Garrido-Píriz *et al.*
Energy, Sustainability and Society (2022) 12:40
https://doi.org/10.1186/s13705-022-00367-z

Energy, Sustainability and Society

RESEARCH

Open Access

A stochastic approach to feasibility analysis of boiler replacement in educational buildings in Extremadura (Spain)

Pablo Garrido-Píriz, Gonzalo Sánchez-Barroso and Justo García-Sanz-Calcedo*

Abstract

Background: Energy efficiency in buildings must be increased in order to reduce both energy intensity and greenhouse gas emissions. This study proposed the replacement of existing diesel boilers with biomass boilers, using four fuels (bulk pellets, wood chip, olive kernel and milled nutshell) to meet the energy demands of educational buildings in the region of Extremadura (Spain). High uncertainty surrounds biomass price prediction affecting the accuracy of economic feasibility analyses; thus, stochastic processes are suitable to support an improvement in the accuracy of predictions. The objective of the study is to demonstrate the feasibility of replacing diesel boilers with biomass boilers in order to revalorize agroforestry residues.

Results: A stochastic simulation of the feasibility of replacing oil-fired boilers with biomass-fired boilers was carried out in this research. Up to 20 million possible scenarios of 10 years of fuel price evolution were simulated by Monte Carlo method based on empirical price trends data. Regression models were built to relate Net Present Values with discount rates, whose statistical dependency was significant. Predictions on financial indicators showed biomass fuels as the most profitable investment, rather than fuel oil. Specifically, in this study, milled nutshell was found the most profitable fuel in the simulation runs, with Net Present Value = 27,151.09 € (standard deviation = 7939.88 €) and Internal Rate of Return = 16.9% (standard deviation = 3.4%).

Conclusions: Continuing to use oil-fired boilers costs more than the purchase and operation of new biomass-fired boilers, since the latter produce a higher cumulative cash flow than the initial investment within the next years. The payback period lies within the range of 4 to 6 years depending on the type of biomass fuel. Getting on the path to sustainability in education buildings can reduce up to 94.4% GHG emissions. This research contributes to promoting the use of low-emission fuels to meet the energy demand of educational buildings. Its results will have a positive effect in the region of Extremadura (Spain), as it boosts the appreciation of agro-industrial waste and economically strengthens the sector.

Keywords: Biomass, Monte Carlo method, Educational buildings, GHG emissions, Sustainability

Background

Buildings are responsible for 40% of the energy demand in the European Union [1]. Actions aimed at satisfying energy demands with renewable resources drive global policies on energy [2, 3]. Specifically, the substitution of oil-fired equipment by other fed by biomass fuels is considered in the Green Deal regarding the Zero Emissions 2050 Long-Term Strategy in Europe [4].

Within the significantly large public real estate sector, there are a large number of educational buildings whose energy consumption is highly substantial [5]. In this context, European laws have been started to demand lately

*Correspondence: jgsanz@unex.es
University of Extremadura, Badajoz, Spain

that new public buildings should perform a nearly zero energy consumption [6]. In the near future, existing buildings must be renovated, since public administrations are required to renew annually at least 3% of total floor area of the buildings whose built surface exceed 500 m^2 [7].

Educational buildings' sustainability can be improved through the renewal of equipment and facilities, substituting fossil-fed boilers by other efficient and renewable technologies such as biomass boilers. Educational buildings will play an outstanding role on the low-carbon economy mainly based on nearly zero-energy buildings [8].

Biomass is being used to satisfy the energy needs of buildings, either in the form of firewood, wood chips or pellets, whose origin can be direct production or agroforestry residues [9]. It was determined that replacing conventional oil-fired thermal systems by systems fed with agroforestry residues had beneficial economic and environmental implications [10]. Replacing oil-fired boilers with gasoil in Spanish households reduced non-renewable primary energy consumption by 92.3% and CO_2 emissions by 93.8%, although primary energy consumption increased by 7.2% [11]. A case study demonstrated the sustainability of sourcing local biomass for self-sustaining thermal energy systems in Spain. [12].

Literature review

Many studies characterized the energy consumption in educational buildings around the world. For educational centres in Madrid (Spain), in an urban environment, lighting and air conditioning were the major contributions. Each one stood for 26% of the total energy consumption, and the third-largest contribution referred to other equipment (20%) [13]. In Taiwan, it was observed that the annual thermal energy consumption ratio was 20.1 kWh/m^2 and 465 kWh/student [14]. In South Korea, most of the energy consumption share referred to the electric equipment and heating systems, due to the trend of implementing electric equipment in HVAC systems, from which 92 MJ/m^2/year (25.55 kWh/m^2/year) corresponded to diesel and 325 MJ/m^2/year to natural gas [15]. In Cyprus, it was concluded that the energy intensity in educational buildings was 62.75 kWh/m^2/year, from which 38.59 kWh/m^2/year corresponded to thermal uses [16].

In Portuguese schools, a total consumption of 67 kWh/m^2 was quantified, and 16 kWh/m^2 of the total consumption referred to the gas contribution [17]. In Ireland, the average heat consumption in schools was 53 kWh/m^2/year [18]. Thermal consumption in Greek schools was estimated at 68 kWh/m^2/year [19]. It was indicated that it was possible to reduce energy consumption by up to 28.75% combining different actions such as increasing walls thicknesses and improving airtightness [20]. Heating energy demand is naturally higher in colder climates. For example, in Norway, the total heating demand for district heating was 72 kWh/m^2/year [21], while in Finland it was 104 kWh/m^2/year [22].

The feasibility of implementing abatement strategies to reduce CO_2 emissions was also studied, achieving a reduction in carbon emissions of 20.8%, by increasing the cost of the infrastructure by 2.2% being implementing biomass boilers one of the key measures [23]. Besides, it was concluded that pellet boilers in small-scale residential energy systems were well perceived by users, both economically and in terms of emissions [24].

All fuel prices are usually regulated by a combination of heterogeneous factors that depend on geographical aspects, a country's development level and energy policies. In Spain, the prices of petroleum-derived fuels are influenced by international markets and regulated by the Ministry of Industry [25]. However, the prices of biomass fuels are not controlled by the authorities, and they are subjected only to the market regulation [26]. In this uncertain context, in which a multitude of interrelated socioeconomic and seasonal factors determine the evolution of biomass prices, the results of the economic feasibility analyses may not adequately predict the profitability of related investments. Thus, stochastic processes are suitable to support an improvement in the accuracy of predictions.

The Monte Carlo method has been widely used to configure possible future scenarios and to evaluate the profitability of investments. A Monte Carlo simulation was applied to calculate the Net Present Value (NPV) and the Levelized Cost of Energy (LCOE) to find the profitability of investing in state-of-the-art nuclear power plants over the next few years [27]. Stochastic simulations were also carried out to predict the price of methanol generated throughout the life cycle of a production plant [28]. Economic considerations related to reusing wastewater with the purpose of helping to reduce water scarcity were made using Monte Carlo [29]. The future development of drainage technology was evaluated through the estimation of the NPV using the prediction of the oil price based on random simulations [30]. Finally, different investment alternatives were assessed to improve the energy efficiency of buildings, trying to maximize the NPV [31].

This study is relevant, because it proposes using low-emission fuels to meet the energy demand of educational buildings. Furthermore, promoting biomass will have a positive effect in the region of Extremadura (Spain), as it boosts the appreciation of agro-industrial waste and economically strengthens the sector.

Multiple future scenarios are considered using the well-established Monte Carlo method to cover and extrapolate the situations to a large sample of possible cases. The study can be applied to other educational buildings, as well as to buildings in other sectors that are supplied by oil-fired boilers.

The main objective of this study is to carry out a quantitative analysis using random variables simulations on multi-fuel biomass boilers feasibility. This work will assist policymakers and managers in making investment decisions on substituting diesel thermal facilities in education institutions. This paper will contribute to the global reduction of GHG emissions as evidence and will be useful to assess and reduce the environmental impact of educational buildings.

