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Composting Heat Recovery for Residential Consumption: An Assessment of Viability

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Abstract: The European heating sector is currently heavily dominated by fossil fuels. Composting is a naturally occurring process in which heat is liberated from the composting substrate at a higher rate than the process needs to support itself. This difference could be harnessed for low-heat applications such as residential consumption, alleviating some of the impacts fossil fuel emissions represent. In this study, the composting heat recovery reported in the literature was compared to the energy demand for space and water heating in four European countries. A review of potential heat production from the waste representative of the residential sector was performed. We found that the theoretically recoverable composting heat does not significantly reduce the need for district heating. However, it can significantly reduce the energy demand for water heating, being able to supply countries such as Greece with between 36% and 100% of the yearly hot water demand, or 12% to 53% of the yearly hot water of countries such as Switzerland, depending on the efficiency of heat recovery.

Keywords: household; compost; heat; recovery; MSW; CO_2

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1. Introduction

Emissions of greenhouse gases have risen uncontrollably since the Industrial Revolution [1]. Burning fossil fuels and the industrial processes that came with the Industrial Revolution led to accelerated CO_2 emissions. Developing countries represent about 80% of the world's population, yet barely represent one-quarter of cumulative global emissions since the Industrial Revolution [2]. Recent studies suggest an intimate relationship between GDP growth and the growth of anthropocentric emissions [3]. It seems that development, often measured by indexes that include values akin to GDP [4], is also therefore tied to increases in CO_2 emissions since increases in emissions can be projected from economic growth [5]. The complication arises with a limited emission quota, the responsibility developed countries might have, and the requirements for development [6]. Rising temperature-stabilization scenarios require emissions to be reduced to zero [6]. As such, all aspects need to be considered, among them residential heat.

According to Polcyn et al. [7], of the total final energy consumed in 2018 in Europe (including but not limited to space and water heating), 26% was used in the residential sector. Almost 49% of this energy came from fossil sources, 37.2% from natural gas, 10.3% from oil products, and about 1.3% from coal [8]. The total final energy consumed in Denmark, Greece, Poland, and Switzerland for the year 2020 can be seen in Tables 1–4, respectively.

This energy consumption, due to its reliance on fossil fuels, produces greenhouse gas emissions [9–11]. The emissions measured in Denmark, Greece, Poland, and Switzerland for the years 2000, 2010, and 2021 can be seen in Figure 1 [12,13]. Despite the reductions achieved, recent studies indicate an increasing trend of world emissions of up to 2200% from pre-industrial emissions by 2040 [14].

Table 1. Final energy consumption in Mtoe of Denmark for the year 2020 [8].

(Mtoe)	Industry	Transport	Residential	Other	Non-Energy Use
Oil	0	0	0	0	0
Oil products	0.45	3.63	0.18	0.46	0.22
Coal	0.1	0	0	0	0
Natural gas	0.67	0.01	0.59	0.24	0
Biofuels and waste	0.2	0.24	0.79	0.11	0
Electricity	0.74	0.04	0.94	0.96	0
Heat	0.09	0	1.58	0.77	0
Solar/tide/wind Geothermal	0	0	0.01	0	0

Table 2. Final energy consumption in Mtoe of Greece for the year 2020 [8].

(Mtoe)	Industry	Transport	Residential	Other	Non-Energy Use
Oil	0	0	0	0	0
Oil products	0.69	4.91	1.29	0.46	0.45
Coal	0.16	0	0	0	0
Natural gas	0.5	0.02	0.44	0.14	0.38
Biofuels and waste	0.16	0.2	0.64	0.05	0
Electricity	1.02	0.02	1.5	1.55	0
Heat	0	0	0.05	0	0
Solar/tide/wind	0	0	0.28	0.01	0
Geothermal	0	0	0	0.01	0

Table 3. Final energy consumption in Mtoe of Poland for the year 2020 [8].

(Mtoe)	Industry	Transport	Residential	Other	Non-Energy Use
Oil	0	0	0	0	0
Oil products	0.85	20.08	0.62	2.76	3.74
Coal	2.87	0	5.2	1.28	0.1
Natural gas	3.86	0.35	3.84	1.19	2.05
Biofuels and waste	2.81	1.04	4.85	0.77	0
Electricity	4.75	0.27	2.58	4.2	0
Heat	0.86	0	3.64	1.14	0
Solar/tide/wind	0	0	0.07	0.01	0
Geothermal	0	0	0.02	0.01	0

Table 4. Final energy consumption in Mtoe of Switzerland for the year 2020 [8].

