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EDITOR-IN-CHIEF'S WORD

Dear readers,

It is my pleasure to present the current issue of Engineering Power, which brings together research addressing key challenges in modern energy and engineering systems. As the global community intensifies efforts toward sustainable development and climate neutrality, engineering research plays a vital role in advancing efficient technologies, improving resource utilization, and supporting the transition to low-carbon energy systems.

The contributions in this issue reflect the growing integration of thermodynamics, energy systems analysis, data-driven methods, and industrial sustainability approaches. Together, they highlight the importance of innovative thinking and interdisciplinary collaboration in tackling complex problems related to energy efficiency, decarbonization, and responsible resource management.

We hope that the research presented here will contribute to ongoing scientific discussion and support the development of practical solutions for a more sustainable and resilient energy future.

I would like to thank the authors and reviewers for their valuable work and commitment to maintaining the quality of Engineering Power.

Editor-in-Chief
Vedran Mornar, President of the Croatian Academy of Engineering

EDITOR'S WORD

Dear readers,

The new issue of the Engineering Power journal is edited by Prof. Neven Duić, PhD. The papers in this issue are thematically linked to the SDEWES conference, held under the auspices of the Croatian Academy of Engineering. In this issue, you can read about the decarbonisation potential of heat pumps, the database structure required for supply-demand matching using recyclable resources, and the potential of alternative propulsion systems, including the relatively underexplored field of pneumatic propulsion. I hope you enjoy reading this issue.

Editor
Bruno Zelić, Vice-President of the Croatian Academy of Engineering

FOREWORD

With a broad vision of integrating diverse systems for long-term sustainability, the international conference series on the sustainable development of energy, water, and environmental frameworks began in the early 21st century. Now in its third decade since its founding in Dubrovnik, Croatia (2002), the call for such an integrated perspective is more urgent than ever. One of the key challenges lies in using surplus from one system as a timely input for another—essential for preserving Earth's life-support systems. Improving efficiency across interconnected domains like electricity, heating, cooling, transport, water, waste, industry, construction, forestry, and agriculture is central to reducing environmental impact while enabling development.

Engineering is well-placed to respond, but it must transcend disciplinary silos. The technical solutions needed to protect the environment without sacrificing modern comforts are inherently interdisciplinary drawing on engineering fields alongside architecture, economics, agriculture, and forestry. This collection of studies spans transport automation, building energy efficiency, and fuel cell technology.

Judging heat pumps only by the First Law overstates their decarbonization; a Second-Law (exergy) analysis shows power-to-heat exergy destruction can add CO_2, warrants a COP-correction, and indicates today's COPs are often insufficient [1]. Sector coupling between waste treatment plants and nearby industries can enhance energy recovery, assuming accurate spatial demand data and a standardized industrial process database are developed to match recyclable thermal resources effectively [2]. Sustainable marine propulsion research is accelerating—especially electric and hybrid systems—but technological and economic limits hinder adoption. Therefore, alternative concepts such as pneumatic propulsion may hold significant unrealized potential. [3].

References

[1] B. Kılkış, "A Second-Law Model for the Decarbonization Potential of Heat Pumps," Engineering Power, vol. 20, no. 2, pp. 2-12, 2025.

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Guest Editor
Neven Duić, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

CONTENT

Birol Kılkış

A Second-law Model for the Decarbonization Potential of Heat Pumps

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Abstract

Based solely on the First Law of Thermodynamics, which addresses energy efficiency, heat pumps are considered to be a major asset for achieving the decarbonization goals of the Paris Agreement. Yet, this approach alone overestimates the potential for decarbonization and conceals certain root causes of carbon dioxide emissions arising from exergy destruction. This paper redefines the decarbonization potential of heat pumps holistically by applying the First and Second Laws of thermodynamics together. This research shows that power-to-heat energy conversion systems are responsible for exergy destruction, leading to additional carbon dioxide emissions, as the destroyed exergy must be offset by other means, possibly by burning fossil fuels. An exergy-based model was developed and used for different scenarios. Results were compared with boilers in heating mode fueled by fossil fuels or biogas, and with adsorption machines in cooling mode. Thermal energy storage systems and their optimal operational regimes for minimum environmental footprint have also been considered and modeled in accordance with the Second Law of Thermodynamics. A correction factor for the coefficient of performance of heat pumps has been developed to account for exergy destruction and emission avoidance associated with typical heat pump operation under electrical and ambient thermal inputs. Results show that today's coefficient of performance must be higher to meet the emissions-mitigation and total electrification targets to mitigate global warming. The Second Law of thermodynamics shows that the case study about the comfort cooling system of a nature center building with ground source heat pumps and photovoltaic panels is responsible for emissions by 0.81 kg CO_2 *emissions/*kW_{en}*-h, rather than saving 1.62 kg* CO_2*/kWen-h by a no-heat pump case, comprising solar photovoltaic panels, adsorption cooling, and desiccant wheel. This case study also shows that the carbon dioxide emission responsibility resulting from exergy destruction during the power-to-heat process is as important as the direct emissions from electric power use. This paper concludes that the exergy destruction-related carbon footprint should not be neglected across all design and application phases to foster better awareness and establish exergy-rational strategy planning towards the Paris Agreement goals.*

Keywords: *Heat pumps; Rational Exergy Management Model; Exergy destructions; Near-zero building; Avoidable CO2 emissions responsibility*

1. Introduction

According to the European Commission (EC), heat pumps are expected to play a key role in the clean energy transition and to help achieve the European Union's (EU) goal of carbon neutrality by 2050 [1]. Europe's heating and cooling energy demand accounts for almost 50% of total gross final energy consumption [2]. To meet demand, the contribution of renewable energy sources, including biomass and heat pumps, is increasing [3]. In this respect, `green electricity-driven` heat pumps are considered to have a key role. These studies all depend on the First Law, which addresses only the quantity of energy and energy efficiency. On the other hand, even if electricity is generated entirely from green energy sources like solar photovoltaic panels, the panels operate at a modest First-Law efficiency, and the remaining exergy (quality) of the solar energy input is wasted (destroyed). The destroyed thermal exergy must be offset by another energy conversion system, like a boiler, which may use fossil fuels. The carbon dioxide emissions from the boiler are, in fact, the responsibility of the solar PV system. Furthermore, the boiler does not generate electric power upstream of thermal energy generation. This is another example of exergy destruction and carbon dioxide emission responsibility in a diminishing return series [4]. Another example is thermal power plants, where waste heat downstream of power generation is wasted in cooling towers, unless it is utilized in district energy systems [5]. These examples show that current energy-efficiency and carbon-footprint analyses are necessary but not sufficient, lacking the additional insights yet to be provided by the Second Law. Despite this, Thomaßen and others conducted parametric studies on the effectiveness of heat pumps in decarbonizing the heating sector in Europe using the First Law [6]. They stated that the existing power sector can accommodate 1.1-1.6 TW_H of heat pumpsFirst Law.

