaz, A.; Sharma, A.; Mohamed, A.; Dobrotă, D.; Alam, T.; Khargotra, R.; Singh, T. Optimal Insulation Assessment, Emission Analysis, and Correlation Formulation for Indian Region. *Buildings* **2023**, *13*, 569. https://doi.org/10.3390/buildings13020569

Academic Editors: Elena Lucchi and Gianpiero Evola

Received: 14 January 2023
Revised: 5 February 2023
Accepted: 13 February 2023
Published: 20 February 2023

1. Introduction

Energy is vital to human existence and advancement. The increasing demand for energy is driven by various factors, such as the development of new technologies, the impact of climate change, and population growth. However, the majority of the world's energy needs are currently met by fossil fuels, which are nonrenewable and finite resources. As a result, these energy sources are becoming increasingly scarce, with depletion happening at an alarming rate. This has led to the urgent need to find sustainable and renewable alternatives to fossil fuels in order to meet the growing energy demands and preserve the planet for future generations [1–3]. The use of thermal energy systems, such as those found in homes and businesses for temperature regulation (heating and cooling), can often result in a loss in thermal energy to the surrounding environment. To counter this, insulation materials are commonly applied to the exterior walls, windows, ceilings, and floors of these buildings. The use of insulation can greatly reduce energy loss and lead to significant energy savings. By minimizing energy loss in this way, the overall carbon footprint of a building can also be reduced [4,5]. The optimum insulation thickness for the exterior walls of a building can depend on several factors, including the climate, location, and intended use of the building. The R-value, which is a measure of thermal resistance, is typically used to determine appropriate insulation thickness for exterior walls. As a general rule, the R-value required for exterior walls in a building depends on the insulation materials, climate zone, overall cost, and building type [6,7]. Nyers et al. [8] developed an investment-saving method for determining the optimal insulation thickness of external walls in Serbia. A mathematical model was developed considering the steady-state one-dimensional heat conduction of walls made up of bricks and polystyrene. The overall savings and payback terms were evaluated at optimal insulation thickness and found to be 8.5 $/m^2 and 1.22 years, respectively. Liu et al. [9] computed the optimal thickness of insulation for external walls in China's cold winter and hot summer zones. A mathematical model that incorporated heat and moisture transfer was developed and used to estimate the annual energy consumption. Two different types of insulation materials, viz., expanded polystyrene (EPS) and extruded polystyrene (XPS), were compared with lifecycle savings and payback period. The optimal insulation thicknesses for XPS and EPS were found at 0.053–0.069 m and 0.081–0.105 m, respectively. The maximum lifecycle saving and the payback period were found at 16.6–28.5 $/m^2 and 1.89–2.56 years, respectively. The results also revealed that the EPS material performed better than XPS, with more lifecycle savings and a shorter payback period. In another study, Yuan et al. [10] considered the effects of both insulation thickness and reflectivity on outer walls in different climatic zones of Japan. The reflectivity and the insulation thickness were supposed to be varied between 0.1 and 0.8 mm and 10 and 100 mm, respectively. The results showed that a low value of reflectivity and thick insulation were preferable for cold regions and vice versa for hot areas. The effect of insulation thickness on enjoinment was studied by Dombayci [11] in Turkey for cold seasons. A one-dimensional steady-state heat conduction model was developed for a sandwiched wall made up of the materials in the following order: plaster, brick, insulation, brick, and plaster. The results revealed that, at optimum insulation thickness, the energy consumption decreased by 46.6%, and the CO_2 and SO_2 emissions were reduced by 41.53%. Kaynakli et al. [12] evaluated the optimum insulation thickness for different applications of insulation material (internal, sandwiched, and external) by taking into account the indoor and outdoor conditions. The key factors on which the optimum thickness of insulation depended were found to be indoor temperature and indoor and outdoor relative humidity. The results indicated that, for low indoor and outdoor relative humidity ($\leq$0.6), the type of insulation application did not affect insulation thickness. However, insulation application over the outer edge of an external wall performed better than all the other cases in the studied conditions. In a different study, Bolattürk [13] evaluated the optimum thickness of foam for sixteen cities from four different climate zones of Turkey. The fuels considered for heating and cooling in their study were coal, natural gas, diesel, LPG, and electricity. The results revealed that the optimum insulation thickness, energy saving, and life cost were in the ranges of 2–17 cm, 22–79%, and 1.3–4.5 years, respectively, depending on the different climate zones. The results also indicated that high values of optimum insulation thickness were evaluated for cold climatic regions with significantly less of a payback period. Mahlia et al. [14] evaluated the optimum insulation thickness for different materials in the climatic conditions of Malaysia and formed correlations as a function of the thermal conductivities of different insulating materials. The result revealed that a nonlinear mathematical model (polynomial) predicted the results most precisely. This correlation was $x_{opt} = a + bk + ck^2$, where a = 0.0818, b = −2.973, and c = 64.6, and "k" in the correlation was the thermal conductivity (W/m °C) of the insulating material. Sisman et al. [15] conducted a study and determined optimal insulation thickness for cities in four different climatic zones of Turkey for stone wool material for heating. These properties constituted equations that could be used to specify the optimum point based on the NDD variable for both external walls and roofs. The external wall equation was $x_{opt} = a \times NDD^b$, where a = 0.001 and b = 0.7533.

India has diversified climatic zones, including hot and dry, warm and humid, composite, cold, and temperate. A few studies have been reported to estimate optimal insulation thicknesses in different climatic zones in India. Sundaram and Bhaskaran [16] optimized insulation thickness for five cities in India, selecting the warm and humid and composite climates. Three different insulating materials attached at the inner sides of outer walls were considered for the study, and various thermo-economic parameters, such as optimum insulation thickness, annual energy cost, annual electric energy consumption, and payback period, were determined. The results revealed that EPS insulation material performed more effectively than the other studied materials in terms of energy saving and payback period. Mishra et al. [17] computed the optimal insulation thickness for Dehradun, located in a cold climatic region of India. Two dissimilar insulation materials, EPS and XPS, were considered for three different walls of dissimilar materials. The heat loss was calculated by the degree day method, and the fuel assumed for heating was natural gas. The results revealed that the optimum insulation thickness and energy saving varied between 5.2 and 7.4 cm and 31.41 and 67.59 $\$/m^2$, respectively. Raza and Aggarwal [18] determined optimum insulation thickness using two different methods, viz., the degree day method and annual full load cooling hours operation. The insulation material was considered to be sandwiched between bricks, and three different insulation materials were investigated. The results revealed that the EPS insulation materials using LPG for heating were the most effective combination. In another study, Singh et al. [19] computed the optimal XPS thickness for various climates of India. The study concluded that, at a 25 °C indoor temperature for all the selected zones, the optimum insulation, annual savings, and payback period were found in the ranges of 0.015–0.031 m, 0.33–2.21 $\$/m^2$, and 3.9–6.7 years, respectively.

The literature survey clearly indicates the necessity of evaluating the optimal insulation thickness to help reduce the amount of energy needed to heat and cool buildings, thus decreasing the amount of greenhouse gas emissions associated with energy production. Therefore, in this study, optimal insulation thickness is evaluated based on the degree day method for ten locations selected from different climatic zones in India. EPS and XPS insulation materials are investigated, and various fuels, such as natural gas, coal, diesel, and electricity, are considered for heating and cooling. In 2015, the United Nations (UN) defined 17 sustainable development goals that address the most pressing global issues [20]. This study is directly related to Target 12 (Responsible Consumption and Production). It is also indirectly related to Target 7, Target 11, and Target 13. These targets frame pressing issues in the construction, energy, and manufacturing sectors that need to be addressed in the next quarter century.

2. Materials and Methods

Calculations were performed for cities in 10 different regions (Jaisalmer, Kota, Mumbai, Chennai, Bhubaneswar, New Delhi, Lucknow, Patna, Srinagar, and Shillong) with different climatic characteristics in Indian climate geography, as shown in Figure 1 [21,22]. Köppen–Geiger climatic classification was utilized to understand climatic attributes on a global scale. These climate groups were expressed in three letters. For Köppen classification, the first letter of these climate groups was as follows: equatorial region (A), arid region (B), hot temperate zone (C), snowy region (D), or polar region (E). The second letter in classification was the rainfall position of the region; the third letter was the region's temperature [21]. Jaisalmer was classified as a tropical and subtropical desert climate (Bwh); Mumbai, Chennai, and Bhubaneswar were classified as tropical savanna climates (Aw); Kota and New Delhi were classified as mid-latitude steppe and desert climates (Bsh); Lucknow and Patna belonged to the monsoon-influenced humid subtropical climate classification (Cwa); Srinagar belonged to the cold desert climate classification (Bwk); and Shillong was classified as a tropical monsoon climate (Am). Aw-Cwa was mid-rainy, and Bwh-Bsh-Bwk was arid and less rainy [22]. Energy need was computed by accepting

T ≤ 15 °C as the degree day value for heating (HDD) and T > 24 °C as the degree day value for cooling (CDD). Annual average values between 2007 and 2016 were used as heating and cooling day degree data; Table 1 shows the annual values of the regions. The data on HDD, CDD, and average temperature for the different locations were collected through the database of the JRC Photovoltaic Geographical Information System (PVGIS) [23]. Coal, natural gas, and diesel were utilized for heating in the lifecycle cost analysis (LCA), while electricity was used for cooling.