(Mtoe)	Industry	Transport	Residential	Other	Non-Energy Use
Oil	0	0	0	0	0
Oil products	0.23	4.78	1.41	0.77	0.43
Coal	0.09	0	0	0	0
Natural gas	0.91	0.03	1.13	0.63	0
Biofuels and waste	0.49	0.18	0.46	0.29	0
Electricity	1.43	0.24	1.66	1.46	0
Heat	0.17	0	0.2	0.14	0
Solar/tide/wind	0	0	0.05	0.01	0
Geothermal	0	0	0	0	0

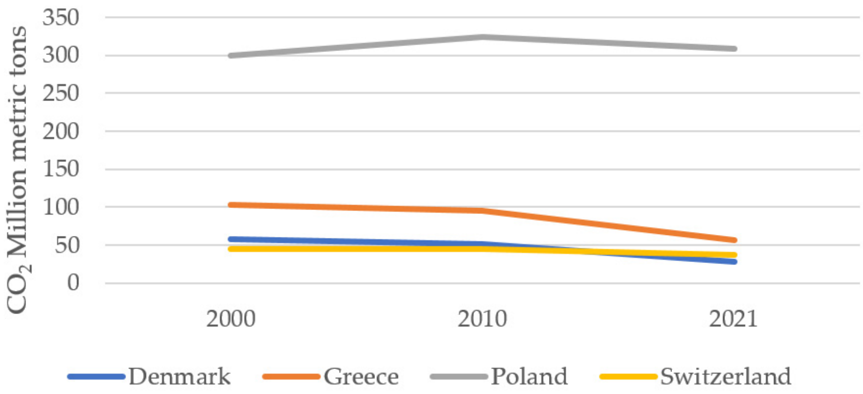


Figure 1. Carbon dioxide emissions for Denmark, Greece, Poland, and Switzerland for the years 2000, 2010, and 2021. Based on data from [12,13].

In 2017, the primary energy source for space and water heating in Europe was natural gas, which contributed 43.4% of the final energy used, followed by biomass at 15.7%, fuel oil at 15.2%, district heating at 12%, electricity at 6.8%, coal with 3.2%, ambient heat at 2.4%, and solar energy at 1.2% [15]. The residential sector represented the highest demand, requiring 67% of the final energy delivered [15]. Of the heat demanded by the residential sector, about 10% was used for water heating and about 67% for space heating, while the rest (about 20%) was used for other end-uses [15]. Of the total final energy delivered to the residential sector, 72.5% was supplied with non-renewable sources [15].

A differentiation can be made between the sources of energy used to supply heat to the residential sector. Figure 2 presents the sources of the final energy delivered for space and water heating. The outer circle represents the energy used for space heating, while the inner circle represents the energy used for water heating. Even though all four are European countries, their respective energy mixes vary drastically from one to the next. Poland, for example, used coal to supply 35% of the space heating demand and 40% of the water heating demand. In contrast, Switzerland relied on fuel oil to supply 25% of the space heating demand and 43% of the water heating demand. Due to its climate, Greece supplied 34% of its space heating demand with solar energy and another 33% with ambient heat but relied on fuel oil to supply 47% of its water heating demand.

Composting is a naturally occurring process in which organic matter is broken down into water, carbon dioxide, simple sugars, and mineral salts in the presence of oxygen and decomposing organisms [16]. The composting process is generally divided into the mesophilic stage (25 °C to 45 °C), thermophilic stage (45 °C to 75 °C), cooling stage, and maturation stage [17]. During the first two stages, mesophilic and thermophilic, the heat production rate is high, making composting an exothermic process [18]. The optimal temperature at which the composting process runs best is given by the "minimum", "maximum", and "optimal" temperatures specific to the microbe strain used [19]. The temperature at which the microbes in charge of the thermophilic stage start to be inhibited is around 67.8 °C [20]. This temperature difference between the maximum microbial [20] temperature (67.8 °C) and the maximum possible (about 75 °C) [17] allows for the possibility of recovering this heat.