TU Delft participated in a project called Dezonnet in the Netherlands, which uses low-temperature solar heat with heat pumps in a small district of Haarlem [7]. The small grid also includes a large underground aquifer-type thermal energy storage (TES) system. Their report claims a large emission-reduction potential from eliminating the use of fossil fuels. However, they did not consider exergy destruction due to power-to-heat conversion by the heat pumps, the small exergy destruction in the solar PVT panels, or exergy destruction attributable to the TES system.

Heat pumps consume electric power, which has a high unit exergy of 0.95 kW_{ex}/kW_{en}, whereas, based on the ideal Carnot cycle, the unit exergy of thermal power is in the range of 0.03 kW_{ex}/kW_{en} in low-temperature heating, 0.02 kW_{ex}/kW_{en} in cooling, including latent loads (dehumidification), and 0.15 kW_{ex}/kW_{en} for domestic hot water (DHW). The large unit exergy mismatch between the electricity used and the thermal energy produced calls for a higher coefficient of performance (*COP*) to offset the exergy destruction. For example, the ideal *COP* for indoor space heating in a regime of a supply temperature of 330 K and a return temperature of 310 K is around 5, according to the ideal Carnot cycle, to match the supply and demand exergy. Otherwise, the exergy mismatch translates into ΔCO_2because the high unit exergy of electric power is grossly destroyed (wasted). This requires recognizing the second law of thermodynamics to assess the environmental impact of heat pumps accurately.

The contribution of a heat pump to CO_2 mitigation may have two aspects. First, a heat pump, which uses renewable energy sources and systems, replaces a boiler that consumes fossil fuels, with a performance coefficient greater than 1. Second, heat pumps can introduce low-enthalpy waste heat and ambient heat (or sink-in cooling) into the energy sector by better matching resource temperatures to demand temperatures. However, a heat pump uses electricity, which has a high unit exergy regardless of how it is generated or from which energy source. The thermal exergy (heat or cold) has a much lower unit exergy. Therefore, the mismatch is responsible for ΔCO_2, and irreversible exergy destruction results.

The objective of this work is to provide sufficient awareness of the ΔCO_2 term, thereby revealing sustainable, more effective measures against global warming by recognizing the direct relationship between exergy destruction and ΔCO_2. The carbon dioxide concentration is measured in the atmosphere, but a major part of the root causes on the ground remain unknown.

2. Development of the Model

To address the major literature gap regarding the exergy-destruction-led carbon dioxide emission responsibilities, an exergy-based model for the complete attribution of the carbon dioxide emission responsibility of temperature-peaking heat pumps has been developed using an exergy-destruction tree to show the expanded carbon footprint trace. The so-called exergy-tracing model comprises four CO_2 footprint backdrops. These are the thermal exergy inputs from the ambient and/or from a limited source such as waste heat; the exergy input for power generation to drive the heat pump; the exergy conversion unit (the heat pump); and useful applications downstream of the heat pump (demand exergies). The rational Exergy Management Model was applied, and the Second Law established a direct link between exergy destruction and the responsibility for nearly avoidable carbon dioxide emissions responsibility, ΔCO_2.

Equation 1-a shows that the ΔCO_2 term is directly proportional to the corresponding exergy destruction, through a proportionality (penalty) factor (k_i). It is a function of the temperature (See Equation 3).

$$\Delta CO_{2-i} = k_i \times E_{Xdesi} \qquad \text{(1-a)}$$

The Rational Exergy Management Efficiency, Ψ_R, is the ratio between the demand exergy (D_x) and the supply exergy (E_x) and provides another direct link between ΔCO_2 and exergy destruction:

$$\Delta CO_2 = k_i \times E_X \times \left(1 - \psi_R\right) \qquad \text{(1-b)}$$

$$E_{Xdesi} = Q_i \times \left(1 - \frac{T_{iapp}}{T_{i\sup ply}}\right) \qquad (2)$$

$$k_i = f(T_{i\sup ply}) = 1.1 + 0.0024 \times \left(T_{i\sup ply} - T_{ref}\right)$$

$$\{T_{ref} \leq T_{isupply} \leq 700\ \text{K}\}\ \text{or;} \qquad (3)$$

$$k_i = 1.507\varepsilon_{desi} + 0.68 \qquad (4)$$

An example from the Westwood Hills Nature Center of the City of St. Louis illustrates the fundamental differences from the current literature of this model, which recognizes exergy destruction-led corresponding ΔCO_2 terms. See Table 1. In contrast, the literature on the Westwood Hills Nature Center claims that an annual operational CO_2 emission savings of more than 60% has been achieved, based on 'energy savings' (First Law only) [8]. The HVAC system for this 1260 m^2 building project (See Figure 1) includes a ground-source heat pump, radiant floor panels, and PV panels. The reported savings rate was limited to the First Law. PV panels generate electric power at a modest first-law efficiency, and the remaining solar exergy is rejected to the ambient without any useful work obtained. The missed thermal power generation opportunity must be offset by either a boiler or a solar flat-plate collector (FPC) to recover the rejected heat's exergy. Table 1 presents typical CO_2 savings as a function of the ΔCO_2 emission responsibility. Grid power has no mitigation potential. Flat-plate collectors (FPCs) and grid power are included for reference. A PV panel generates power at a modest efficiency, like 0.2. The remaining portion of the total solar exergy is destroyed and must be offset by other equipment, such as a boiler. A heat pump uses high-exergy power and generates only thermal exergy of lower value. Even if the *COP* is greater than 1, exergy destruction still occurs. Table 1 shows that the ratio of the ΔCO_2 terms revealed by the exergy-based model is substantially greater than the CO_2 emissions or savings according to the First Law. These results show the importance and essence of the new model.