Methods

At first, sampled educational buildings and their corresponding energy consumption were characterized, and the cost of undertaking a change in the heating technology was assessed for each building. Then, the evolution of the available fuel prices over a 5-year period was characterized. The gathered information set the boundary conditions to apply Monte Carlo method and simulate 2000 scenarios of future prices for each fuel, considering fuel prices variations as random variables. A random variable is considered to be a variable of an experiment not yet performed that can take different values depending on the boundary conditions. These results were used to obtain the value of the economic viability parameters corresponding to each investment. It was possible to characterize the economic viability parameters for the period of 10 years, using a Monte Carlo method. The study included 2000 simulations of the economic viability parameters. Each simulation combined 2000 subsequent simulations for each interannual price variation rate. Those simulations were applied for each fuel: diesel, pellet, wood chip, olive kernel and milled nutshell. The study was composed by 20 million simulations, carried out in a spreadsheet, simulating the different random variables in order to explore multiple scenarios.

The methodology workflow is shown in Fig. 1. The educational buildings in the sample and their energy consumption were identified, evaluating the cost of investment in biomass-based technology. Subsequently, the evolution of available fuel prices was characterized. The compiled information defined the boundary conditions to apply the Monte Carlo method and simulate 2000 future price scenarios for each fuel, considering price variations as random components over a 10-year future horizon. The study included 2000 simulations of the economic feasibility parameters, which combined 2000 subsequent simulations for each year-to-year price variation rate for each fuel: diesel, pellet, wood chip, olive

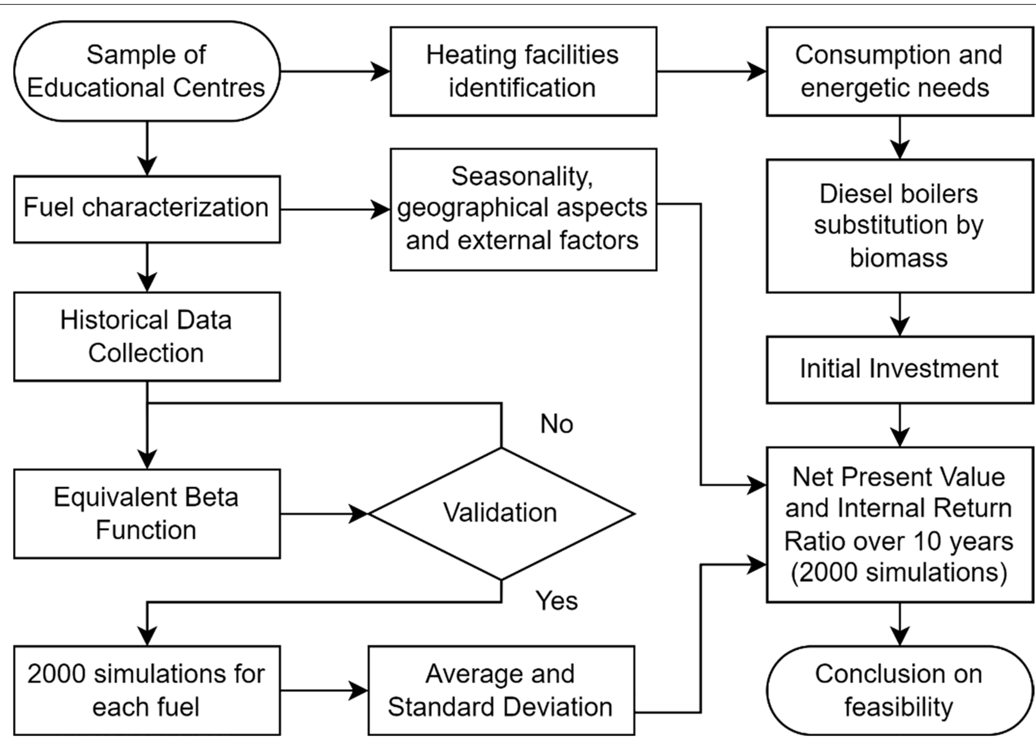

Fig. 1 Methodology workflow

kernel and milled nutshell. Therefore, 20 million cases were simulated in the study using ad hoc spreadsheets. A sufficiently large number of simulations were considered to obtain convergent and realistic values within a reasonable uncertainty.

Study area and sampled buildings characterization

The energy consumption of 12 educational buildings in Extremadura (Spain) was analysed during the period 2016–2020. Extremadura is a region in southwestern Spain bordering Portugal. The Mediterranean climate is the dominant one in Extremadura, which is softened by the advection of maritime air masses from the Atlantic. The energy generation mix in Extremadura is mainly based on nuclear technology and covers peak demand with renewable energy (hydro, solar, wind and biomass).

Extremadura has 966 schools in operation, of which 113 are privately owned and the rest are public. The vast majority use diesel boilers for both heating and DHW. The items in the sample have characteristics that represent all the educational buildings in the region that had a diesel boiler for heating and DHW. Built area, number of students, annual energy consumption and boiler performance can be classified into three representative population groups: large, medium, and small. Average annual thermal consumption during the period 2016–2020, technical characteristics of the boiler and functional parameters of each building are shown in Table 1. The audit was conducted in accordance with the standard EN 16247-2:2014 [32], establishing the requirements, methodology and deliverables for an energy audit of a building.

The annual energy consumption of the analysed centres depended mainly on the characteristics, construction features and size, although the operating time of use, the boiler fuel, and the weather conditions were similar among centres. The operating regime for all the boilers was from October to March, with an average of 20 days a month for 5 h/day, depending on the actual operating conditions. For each building, the energy demand was obtained from an energy audit, on base of the boiler size.

The buildings of the sample had one or two built floors above ground, with a constructed area of between 1000 and 2000 m^2 per floor—depending on the number of students—with external enclosures with the following constructive characteristics: double brickwork with air chamber, rendering on the outside and plaster on the inside, flat roof and floor slab. All the selected buildings used diesel as fuel to satisfy their thermal needs.

The replacement of diesel boilers by commercial biomass boilers was proposed after analysing the energy consumption profile of each educational building. The boilers were chosen from a range of biomass multi-fuel boilers, so their nominal power could satisfy the thermal needs of the sample of educational buildings. When selecting the new heat generators, Spanish thermal regulations were complied with [33]. The characteristics of the commercial boilers are shown in Table 2.

All boilers consisted of a steel boiler body with a cast iron burner which used a mechanical feeding system. The boiler gate was designed so that the inspection and cleaning was adequate, while maintaining insulation. The feed hopper had a variable range of volumes, depending on the power of the boiler. A screw conveyor transports fuel inside the device, and other elements were three smoke passages and air controls in both the primary circuit and the secondary circuit. The boiler working pressure could rise up to 3 bar and its efficiency could reach performances of up to 97.4%.

Table 1 Educational buildings features of the sample

ID	Built area (m^2)	Students	Annual consumption (kWh)	Boiler performance (%)	Annual energy costs (€)	Annual maintenance costs (€)
EB01	3029	63	89,820	80	7102.84	404.19
EB02	3785	460	49,900	88	3946.02	202.10
EB03	4227	427	99,800	88	7892.04	404.19
EB04	2155	243	89,820	80	7102.84	404.19
EB05	642	140	39,920	82	3156.82	161.68
EB06	6994	81	191,342	90	15,131.06	947.14
EB07	2652	172	95,671	92	7565.53	430.52
EB08	1736	199	146,462	86	11,582.01	724.99
EB09	2573	222	85,648	80	6772.92	423.96
EB10	2770	101	69,840	90	5522.85	314.28
EB11	3447	233	79,241	90	6266.27	356.58
EB12	1517	321	104,720	86	8281.11	706.86

Table 2 Features of the range of biomass boilers

Parameter	Value
Effective power (kW)	80–400
Boiler body	Steel
Burner	Cast iron
Maximum pressure (bar)	3
Hopper volume (l)	190–3800
Performance (%)	88.5–97.4

A screw conveyor supplies fuel to the boiler at the appropriate speed to ensure adequate internal thermal conditions. The auger was designed to work with all sizes of biomass analysed in this work. Therefore, the screw conveyor will allow the multi-fuel boiler to be supplied with the different biomass fuels without the risk of clogging. Boilers can be fed by different solid fuels, but not simultaneously. In order to change fuels, minor adjustments have to be made. The diagram of the biomass-fired heating system at educational buildings is shown in Fig. 2.