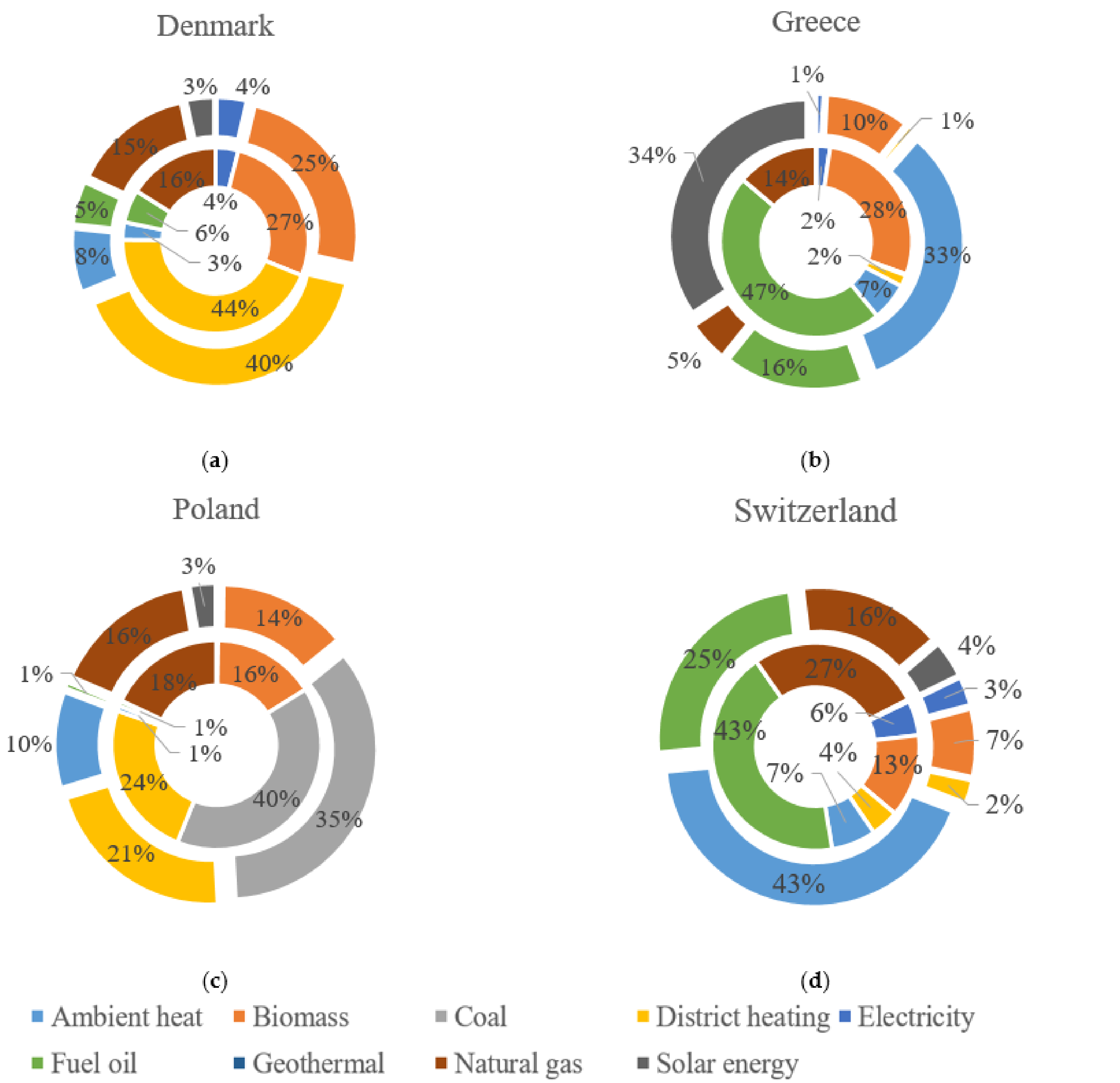


Figure 2. Space (outer circle) and water (inner circle) heating final energy source for (**a**) Denmark, (**b**) Greece, (**c**) Poland, and (**d**) Switzerland. Data used for the graphs from [15].

A possible use of the heat recovered from the composting process could be to reduce the share of fossil fuels used for residential heating. The exothermic quality of composting [18] is not a new subject and many studies have been conducted on both heat production (Table 5) and heat recovery (Table 6). Table 5 presents the heat produced during the composting process by using different substrates representative of the residential sector [21]. These values were calculated using either the degradation method (DD), heat balance method (HB), oxygen consumption method (OC), or temperature method (TEM) by the respective authors.

Table 5. Heat production from composting using different substrates. Table adapted from [17].

Substrate	Heat Production	Method	Reference
OFMSW	0.75 kWh/kg BOM	DD	[22]
Food waste, wood waste	0.74–1.19 kWh/kg BOM	DD and HB	[23]
Food waste, wood chips	1.19 kWh/kg DM	OC	[24]
Kitchen waste, garden waste	0.39 kWh/kg WW	HB	[25]
Food waste, saw dust, manure compost	0.83 kWh/kg WW	TEM	[26]

Note: OFMSW refers to the organic fraction of municipal solid waste.

Table 6. Composting heat recovery from substrates representative of or similar to the residential sector. Table adapted from [17].

Substrate	Heat Recovery (kWh th/kg)	Reference
Sludge, fat, poplar, sawdust	0.22	[27]
Wood	1.18	[28]
Wood chips, horse manure, vegetable waste, and leaves	0.45–0.62	[29]
Food waste, green waste	0.30	[30]
Wood chips, horse manure, fresh grass, leaves, matured compost	0.14	[31]
Cow manure, horse manure/bedding mix, waste hay	0.13–0.24	[32]
Food waste, yard waste, mixed paper	1.11–1.38	[33]
OFMSW	0.61	[34]
Fruit waste, meat waste, paper and yard waste	0.05–1.25	[35]
Municipal waste	0.45–0.6	[36]

Note: OFMSW refers to the organic fraction of municipal solid waste.

This work aims to answer the following questions: Has the possibility and viability of using composting heat to supply some of the residential sector's demand been widely studied? Can the heat recovered from the composting of household waste produce enough heat to reduce the demand for fossil fuel-based heating? How much CO_2 could be avoided if composting heat replaced standard fuels for combined heat and power (CHP) generation?

Therefore, the objectives of the present paper are:

- Perform a broad literature review to assess the research interest in residential use of composting heat.
- Identify whether the heat recovered from the composting process can supply enough heat to the residential sector to decrease the heat demand from fossil sources.
- Assess the possible emissions avoided by using heat recovered from household size composting for space and water heating.

2. Materials and Methods

In this section, the methodology followed is described. The steps followed in order of appearance are research interest assessment, calculation of the possible heat to be supplied from composting heat, heat demand yearly shape and monthly demand assessment, and lastly, calculation of the possible carbon dioxide emissions avoided in one year by using composting heat to supply part of the residential heat demand.

2.1. Research Interest Review

The research interest was assessed by using Scopus [37]. Papers whose primary subject was "Composting" and "Heat" were assessed. The search results were filtered to be within the areas of "environment", "Energy", and "Engineering". The abstract of each search result was then analyzed for keywords using Python 3 [38]. The degree of interest was the number of papers that featured specific keywords. The keywords extracted from the abstracts were not filtered again to portray the raw results and avoid possible biases. The results were then tabulated and graphed. These can be found in Section 3.