Fig. 1. Net-Zero Certified Building [8]

Table 1. Actual CO_2 Mitigation Ratios of Typical Energy Conversion Equipment When the Second Law is Considering the ΔCO_2 term

Equipment	Apparent CO_2 mitigation potential (First Law)	ΔCO_2 Responsibility	$R = \Delta CO_2 / CO_2$	Correction factor for CO_2 mitigation of the original claim $1/(1+R)$	Corrected mitigation potential
	kg CO_2/$kW_{en-}h$				
PV*	0.5	2.0	4	0.2	0.1 kg CO_2/$kW_{en}h$
Heat Pump	0.6	0.56	1.3	0.43	0.26
Flat-plate collectors	0.23	1.32	5.74	0.15 %	0.034
Grid Power	(-) 0.3 (no saving)	0.54	1.42	no saving	none

* Replacing grid power from a natural gas power plant and assuming that on-site PV panels feed the grid at the plant first.

When the installed capacities of PV panels and the ground-source heat pump, alongside the grid power exchange, are considered, the claimed emission savings need to be corrected by the factor (R). See Table 1. Then, the 60% savings claimed by the Author [8] are reduced to 26%. Furthermore, ground heat exchangers, PV panels, and radiant floors are embodied-CO2-intensive systems and equipment. In addition, the pumping needs for the thirty-two vertical bores in their project (76 m deep) consume a considerable amount of electrical energy. A life-cycle proration of the embodiments and emission responsibility of the borehole pumps further reduces the actual savings. Therefore, it is prudent to conclude that the actual emission savings will be less than 20%.

Kalkan et al. describe a similar project in their new system installed at the Highfield campus of the University of Southampton [9]. This system is an addition to the existing mini-CHP district energy system, with PV panels and heat pumps. This addition is identical to the configuration of the previous case. The PV+HP combination is like the data presented in Table 1. In both cases, PV panels destroy thermal exergy downstream, and heat pumps destroy most of the electrical power exergy upstream of heating or cooling. Figure 2 shows the conven-tional heat pump system in heating mode, as described by Kalkan et al. [9]. The measured COP is about 3.7.

This low COP value is responsible for DCO2 emissions, which contradicts the general statement reproduced below [10]:

'.. Studies have also shown that HPs have the potential to greatly reduce greenhouse gas emissions, particularly those of CO_2.'

These two cases refer only to the First Law of thermodynamics and ignore the ΔCO_2 component. This is a result of the misconception that renewable energy systems, such as solar energy, are free of CO_2 emissions during operation, except for their embodied emissions [11]. Despite such gaps between theory and practice, heat pumps are seeing increasing sales in EU countries. For example, the United Kingdom announced its target to install 600,000 heat pumps by 2028. Regulators claim that even when fossil-fuel-based electricity powers the heat pump, it consumes only one-third (mitigation potential of 2/3) as much as a boiler would [12, 13]. Such a claim is based solely on 1/*COP* in heating mode, yielding a savings of 0.60 after accounting for some parasitic losses. In fact, Table 1 shows a correction factor of 0.43 for the heat pump, which excludes the exergy destructions at the grid power plant: 0.60×0.43 = 0.26. When these exergy destruction-led ΔCO_2 values are also incorporated, the net mitigation potential becomes less, or even negative, depending on the central power plant mix, and depending on the fossil fuels used. If renewable energy systems provide the electricity, the condition may only slightly improve, because these systems also carry ΔCO_2 terms.

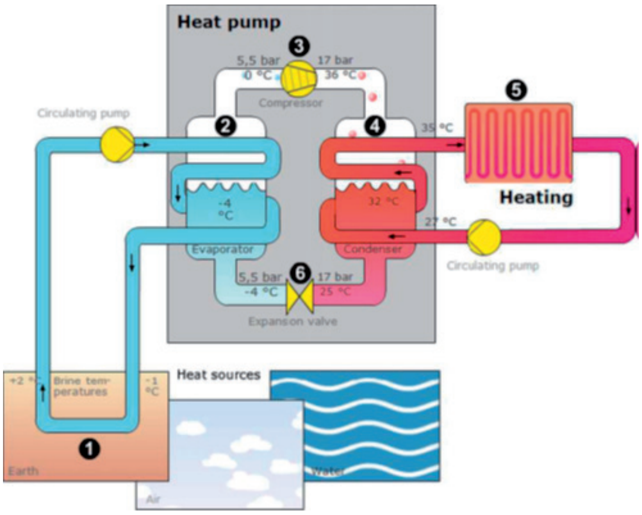

Fig. 2. Layout of a Heat Pump System in the Heating Mode [9]

Fig. 3 shows the thermal layout of a temperature-peaking heat pump that does not mitigate emissions, even though it may receive power from onsite solar PV panels and utilize waste heat. In particular, solar PV roof tiles with an unverified first-law efficiency of 0.25, connected to heat pumps, are lately claimed to achieve 20% energy savings [14]. But they ignore ΔCO_2 and emissions responsibilities. In addition, they did not account for the exergy deficit of electric-powered fans used to circulate air beneath the tiles to preheat outdoor air before it enters the heat pump. For this case, the waste heat in Figure 3 is replaced by thermal solar energy absorbed by the roof tiles, leading to a solar photo-voltaic-thermal system, PVT. The temperature-peaking *COP* of the heat pump must be at least 11 to maintain an exergy balance between the electric and thermal powers supplied [15].