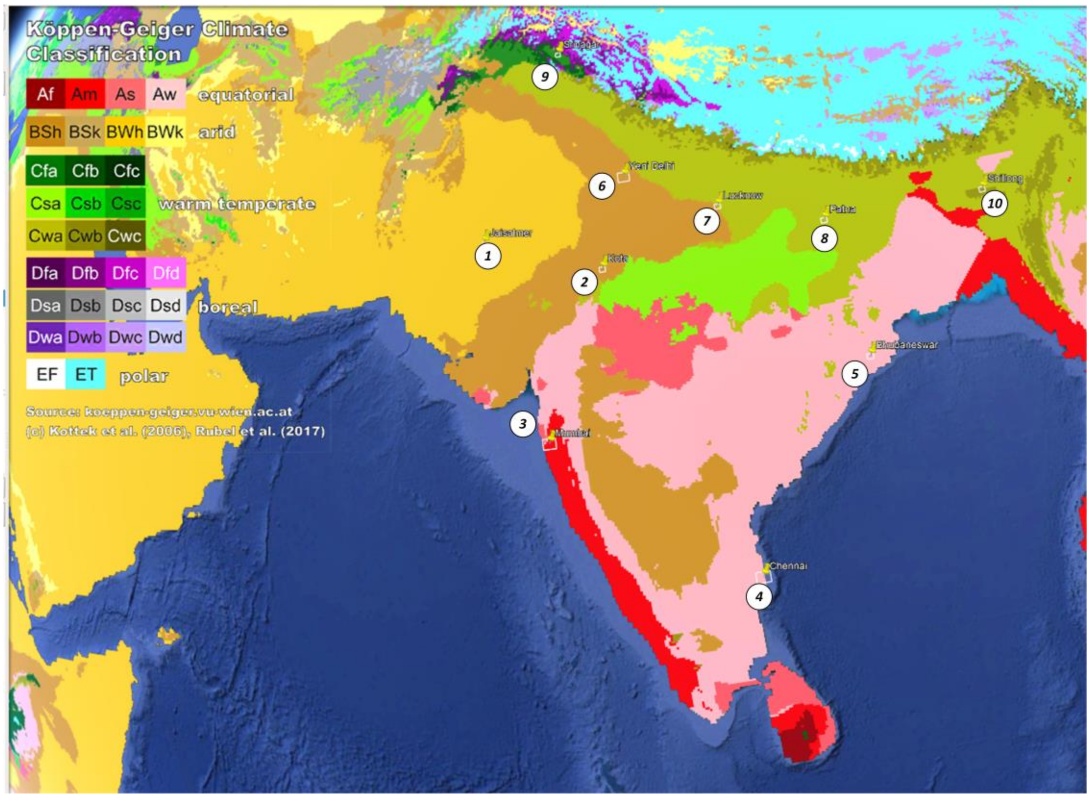

Figure 1. Selected Indian cities' geographic locations.

Table 1. Cooling and heating values of the selected cities [23].

No.	City	Latitude (Degree)	Altitude (m)	HDD (°C/Year)	CDD (°C/Year)	Average Temp. (°C/Year)	Process	Climate
1	Jaisalmer	29.90 N	225	43	2565	27.38	Cooling	Hot dry
2	Kota	25.20 N	271	87	2123	26	Cooling	Hot dry
3	Mumbai	19.07 N	14	0	2092	26.82	Cooling	Warm humid
4	Chennai	13.08 N	6.7	0	2485	27.82	Cooling	Warm humid
5	Bhubaneswar	20.29 N	58	1	1895	26.24	Cooling	Warm humid
6	New Delhi	28.61 N	216	267	1791	24.34	Cooling	Composite
7	Lucknow	26.85 N	123	144	1842	24.89	Cooling	Composite
8	Patna	25.59 N	53	75	1791	25.02	Cooling	Composite
9	Srinagar	34.08 N	1585	2109	26	13.14	Heating	Cold
10	Shillong	25.57 N	1525	815	0	16.04	Heating	Cold

2.1. Building Wall Model

The largest heat losses in buildings are reported through walls, floors, roofs, and windows, with a total energy loss of nearly 15–35% [24]. Heat losses and gains arising from buildings vary by architecture, location, and structural materials. The highest loss rate in a building is due to exterior walls and, if optimum insulation is provided, 50% to 60% of the energy can be saved [25]. Therefore, insulation for external walls is an investment for maximum energy gain. Walls are made up of a single layer nowadays, but they may also be considered as a construction component made up of two or more layers and elements [26].

The optimal insulation thickness was found in this investigation by considering that heat losses only occurred through outer walls. The wall model, as shown in Figure 2, was composed of interior plaster, insulating material, concrete, and exterior plaster. Table 2 displays the properties of these wall components [27,28].

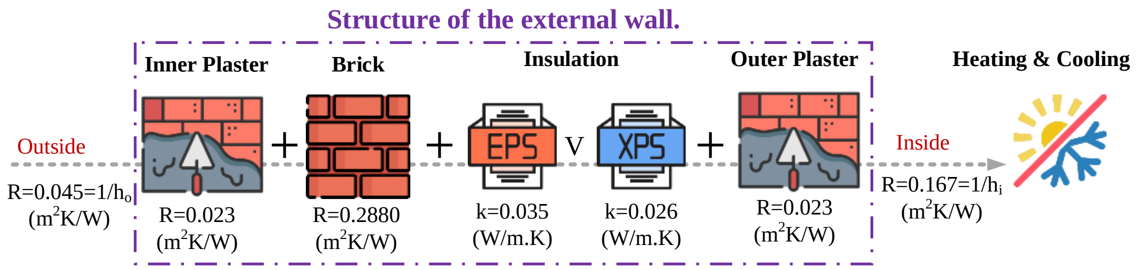

Figure 2. The exterior wall model in the study and the characteristics of its components.

Table 2. Construction of walls used in the analysis [27,28].

Wall Type	Density (kg·m^{-3})	Thickness (m)	Thermal Conductivity (W/m·K)	Thermal Resistance (m^{2}K/W)	Thermal Resistance R_{TW} (Total Wall) (m^{2}K/W)
Inner plaster	1200	0.02	0.85	0.0230	
Hollow brick	750	0.13	0.45	0.2880	
Outer plaster	1100	0.02	0.85	0.0230	0.548
R inside	-	-	-	0.1670	
R outside	-	-	-	0.0450	

The overall heat transfer coefficient (U) was determined using Equation (1) [29]:

$$\boldsymbol{U} = \frac{\mathbf{1}}{\boldsymbol{R_i} + \boldsymbol{R_w} + \boldsymbol{R_{izo}} + \boldsymbol{R_o}} \qquad \left(\mathrm{W/m^2K}\right) \tag{1}$$

In Equation (1), R_i represents the thermal resistance of the inner surface, and R_o represents the thermal resistance of the outer surface. R_w is the thermal resistance of the wall layers that are not insulated, and R_{izo} is the insulation material's thermal resistance computed with Equation (2). In this equation, x is the insulation material's thickness, and k is the insulation material's thermal conductivity coefficient. The values of k were considered as 0.026 W/m·K and 0.035 W/m·K for XPS and EPS with costs (C_i) of 46.35 \$/m^3 and 105.94 \$/m^3, respectively [16].

$$\boldsymbol{R_{izo}} = \frac{\boldsymbol{x}}{\boldsymbol{k}} \tag{2}$$

2.2. Building Wall Heating Load

Windows, ceilings, floors, exterior walls, and air infiltration result in heat losses arising in buildings. Calculations were revised in this analysis by assuming that they came only from the outer wall. For the outer wall, the heat loss was computed using Equation (3) [30]:

$$q = \boldsymbol{U}.\Delta \boldsymbol{T} \tag{3}$$

where ΔT is the temperature difference, and U is the total heat transfer coefficient. The number of degree days (NDD) and U were implemented to compute the yearly heat loss q_A (W/m^2) of the unit surface:

$$\mathbf{q}_A = (\mathbf{3600} \times \mathbf{24}).\mathbf{NDD.U} \tag{4}$$

Equation (5) provides the E_A (J/m^2-year) yearly energy required for heating and was computed by dividing q_A by the system efficiency:

$$\mathbf{E_A} = \frac{\mathbf{86400}.\boldsymbol{NDD.U}}{\boldsymbol{\eta}} = \frac{\mathbf{86400}.\boldsymbol{NDD}}{(\boldsymbol{R_{TW}} + \boldsymbol{R_{izo}}).\boldsymbol{\eta}} \tag{5}$$