To answer the objective question of "Can the heat recovered from the composting of household waste produce enough heat to reduce the heating bill of cold countries?", the following steps were taken: description of the possible heat supply, and characterization of the heat demand in European countries. The countries selected were Poland, Switzerland, Greece, and Denmark. The countries were selected solely based on the availability of whether previous work on the subject had been published. This selection served a dual purpose of data validation, as it was based on peer-reviewed papers, and as a result, ties in, as the results presented here are arguably relevant, so this work can serve as a step towards solving the issues presented in the reference papers.

2.2. Heat Supply

The theoretical available recoverable heat was calculated by taking the heat production values from the organic fraction of municipal solid waste (Table 7). Each was assumed to be attainable in all the locations (Denmark, Greece, Poland, and Switzerland). The heat production values were multiplied by the amount of waste production per capita (W) [39] and by a recovery efficiency factor derived from the work of Walther et al. [40]. Equation (1) [41,42] describes this calculation.

$$Q_R[\text{kWh}] = Q_{P,i}\left[\frac{\text{kWh}}{\text{kg}}\right] \times W[\text{kg}] \times \eta_R \tag{1}$$

Table 7. Monthly production of OFMSW per person [39].

	OFMSW Kg/Person
January	3.30
February	2.76
March	3.21
April	3.49
May	3.67
June	4.44
July	4.25
August	4.13
September	3.08
October	3.80
November	3.61
December	3.14

The waste production is assumed to be representative of all the locations presented in this paper; therefore, the quantity of waste production remains constant from country to country. The recovery efficiency derived was 0.37 [40]. This efficiency factor includes incomplete reaction, edge effects, and heat losses due to aeration. A lower value (0.25) was also used to account for other human-influenced losses and potential transmission losses. Therefore, the upper edge of the graphs of recoverable heat (found in Section 3) uses Qp of 1.19 kWh/kg and 0.37 recovery efficiency, while the lower edge uses Qp of 0.39 kWh/kg and an artificial recovery efficiency of 0.25.

As reported in the literature, the heat recovery rate of substrates akin to residential or household waste is given a yearly distribution by multiplying the heat per quantity of substrate (kWh/kg) with the average waste produced by one person, as found in Table 7.

To generate values representative of the countries studied, the average household size of each country was used to estimate the waste production and, therefore, the heat recovery. The average household size can be seen in Table 8.

Table 8. Average household size in countries studied.

Country	Average Household Size	Reference
Denmark	2.09	[43]
Greece	2.6	[44]
Poland	2.48	[45]
Switzerland	2.202	[46]

2.3. Heat Demand

The heat demand in each country was calculated to ascertain how much heat would be needed. Since the data available are yearly, the monthly demand was derived. For this, a monthly characterization was performed, followed by adapting the yearly demand to the demand curve shape obtained.

2.3.1. Monthly Characterization (Demand Shape)

Because the values of heat demand were in kWh/m^2 yr, a shape for the values for the different locations used was needed. A theoretical room was calculated in each country. The heat losses of this room of 3 × 12 × 3.2 m with two doors and four windows in each of the studied countries were calculated. The calculation follows Equation (2):

$$Q_{LT} = \sum(Q_{S,i}) + Q_{Inf} \quad (2)$$

where Q_{LT} is the total heat losses, $Q_{S,i}$ is the surface losses for each of the "i" surfaces that make up the room, and Q_{Inf} is the heat losses due to air exchanges and infiltration, as shown in Equation (5).

$$Q_S = U\left[\frac{W}{m^2K}\right] \times A\left[m^2\right] \times \Delta T[K] \quad (3)$$

where U represents the U-value (Table 9), which measures how effectively a material performs as an insulator [47]. It represents the reciprocal of the sum of thermal resistances (R-value) of each material that makes up a building element [47]. The thermal resistance is calculated by multiplying the thickness of the element by its respective conductivity (k-value or λ-value) [47]; see Equation (4). A is the area of the surface and ΔT is the difference between the ambient temperature shown in Table 10 and the design temperature (20 °C).

$$U = \frac{1}{\sum Thickness_i\ [m]/Conductivity_i\ [W/mK]} \quad (4)$$

The values used for the theoretical residence used to generate the consumption shape are the reference values found in DIN 4108 Bbl 2 [48], shown in Table 9.

$$Q_{inf} = V[m^3] \times ACH \times \Delta T[K] \times 0.005 \quad (5)$$

where V is the volume of the room (115.2 m^3), ACH is the air exchanges per hour (4 [49] + 1.3 [50]), and 0.005 is the air's specific heat.

The minimum temperatures for each month were used for the difference between the ambient and design temperature. Table 10 presents the temperatures used for each month in the countries studied.

Table 9. U-values of building surfaces [48,51].

Surface	U (W/m^2 K)
Outer wall to air	0.28
Window	1.3
Exterior door	1.5
Roof	0.2

Table 10. Ambient temperatures used for calculations in degree Celsius.