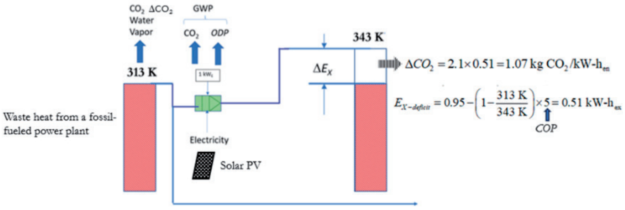

Fig. 3. Primary Exergy Destruction in a Temperature-Peaking Heat Pump

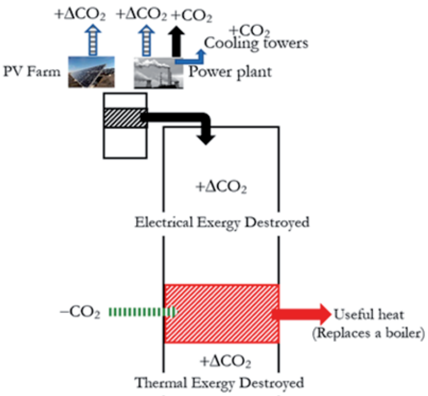

Fig. 4. The Past and The Present of CO_2 Emissions: The Responsibility of a Heat Pump

The past and current CO_2 emissions of a heat pump are shown in more detail in Figure 4. This carbon-tracing model comprises four CO_2 footprint backdrops, shown in the CO_2 emission tree in Figure 5.

1- Input Exergies for Heat, E_X: This first backdrop concerns thermal exergy utilized from ambient heat or a limited source like sewer heat at an amount of Q_1 and the source temperature *Ts*.

2- Input Exergies for Power, E_{XS}: This backdrop concerns input fuel, renewables, or waste power, including steam (electrical or mechanical), at an amount Q_2, for generating the electric power necessary to drive the heat pump. This power is used internally by the heat pump at backdrop 3.

3- Exergy Conversion, HP: Heat Pumps, power-to-heat (or cold).

4- Applications. Demand Exergies, D_X: The model associates the CO_2 trace with application selection and temperature matching, and optimizes this final backdrop downstream of the heat pump, including exergy destructions at demand points and processes.

The exergy flow bar of each backdrop is shown in Figure 5. These backdrops are holistically combined to form the most general (complete) CO_2 footprint model for heat pumps. Each diagram on the ideal Carnot cycle equivalent temperature scale shows all possible emission responsibilities, which render nearly avoidable CO_2 emissions, namely, $+\Delta CO_2$. T_{ref} is the return temperature to the ambient (sink) or the limited thermal exergy source. In this trace model, the heat pump and the input exergy (1) replace natural gas-fired condensing boilers, rendering carbon mitigation of $-CO_2$. The complete trace ΣCO_2 is $+\Delta CO_2$ $-CO_2$. There are eight major exergy destructions, including parasitic losses and grid losses. Each is responsible for ΔCO_2. T_f is the source temperature and establishes the vertical axis in Figure 5; it may be represented by a virtual source temperature, T_f^*, for non-thermal energy sources such as wind energy.

$$k_i = 1.507\varepsilon_{desi} + 0.68 \tag{5}$$

$$COP_{HP} = \left(a - b\left|T_{D1} - T_{S1}\right|\right) \tag{6}$$

$$COP_{HP_{corrected}} = COP_{HP} \times F_c = \left(a - b\left|T_{D1} - T_{S1}\right|\right) \times F_c \tag{7}$$

$$F_c = \frac{\dfrac{COP_{HP} \times \left(1 - \dfrac{T_{H2}}{T_{H1}}\right)}{0.95 + \left(COP_{HP} - 1\right) \times \left(1 - \dfrac{T_{ref}}{T_S}\right)}}{COP_{HP} \times \dfrac{\left(1 - \dfrac{T_{H2}}{T_{H1}}\right)}{0.95}} \tag{8}$$

$$E_{Xj} = \varepsilon_j \times Q_j = \left(1 - \frac{T_{1j}}{T_{2j}}\right) \times Q_j \tag{9}$$

Specific steam exergy: Sometimes, waste steam may also be used as a limited exergy source. Then Equation 10 determines the unit supply exergy from the waste steam.

$$\varepsilon_{steam} = \left(2676 + 1.60 \times \left[T_{steam} - T_{sat}\right]\right) - 7.2 \times T_{steam} \tag{10}$$

$$\varepsilon_{steam} = \frac{E_{Xsteam}\left[\text{kW-h}_{ex}/\text{kg}\right] \times \dot{m}_{steam}[\text{kg/h}]}{\dot{Q}_{steam}[\text{kW}]} \tag{11}$$

From equations 10 or 11:

$$T'_{f-steam} = \frac{T_{ref}}{1 - \varepsilon_{steam}} \tag{12}$$

<u>Virtual pressure temperature</u>: The compressor of a heat pump may be driven by a pressurized fluid. In terms of the ideal Carnot cycle, a thermal equivalent, the virtual source temperature, T'_p, may be expressed for a unit source volume ($V = 1$) at a pressure P_f, reference environment temperature, T_{ref} (283 K), and the reference pressure, $P_{ref,}$ which is equal to one atm (1.01×10^5 Pa). T_p is using the potential and thermal energy analogy.

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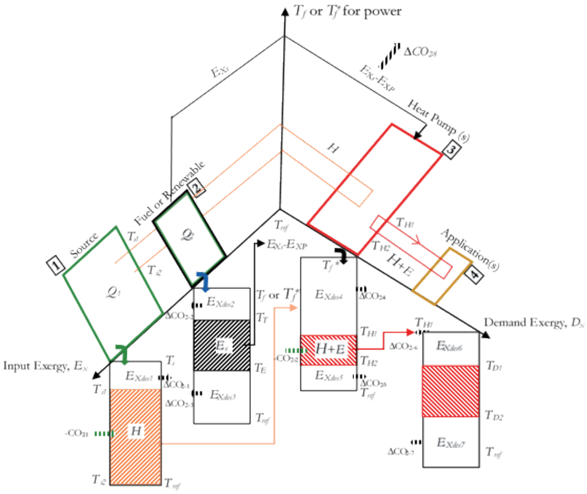


Fig. 5. Exergy-Based Complete CO2 Emission Tree of a Temperature-Peaking Heat Pump.