Apart from the boiler investment and assembly, other complementary elements such as silos, chimneys and filters were considered. The biomass boilers were sized so that they could satisfy the same thermal needs as in the previous scenario in which diesel was used. A slight superior performance was also found in biomass boilers in comparison to diesel boilers, especially with assessing the old ones, since they provided additional brute energy savings.

Fuel characterization

The defining parameters of the available biomass fuels are shown in Table 3: lower heating value (LHV), density (ρ), diameter (D), length (L), wet basis moisture content (M_w), sulphur (S) and ash content (Ψ), which are obtained through subjecting fuels to common thermal

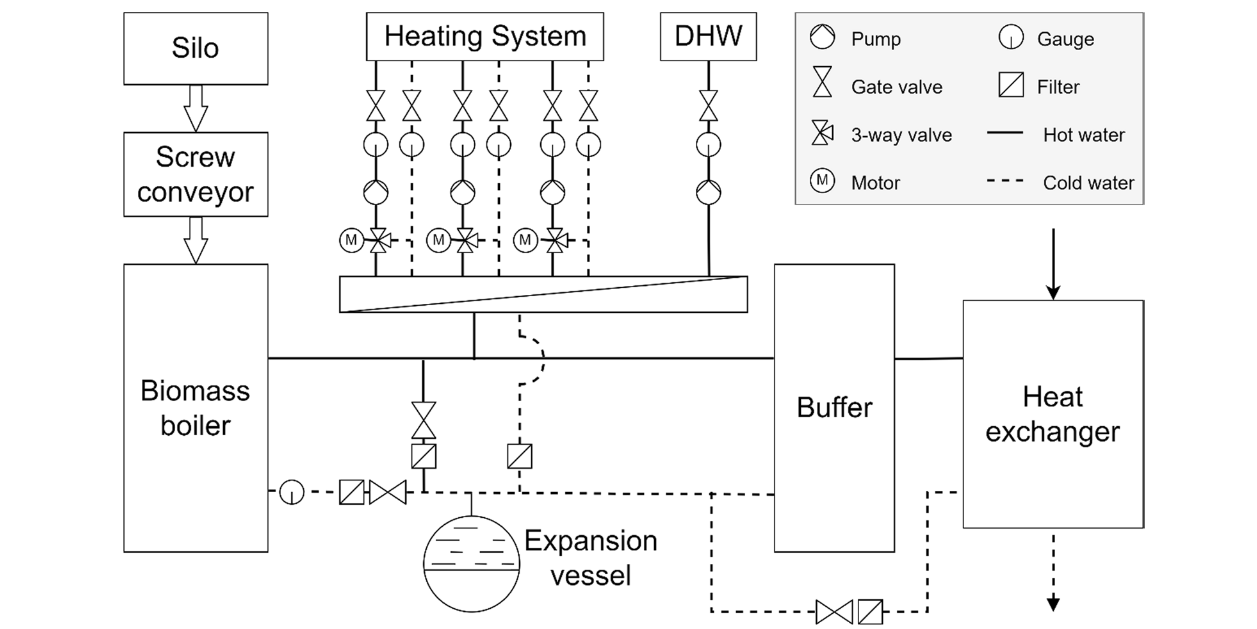

Fig. 2 Diagram of the biomass-fired heating system

Table 3 Solid biofuels composition in Spain. Source: [35]

Fuel	LHV (kWh/kg)	ρ (kg/m^3)	D (mm)	L (mm)	M_w (%)	S (%)	Ψ (%)	Fixed carbon (%)	Volatile matter (%)
Bulk pellets	4.7–5.3	1000–1400	4–10	< 40	< 12	≤ 0.04	< 1.5	48.1	85.3
Wood chip (class 1)	2.8–4.4	200–320	–	≤ 63	20–45	≤ 0.20	≤ 3.0	46.6	89.1
Olive kernel	5.0–5.3	650–700	–	3–5	7–12	≤ 0.01	≈ 3.5	21.9	76.4
Milled nutshell	4.4–5.3	470	–	< 30	8–15	–	–	34.9	76.1

LHV: low heating value, ρ: density, D: diameter, L: length, M_w: moisture content, S: sulphur content and Ψ: ash content processes [34]. For each fuel, typical parameters in commercial fuels in Spain are shown [35].

The maintenance cost depends mainly on the type of fuel used. Oil-fired boilers have lower maintenance costs because the combustion generates hardly any ash. However, solid fuel has a high percentage of ash that must be removed frequently.

In addition, the composition of some types of biomasses is heterogeneous, which can lead to maintenance cost overruns. Biomass for energy production—bulk pellets and wood chips—have regulated parameters such as calorific value, humidity, dimensions, ash content, chlorine, density and traceability, among others [36]. However, agroforestry by-products and residues such as olive kernels and dried milled nut shells are not regulated, and their composition is indicative. Therefore, maintenance costs are higher for biomass boilers.

Periodic maintenance is required for biomass boilers due to ash and non-combusted elements and slugging appearance, which is not applicable to diesel boilers. It was reasonable that maintenance cost of solid-fuel-fed boilers ranked higher than those fed by liquid fuels, due to non-combusted elements and ash that need to be removed frequently. In addition, maintenance costs are linked to the heterogeneity of the fuel, especially in biomass. Biomass aimed at energy production—bulk pellets and wood chip—had regulated parameters of humidity, dimensions, ash content, chlorine content, density, and the origin of the fuel, among others. Subproducts like olive kernels and dried milled nut shells are regulated by national and international standards [36].

Costs associated with maintenance depend on several factors and can be expressed as a function of the consumption. These values were considered: 0.0045 €/kWh for diesel boilers, 0.0120 €/kWh for pellets and wood chip and 0.0150 €/kWh for olive kernel and milled nutshell. This data was obtained based on previous studies [37]. It seemed logical that the boilers fed with solid biofuels required a more intensive maintenance regime (ash removal, filter cleaning, etc.), compared to those fed with liquid fuel, as the combustion of the latter is way cleaner.

Based on historical data, the monthly price variation for diesel [25] and the trimestral price variation for biofuels [26] were obtained for the 2016–2020 period. This information would serve as an input for the stochastic simulation to evaluate possible future scenarios.

Stochastic simulation

The historical data on fuel prices evolutions were approximated to an equivalent beta distribution. The beta distribution is a type of probability distribution that can be fitted to the shape of a histogram of data. This approximation takes the original shape of the dataset and serves as boundary conditions to generate random scenarios with a similar probability distribution. This ensures that the random simulations are appropriate for the sample. Consequently, historical data served as an input to the simulations, and it established the limits to estimate the future price of fuels.

The NPV depends on the rates of change of fuels, initial investment, and cash flow. The rate of change of fuel prices in future years is unknown but has been simulated based on historical data. Therefore, the NPV data are affected by the uncertainty of fuel price variation. Through this analysis, the fluctuation of the possible price variations for different fuels was modelled to determine a reasonable discount rate with an acceptable margin of uncertainty. The Beta distribution function is shown in Eq. (1):

$$B(\alpha, \beta) = \int_a^b x^{\alpha-1}(1-x)^{\beta-1}dx, \tag{1}$$

where x is a random variable associated with the price of each fuel (in €), between the minimum and the maximum value it can take according to the data history, and α and β are the shape parameters of the beta distribution.