	Poland [52]	Denmark [53]	Switzerland [54]	Greece [55]
January	−9	−0.61	−1	5.2
February	−8	−0.69	−2	5.5
March	−3	0.61	2	7
April	1	3.58	6	9.7
May	7	7.15	9	13.5
June	12	10.49	13	17.4
July	14	12.96	15	19.8
August	13	12.92	14	19.8
September	10	10.41	11	17.1
October	3	6.83	7	13.6
November	−1	3.34	3	9.9
December	−6	0.46	0	7

Since the theoretical room has similar characteristics in size, materials, and composition, the difference between the trend lines of each country lies in the difference between their respective weather characteristics (Table 10).

This room was only used to generate the shape of consumption, that is, when and how much heat would be demanded throughout the year. With the shapes generated for each country, the measurements (kWh/m^2 yr) can follow the generated shapes to obtain a natural heat demand curve for the countries studied.

2.3.2. Adapting Data to Shape

With the shape of the heat losses drawn, a normalization was made to obtain the percentual increase or decrease from the average annual heat loss. The actual heat consumption [15,56] for space heating (SH) and water heating (WH) for each location (Table 11) were then multiplied by these factors to obtain the theoretical monthly heat demand variation.

Table 11. Heating demand and space heating to water heating ratio [15,56].

Country	SH + WH		SH to WH Ratio	Av. Floor Space (Single Family)
	[56]		[15]	[15]
Denmark	144.1	kWh/m^2 yr	93%	170 [m^2/dwell.]
Greece	108.4	kWh/m^2 yr	84%	53.49 [m^2/dwell.]
Poland	261.1	kWh/m^2 yr	93%	122.02 [m^2/dwell.]
Switzerland	172	kWh/m^2 yr	90%	142.40 [m^2/dwell.]

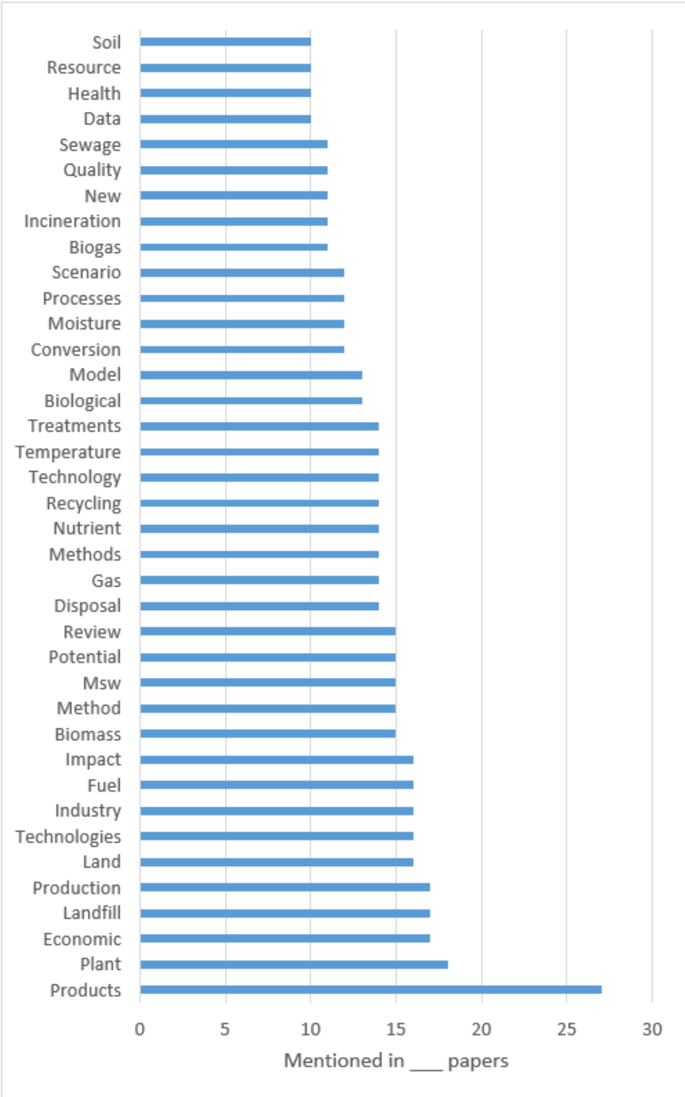
The space heating demand follows the theoretical monthly shape described above. For the water heating demand, two results are presented. The first one uses the same shape as the space heating. For the second one, an additional assumption was made in which heated water is consumed more regularly throughout the year.

2.4. Carbon Emissions Avoided

For this step, we calculated the carbon dioxide (equivalent) that would be emitted if the heat supplied from composting was instead supplied with natural gas as the primary energy carrier, assuming that the heat is generated with a natural gas combined heat and power (CHP) plant. The calculation is based on the work by Eriksson et al. [57], in which for every 65 MW of "useful energy" generated, 10 MW is electric and 55 MW is thermal. Moreover, depending on the power source, the emissions of carbon dioxide equivalent are 212 g CO_2/MJ_{el} for coal condensate [58], 81.9 g CO_2/MJ_{el} for oil condensate [59], and 60.3 g CO_2/MJ_{el} for natural gas [59].