$$T'_p = \frac{T_{ref}}{1 + c'\left(1 - \frac{P_f}{P_{ref}}\right)} \tag{13}$$

Here, *c'* is a combined constant involving the conversion of units, unit exergy of potential (mechanical) energy, which is 0.95 kW_{en}-h/kW_{ex}-h, and $P_{ref.}$

<u>Sensitivity and emission analysis:</u> The *COP* value of a heat pump is crucial for sizing it for design conditions and for minimizing its CO_2 and ΔCO_2 emission responsibilities. For a given thermal load, the size, and therefore the ozone-depleting potential and global warming potential due to refrigerant leakage, decreases. The available supply temperature to the heat pump, $T_{sup,}$ is important, namely, CO_2, and ΔCO_2.

$$COP = a - b \times \left(T_{\sup} - T_R\right) = a - b \times \Delta T_{peak} \tag{14}$$

$$\frac{\partial COP}{\partial T_{\sup}} = -b \tag{15}$$

$$\Delta CO_2 = k_i \times \left(\frac{0.95}{COP} - \left[1 - \frac{T_{ref}}{T_{\sup}}\right]\right) \tag{16}$$

$$\frac{\partial \Delta CO_2}{\partial COP} = -k_i \times \left(\frac{0.95}{COP^2}\right) \tag{17}$$

$$\frac{\partial \Delta CO_2}{\partial T_{\sup}} = \frac{\partial \Delta CO_2}{\partial COP} \cdot \frac{\partial COP}{\partial T_{\sup}} = \frac{0.95 \times k_i \times b}{\left[a - b\left(T_{\sup} - T_R\right)\right]^2} \tag{18}$$

In Equation 18, the term (T_{sup}-T_R) is the temperature peaking demand, D$T_{peak,}$ from a heat pump. The higher the peaking temperature is, the higher the sensitivity of the ΔCO_2 emission responsibility. On the other hand, ΔTpeak depends on T_{sup} due to *COP* considerations. For example, if the reservoir temperature, $T_{sup,}$ is too low, an exceedingly elevated temperature, T_{app}, required by a certain application may compromise the *COP* extensively (See Equation 13). The pressure loss for the pumping circuitry between the reservoir and the application service of a heat pump is given in Equation 19. Furthermore, the pumping-related power demand and, thus, the CO_2 emissions from a grid can be expressed in terms of T_{sup}. (Equations 20 and 21).

$$\Delta T_{peak} \le eT^f_{\sup} \tag{19}$$

$$\Delta P = c\Delta T^d_{app} = c\left(e \times T^f_{\sup}\right)^d \tag{20}$$

$$CO_2 = c_K \times PEF \times c \times e^d \times T^{f+d}_{\sup} \tag{21}$$

Fig. 6 shows Equations 17 and 21 in terms of T_{sup} for a typical set of design and operational variables.

$$\frac{\partial CO_2}{\partial T_{\sup}} = c_K \times \frac{PEF}{\eta_{Ip-m}} \times e^d \times (f+d) \times T_{\sup}^{(f+d-1)} = Z \times T_{\sup}^{(f+d-1)} \tag{22}$$

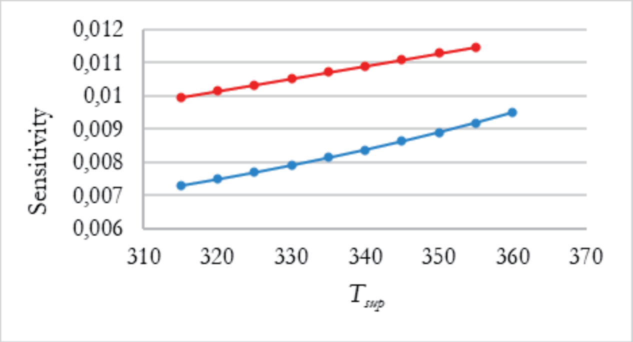


Fig. 6. Sensitivity of Emissions with T_{sup}.

Fig. 6 shows that both emission sensitivities increase with T_{sup}, thus DT_{peak}. The same relationship also holds for the CO_2 and ΔCO_2 terms. Therefore, for a given T_R, the maximum peaking temperature is limited and requires demand-side management to bring the temperature as close as possible to the resource temperature.

Sometimes the heat pump is supplied by a finite heat source. An example is seasonal thermal storage in an underground aquifer within the district energy system in Haarlem, the Netherlands [16, 17, 18]. In a similar case, Rosato et al. simulated a district solar heating and cooling system for heating, cooling, and domestic hot water in six buildings in Naples [19]. The system includes FPCs, PVs, seasonal borehole storage, and electrical energy storage. Using only the First Law, they concluded that CO_2 emissions are reduced by about 38.4%. Yet, for the renewable energy systems shown in Table 1, with their ΔCO_2 emission responsibilities, the actual CO_2 emission savings are about 20% lower than their claim. The underground seasonal aquifer system is modeled in Figure 7. The heat pump with the given *COP* properties peaks the resource temperature, T_R (in the aquifer), at T_{sup}, corresponding to the floor-heating temperature in the building.

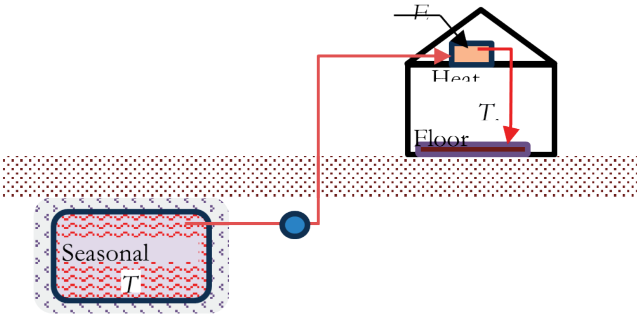


Fig. 7. A Building with Seasonal TES, Floor Heating, and a Heat Pump

T_{app} is ideally equal to T_{sup}. The aquifer is assumed to be perfectly insulated. Let *X* amount of thermal energy be delivered from TES. The power demand of the circulation pump is ignored. Let the original thermal energy stored be equal to *Y*. Let the thermal energy already used in the TES be equal to the term (*Y*). Regarding the actual benefits of underground thermal energy storage, concerning the exergy extracted from TES and delivered to the building(s), the question is whether the left-hand side of Equation 23 is greater, equal, or smaller than the right-hand side of the same equationThe right-hand side represents the initial condition, and when the TES is full, and the heat pump has not yet started to operate to peak supply temperature (*X*=0).