The shape coefficients α and β were adjusted for each fuel through an iterative process until the beta function resembled the quarterly price variation histogram. There were two leading conditions for the iterative process: (1) matching the mean of the estimated distribution with the mean variation of the data history collection—with no exceptions—and (2) including 95% of the historical data between the lower and upper limits of the beta simulation.

Although there is unavoidable uncertainty in the simulations, the probability density function of the forecasts has a similar shape to the histogram of the historic data. Thus, applying the Monte Carlo method together with the adaptability of the Beta distribution reduces the forecasts to an acceptable level of uncertainty.

Economic feasibility analysis

With this approximation, feasibility was assessed by using the random numbers algorithm. Given that the annual price variation rates were known for each fuel, a discount rate was simulated between 0 and 10% within a uniform probability distribution, and thus feasibility parameters were evaluated.

NPV was considered as a key factor to indicate the investment profitability in a 10-year period. NPV allowed to assess the cash flow subjected to variations such as inflation or the discount rate. For each fuel j, a single NPV was obtained through Eq. (2):

$$\mathrm{NPV}_{n,j} = \sum_{t=1}^{n} \frac{\mathrm{CF}_{j,t}}{(1+k)^t} - I_{o,j}, \quad (2)$$

being $\mathrm{NPV}_{n,j}$ the NPV for each fuel j in n years' time, $\mathrm{CF}_{j,t}$ the cash flow for each year t, k was the discount rate or capital cost, and $I_{o,j}$ was the initial investment of the biomass boiler implementation, depending on the building's energy needs. The initial investment includes the removal of the old diesel boiler, the purchase and installation of the biomass boiler and the adaptation works for the correct operation of the new boiler. No costs are foreseen beyond the storage in the silo of the installation. In the calculation process, an average load regime in the biomass boiler has been considered.

The cash flow $\mathrm{CF}_{j,t}$ was the difference between diesel boilers costs ($C_{D,t}$) and biomass boilers costs for each biofuel j ($C_{j,t}$) and expressed on a yearly basis for each year t. These costs include the operation and maintenance of the installation. Updated costs for each year were defined in Eq. (3) for diesel and for biomass fuels in Eq. (4):

$$C_{D,t} = C_{D,1} \cdot (1 + \mathrm{IR}_D)^t, \quad (3)$$

$$C_{j,t} = C_{j,1} \cdot \left(1 + \mathrm{IR}_j\right)^t \forall j \in \{1, 2, 3, 4\}, \quad (4)$$

where $C_{j,t}$ was the cash flow for the year t, $C_{j,1}$ was the cash flow for the first year, IR_D is the diesel annual variation rate, and IR_j is the annual variation rate for each biomass fuel: (1) bulk pellets, (2) wood chip, (3) olive kernel, and (4) milled nutshell. In addition, the Internal Rate of Return (IRR), as well as the k value which nullifies NPV of Eq. (2).

Up to 2000 iterations were made in order to determine the averaged NPV and a linear regression equation for each case. Later, the adjustment was subjected to revision, assessing whether $R^2 \geq 0.80$. Taking the subsequent 2000 simulations into account to determine a price variation rate for each NPV, and repeating this calculation for each fuel, 20 million simulations were achieved in an ad hoc spreadsheet.

Finally, to determine which fuel was the most suitable regarding the diesel boiler substitution, economic parameters, seasonality, availability, and opportunities of supplying biomass to educational buildings were assessed.

Emissions comparison and energy consumption

Regarding greenhouse gas emissions, CO_2, CO and NO_x emissions were considered as the most significant parameters in these facilities in terms of environmental impact. A comparison was made between the emissions corresponding to centres whose boilers were fed by diesel and the same buildings using biomass-fed boilers. For this study, the well-established conversion factors in Spain shown in Table 4 were taken as a references [38–40], which provides data applicable to energy consumption in the process for the European Energy Mix.

A higher efficiency of biomass boilers compared to oil-fired boilers was considered because the existing ones were older technology and less energy efficient, considering the same thermal demand in both boilers.

Results

Price variation rates

Different rates of variation were simulated from a beta distribution function which is made up of the shape parameters α and β and simulated between lower and upper limits. These limits are set by the minima and maxima in the historical data in the period 2016–2020 within the interval $(\overline{x} - 3\sigma, \overline{x} + 3\sigma)$ for each fuel, where $\overline{x}$ is the average of the variance of each fuel and σ is its standard deviation.

The averaged values from the historical data and their equivalent beta distribution function parameters (shape factors α and β, and limits $\overline{x} + 3\sigma$) are shown in both Table 5 and Fig. 3 for each fuel. On the Y-axis, the frequencies of the distributions are plotted. The left Y-axis represents the frequency according to historical data and the right Y-axis represents the simulated beta distribution. The grey shading shows the probability distribution given by the simulation.

The average annual price variation rate estimated for the target fuels within a 10-year time span is shown in Table 6. The higher variation rate corresponded to milled nutshell, followed up by diesel, olive kernel, bulk pellets and wood chip.

Economic feasibility analysis

The highest change rate is for milled nutshell, followed by olive kernel, diesel, bulk pellets, and finally wood chips. NPV corresponding to the current diesel boilers substitution by boilers fed by each of the listed analysed fuels is shown in Fig. 3. NPV performs a negative slope in each case, showing lower results as the discount rate rises, which can be linked to the Consumer Price Index. The discount rate shows a linear probability distribution between 0 and 10%.

The slope of the linear fits in Fig. 4 determined the volatility of the change rates for the different fuels against different discount rates. The highest slope in absolute value corresponded to milled nutshell, so it had a higher volatility

Table 4 Energy-to-emissions conversion factors. Source: [38–40]

	CO_2 (kg/kWh)	CO (kg/kWh)	NO_x (kg/kWh)
Diesel	0.311	$1.26 \cdot 10^{-4}$	$1.80 \cdot 10^{-5}$
Biomass	0.018	0.040	$2.59 \cdot 10^{-2}$

Table 5 Beta distribution parameters

Combustible	Mean annual inflation rate (5-year span) (%)	Standard deviation (5-year span) (%)	*α*	*β*	Lower limit ($\bar{x} - 3\sigma$) (%)	Upper limit ($\bar{x} + 3\sigma$) (%)
Diesel	3.43	0.23	2.22	2.72	− 3.84	5.39
Bulk pellets	2.20	0.92	0.64	1.09	− 3.73	7.83
Wood chip	0.22	1.10	2.52	1.33	− 11.05	5.90
Olive kernel	4.58	2.49	0.49	0.93	− 6.93	16.64
Milled nutshell	5.01	1.97	3.73	3.30	− 13.47	14.31