3. Results

A total of 1585 keywords were identified from the 685 papers found on Scopus within the areas of composting, heat, environment, energy, and engineering. The keywords that appeared in more than 15 papers can be seen in Figure 3b. Figure 3a presents the keywords with more than ten mentions that deal directly with research interest. Some, such as "Products", present more mentions in Figure 3a than Figure 3b. This difference is due to the similarity of words, as singular and plural versions merged. Out of all the papers reviewed in this manner, ten (10) dealt with municipal solid waste (9 with "municipal" as the keyword, 1 with "MSW" (municipal solid waste) as the keyword), seven papers mentioned "building", seven mentioned "wte" waste to energy, and four dealt with households (2 "household", 1 "house", and 1 "houses"). This lack of representation shows that, even though composting is a widely researched topic when heat is concerned, the application of this heat in household consumption has not been widely studied.



(a)

Keyword	Documents
Waste	109
Energy	57
Environmental	55
Composting	52
Process	44
Treatment	39
Organic	38
Management	33
Sludge	31
Solid	30
Wastes	30
Anaerobic	28
Compost	27
Heat	27
Cycle	26
Recovery	26
Materials	23
Water	22
Analysis	21
Carbon	21
Digestion	20
Emissions	20
Results	20
Different	19
Food	19
Manure	18
Products	18
Economic	17
Landfill	17
Production	17
Land	16
Technologies	16

(b)

Figure 3. (**a**) Research interest. (**b**) Most-mentioned keywords.

Based on the literature reviewed and the calculations made on the assumption that the heat released from composting the substrates mentioned in Table 5 is similar and attainable in all four countries studied, the recoverable heat from composting could reach a minimum range of 0.30–1.36 kWh in September and a maximum range of 0.43–1.93 kWh in June.

This is observable in Figure 4. The recoverable heat presented in Figure 4 represents the composting of the waste generated by one person. This paper works on the assumption that one person would generate the same amount of waste regardless of the country the person is located in.

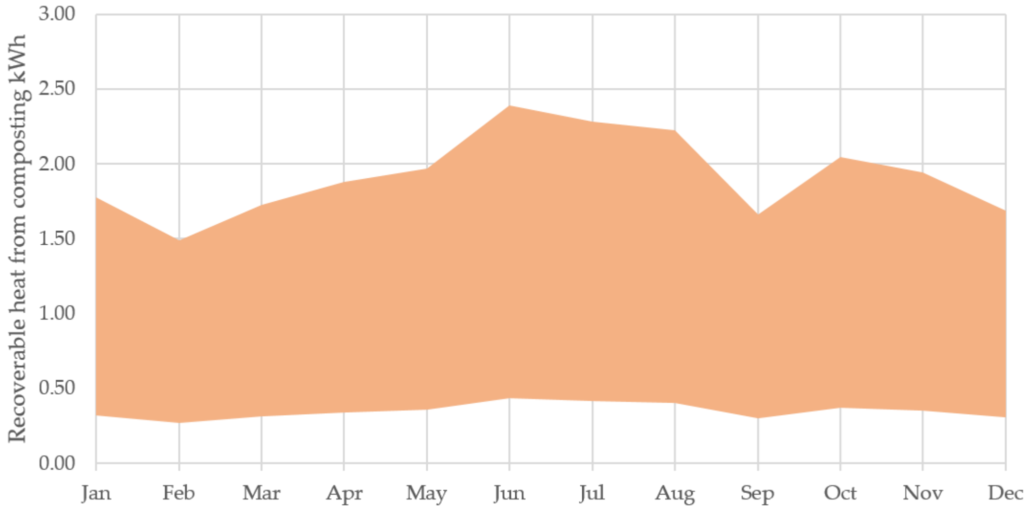


Figure 4. Recoverable heat from composting organic waste produced by one person.

Composting the waste generated by either one person or the average family size of each country results in a negligible amount of heat compared to the countries' space heating demand (Table 8). The recovered heat can only supply enough heat during the hot part of the year for countries with similar climate conditions to Greece. Colder climates, such as Poland, Switzerland, and Denmark, require more heat throughout the year than the composting of household waste can generate, as seen in Figure 5.

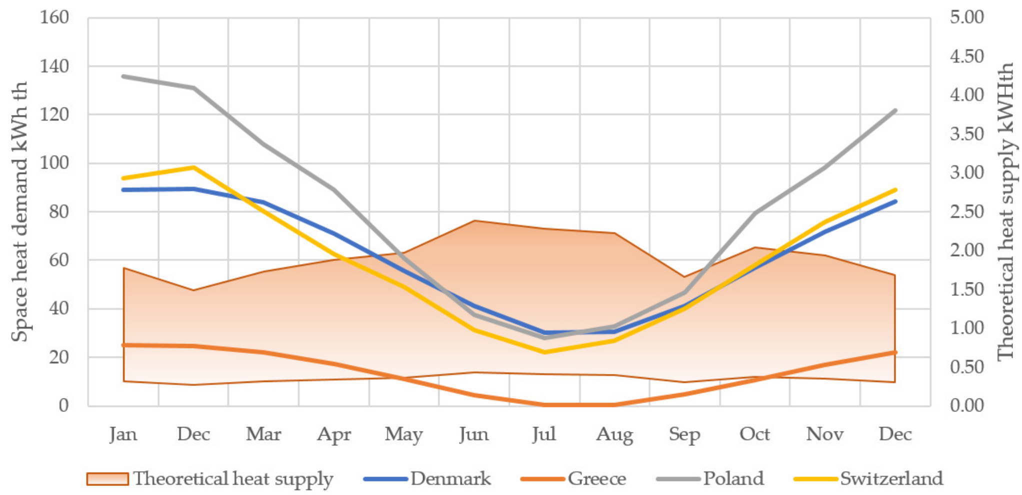
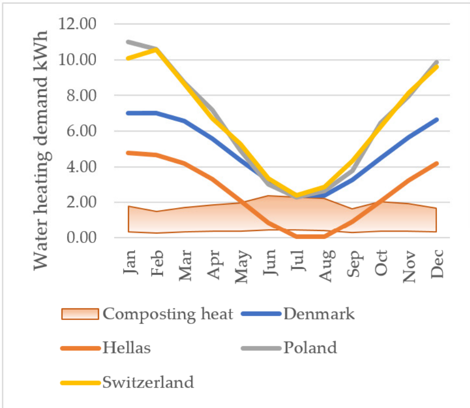