$$(Y-X)\times\left(1-\frac{T_{ref}}{T_R^{'}}\right)+Q_{app}\times\left(1-\frac{T_{ref}}{T_{\sup}}\right) <=>?\ Y\times\left(1-\frac{T_{ref}}{T_R}\right) \tag{23}$$

Left in the Tank Supplied to Building Full Tank

$$\Delta T_{peak} = T_{sup} - T_{R'} \tag{24}$$

$$Q_{app} = \frac{X}{\left(1-\frac{1}{COP}\right)} = \frac{X}{\left(1-\frac{1}{a-b\Delta T_{peak}}\right)} \tag{25}$$

The denominator in Equation 25 represents the thermal contribution by the electrical energy consumed by the compressor to Q_{app} in the heating mode. However, the electrical energy consumed by the heat pump has an exergy destruction penalty because the heat pump (power-to-heat system) destroys exergy upstream of the thermal exergy that it delivers. Therefore, Equation 25 is corrected such that Q_{app} is given by Equation 26. Here, 283 K is the reference temperature, T_{ref}.

$$Q_{app} = \frac{X}{\left(1-\frac{1}{COP}\right)} = \frac{X}{\left\{\left(1-\frac{1}{a-b\Delta T_{peak}}\right)\times\left(0.95-\left(1-\frac{283K}{T_R^{'}+\Delta T_{peak}}\right)\right)\right\}} \tag{26}$$

Dividing both sides by *Y*, and taking *Y* arbitrarily to be unity:

$$(1-X)\times\left(1-\frac{T_{ref}}{T_R^{'}}\right)+\left(X\left[1-\frac{1}{\left(a-b\Delta T_{peak}\right)\times\left(\frac{0.95}{COP}-(1-\frac{T_{ref}}{\left(T_R^{'}+\Delta T_{peak}\right)}\right)}\right]^{-1}\right)\times\left(1-\frac{T_{ref}}{T_R^{'}+\Delta T_{peak}}\right)<=>?\ \left(1-\frac{T_{ref}}{T_R}\right) \tag{27}$$

$$T_R^{'} \square \left(T_R - T_{ref}\right)\times\left(1-\dot{X}\right)+T_{ref} \tag{28}$$

The decision concerning Equation 27 is a function of DT_{peak}, and (*X*). The right-hand side of the equation is constant for given T_{ref} and T_R. According to Figure 8, for a temperature peaking, DT_{peak} of 5 K, the TES operation is limited to *X*=0.75. This means that if the heat pump continues to extract thermal exergy from TES, the net emission responsibility becomes positive. In other words, otherwise, if the system continues operating, it will be responsible for ΔCO_2, because the exergy on the RHS of Equation 27 will be less than that on the LHS, corresponding to the initial condition (no thermal discharge from the TES tank). This means the TES tank volume will be effectively used until the tank is discharged up to 75%. Therefore, the tank size must be proportionately larger to utilize the full thermal energy from the initial thermal charging, leaving a margin of about 25% in the tank. When DT_{peak} is set to 10 K, the X limit is slightly lower. However, for higher DT_{peak} values, such as 15 K, using TES will not be exergy-efficient.

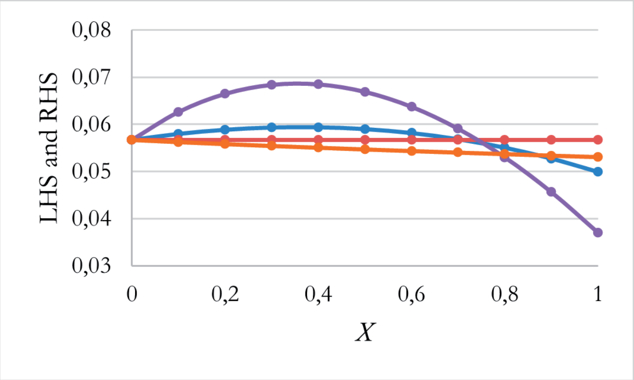


Fig. 8. Permissible X is a Function of ΔT_{peak}. T_R =300 K. T_{ref}= 283 K, a =4, b =0.02 K^{-1}

The peak exergy rationality occurs at $X = 0.36$ for ΔT_{peak} = 5 K. Figure 8 further shows that, for low-enthalpy thermal energy sources ΔT_{peak} must be small to utilize the maximum energy stored in TES for no ΔCO_2. Figure 9 repeats Figure 8 for T_R = 320 K and shows that the TES performance is also sensitive to the resource temperature. For example, the X value is higher (>0,9) and almost the same across the tree ΔT_{peak} cases. TES for ΔT_{peak} = 15 K also becomes exergy rational. Changes in ΔCO_2 also diminish. Therefore, any change in the TES resource temperature during charging must be closely monitored. Results may also change with the specific performance parameters of the heat pump used, namely (a) and (b). The heat pump has a cooling *COP* of four at design conditions. For 1 kW_{en}-h of cooling at 7°C/12°C (280 K/285 K) regime, the heat pump requires 0.25 kW_{en}-h of solar electricity generated by the PV panels on board, with a first-law efficiency of 0.20.

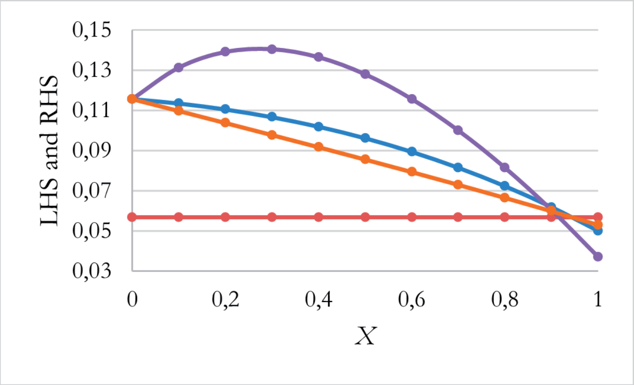


Fig. 9. Permissible X is a Function of ΔT_{peak}. T_R =300 K. T_{ref}= 283 K, a =4, b =0.02 K^{-1}

These results underline the importance of the Second Law and show that, from an exergy perspective the rate of temperature peaking must be carefully determined. If this temperature provides a T_{sup}, which is below the demand temperature, then the rest of the solution must be continued at the selection of the equipment type and size step on the demand side (in this case the building) by closing the temperature gap, either by oversizing the floor panel in terms of closer heat transfer tube spacing [20] or a different type of heating unit [21].