Equation (6) calculates the m_{fA} (kg/m^2-year) fuel amount consumed in a year:

$$\boldsymbol{m_{fA}} = \frac{\mathbf{86400}.\boldsymbol{NDD}}{(\boldsymbol{R_{TW}} + \boldsymbol{R_{izo}}).\boldsymbol{H_u}.\boldsymbol{\eta}} \tag{6}$$

Equation (7) calculates the annual energy cost $C_{A,H}$ ($\$/m^2$-year) utilized for heating a unit area:

$$\boldsymbol{C_{A,H}} = \frac{\mathbf{86400}.\boldsymbol{HDD}.\boldsymbol{C_f}}{(\boldsymbol{R_{TW}} + \boldsymbol{R_{izo}}).\boldsymbol{\eta}.\boldsymbol{H_u}.} \tag{7}$$

As shown in Table 3 [31], H_u is the fuel lower heat value, η is the the fuel efficiency, and C_f is the fuel price. Equation (8) computes the cost of cooling with respect to the amount of energy utilized:

$$\boldsymbol{C_{A,C}} = \frac{\mathbf{86400}.\boldsymbol{CDD}.\boldsymbol{C_f}}{(\boldsymbol{R_{TW}} + \boldsymbol{R_{izo}}).\ \boldsymbol{COP}} \tag{8}$$

Here, COP is the cooling system performance coefficient taken as 2.5 [32]. The values of C_f, H_u, and η are listed in Table 3.

Table 3. Considered fuel characteristics [31,33].

Fuel	**Chemical Equation**	**C_f**	**η**	**H_u**
Coal	$C_{5.85}H_{5.26}O_{1.13}S_{0.008}N_{0.077}$	0.16610 $/kg	0.65	21.113×10^6 J/kg
Natural gas	$C_{1.05}H_4O_{0.034}N_{0.022}$	0.1305 $\$/m^3$	0.93	34.526×10^6 J/m^3
Diesel	$C_{7.3125}\ H_{10.407}\ O_{0.04}\ S_{0.026}\ N_{0.02}$	0.69981 $/kg	0.80	42.911×10^6 J/kg
Electricity	-	0.08 $/kWh	0.99	3.5990×10^6 J/kWh

2.3. Optimal Insulation Analysis

The purpose was to reduce insulation costs by analyzing the optimal thickness of insulation desired for a building. The building's overall heating cost was calculated using LCCA by combining the energy price, any insulation price, the future value factor (PWF), and time (N) [34,35]. For the PWF price, the real interest rate (r) was determined based on two different terms using Equation (9), depending on the interest rate (φ) and the inflation rate (i):

$$\text{If } \varphi > \text{i then } \mathbf{r} = \frac{\boldsymbol{\varphi} - \mathbf{i}}{\mathbf{1} + \mathbf{i}};\ \textbf{If } \text{i} > \varphi \text{ then } \mathbf{r} = \frac{\mathbf{i} - \boldsymbol{\varphi}}{\mathbf{1} + \boldsymbol{\varphi}} \tag{9}$$

For a ten-year process, current values were calculated using Equation (10) with inflation and interest rates of 4% and 8%, respectively [36,37]:

$$\boldsymbol{PWF} = \frac{(\boldsymbol{r} + \mathbf{1})^{\boldsymbol{N}}}{(\boldsymbol{r} + \mathbf{1})^{\boldsymbol{N}}.\boldsymbol{r}} \tag{10}$$

Equation (11) calculates the total C_T ($) cost of an isolated building, where x and C_i are the used insulation material's thickness (m) and unit price ($/$m^3$), respectively:

$$C_T = C_A.PWF + C_i.x \tag{11}$$

For optimal insulation thickness x_{opt} (m), the total cost must be minimal and was determined as follows:

$$\frac{dC_T}{dx} = \frac{d}{dx}.(C_A.PWF + C_i.\, x) \tag{12}$$

$$\frac{dC_T}{dx} = 0 \tag{13}$$

$$x_{opt} = \sqrt{86400}\,.\left(\frac{NDD.\,C_f.PWF.k}{H_U.C_i.\eta}\right)^{1/2} - k.R_{TW} \tag{14}$$

Equation (15) calculates the cost of the lifecycle (p_b) following the profit from the investment made. In this equation, the S_A represents annual savings:

$$p_b = \frac{C_T}{S_A} \tag{15}$$

2.4. Environmental Analysis

The steadily rising global population needs greater and greater quantities of energy every day. The related increasing energy demand has been generally utilized to heat houses. This demand is mainly supplied by fossil fuels, which are the widest and cheapest sources of energy, leading to the emission of greenhouse gases and harmful pollutants. Heating costs can be reduced by a certain degree with a certain increment in insulation thickness. The general chemical formula of combustion for fuel is expressed by Equation (16) [38]:

$$C_x + H_z + O_w + S_y + N_t + \alpha.A(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{z}{2}\right)H_2O + ySO_2 + B.O_2 + E.N_2 \tag{16}$$

Here, the constants (A, B, and E) are calculated as follows:

$$A = \left(x + y + \frac{z}{4} - \frac{w}{2}\right) \tag{17}$$

$$B = \left(x + y + \frac{z}{4} - \frac{w}{2}\right).(\alpha - 1) \tag{18}$$

$$E = 3.76\alpha\,.\left(x + y + \frac{z}{4} - \frac{w}{4}\right) + \frac{t}{2} \tag{19}$$

SO_X and CO emissions are neglected in Equation (16). The emission rates of combustion products resulting from the burning of 1 kg of fuel can be calculated in Equations (20) and (21) [39]:

$$MCO_2 = \frac{x\ CO_2}{M} \equiv kg\ \ CO_2/kg\,fuel \tag{20}$$

$$MSO_2 = \frac{y\ SO_2}{M} \equiv kg\ \ SO_2/kg\,fuel \tag{21}$$

Here, M (kg/kmol) is the molar weight of the fuel determined as follows:

$$M = 12x + z + 16w + 32y + 14t \tag{22}$$

Depending on the total fuel consumption, emission values can be calculated using Equations (23) and (24):

$$mCO_2 = \frac{44.x}{M} m_{fA} \tag{23}$$

$$mSO_2 = \frac{64.y}{M} m_{fA} \tag{24}$$

3. Results and Discussion

3.1. Optimal Insulation Thickness

Optimal insulation thickness varied with fuel type, insulating material, and climate. Heat losses in buildings displayed a downtrend. Therefore, the heat losses and heat loads of buildings decreased. As a result, the overall amounts of fuel and emissions were reduced all at once. However, the overall cost (fuel and insulation) reduced initially and then climbed again after the minimal figure was reached. The ideal insulation thickness was determined by the point at which the overall cost was the lowest. Investment cost and total cost both increased due to unnecessarily increased insulation thickness. Figure 3 illustrates the relationship between the total cost of insulation thickness and externally insulated wall applications.