Figure 5. Space heating demand and recoverable heat from composting organic waste produced by one person.

Composting heat, however, can supply at least 25% of the water heating demand of all four countries when the water heating demand behaves similarly to the space heating demand. That is, they follow the same consumption shape; see Figure 6a. When the waste production is proportionate to the average family size (Table 8), the complete demand can be supplied by composting heat during warm months (Figure 6b).



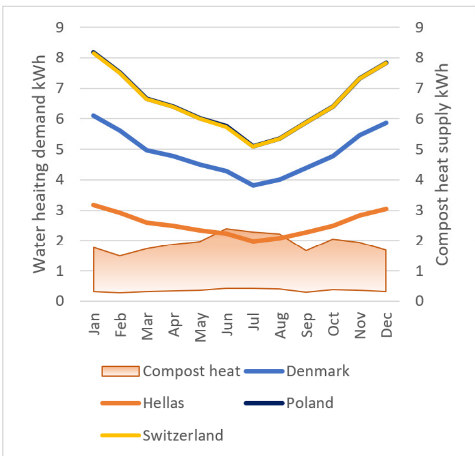
(a)

Month	Denmark	Greece	Poland	Switzerland
Jan	43%	79%	33%	32%
Feb	36%	68%	28%	25%
Mar	45%	88%	40%	36%
Apr	58%	100%	53%	50%
May	77%	100%	81%	67%
Jun	100%	100%	100%	100%
Jul	100%	100%	100%	100%
Aug	100%	100%	100%	100%
Sept	87%	100%	89%	69%
Oct	78%	100%	64%	59%
Nov	59%	100%	50%	43%
Dec	44%	86%	35%	32%

(b)

Figure 6. (**a**) Water heating demand and recoverable heat from composting organic waste produced by one person. (**b**) Monthly percentage of coverage from composting heat produced by the average household size in each country.

If the hot water consumption has a softer trend (following the assumption that hot water is more evenly used throughout the year), the composting heat can supply at least 15% of the hot water demand on its higher heat recovery rate with the waste produced by one person (see Figure 7a). When the waste is again proportionate to the average family size, about 40% of the monthly demand in all four countries can be supplied, with Greece fully supplying any need for hot water from composting heat throughout the year. Poland and Switzerland, being colder, would require extra heating from other sources regardless of the month, Figure 7b.



(a)

Month	Denmark	Greece	Poland	Switzerland
Jan	50%	100%	44%	39%
Feb	45%	100%	40%	36%
Mar	59%	100%	53%	47%
Apr	67%	100%	60%	53%
May	75%	100%	67%	59%
Jun	95%	100%	84%	75%
Jul	100%	100%	91%	81%
Aug	95%	100%	84%	75%
Sept	65%	100%	57%	51%
Oct	73%	100%	65%	58%
Nov	61%	100%	54%	48%
Dec	49%	100%	44%	39%

(b)

Figure 7. (**a**) Water heating demand soft trend and recoverable heat from composting from organic waste produced by one person. (**b**) Monthly percentage of coverage from composting heat produced by the average-sized household in each country.

The results presented so far are derived from the calculations made as described in Section 2 using heat production rates from the literature (Table 5). However, values of heat recovery have also been reported in the literature (Table 6). Using these reported heat recovery values (kWh th/kg) multiplied by the quantity of waste produced by one person results in available heat equivalent to that obtained using the calculations presented. This result validates the method and presents the heat obtainable from different substrates similar to household waste. These values can be found in Table 12. The minimum theoretical recoverable heat (0.14 kWh) comes from a fruit, meat, paper, and yard waste substrate. The maximum (5.24 kWh) is obtained by composting wood waste.

Table 12. Theoretical heat recovery from modeled heat production from waste produced by one person.