3. Results

The case study shows that comfort cooling using a heat pump driven by on-site (Roof type) photovoltaic panels results in CO_2 emissions per kW_{en}-h of cooling, including latent loads from dehumidification. Figure 10 shows the system's general layout. Although the system saves energy and eliminates the use of fossil fuels, exergy destructions, namely E_{X-1} and E_{X-2}, lead to Δ_{CO2-1} and Δ_{CO2-1}.

The unit exergies for cooling and electricity are 0.0106 kW_{ex}-h and 0.95 kW_{en}-h, respectively. For heat pump:

$$E_{X-PV} = 0.25\ \mathrm{kW}_{en}\text{-h} \times 0.95\mathrm{kW}_{ex}\text{-h/kW}_{en}\text{-h} = 0.2375\ \mathrm{kW}_{ex}\text{-h}$$

$$E_{X-des2} = 0.2375\ \mathrm{kW}_{ex}\text{-h-}0.0106\ \mathrm{kW}_{ex}\text{-h} = 0.2269\ \mathrm{kW}_{ex}\text{-h}$$

$$\Delta CO_{2-2} = 2.1 \times 0.2269 = 0.4765\ \mathrm{kg\ CO_2/h}$$ For PV Panel:

$$E_{X-des1} = \left(\frac{0.25}{0.2}\right) \times \left[0.95\text{-}(1\text{-}0.2) \times \left(1\text{-}\frac{283\ \mathrm{K}}{340\ \mathrm{K}}\right)\right] = 0.816\ \mathrm{kW\text{-}h_{EX}}$$

$$\Delta CO_{2-2} = 1.1 \times 0.816 = 0.8976\ \mathrm{kg\ CO_2/h},$$

$$\sum \Delta CO_{2-2} = 1.1 \times 0.816 = 1.374\ \mathrm{kg\ CO_2/h}$$

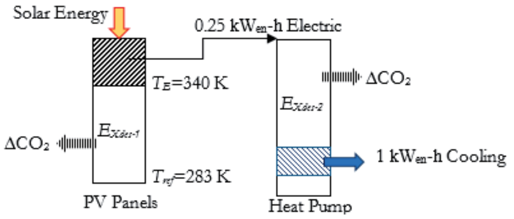


Fig. 10. Exergy Destructions in a PV-Driven Heat Pump System for Comfort Cooling. *COP*=4

On the other hand, this system replaces the on-site generator, with 0.35 efficiency, using natural gas:

$$CO_{2-saving} = \left[\frac{0.25}{0.85} \times 0.2 + 1.1 \times (0.87 - 0.95 \times 0.35)\right] = 0.5631\ \mathrm{kg\ CO_2/kW\text{-}h}$$

According to this calculation, replacing a chiller with a heat pump does not change emissions. Consequently, the net CO_2 emission responsibility will be +0.8109 kg CO_2/kW_{en}-h for comfort cooling. This is a negative CO_2 mitigation potential, although the systems seem carbon-free, without embodiments. Results show that even if renewable energy systems are completely used, unless higher *COP* values are achieved in the heat pump industry, heat pumps do not save emissions in the energy stock when the second law is considered. However, this law also offers better solutions, such as using the heat from a solar PVT panel. In this case, the low-enthalpy heat may drive an adsorption cooling machine (ADS) for sensible cooling and a desiccant wheel, both of which replace the functions of a heat pump. This alternative is shown in Figure 11. Table 1 compares the results of Figures 10 and 11. The desiccant wheel utilizes exhaust cold and little electricity. [22]. Table 2 shows that the alternative solar cooling system mitigates CO_2 emissions, with the heat pump accountable for those emissions. The overall difference between these two systems is 1.616 kg CO_2/kW_{en}-h of cooling. The parasitic power and heat of the ADS system are ignored. The ADS system's waste heat regenerates the desiccant system.

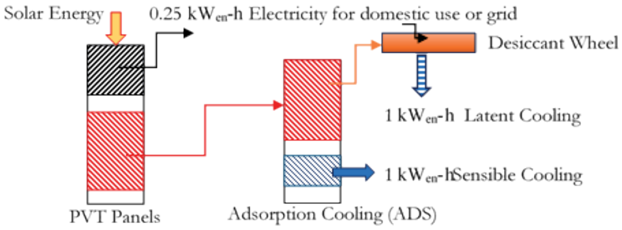
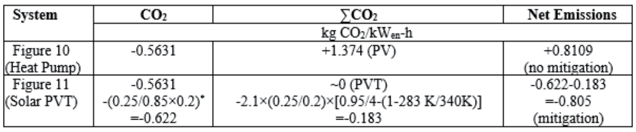


Fig. 11. Alternative Solar Cooling System Without a Heat Pump

Table 2. Comparison of Figures 10 and 11.