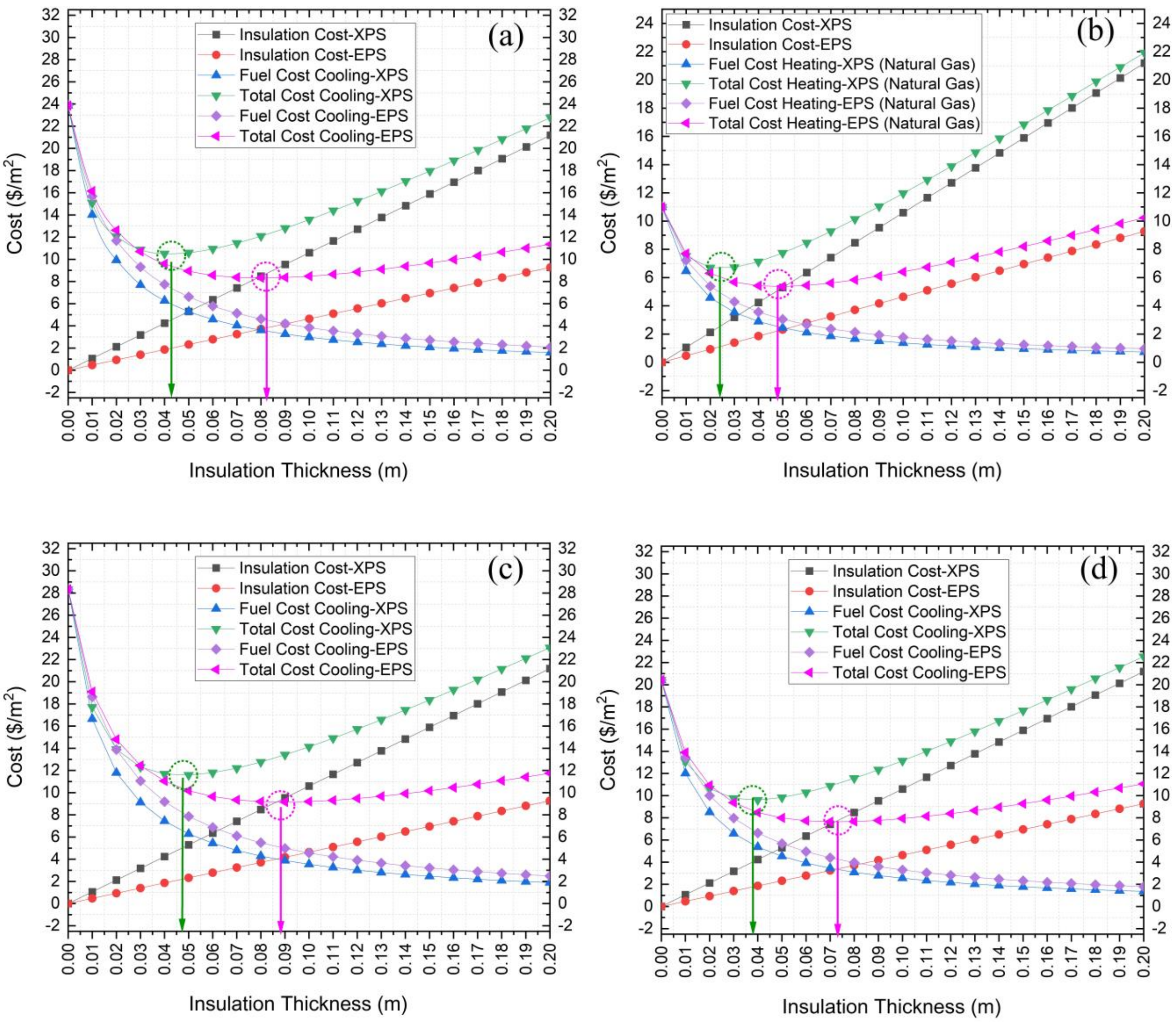

Figure 3. Cost–insulation thickness relationship for EPS and XPS insulation materials: (**a**) Mumbai, (**b**) Srinigar, (**c**) Chennai, and (**d**) Patna.

Optimal insulation thickness was computed for various fuels and insulating materials using Equation (14). The results can be seen in Tables 4 and 5 for externally insulated walls in Jaisalmer, Kota, Mumbai, Chennai, Bhubaneswar, New Delhi, Lucknow, and Patna for cooling, as well as in Srinagar and Shillong for heating. Insulation became meaningless because of the initial investment cost and economic parameters in solutions for low numbers of degree days. It can be seen when Table 4 is reviewed that XPS had differences compared to EPS in using electricity for cooling when analyzing the optimal insulation thickness. The lowest thermal insulation thickness values related to using XPS material in building insulation were in New Delhi (Bsh) and Patna (Cwa), which were in the composite climatic zone, by 0.0382 (m). The highest value was in Jaiselmer by 0.0484 (m), which was in a hot and dry region.

Table 4. Results of various insulation materials for cooling.

Materials	X_{opt} (m)	Annual Savings ($/m^2)	Payback Period (Years)	Annual Savings Rate (%)
		Jaisalmer		
XPS	0.0484	17.47	1.96	40.28
EPS	0.0908	19.94	1.49	31.83
		Kota		
XPS	0.0428	13.63	2.16	43.71
EPS	0.0809	15.82	1.64	34.66
		Mumbai		
XPS	0.0424	13.36	2.18	43.99
EPS	0.0802	15.54	1.65	34.89
		Chennai		
XPS	0.0475	16.77	1.99	40.84
EPS	0.0891	19.19	1.51	32.29
		Bhubaneswar		
XPS	0.0401	11.70	2.29	45.88
EPS	0.0754	13.73	1.74	36.46
		New Delhi		
XPS	0.0382	10.83	2.36	46.99
EPS	0.0728	12.79	1.79	37.38
		Lucknow		
XPS	0.0389	11.25	2.33	46.44
EPS	0.0741	13.25	1.77	36.92
		Patna		
XPS	0.0382	10.83	2.36	46.99
EPS	0.0728	12.79	1.79	37.38

Table 5. Results of various insulation materials for heating.

Fuel	Materials	X_{opt} (m)	Annual Savings ($/m^2)	Payback Period (Years)	Annual Savings Rate (%)
			Srinagar		
Natural gas	XPS	0.0242	4.36	3.27	60.39
	EPS	0.0483	5.63	2.47	48.80
Coal	XPS	0.0188	2.62	3.86	67.70
	EPS	0.0387	3.62	2.91	55.29
Diesel	XPS	0.0834	51.73	1.24	27.06
	EPS	0.1522	55.92	0.95	21.15
			Shillong		
Natural gas	XPS	0.0097	0.69	5.49	83.69
	EPS	0.0227	1.25	4.11	70.57
Coal	XPS	0.0063	0.29	6.52	90.66
	EPS	0.0168	0.68	4.85	78.19
Diesel	XPS	0.0465	16.05	2.03	41.44
	EPS	0.0873	18.42	1.54	32.79

New Delhi, Patna, and Jaisalmer had the highest values by 0.0908 (m) for cooling when EPS material was used in building insulation. These values proportionally varied by degree day number. The results for XPS material under a cooling load were 2.20 years on average (the payback period was 1.96 (years) at least and 2.36 (years) at best). The annual savings were 10.83 ($\$/m^2$) at least, 17.47 ($\$/m^2$) at best, and 13.23 ($\$/m^2$) on average. The annual savings rate was 40.28 (%) at least, 46.99 (%) at best, and 44.39 (%) on average. According to the results for the EPS material, the payback period was 1.49 (years) at least, 1.79 (years) at best, and 1.67 years on average. The annual savings were 12.79 ($\$/m^2$) at least, 19.94 ($\$/m^2$) at best, and 15.38 ($\$/m^2$) on average. The annual savings rate was 31.83 (%) at least, 37.38 (%) at best, and 35.22 (%) on average. According to the average results for both materials, 0.0607 (m) was the optimal insulation thickness, 1.93 (years) was the payback period, 14.30 was the annual savings ($\$/m^2$), and 39.80 (%) was the annual savings rate. Cities located in a hot climate zone only consumed energy for cooling. It can be seen that serious energy savings could be achieved with products selected in the optimum thickness values from insulation materials ranging from 0.1 cm to 0.12 cm in the current market.

Insulating properties of XPS and EPS materials in the cases of using natural gas, coal, and diesel fuel under a heating load can be seen in Table 5.

The lowest insulation thickness for XPS material was 0.0063 (m) for coal (Shillong); the highest value was 0.0834 (m) for diesel fuel (Srinagar). The lowest and highest values for EPS material for the same regions and types of fuels, respectively, were 0.0168 (m) and 0.1522. Regarding the results for XPS material under a heating load, the payback period was 1.24 (years) at least, 6.52 (years) at best, and 3.74 years on average. The annual savings were 0.29 ($\$/m^2$) at least, 51.73 ($\$/m^2$) at best, and 12.62 ($\$/m^2$) on average. The annual savings rate was 27.06 (%) at least, 90.66 (%) at best, and 61.82 (%) on average. According to the results for EPS material, the payback period was 0.95 (years) at least, 4.85 (years) at best, and 2.80 years on average. The annual savings were 0.68 ($\$/m^2$) at least, 55.92 ($\$/m^2$) at best, and 14.25 ($\$/m^2$) on average. The annual savings rate was 21.15 (%) at least, 78.19 (%) at best, and 51.13 (%) on average.

Regarding the average results in both regions for both materials, 0.0462 (m) was the optimal insulation thickness, the payback period was 3.27 (years), 13.43 was the annual savings ($\$/m^2$), and 56.47 (%) was the annual savings rate. The three main parameters that affected the results were fuel components, insulating properties, and the number of degree days. In general terms, variables were close to each other for India; good results for both heating and cooling were obtained.

3.2. Environmental Analysis

Figure 4 shows changes based on insulation thickness in the annual CO_2 and SO_2 gases. The CO_2 emissions at different values of insulation thickness and for different types of fuels are presented in Figure 4a. For both EPS and XPS materials, the highest and lowest CO_2 emissions were observed corresponding to coal and diesel, respectively. Fuel quantity for heating unit volume decreased with increasing insulation thickness. This is because there was an observed decrease in the emission of deleterious gases. According to the average results in two different cities, XPS and EPS respectively became 66% and 52% in the case of providing insulation and optimal insulation thickness. In addition, a decrease was seen in SO_2 and CO_2 emission values, with more sustainable ecological environmental structures.