	January	February	March	April	May	June	July	August	September	October	November	December
Sludge, fat, poplar, sawdust	0.73	0.61	0.71	0.77	0.81	0.98	0.93	0.91	0.68	0.84	0.79	0.69
Wood	3.89	3.26	3.79	4.12	4.33	5.24	5.01	4.88	3.64	4.49	4.26	3.71
Wood chips, horse manure, vegetable waste, and leaves	1.48	1.24	1.44	1.57	1.65	2.00	1.91	1.86	1.39	1.71	1.62	1.41
Food waste, green waste	0.99	0.83	0.96	1.05	1.10	1.33	1.27	1.24	0.92	1.14	1.08	0.94
Wood chips, horse manure, fresh grass, leaves, matured compost	0.46	0.39	0.45	0.49	0.51	0.62	0.59	0.58	0.43	0.53	0.51	0.44
Cow manure, horse manure/bedding mix, waste hay	0.43	0.36	0.42	0.45	0.48	0.58	0.55	0.54	0.40	0.49	0.47	0.41
OFMSW	2.01	1.69	1.96	2.13	2.24	2.71	2.59	2.52	1.88	2.32	2.20	1.92
Food waste, yard waste, mixed paper	3.66	3.07	3.56	3.88	4.07	4.93	4.71	4.59	3.42	4.22	4.01	3.49
Fruit waste, meat waste, paper, and yard waste	0.16	0.14	0.16	0.17	0.18	0.22	0.21	0.21	0.15	0.19	0.18	0.16
Municipal waste	1.48	1.24	1.44	1.57	1.65	2.00	1.91	1.86	1.39	1.71	1.62	1.41

Suppose fossil fuels instead supply the heat that composting could provide in one year; the emissions of CO_2 equivalent range between 5.3 and 6.6 tons of CO_2 eq when natural gas is used. The emissions avoided by using composting heat instead of fossil fuels can be seen in Table 13.

Table 13. Carbon dioxide avoided from using composting heat instead of different fossil fuels for each study region.

Country	Natural Gas (Ton CO_2eq)	Oil Condensate (Ton CO_2eq)	Coal Condensate (Ton CO_2eq)
Denmark	5.300	7.199	18.635
Greece	6.594	8.956	23.182
Poland	6.290	8.542	22.112
Switzerland	5.584	7.585	19.634

Note: CO_2eq refers to carbon dioxide equivalent.

If the space and water heating supplied to the target countries were to be produced from renewable sources in their entirety, that is, if the sections labeled "coal", "oil", and "natural gas", as well as the portion of the "electricity" label generated using the fossil fuels in Figure 2 were replaced by renewables. The number of emissions avoided would be as shown in Table 14. The country that would benefit the most emission-wise would be Poland, with 22 thousand tons of CO_2 emissions from water heating and 180 thousand tons of CO_2 emissions avoided from space heating.

Table 14. Tons of CO_2 avoided if all the fossil-based residential heating was replaced with renewable energy base heat.

SH	Denmark	Greece	Poland	Switzerland
Coal	4205	2839	17,802	4692
Oil	12,538	8466	53,087	13,992
Nat. Gas	25,922	17,503	109,755	28,927
Total	42,664	28,808	180,644	47,610
WH	**Denmark**	**Greece**	**Poland**	**Switzerland**
Coal	1094	2313	5119	1916
Oil	1193	2523	5583	2090
Nat. Gas	2493	5270	11,662	4366
Total	4780	10,107	22,364	8372

4. Conclusions

Composting is not a new subject. Heat from composting has been widely studied, with 685 peer-reviewed papers in the Scopus search engine. However, the viability of the application or utilization of recoverable composting heat for the residential sector has not been widely studied. The lack of research is evident in the number of papers published. Of all the papers on composting heat, only eleven mention being targeted to the residential sector. This work, although primarily a review, tries to fill a small part of this evident gap by proving that compost heat is viable for household use.

Composting, an exothermal process, releases heat while decomposing the composting substrate. According to the literature reviewed, the heat recoverable during the composting process ranges between 0.39 and 1.19 kWh/kg of the substrate when the substrate is representative of residential dwellers. The waste produced by one person is not nearly enough to supply a portion of the space heating demand of a household to be of any significance.

Compost heat, however, can supply a significant amount of the water heating demand of a household. Depending on the efficiency of heat recovery, compost heat could supply between 36% and 100% of the yearly hot water demand of Greece, between 15% and 67% of the yearly hot water demand of Denmark, between 13% and 60% of the yearly hot water demand of Poland, and between 12% and 53% of the yearly hot water demand of Switzerland.

If composting heat were to replace fossil fuel-based heat generation, a maximum of 23 tons of CO_2 from using coal condensate could be avoided, about 9 tons of CO_2 from oil condensate, or around 6 tons of CO_2 from natural gas, provided that the composting heat recovery is at its highest efficiency. However, if all the fossil fuel-based residential heat was replaced entirely with renewable energy-based heat in Poland, then as much as 180,000 tons of CO_2 emissions a year could be avoided from space heating alone.

Although entirely theoretical, this paper identified possible uses for compost heat in households. The next step in this work would be experimentally proving that the calculated hot water demand could be supplied with household-scale composting. Moreover, life cycle assessments could be performed to fully ascertain whether providing heat from composting is a better option than current methods of heat supply.

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Nomenclature

Mtoe	Mega tons of oil equivalent
DD	Degradation method
HB	Heat balance method
OC	Oxygen consumption method
TEM	Temperature method
BOM	Biodegradable organic matter
DM	Dry matter
WW	Wet weight
OFMSW	Organic fraction of municipal solid waste
QR	Recoverable heat
QP	Heat production
W	Weight
Nr	Heat recovery efficiency
QLT	Total heat losses
QS	Surface heat losses
Qinf	Infiltration losses
U	Reciprocal of the sum of thermal resistances (1/R)
R	Thermal resistance
A	Area
T	Temperature
V	Volume

ACH	Air exchanges per hour
SH	Space heating
WH	Water heating

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