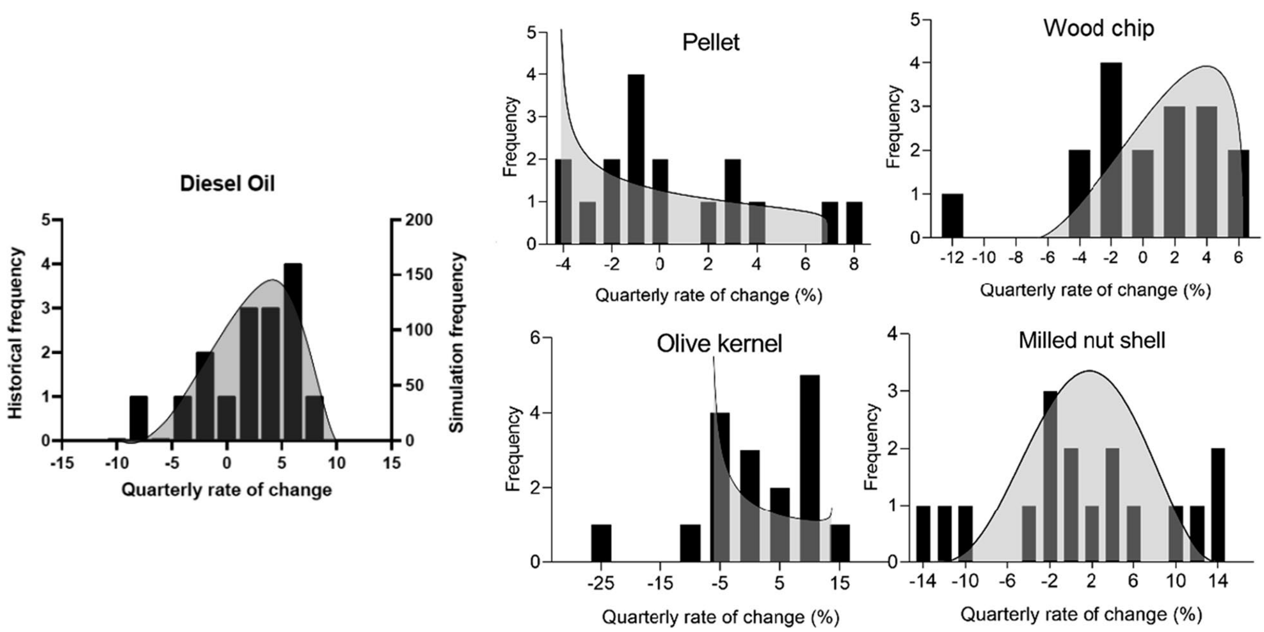

Fig. 3 Fuels historical variations and beta approximation chart

Table 6 Annual price variation rate for each fuel

Fuel	Annual price variation rate	
	Mean (%)	Standard deviation (%)
Diesel	3.82	0.47
Bulk pellets	2.35	0.28
Wood chip	0.32	0.30
Olive kernel	4.85	0.60
Milled nutshell	5.29	0.41

than the rest of the fuels, whereas the wood chip shows more stability in this regard.

The average values of financial indicators related to the investments for each fuel are listed in Table 7. On the one side, milled nutshell performs better average financial outcomes—higher NPV and IRR—although it shows the higher standard deviation. On the other side, bulk pellets perform lower financial outcomes—lower NPV and IRR.

Both aggregate costs and cumulative cash flows related to the biomass alternatives are shown in Fig. 4, considering historical year-to-year price rates against a constant discount rate. It could be proved that aggregate costs in 10 years would be higher if diesel boilers are kept operative. Cumulative cash flow layout showed a comparison of all biomass fuels against a baseline defined by a boiler fed by diesel. In this case, investments were shown to be amortized in between 4 years for milled nutshell and 6 years for bulk pellets.

In Fig. 5a, the aggregate costs of operating boilers with both diesel and biomass alternatives are plotted. The aggregate costs over 10 years are higher if the diesel boilers were kept in operation. In Fig. 5b, the cumulative cash flows of all biomass fuels have been plotted with respect to a diesel boiler set as a reference. In this case,

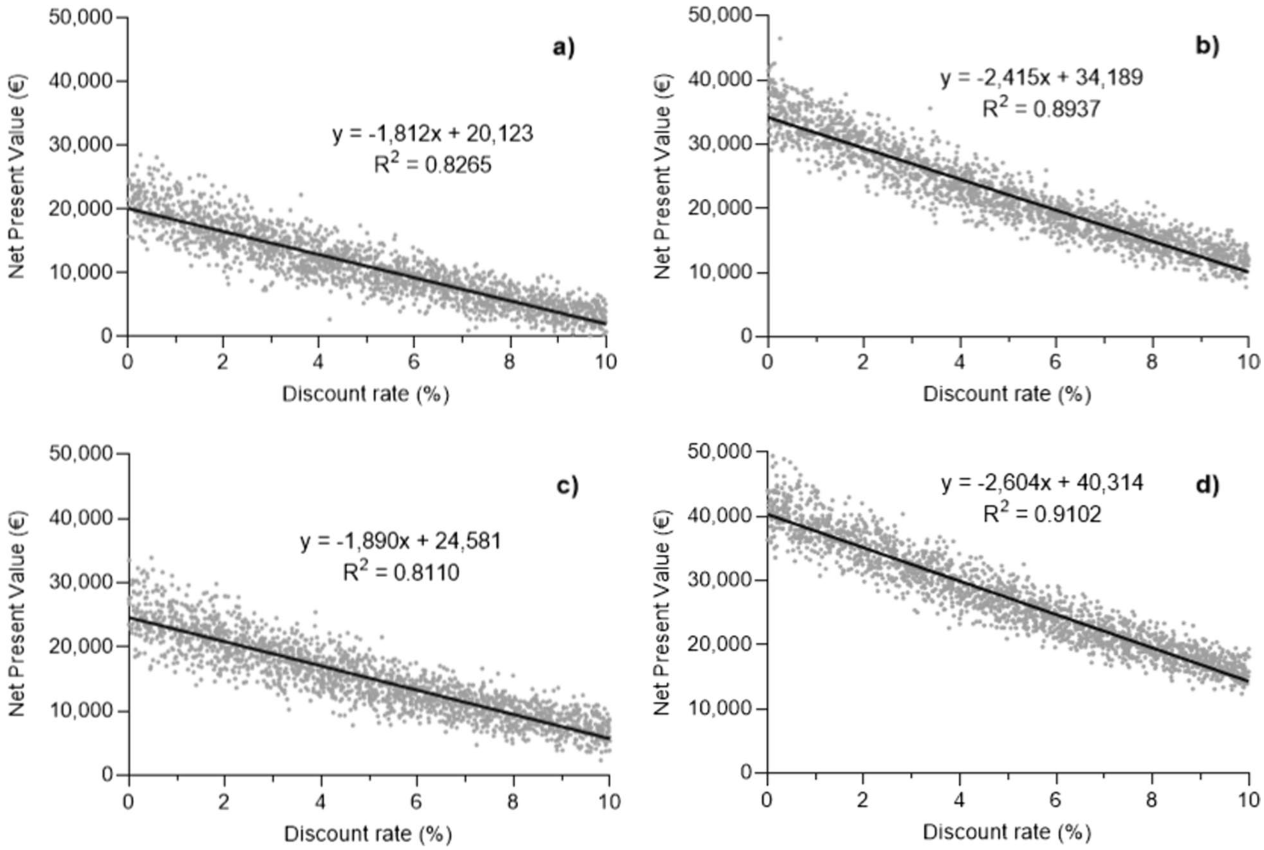

Fig. 4 Estimated Net Present Value for discount rates of **a** bulk pellet, **b** wood chip, **c** olive kernel and **d** milled nutshell

Table 7 Investments financial indicators for each fuel

Biomass fuel	NPV		IRR		Average aggregate operation costs (10-year span)	Average cumulative cash flow
	Mean	Standard deviation	Mean	Standard deviation		(10-year span)
Diesel	–	–	–	–	102,905.70€	–
Bulk pellets	11 051.80€	5683.60€	7.1%	3.2%	78,759.06€	24,146.64€
Wood chip	22 204.55€	7406.49€	13.6%	3.3%	62,795.60€	40,110.10€
Olive kernel	15 174.83€	5953.63€	10.5%	3.3%	67,882.08€	35,023.62€
Milled nutshell	27 151.09€	7939.88€	16.9%	3.4%	60,467.44€	42,438.26€

the investments are amortized over 4 years for milled nutshells and 6 years for bulk pellet.

Emissions into the environment

Assuming the above energy-to-emissions conversion factors, the emissions results are presented in Fig. 6. A 4.03% consumption difference was identified, as new biomass boilers showed a slight better performance than older ones because of aging effects, not because of the fuel source.