3.3. Degree Days and Correlations

There have been some studies that have proposed methods to optimize the thicknesses of insulation materials. For example, Mahlia et al. [14] used the thermal conductivity (k) of different insulation materials to compute the optimal values. However, they did not consider the needed annual energy of buildings. On the contrary, Sisman et al. [15] computed optimal values using NDD but without using the k value of the insulation material. The results have shown that these two proposed methods are promising. However, a question arises here: what if both parameters, the *k* value of the insulation material and NDD, were used to compute optimal thickness? To investigate this problem, we tried to develop a mathematical model that used both parameters (*k* and *NDD*). The model was developed using a multiple linear regression method, which is a machine-learning technique [40,41]. Equation (25) is a general form of the model:

$$\mathbf{x_{opt} = a + b.k + c.NDD} \quad (25)$$

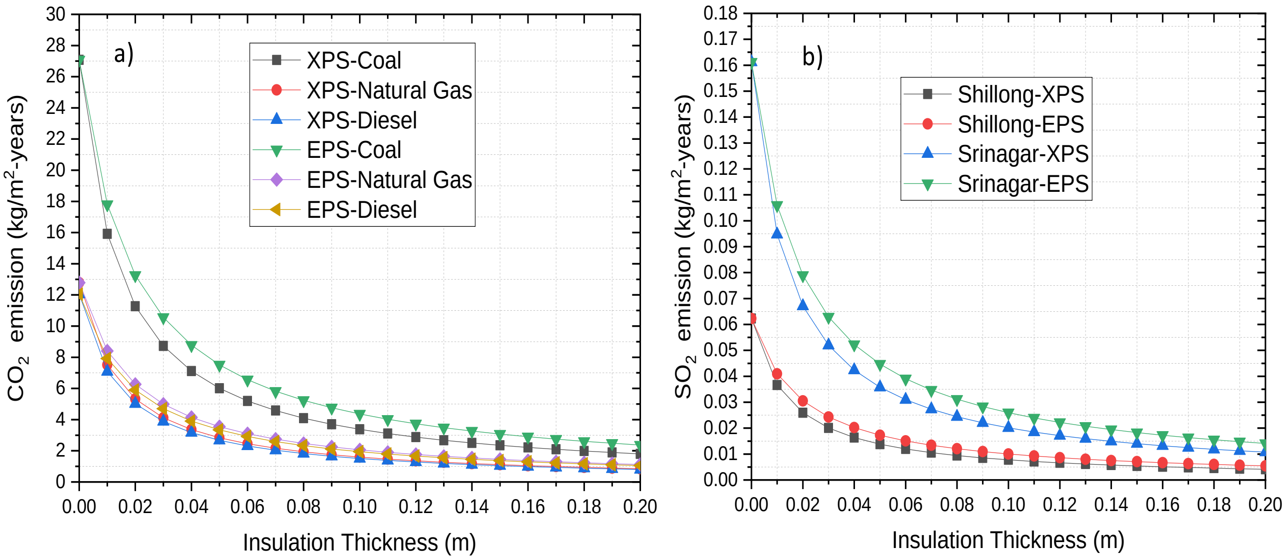

Figure 4. Fuel gas emission–insulation thickness: (**a**) CO_2 (Shillong) (**b**) SO_2-Coal (Shillong and Srinagar).

The optimal values of *a*, *b*, and *c* in Equation (25) were configured using the multiple curve-fitting tool in MATLAB for electricity, natural gas, coal, and diesel separately. For simplicity, we called these configurations Model (26), Model (27), Model (28), and Model (29), respectively.

Table 6 shows these configurations and their results. The results were validated by common statistical methods [42]. The R^2 values of all these correlations statistically varied from 0.9943 to 0.9598; related values were close to ($R \leq 1$). The root mean square error (RMSE) value was 0.0016 at best and 0.0140 at least because of the high harmony between the estimated and computed values. The sum of squares error (SSE) value was 2.209×10^{-5} at best and 1.96×10^{-4} at least. The ideal was zero in these two statistical methods (RMSE ≥ 0) -(SSE ≥ 0). Both the RMSE and SSE values were close to zero, and they gave consistent results. Figure 5 illustrates graphs of the optimal insulation thicknesses of the used insulating (XPS and EPS) materials, as computed by Equation (14) for different fuels.

Table 6. Developed model regression constants.

Fuel	Model	a	b	c	R^2	SSE	RMSE
Electricity	26	−0.1039	4.161	1.823×10^{-5}	0.9943	3.443×10^{-5}	0.0016
Natural gas	27	−0.05929	2.061	1.549×10^{-5}	0.9604	3.08×10^{-5}	0.0055
Coal	28	−0.05079	1.689	1.329×10^{-5}	0.9598	2.209×10^{-5}	0.0047
Diesel	29	−0.1509	6.089	3.934×10^{-5}	0.9661	1.96×10^{-4}	0.0140

The results obtained with the configurations of Equation (16) for electricity, natural gas, coal, and diesel (electricity: Model (26); natural gas: Model (27); coal: Model (28); diesel: Model (29)) were compared with previous works [14,15] and the reference values computed for different climate regions [17,19,33,43–45]. The comparison results are reported in Table 7. The heat map in Table 7 shows how close the computed thicknesses in each row were to the optimal thickness (reference value). These values in each row are the absolute values of the differences between the computed thicknesses and the reference value, i.e., errors of the model. Red shows the lowest error, green shows the highest error, and yellow shows the average error. Sisman's model always had the highest error, while the others had similar errors in most cases. The mean errors of our model, Mahlia's model [14], and Sisman's model [15] for the instances in which we trained our model (instances 1–28 in Table 7) were 0.0713, 0.807, and 6.3, respectively. The mean errors of these models on the other cases in which we tested our model (cases 29–60 in Table 7) were 1.136, 2.023, and 10.868, respectively. When we considered all the instances in the table, the mean errors were 0.639, 1.456, and 8.737, respectively. The results show that Sisman's model performs poorly in all the cases we tested, while others (Mahlia's and our model) performed relatively well. When one compares our model with Mahlia's model considering their mean errors, one can see that our model is superior to Mahlia's model. Furthermore, this superiority was not only in the training instances but also in the testing instances.

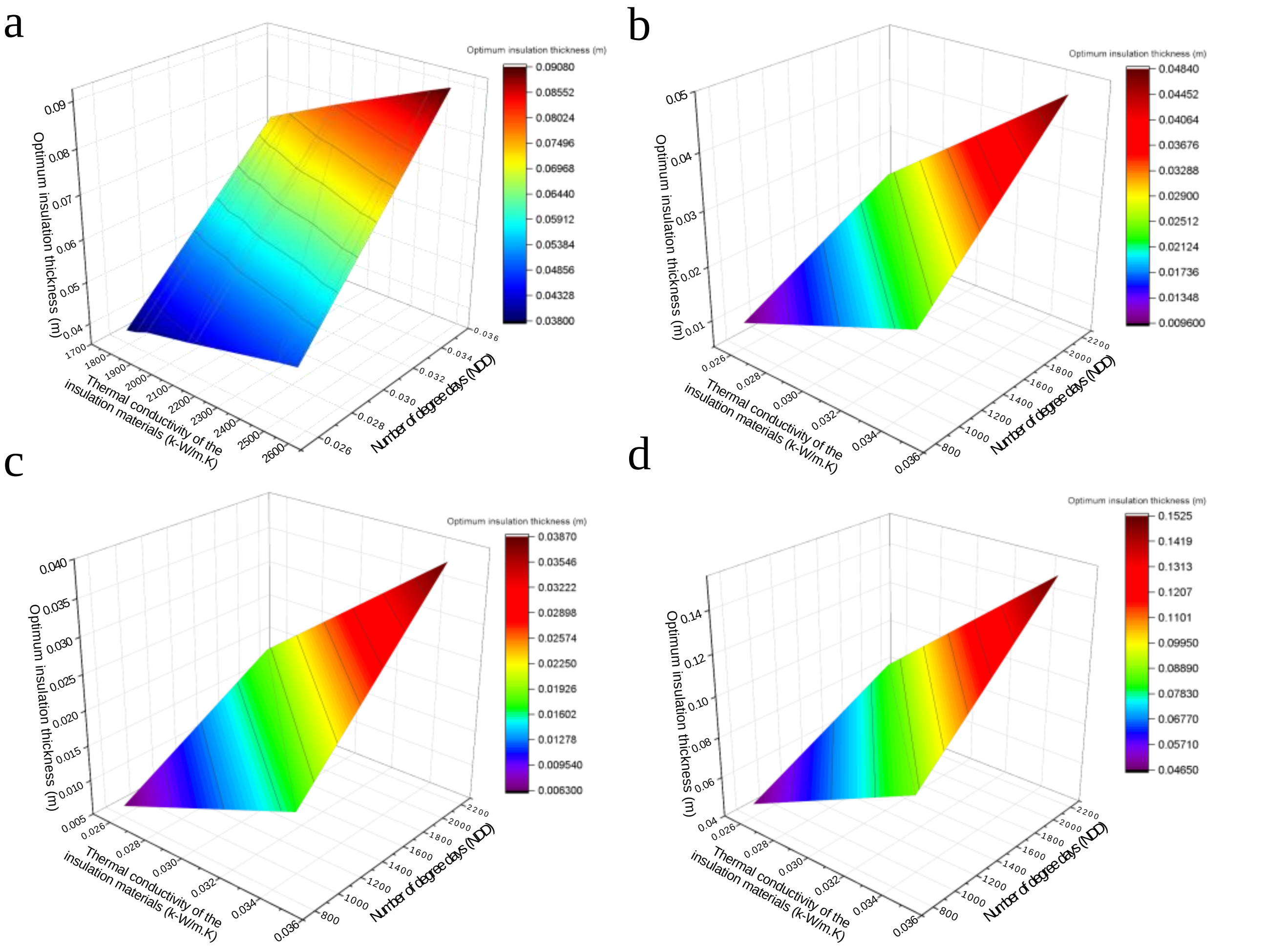

Figure 5. Optimal insulation thickness and k-NDD values: (**a**) electricity; (**b**) natural gas; (**c**) coal; (**d**) diesel.

Table 7. Relative error statistical results of reference results with estimated models.

Case	Location		Reference							Ref. Value	Relative Error (Er) %		
											Developed Model (Low)	Previous Models (Mid)	(High)
	Country	City	Reference	Climate	NDD	Process	Fuel	Material	k (W/m·K)	x_{opt} (m)	Developed Eq. for Corresponding Fuel	Mahlia et al. [14]	Sisman et al. [15]
1	India	Jaisalmer	Present Study	Bwh	2565	Cooling	Electricity	XPS	0.0260	0.0484	0.0536	0.0047	6.6422
2	India	Jaisalmer	Present Study	Bwh	2565	Cooling	Electricity	EPS	0.035	0.0908	0.0261	0.3736	3.0736
3	India	Kota	Present Study	Bsh	2123	Cooling	Electricity	XPS	0.026	0.0428	0.0033	0.1255	6.4946
4	India	Kota	Present Study	Bsh	2123	Cooling	Electricity	EPS	0.035	0.0809	0.0064	0.2969	2.965
5	India	Mumbai	Present Study	Aw	2092	Cooling	Electricity	XPS	0.026	0.0424	0.0006	0.1361	6.4819
6	India	Mumbai	Present Study	Aw	2092	Cooling	Electricity	EPS	0.035	0.0802	0.0048	0.2908	2.9555
7	India	Chennai	Present Study	Aw	2485	Cooling	Electricity	XPS	0.026	0.0475	0.0429	0.0141	6.6034
8	India	Chennai	Present Study	Aw	2485	Cooling	Electricity	EPS	0.035	0.0891	0.0238	0.3616	3.0534
9	India	Bhubaneswar	Present Study	Aw	1895	Cooling	Electricity	XPS	0.026	0.0401	0.0327	0.2013	6.3431
10	India	Bhubaneswar	Present Study	Aw	1895	Cooling	Electricity	EPS	0.035	0.0754	0.011	0.2456	2.9053
11	India	New Delhi	Present Study	Aw	1791	Cooling	Electricity	XPS	0.026	0.0382	0.0342	0.261	6.3874
12	India	New Delhi	Present Study	Aw	1791	Cooling	Electricity	EPS	0.035	0.0728	0.021	0.2187	2.8764
13	India	Lucknow	Present Study	Cwa	1842	Cooling	Electricity	XPS	0.026	0.0389	0.0277	0.2383	6.4096
14	India	Lucknow	Present Study	Cwa	1842	Cooling	Electricity	EPS	0.035	0.0741	0.0157	0.2324	2.8898
15	India	Patna	Present Study	Cwa	1791	Cooling	Electricity	XPS	0.026	0.0382	0.0342	0.261	6.3874
16	India	Patna	Present Study	Cwa	1791	Cooling	Electricity	EPS	0.035	0.0728	0.021	0.2187	2.8764
17	India	Srinagar	Present Study	Bwk	2109	Heating	Natural gas	XPS	0.026	0.0242	0.1142	0.9906	12.189
18	India	Srinagar	Present Study	Bwk	2109	Heating	Natural gas	EPS	0.035	0.0483	0.0577	0.1776	5.6081
19	India	Srinagar	Present Study	Bwk	2109	Heating	Coal	XPS	0.026	0.0188	0.1251	1.5623	15.9773
20	India	Srinagar	Present Study	Bwk	2109	Heating	Coal	EPS	0.035	0.0387	0.0606	0.4698	7.2474
21	India	Srinagar	Present Study	Bwk	2109	Heating	Diesel	XPS	0.026	0.0834	0.0837	0.4224	2.827
22	India	Srinagar	Present Study	Bwk	2109	Heating	Diesel	EPS	0.035	0.1522	0.0461	0.6263	1.0971
23	India	Shillong	Present Study	Am	815	Heating	Natural gas	XPS	0.026	0.0097	0.2866	3.9661	15.0769
24	India	Shillong	Present Study	Am	815	Heating	Natural gas	EPS	0.035	0.0227	0.122	1.5057	5.8699
25	India	Shillong	Present Study	Am	815	Heating	Coal	XPS	0.026	0.0063	0.3722	6.6463	23.7534
26	India	Shillong	Present Study	Am	815	Heating	Coal	EPS	0.035	0.0168	0.1403	2.3857	8.2825
27	India	Shillong	Present Study	Am	815	Heating	Diesel	XPS	0.026	0.0465	0.1511	0.0359	2.3537
28	India	Shillong	Present Study	Am	815	Heating	Diesel	EPS	0.035	0.0873	0.0799	0.3485	0.7863
29	Libya	Tripoli	[43]	Csa	492	Cooling	Electricity	EPS	0.037	0.069	0.1452	0.127	0.5453
30	Turkey	Adana	[33]	Csa	874	Heating	Natural gas	XPS	0.024	0.069	0.9462	0.3093	1.3823
31	Turkey	Adana	[33]	Csa	874	Heating	Natural gas	EPS	0.035	0.069	0.6176	0.1757	1.3823
32	Turkey	Adana	[33]	Csa	874	Heating	Natural gas	Glass wool	0.05	0.024	1.3874	2.9438	5.849
33	Turkey	Adana	[33]	Csa	874	Heating	Natural gas	Rock wool	0.048	0.035	0.5193	1.5124	3.6965
34	Turkey	Adana	[33]	Csa	874	Heating	Natural gas	Polyurethane	0.017	0.05	1.2143	0.0014	2.2875
35	Turkey	Adana	[33]	Csa	874	Heating	Coal	XPS	0.031	0.048	0.7253	0.0774	2.4245
36	Turkey	Adana	[33]	Csa	874	Heating	Coal	EPS	0.044	0.017	1.0671	3.4737	8.6692
37	Turkey	Adana	[33]	Csa	874	Heating	Coal	Glass wool	0.061	0.031	1.0598	3.5427	4.3025