For diesel boilers, energy demands showed an annual consumption of 1142.18 MWh, while the same annual heating needs could be achieved with 1096.14 MWh using new biomass boilers. CO_2 emissions could be cut down up to 94.4%, however, CO emissions increased 304-fold and NOx emissions increased 1380-fold.

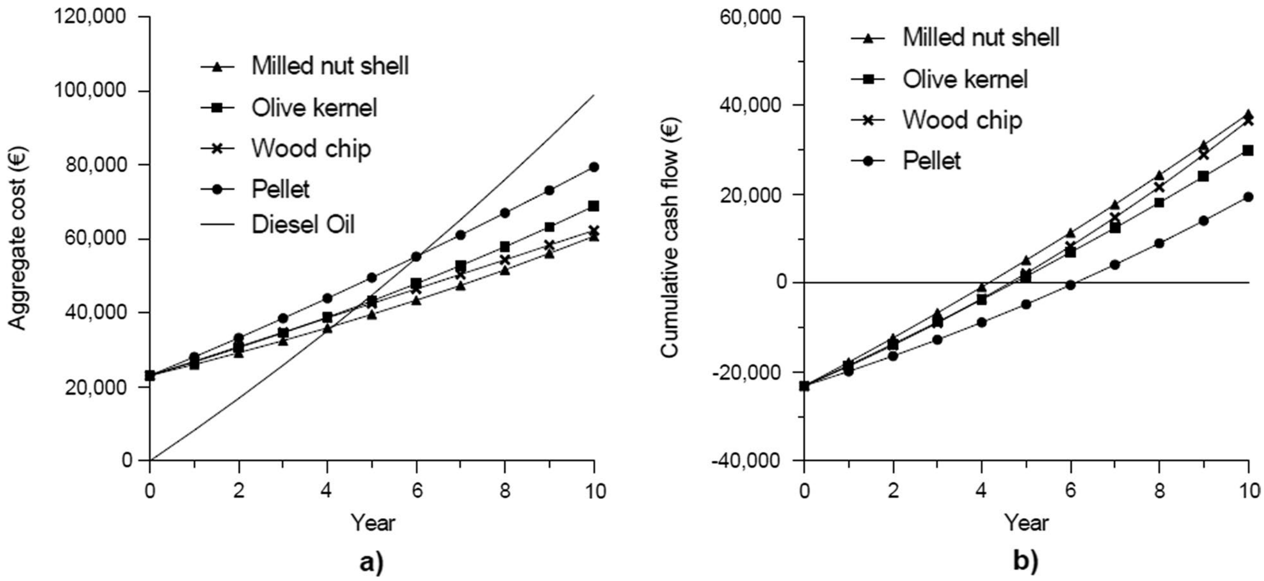

Fig. 5 Average aggregate operation costs (**a**) and average cumulative cash flow using diesel as a baseline (**b**)

Based on the features of the sample of educational buildings, it was obtained that average annual consumption stood for 32.15 kWh/m^2 and 429.07 kWh/student with current diesel boilers, whereas biomass multi-fuel boilers stood for 30.85 kWh/m^2 and 411.77 kWh/student.

Discussion

Among the advantages of the introduction of biomass boilers in educational buildings, it could be found that there was proximity and versatility regarding the biomass fuels procurement, especially in a predominantly rural community where agroforestry residues and tree masses abounded. The key factors of using biomass in school buildings were the close origin of the fuel and the significant cost savings reported [41]. This research was carried out in a predominantly underpopulated rural area. Consuming locally produced fuel was a strategy to attract and set population, as well as maintain the forests' health and enhance the usage of agricultural waste [42].

Biomass boilers modular design allowed solutions to be scaled with a proportional relationship between price and power. Consequently, fuel price was the determining external factor regarding investment profitability, not the scale of the solution. Financial indicators were favourable in all fuel substitution cases, so it would be economically viable to undertake any of the investments. Depending on the fuel, the investment in a biomass thermal facility could be amortized between the 4th and the 6th year depending on the type of fuel.

The sensitivity of the NPV with respect to the update rate was considerably different between the cases. In descending order, the highest sensitivity stood for chipped wood, followed by olive kernel, milled nutshells, and bulk pellets. This could arise as the result of the hypothesis formulation, based on the historical fuel data and the high variability in the evolution of the price of seasonal biomass fuels [43, 44].

The results showed that regardless if the scenario—optimistic with low discount rates or pessimistic with high discount rates—milled nutshell is positioned as the most advantageous alternative, while the bulk pellet yields the worst financial result among the biomass fuels studied.

Despite this, the NPV of the bulk pellet had a lower sensitivity to the variation of the discount rate. In addition, bulk pellet and wood chip supplies were continuous

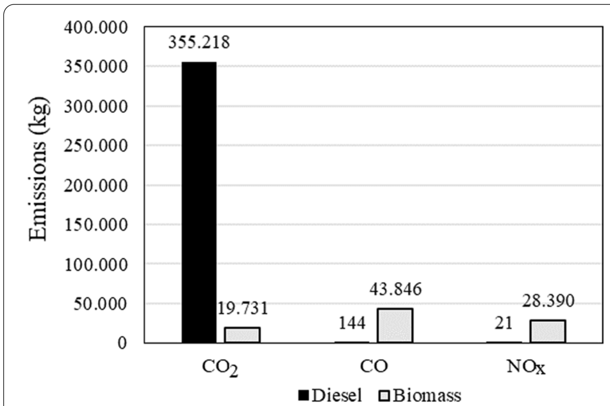

Fig. 6 Comparison of emissions between diesel and biomass fuels

unlike other crop-dependent fuels, so they did not need to be stored in large quantities. In addition, they had more homogeneous physicochemical characteristics than other fuels [45]. This was not the case for nutshells, which, since it is seasonal, required huge storage needs. Plus, physicochemical characteristics were not homogeneous, and transport costs could be entailed if biomass was not produced locally [46]. Notwithstanding, olive kernel production coincides with the heating consumption period. Therefore, this match between supply and demand could be beneficial to reduce the cost due to seasonality.

However, certain disadvantages tied to biomass renewable fuels and benefits of using diesel must be considered. It was pointed out that refined diesel boilers have lower particulate matter emissions—CO and NO_x—than biomass boilers with reduced efficiency, which was especially relevant in public buildings used by people sensitive to pollution [47]. Biomass had to meet quality and traceability standards to ensure that they did not become a source of large-scale pollution and therefore generate a severe impact on people with respiratory and cardiovascular conditions. The problems arising from particulate matter emissions in large biomass boilers could be solved by including electrostatic precipitators for cleaning and filtering the fuel gas, requiring a considerable amount of space for treatment that may not be foreseen in the project and an eventual cost increase [48].

Fire risk in biomass boilers enclosures was relatively high compared to oil-fired installations [49]. A special fire risk must be considered in these installations, as the backfire in the screw conveyor, which connects the boiler and the silo, can be catastrophic. For this reason, these installations incorporate a flap in the biomass boiler to prevent flame flashback [50]. This was mainly due to accumulation of fuel in silos, large volume, and flammability. In order to mitigate the effects of an eventual fire, it was desirable to strictly store the necessary amount of fuel in a short period of time and perform a periodic and continuous fuel supply [51]. This could result in a conflict with the inherent seasonality of agro-industrial waste that could be exploited as biomass.

One of the main difficulties in undertaking the technology change is the need to carry out additional works to adapt current facilities to biomass requirements. Additional works, which were foreseen in the initial investment, consisted of building biomass accumulation silos and equipment to supply fuel, such as screw conveyors. Depending on the building characteristics, the lack of space, lack of conditioning of the boiler room or the obstacle presence could make the initial investment more expensive [52, 53], which would result in a lower profitability of the operation.