Table 7. *Cont.*

Case	Location		Reference							Ref. Value	Relative Error (Er) % — Developed Model	Previous Models	
											Low	Mid	High
	Country	City	Reference	Climate	NDD	Process	Fuel	Material	k (W/m·K)	x_{opt} (m)	Developed Eq. for Corresponding Fuel	Mahlia et al. [14]	Sisman et al. [15]
38	Turkey	Adana	[33]	Csa	874	Heating	Coal	Rock wool	0.059	0.044	0.3745	1.9833	2.7358
39	Turkey	Adana	[33]	Csa	874	Heating	Coal	Polyurethane	0.022	0.061	1.0331	0.2187	1.6947
40	Palestine	Jericho	[44]	Csa	1989	Cooling	Electricity	Polystyrene	0.038	0.059	0.5325	0.0527	4.1762
41	Palestine	Hebron	[44]	Dfb	456	Cooling	Electricity	Polystyrene	0.038	0.022	1.8404	1.8231	3.5769
42	Palestine	Jerusalem	[44]	Csa	768	Cooling	Electricity	Polystyrene	0.038	0.049	0.3913	0.2675	2.0433
43	Palestine	Tulkarem	[44]	Csa	1066	Cooling	Electricity	Polystyrene	0.038	0.057	0.2913	0.0896	2.3492
44	Palestine	Gaza	[44]	Bsh	1097	Cooling	Electricity	Polystyrene	0.038	0.062	0.1962	0.0017	2.1463
45	Palestine	Bethelem	[44]	Csa	971	Cooling	Electricity	Polystyrene	0.038	0.053	0.3561	0.1719	2.3573
46	Palestine	Jenin	[44]	Csa	1399	Cooling	Electricity	Polystyrene	0.038	0.068	0.1716	0.0866	2.4454
47	Palestine	Nablus	[44]	Csa	854	Cooling	Electricity	Polystyrene	0.038	0.052	0.3412	0.1944	2.1064
48	Turkey	Ağrı	[45]	Dsb	4423	Heating	Coal	XPS	0.031	0.0261	1.3123	0.9815	20.3638
49	Turkey	Ağrı	[45]	Dsb	4423	Heating	Natural gas	XPS	0.031	0.0314	1.3284	0.6471	16.7578
50	Turkey	Aydın	[45]	Csa	1213	Heating	Coal	XPS	0.031	0.0022	7.0408	22.508	94.6422
51	Turkey	Aydın	[45]	Csa	1213	Heating	Natural gas	XPS	0.031	0.005	3.6781	9.3435	41.0826
52	Turkey	Elazığ	[45]	Dsa	2653	Heating	Coal	XPS	0.031	0.019	0.9383	1.722	18.9686
53	Turkey	Elazığ	[45]	Dsa	2653	Heating	Natural gas	XPS	0.031	0.0182	1.5108	1.8416	19.8463
54	Turkey	Kocaeli	[45]	Cfa	1786	Heating	Coal	XPS	0.031	0.0113	1.2394	3.5768	23.9209
55	Turkey	Kocaeli	[45]	Cfa	1786	Heating	Natural gas	XPS	0.031	0.0106	2.044	3.879	25.5666
56	India	-	[19]	Hot and humid	1288	Cooling	Electricity	XPS	0.036	0.028	1.476	1.0891	6.8622
57	India	-	[19]	Hot and dry	1111	Cooling	Electricity	XPS	0.036	0.031	1.1323	0.8869	5.3529
58	India	-	[19]	Composite	1121	Cooling	Electricity	XPS	0.036	0.031	1.1382	0.8869	5.396
59	India	Dehradun	[17]	Cfa	3587	Heating	Natural gas	XPS	0.033	0.057	0.1278	0.0519	7.3542
60	India	Dehradun	[17]	Cfa	3587	Heating	Natural gas	EPS	0.031	0.073	0.1758	0.2915	5.5231

4. Conclusions and Recommendations

The current study examined how different insulation materials and fuel types affected commercial and domestic building cooling and heating performances in different climatic zones of India. The following conclusions can be drawn from the current study:

- For sites situated in hot and dry, warm and humid, and composite climatic regions, the ranges of XPS insulation thickness, annual savings, and payback period for these regions were found as 0.0382–0.0484 m, 10.83–17.47 $/m^2, and 1.93–2.36 years, respectively. Similarly, these ranges for EPS insulation thickness, annual savings, and payback period were 0.0728–0.0908 m, 12.79–19.9347 $/m^2, and 1.49–1.79 years, respectively.
- For sites situated in cold climatic regions, the ranges of XPS insulation thickness, annual savings, and payback period were 0.0097–0.0834 m, 0.29–51.73 $/m^2, and 1.24–6.52 years, respectively. The ranges for EPS insulation thickness, annual savings, and payback period were 0.0168–0.1522 m, 0.68–55.92 $/m^2, and 0.95–4.85 years, respectively.
- The ranges of GHG emissions for XPS material with natural gas, coal, and diesel fuels were 9.67–11.28 kg/m^2-year, 27.12–32.68 kg/m^2-year, and 2.89–4.51 kg/m^2-year, respectively. Similarly, the ranges of GHG emissions for EPS material with natural gas, coal, and diesel fuels were 5.39–9.17 kg/m^2-year, 9.47–23.75 kg/m^2-year, and 2.26–3.43 kg/m^2-year, respectively.
- The optimal insulation thickness for XPS material was lower than that of EPS material, while the payback period and annual savings for XPS material were greater and lower, respectively, than those of EPS material in all the circumstances.

- XPS was proved to be more effective than EPS, and the correlations obtained could aid in the determination of optimal insulation thickness for a specific location based on the number of degree days.

The study showed that using insulation on building exterior walls led to significant annual savings and had a payback period of less than five years, making it economically feasible. The study also found that increasing insulation thickness reduced GHG emissions from heating fuels. Future research can determine the best insulation thicknesses for different climate zones and materials.

Author Contributions: Conceptualization, M.A.K., A.Y. and A.S.; Data curation, M.A.K., A.Y. and A.S.; Investigation, M.A.K., A.Y., A.S. and R.K. Methodology, M.A.K., A.Y. and R.K., Software, M.A.K., A.Y., A.S. and R.K., Visualization, M.A.K., A.S. and T.S., Writing—original draft, M.A.K., A.Y. and A.S. Writing—review and editing, M.A.K., A.M., D.D., T.A. and T.S., Validation, A.Y. and A.S., Resources, A.M., D.D., T.A. and T.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Data available on request.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Am	tropical monsoon climate
Aw	tropical savanna climate
Bsk	cold semi-arid (steppe) climate
$C_{A.C}$	annual cooling energy cost ($/m^2-year)
$C_{A.H}$	annual heating energy cost ($/m^2-year)
C_i	cost of insulation in ($/m^3)
CDD	cooling degree days (°C-days)
C_f	price of fuel ($/kg; $/m^3)
Csa	hot summer mediterranean climate
Csb	warm summer mediterranean climate
C_T	total cost ($)
CO_2	carbon dioxide
Dbf	warm summer humid continental climate
E_A	annual energy requirement (J/m^2-year)
EPS	expanded polystyrene
g	inflation rate
HDD	heating degree days (°C-days)
H_u	heating value of fuel (J/kg; J/m^3; J/kwh)
i	interest rate
k	thermal conductivity of insulation material (W/m K)
LCA	lifecycle cost analysis
M	molar weight of fuel
m_{fA}	amount of fuel consumed per year (kg/m^2-year)
N	lifetime (years)
NDD	number of (degree days (°C-days)
p_b	payback period (years)
PWF	present worth factor
q	heat loss (MJ m^2 year^{-1})
q_A	annual heat loss in unit area (J/m^2-year)
r	actual interest rate
R_i	inside air film thermal resistances (m^{2}K/W)
R_{izo}	thermal resistance of insulation layer (m^{2}K/W)
R_o	outside air film thermal resistance (m^{2}K/W)
R_{TW}	sum of Ri.Rw.Ro (m^{2}K/W)
R_w	total thermal resistance of wall materials without insulation (m^{2}K/W)
S_A	annual savings ($/m^2)
SO_2	sulfur dioxide
U	overall heat transfer coefficient (W/m^{2}K)
x	thickness of insulation material (m)
x_{opt}	optimum insulation thickness (m)
XPS	extruded polystyrene
Greek letters	
η	heating system efficiency
ΔT	temperature difference (°C)
Subscripts	
A	annual
C	cooling
H	heating
i	inside
izo	insulation
o	outside
opt	optimum
t	total
w	wall