Although the results of this work cannot be directly compared with other studies evaluating the replacement of oil-fired boilers by biomass-fired boilers, the findings are similar to other studies carried out for residential buildings in Spain [11] and even for case studies in Chile [54] and Canada [55]. Nevertheless, users were generally willing to switch to biomass boilers even though there were some problems arising from the variance in ash content, fuel moisture or CO emissions, which are especially high if the boiler maintenance is poor [56]. These drawbacks have also been reported in research that has addressed this issue [57].

Apart from investing in thermal equipment replacement, other options regarding reducing environmental impact were improving insulation, optimizing, and adjusting equipment scheduling according to environmental conditions, as well as encouraging a fair use of thermal equipment within the education community. In this line, a methodology was described to identify energy consumption patterns in large buildings and determine optimal insulation and dimensional ratios [58].

The environmental impact of biomass for energy purposes has been widely explored [59], pointing out that using forest waste to compensate for carbon loss associated with the extraction processes is an interesting forestry management option from an environmental and economic point of view [60]. Additionally, olive kernel and milled nutshell revalorization and introduction as an input in biomass supply chain had a very positive impact regarding circular economy [61]. The region where the study has been carried out outstood in agroindustry, and these fuels could be produced close to the consumption points [62]. Biomass boilers were chosen in order to reuse agricultural waste, which is abundant in the study area [42], in addition to meeting heating energy demands with a reduced carbon footprint [63]. These measures could help to meet the energy demands in educational buildings, enhance the agroindustry network, take advantage of the waste, and improve profitability.

The widespread use of biomass fuel on a large scale could lead to an increase in demand, and thus to higher biofuel prices. However, the low current use of biomass for thermal use in the region analysed is an indicator that prices are not expected to increase in the medium term [42]. Future work should aim at monitoring the evolution of the use and price of these fuels for medium-term simulations using the Monte Carlo method under new boundary conditions.

Because the boundary conditions are determined by the availability of data, the study is limited, future lines of research can be directed towards the possibility of hybridization of biomass with other renewable energies. For example, photovoltaic panels can be considered as an auxiliary supply for pressure equipment, solar thermal as a backup for DHW, or lithium-ion batteries for storing surplus electricity production.

Other future lines of work should be aimed at minimizing consumption profiles in schools and other educational buildings, as well as their environmental impact. New fuels beyond bulk pellets, wood chip, olive kernel and milled nutshell such as non-solid biofuels (biogas or biodiesel), alternative fuels (algae or Nymphaeaceae) should be explored.

Conclusions

It was proved that agroindustry waste such as olive kernel and milled nutshell could be seen as a reliable alternative regarding the biomass boiler procurement chain of educational buildings. In a 10-year timespan, it was observed through simulations that a 27,151.09 € NPV could be achieved by using nutshell, considering the standard deviation as 7939.88 €. The estimation on IRR was 16.9% for milled nutshell. Other biomass alternatives showed profitable results. Using wood chip, a 22,204.55 € NPV could be achieved in the same 10-year timespan, with a standard deviation of 7406.49 €. Its main advantages against other biomass fuels were the continuous procurement, the reduction in storage requirements and their homogeneous chemical properties, in contrast with milled nutshell.

It was observed that aggregate costs associated with maintaining diesel boilers operation was higher than any other alternative investments. These investments showed a higher order cumulative cash flow compared to the initial investment, which could be amortized over a 4–6 year period, depending on the biomass fuel. From those results, energy savings of 4.03% could be achieved, and CO_2 emissions could be cut out by 94.4%.

In this line, it was observed that a multi-fuel boiler is an interesting solution regarding not only profitability, but also seasonality. The consumption profile could be characterized with wood chip as a basis and milled nutshell in favourable seasons, although if supply was not possible, olive kernel would be an interesting option depending on the area and the seasonality stage.

This research contributes theoretically by establishing a robust methodological framework for analysing the economic viability of renewable energy investments in the context of high uncertainty of fuel price developments. Furthermore, its practical contributions promote sustainability in public buildings and reaffirm the cost-effectiveness of investments to reduce GHG emissions.

Abbreviations

CF: Cash flow; DHW: Domestic hot water; GHG: Greenhouse gas; HVAC: Heating, ventilation and air conditioning; IRR: Internal Rate of Return; LCOE: Levelized Cost of Energy; LHV: Lower heating value; NPV: Net Present Value.

Acknowledgements

The authors wish to acknowledge the European Regional Development Fund for the financial support to this research.

Author contributions

Conceptualization, JG-SC; data curation, GS-B and PG-P; formal analysis, GS-B and JG-SC; investigation, GS-B, PG-P and JG-SC; project administration, JG-SC; resources, PG-P software, PG-P; supervision, JG-SC; validation, JG-SC; visualization, GS-B; writing—original draft, PG-P. All authors read and approved the final manuscript.

Funding

This research was funded by VI Regional Research, Technological Development and Innovation Plan of the General Government of Extremadura, Grants number GR18029 and GR21098.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 17 May 2022 Accepted: 12 September 2022
Published online: 19 September 2022

References

1. Eurostat (2019) Energy balance guide—Energy consumption in year 2017. European Commission, Brussels
2. The Federal Government of Germany (2016) Climate Action Plan 2050—principles and goals of the German government's climate policy. The Federal Government of Germany, Berlin
3. European Commission (2020) Stepping up Europe's 2030 climate ambition—investing in a climate-neutral future for the benefit of our people. European Commission, Brussels
4. European Commission (2019) The European Green Deal. European Commission, Brussels
5. U. S. Department of Energy (2020) Energy efficiency and renewable energy-building technologies program. US Department of Energy, Washington
6. European Parliament and Council. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).
7. European Parliament and Council. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance. 2012.
8. López-Ochoa LM, Bobadilla-Martínez D, Las-Heras-Casas J, López-González LM (2019) Towards nearly zero-energy educational buildings with the implementation of the Energy Performance of Buildings Directive via energy rehabilitation in cold Mediterranean zones: the case of Spain. Energy Rep 5:1488–1508