References

1. Kallioğlu, M.A.; Ercan, U.; Avcı, A.S.; Fidan, C.; Karakaya, H. Empirical Modeling between Degree Days and Optimum Insulation Thickness for External Wall. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**, *42*, 1314–1334. [CrossRef]
2. Altun, A.F. Determination of Optimum Building Envelope Parameters of a Room Concerning Window-to-Wall Ratio, Orientation, Insulation Thickness and Window Type. *Buildings* **2022**, *12*, 383. [CrossRef]
3. Wang, H.; Huang, Y.; Yang, L. Integrated Economic and Environmental Assessment-Based Optimization Design Method of Building Roof Thermal Insulation. *Buildings* **2022**, *12*, 916. [CrossRef]
4. Shaik, S.; Gorantla, K.; Ghosh, A.; Arumugam, C.; Maduru, V.R. Energy Savings and Carbon Emission Mitigation Prospective of Building's Glazing Variety, Window-to-Wall Ratio and Wall Thickness. *Energies* **2021**, *14*, 8020. [CrossRef]
5. Skaar, C.; Gaarder, J.-E.; Bunkholt, N.S.; Sletnes, M. Energy Upgrading of Basement Exterior Walls: The Good, the Bad and the Ugly. *Buildings* **2023**, *13*, 133. [CrossRef]
6. Kallioğlu, M.A.; Sharma, A.; Chinnasamy, V.; Chauhan, R.; Singh, T. Optimum Insulation Thickness Assessment of Different Insulation Materials for Mid-Latitude Steppe and Desert Climate (BSH) Region of India. *Mater. Today Proc.* **2020**, *44*, 4421–4424. [CrossRef]
7. Xu, H.; Ding, J.; Li, T.; Mu, C.; Gu, X.; Wang, R. A Study on Optimum Insulation Thickness in Walls of Chinese Solar Greenhouse for Energy Saving. *Agronomy* **2022**, *12*, 1104.
8. Nyers, J.; Kajtar, L.; Tomić, S.; Nyers, A. Investment-Savings Method for Energy-Economic Optimization of External Wall Thermal Insulation Thickness. *Energy Build.* **2015**, *86*, 268–274. [CrossRef]
9. Liu, X.; Chen, Y.; Ge, H.; Fazio, P.; Chen, G. Determination of Optimum Insulation Thickness of Exterior Wall with Moisture Transfer in Hot Summer and Cold Winter Zone of China. *Procedia Eng.* **2015**, *121*, 1008–1015. [CrossRef]
10. Yuan, J.; Farnham, C.; Emura, K.; Alam, M.A. Proposal for Optimum Combination of Reflectivity and Insulation Thickness of Building Exterior Walls for Annual Thermal Load in Japan. *Build. Environ.* **2016**, *103*, 228–237. [CrossRef]
11. Dombaycı, Ö.A. The Environmental Impact of Optimum Insulation Thickness for External Walls of Buildings. *Build. Environ.* **2007**, *42*, 3855–3859. [CrossRef]
12. Kaynakli, O.; Bademlioglu, A.H.; Ufat, H.T. Determination of Optimum Insulation Thickness for Different Insulation Applications Considering Condensation. *Teh. Vjesn.* **2018**, *25*, 32–42.
13. Bolattürk, A. Determination of Optimum Insulation Thickness for Building Walls with Respect to Various Fuels and Climate Zones in Turkey. *Appl. Therm. Eng.* **2006**, *26*, 1301–1309. [CrossRef]
14. Mahlia, T.M.I.; Taufiq, B.N.; Masjuki, H.H. Correlation between Thermal Conductivity and the Thickness of Selected Insulation Materials for Building Wall. *Energy Build.* **2007**, *39*, 182–187. [CrossRef]
15. Sisman, N.; Kahya, E.; Aras, N.; Aras, H. Determination of Optimum Insulation Thicknesses of the External Walls and Roof (Ceiling) for Turkey's Different Degree-Day Regions. *Energy Policy* **2007**, *35*, 5151–5155. [CrossRef]
16. Shanmuga Sundaram, A.; Bhaskaran, A. Optimum Insulation Thickness of Walls for Energy-Saving in Hot Regions of India. *Int. J. Sustain. Energy* **2014**, *33*, 213–226. [CrossRef]
17. Mishra, S.; Usmani, J.A.; Varshney, S. Energy Saving Analysis in Building Walls through Thermal Insulation System. *Int. J. Eng. Res. Appl.* **2012**, *2*, 128–135.
18. Raza, A.; Aggarwal, V. Evaluation of Optimum Insulation Thickness for Cost Saving of Wall Design in India. Available online: https://www.researchsquare.com/article/rs-1565499/v1.pdf (accessed on 13 October 2022).
19. Singh, H.K.; Prakash, R.; Shukla, K.K. Economic Insulation Thickness of External Walls in Hot and Composite Regions of India. In Proceedings of the Global Conference on Renewable Energy GCRE2016, Patna, India, 4–6 March 2016; p. 6.
20. Clark, H.; Wu, H. The Sustainable Development Goals: 17 Goals to Transform Our World. In *Furthering Work United Nations*; UN: New York, NY, USA, 2016; pp. 36–54.
21. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger Climate Classification Updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
22. Rubel, F.; Brugger, K.; Haslinger, K.; Auer, I. The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. *Meteorol. Z.* **2017**, *26*, 115–125. [CrossRef]
23. JRC Photovoltaic Geographical Information System (PVGIS)—European Commission. Available online: https://re.jrc.ec.europa.eu/pvg_tools/en/#MR (accessed on 15 February 2022).
24. Szokolay, S. *Introduction to Architectural Science*; Routledge: London, UK, 2012.
25. Shehadi, M. Energy Consumption Optimization Measures for Buildings in the Midwest Regions of USA. *Buildings* **2018**, *8*, 170. [CrossRef]
26. Kon, O.; Caner, İ. The Effect of External Wall Insulation on Mold and Moisture on the Buildings. *Buildings* **2022**, *12*, 521. [CrossRef]
27. Aditya, L.; Mahlia, T.M.I.; Rismanchi, B.; Ng, H.M.; Hasan, M.H.; Metselaar, H.S.C.; Muraza, O.; Aditiya, H.B. A Review on Insulation Materials for Energy Conservation in Buildings. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1352–1365. [CrossRef]
28. Standard, T. 825 (TS 825). In *Thermal Insulation in Buildings*; Official Gazette (23725): Ankara, Turkey, 1999; Volume 14.
29. Nellis, G.; Klein, S. *Heat Transfer*; Cambridge University Press: Cambridge, UK, 2008; ISBN 1-139-47661-0.
30. Qian, X.; Lee, S.W.; Yang, Y. Heat Transfer Coefficient Estimation and Performance Evaluation of Shell and Tube Heat Exchanger Using Flue Gas. *Processes* **2021**, *9*, 939. [CrossRef]

31. Statistics, E.; Central Statistics Office, Ministry of Statistics and Programme Implementation. Govt. India New Delhi (22nd Issue) 2015. Available online: www.mospi.gov (accessed on 8 February 2022).
32. Cengel, Y. *Heat and Mass Transfer: Fundamentals and Applications*; McGraw-Hill Higher Education: Columbus, OH, USA, 2014.
33. Kurekci, N.A. Determination of Optimum Insulation Thickness for Building Walls by Using Heating and Cooling Degree-Day Values of All Turkey's Provincial Centers. *Energy Build.* **2016**, *118*, 197–213. [CrossRef]
34. Llantoy, N.; Chàfer, M.; Cabeza, L.F. A Comparative Life Cycle Assessment (LCA) of Different Insulation Materials for Buildings in the Continental Mediterranean Climate. *Energy Build.* **2020**, *225*, 110323. [CrossRef]
35. Hasan, A. Optimizing Insulation Thickness for Buildings Using Life Cycle Cost. *Appl. Energy* **1999**, *63*, 115–124. [CrossRef]
36. Inflation Rate in India 1984–2024. Available online: https://www.statista.com/statistics/271322/inflation-rate-in-india/ (accessed on 16 August 2020).
37. SBI—Loans, Accounts, Cards, Investment, Deposits, Net Banking—Personal Banking. Available online: https://sbi.co.in/ (accessed on 23 February 2021).
38. Yildiz, A.; Gurlek, G.; Erkek, M.; Ozbalta, N. Economical and Environmental Analyses of Thermal Insulation Thickness in Buildings. *J. Therm. Sci. Technol.* **2008**, *28*, 25–34.
39. Ozel, M. Cost Analysis for Optimum Thicknesses and Environmental Impacts of Different Insulation Materials. *Energy Build.* **2012**, *49*, 552–559. [CrossRef]
40. Asadi, S.; Amiri, S.S.; Mottahedi, M. On the Development of Multi-Linear Regression Analysis to Assess Energy Consumption in the Early Stages of Building Design. *Energy Build.* **2014**, *85*, 246–255. [CrossRef]
41. Chapra, S.C.; Canale, R.P. *Numerical Methods for Engineers*; McGraw-Hill Higher Education: Boston, MA, USA, 2010.
42. Qian, X.; Lee, S.; Soto, A.; Chen, G. Regression Model to Predict the Higher Heating Value of Poultry Waste from Proximate Analysis. *Resources* **2018**, *7*, 39. [CrossRef]
43. Alghoul, S.K.; Gwesha, A.O.; Naas, A.M. The Effect of Electricity Price on Saving Energy Transmitted from External Building Walls. *Energy Res. J.* **2016**, *7*, 1–9. [CrossRef]
44. Alsayed, M.F.; Tayeh, R.A. Life Cycle Cost Analysis for Determining Optimal Insulation Thickness in Palestinian Buildings. *J. Build. Eng.* **2019**, *22*, 101–112. [CrossRef]
45. Ucar, A.; Balo, F. Effect of Fuel Type on the Optimum Thickness of Selected Insulation Materials for the Four Different Climatic Regions of Turkey. *Appl. Energy* **2009**, *86*, 730–736. [CrossRef]