9. Perea-Moreno A-J, Perea-Moreno M-Á, Hernandez-Escobedo Q, Manzano-Agugliaro F (2017) Towards forest sustainability in Mediterranean countries using biomass as fuel for heating. J Clean Prod 156:624–634
10. Mateos E, Ormaetxea L (2019) Sustainable renewable energy by means of using residual forest biomass. Energies 12:13
11. Las-Heras-Casas J, López-Ochoa LM, Paredes-Sánchez JP, López-González LM (2018) Implementation of biomass boilers for heating and domestic hot water in multi-family buildings in Spain: Energy, environmental, and economic assessment. J Clean Prod 176:590–603
12. Paredes-Sánchez JP, López-Ochoa LM, López-González LM, Las-Heras-Casas J, Xiberta-Bernat J (2018) Energy utilization for distributed thermal production in rural areas: a case study of a self-sustaining system in Spain. Energy Convers Manag 174:1014–1023
13. Institute for the Diversification and Saving of Energy (2011) Guide to energy saving and efficiency in educational institutions. Institute for the Diversification and Saving of Energy, Madrid
14. Wang JC (2019) Energy consumption in elementary and high schools in Taiwan. J Clean Prod 227:1107–1116
15. Kim T-W, Lee K-G, Hong W-H (2012) Energy consumption characteristics of the elementary schools in South Korea. Energy Build 54:480–489
16. Katafygiotou MC, Serghides DK (2014) Analysis of structural elements and energy consumption of school building stock in Cyprus: energy simulations and upgrade scenarios of a typical school. Energy Build 72:8–16
17. Lourenço P, Pinheiro MD, Heitor T (2014) From indicators to strategies: key performance strategies for sustainable energy use in Portuguese school buildings. Energy Build 85:212–224
18. Hernandez P, Burke K, Lewis JO (2008) Development of energy performance benchmarks and building energy ratings for non-domestic buildings: an example for Irish primary schools. Energy Build 40:249–254
19. Santamouris M, Mihalakakou G, Patargias P, Gaitani N, Sfakianaki K, Papaglastra M et al (2007) Using intelligent clustering techniques to classify the energy performance of school buildings. Energy Build 39:45–51
20. Dimoudi A, Kostarela P (2009) Energy monitoring and conservation potential in school buildings in the C′ climatic zone of Greece. Renew Energy 34:289–296
21. Ding Y, Brattebø H, Nord N (2021) A systematic approach for data analysis and prediction methods for annual energy profiles: an example for school buildings in Norway. Energy Build 247:111160
22. Niemelä T, Kosonen R, Jokisalo J (2016) Cost-optimal energy performance renovation measures of educational buildings in cold climate. Appl Energy 183:1005–1020
23. Alavijeh NM, Steen D, Norwood Z, Tuan LA, Agathokleous C (2020) Cost-effectiveness of carbon emission abatement strategies for a local multi-energy system—a case study of Chalmers university of technology campus. Energies 13:1626
24. Nižetić S, Papadopoulos A, Radica G, Zanki V, Arıcı M (2019) Using pellet fuels for residential heating: a field study on its efficiency and the users' satisfaction. Energy Build 184:193–204
25. Ministry for Ecological Transition and the Demographic Challenge. Historical fuel prices. Madrid; 2020.
26. Institute for the Diversification and Saving of Energy. Biomass for thermal uses price report. Madrid; 2020.
27. Wealer B, Bauer S, Hirschhausen CV, Kemfert C, Göke L (2021) Investing into third generation nuclear power plants—review of recent trends and analysis of future investments using Monte Carlo Simulation. Renew Sustain Energy Rev 143:110836
28. Puig-Gamero M, Trapero JR, Pedregal DJ, Sánchez P, Sanchez-Silva L (2021) Impact of the forecast price on economic results for methanol production from olive waste. Fuel 295:120631
29. Garcia X, Pargament D (2015) Reusing wastewater to cope with water scarcity: economic, social and environmental considerations for decision-making. Resour Conserv Recycl 101:154–166
30. Rui Z, Wang X, Zhang Z, Lu J, Chen G, Zhou X et al (2018) A realistic and integrated model for evaluating oil sands development with Steam Assisted Gravity Drainage technology in Canada. Appl Energy 213:76–91
31. Kumbaroğlu G, Madlener R (2012) Evaluation of economically optimal retrofit investment options for energy savings in buildings. Energy Build 49:327–334
32. European Standards. EN 16247-2:2014 energy audits—part 2: buildings. 2014.
33. Ministry of Energy. Regulation of thermal installations in buildings (RITE). Government of Spain. 2013.
34. Skoulou V, Swiderski A, Yang W, Zabaniotou A (2009) Process characteristics and products of olive kernel high temperature steam gasification (HTSG). Bioresour Technol 100:2444–2451
35. Institute for the Diversification and Saving of Energy. Technical guide—Thermal biomass installations in buildings. Madrid; 2009.
36. International Organization for Standardization. ISO 17225 Solid biofuels—fuel specifications and classes.
37. Karras T, Brosowski A, Thrän D (2022) A Review on supply costs and prices of residual biomass in techno-economic models for Europe. Sustainability 14:7473
38. Ministry of Industry (2016) CO2 emissions factors and coefficients of transition to primary energy of different final energy sources consumed in the building sector in Spain. Ministry of Industry, Madrid
39. Edwards R, Hass H, Larivé J-F, Lonza L, Mass H, Rickeard D et al (2013) Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Publication Office of the European Union, Luxembourg
40. Environmental Protection Agency. Greenhouse gas emission factors hub. 2022.
41. Skinner RG (2012) A tale of two biomass boilers. Energy Eng 109:24–52
42. López-Rodríguez F, García Sanz-Calcedo J, Moral-García FJ (2019) Spatial analysis of residual biomass and location of future storage centers in the Southwest of Europe. Energies (Basel) 12:1978
43. Giuliano A, Poletto M, Barletta D (2016) Process optimization of a multi-product biorefinery: the effect of biomass seasonality. Chem Eng Res Des 107:236–252
44. Titus BD, Brown K, Helmisaari H-S, Vanguelova E, Stupak I, Evans A et al (2021) Sustainable forest biomass: a review of current residue harvesting guidelines. Energy Sustain Soc 11:10
45. Wang T, Zhai Y, Zhu Y, Li C, Zeng G (2018) A review of the hydrothermal carbonization of biomass waste for hydrochar formation: process conditions, fundamentals, and physicochemical properties. Renew Sustain Energy Rev 90:223–247
46. Golecha R, Gan J (2016) Biomass transport cost from field to conversion facility when biomass yield density and road network vary with transport radius. Appl Energy 164:321–331
47. Rector L, Miller PJ, Snook S, Ahmadi M (2017) Comparative emissions characterization of a small-scale wood chip-fired boiler and an oil-fired boiler in a school setting. Biomass Bioenergy 107:254–260
48. Jaworek A, Sobczyk AT, Marchewicz A, Krupa A, Czech T (2021) Particulate matter emission control from small residential boilers after biomass combustion. A review. Renew Sustain Energy Rev 137:110446
49. Al-Kassir A, Coelho P, García-Sanz-Calcedo J, Moral F, Kassir Al-Karany R, Yusaf T (2018) An experimental technology of drying and clean combustion of biomass residues. Appl Sci 8:905
50. Webb E, Chambers J, Webster K (2018) Addressing fire risk in biomass storage. Resour Magaz 25:47
51. National Fire Protection Association (2018) NFPA 1—fire prevention code. National Fire Protection Association, Quincy
52. Nunes LJR, Causer TP, Ciolkosz D (2020) Biomass for energy: a review on supply chain management models. Renew Sustain Energy Rev 120:109658
53. Stupak I, Mansoor M, Smith CT (2021) Conceptual framework for increasing legitimacy and trust of sustainability governance. Energy Sustain Soc 11:5
54. Niklitschek ME, Labbé R, Guerrero J (2020) Heating and hot water with wood chips Is it convenient to replace firewood boilers in southern Chile? Energy Sustain Dev 55:24–31
55. Buss J, Mansuy N, Laganière J, Persson D (2022) Greenhouse gas mitigation potential of replacing diesel fuel with wood-based bioenergy in an arctic Indigenous community: a pilot study in Fort McPherson, Canada. Biomass Bioenergy 159:106367
56. Macek K, Endel P, Cauchi N, Abate A (2017) Long-term predictive maintenance: a study of optimal cleaning of biomass boilers. Energy Build 150:111–117
57. Proszak-Miąsik D, Rybak-Wilusz E, Rabczak S (2020) Ecological and financial effects of coal-fired boiler replacement with alternative fuels. J Ecol Eng 21:1–7

58. Capozzoli A, Grassi D, Causone F (2015) Estimation models of heating energy consumption in schools for local authorities planning. Energy Build 105:302–313
59. Gómez-García E (2021) Estimation of primary forest harvest residues and potential bioenergy production from fast-growing tree species in NW Spain. Biomass Bioenergy 148:106055
60. Repo A, Ahtikoski A, Liski J (2015) Cost of turning forest residue bioenergy to carbon neutral. For Policy Econ 57:12–21
61. Ingrao C, Bacenetti J, Bezama A, Blok V, Goglio P, Koukios EG et al (2018) The potential roles of bio-economy in the transition to equitable, sustainable, post fossil-carbon societies: findings from this virtual special issue. J Clean Prod 204:471–488
62. Duque-Acevedo M, Belmonte-Ureña LJ, Batlles-delaFuente A, Camacho-Ferre F (2022) Management of agricultural waste biomass: a case study of fruit and vegetable producer organizations in southeast Spain. J Clean Prod 359:131972
63. Mohamed A, Hasan A, Sirén K (2014) Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. Appl Energy 114:385–399

Publisher's Note