System	CO_2	$\sum CO_2$	Net Emissions
	kg CO_2/kW_{en}-h		
Figure 10 (Heat Pump)	-0.5631	+1.374 (PV)	+0.8109 (no mitigation)
Figure 11 (Solar PVT)	-0.5631 -(0.25/0.85×0.2)* =-0.622	~0 (PVT) -2.1×(0.25/0.2)×[0.95/4-(1-283 K/340K)] =-0.183	-0.622-0.183 =-0.805 (mitigation)

* Replaces both a generator and a boiler

4. Discussion of results and conclusions

The results of the exergy-based model, when applied to the case studies, show that the current practice of using solar energy with heat pumps results in emissions rather than a sustainable mitigation strategy. The second law of thermodynamics showed that the case study about the comfort cooling system of the nature center building with ground source heat pumps and photovoltaic panels is responsible for emissions by 0.81 kg CO_2 emissions/kW_{en}-h, rather than saving 1.616 kg CO_2/kW_{en}-h by an alternative without a heat pump, comprising solar photovoltaic panels, adsorption cooling, and desiccant wheel. The graphical display in Figure 5, namely the exergy-based complete CO_2 emission tree for a temperature-peaking heat pump, shows the number of ΔCO_2 emission points in such an application and helps designers identify and minimize them. There are four primary exergy destruction points: the source, the fuel or renewables, the heat pump, and the demand point. The corresponding exergy flow bars show that renewables are not free of $\Delta CO_{2,}$ but can be minimized. For example, a PV panel may be replaced by a PVT panel if the climate and solar insolation are suitable.

These examples show that the crucial gap in the literature on global warming is the lack of understanding of the direct link between destruction and CO_2-emission responsibility, named ΔCO_2. In the energy sector, ΔCO_2 is generally higher than direct CO_2 emissions at the source, meaning that as long as the literature gap exists, the global warming issue will not be properly resolved, because the root causes of ΔCO_2 will be kept hidden, leading to missed solution opportunities concerning minimizing exergy destructions, thus CO_2 emissions. A for CO_2. This research aims to provide in-depth insight and greater awareness of the ΔCO_2 term in the quest to achieve the Paris Agreement goals on time and sustainably. The exceedance of ΔCO_2 is exemplified in Table 1. The correction factor for the standard *COP* definition, $F_{c,}$ is also important. Equation 8 gives this value for the following sample input data:

$$F_c = \frac{\dfrac{4\times\left(1-\dfrac{310\text{ K}}{330\text{ K}}\right)}{0.95+\left(4-1\right)\times\left(1-\dfrac{283\text{ K}}{340\text{ K}}\right)}}{\dfrac{4\times\left(1-\dfrac{310\text{ K}}{330\text{ K}}\right)}{0.95}} = 0.724$$

Therefore, the corrected *COP* becomes 4 × 0.724 = 2.84.

This result reflects the actual CO_2 emissions. If the electric power comes from a natural gas power plant and the Primary Energy Facor, *PEF* for EU countries is equal to 2.5, the CO_2 emission due to power demand by a heat pump with an uncorrected *COP* of four will be 0.173 kg CO_2/kW_{en}-h, instead of 0.125 kg CO_2/kW_{en}-h, which is what the sector calculates by using the First Law. When the difference of 0.048 kg CO_2/kWh_{en} is multiplied by 600,000 heat pumps to be installed in the United Kingdom until 2028, it means that 144 tons of CO_2 per hour will remain unaccounted for. Figure 6 shows that, when operating heat pumps at varying supply temperatures, the control may not be sufficient to minimize emissions due to the high sensitivities of both CO_2 and ΔCO_2. In addition, the demand side must be dynamically managed to stabilize the supply temperature and better meet demand. For example, a heat pump-assisted heat recovery system operates under varying outdoor and indoor conditions, and the supply temperature to the heat pump varies, along with the demand temperatures on the supply side of the heat pump [23]. Therefore, the heat recovery unit must be controlled to stabilize temperatures and reduce the heat pump's sensitivity.

An important result from modeling an underground labyrinth TES coupled with a heat pump is that the available seasonal thermal energy storage is limited. It depends on the stored heat temperature and the required peaking temperature. The higher the stored heat's temperature, the lower the effect of this constraint. Results may also depend on the performance parameters of the heat pump, namely (*a*) and (*b*). Future studies will focus on the impact of these parameters on the thermal energy's usability in the TES tank.

In conclusion, this research has provided important clues for the design, selection, and control of temperature-peaking systems and equipment using heat pumps and thermal energy storage of low-enthalpy energy sources, which are abundant but remain largely untapped. The total electrification strategy and transition to green energy sources and systems see heat pumps as a key asset for decarbonization efforts. However, this paper shows that, from an exergy destruction perspective, particularly in the power-to-heat process of a heat pump, the *COP* must be higher to reduce the exergy destruction-led ΔCO_2. Thermal energy storage is seen as another important asset in utilizing waste heat sources. However, if the source is limited for a given period, such as seasonal thermal energy storage systems, the stored thermal energy may not be fully utilized during the heating season. The example of the underground thermal energy storage system in the Haarlem district receives heat from heat pumps operating in cooling mode in summer and stores it in an aquifer. Therefore, the thermal capacity is limited depending on the rejected heat from heat pumps. This makes its design and operation crucial to the system's performance and dependent on the cooling and heating degree hours of the specific climatic region. In the heating season, no further thermal energy is received. Firstly, such systems are effective if the heating and cooling degree hours are similar, and the reject heat temperature is high enough. Secondly, the useful part of the thermal energy stored depends on the peaking temperature required for the given systems and equipment used in the buildings. Sample results indicate that the peaking temperature may be responsible for ΔCO_2 emissions, which have not been accounted for in the district heating, heat pump, and thermal energy storage industries. Furthermore, the selection of the location of central TES systems, the distance between the aquifer and the district, and the piping type and size are important, because the required pumping power using electricity with a high unit exergy relative to the thermal energy stored may result in a large ΔCO_2 responsibility. The carbon mitigation potential of heat pumps and solar energy systems is lower than first-law calculations predict. A correction factor for the coefficient of performance has been developed, accounting for the exergy destruction and the potential for emission avoidance of a typical heat pump with respect to its electrical and ambient thermal inputs. This correction factor is easy to implement and is expected to resolve the ΔCO_2 emission issue in the heat pump sector, enabling more realistic predictions of decarbonization potential in the field. Further studies may focus on reviewing decarbonization directives and standards to incorporate the second law alongside the First Law. Some efforts in this respect are already documented in the literature, such as the Science Europe report, which describes the situation and urges industry to consider exergy. In the same vein, the net-zero definitions must be revised to ensure these buildings become truly net-zero in terms of exergy. In this quest, however, the ΔCO_2 terms play a significant role in the built environment and should not be neglected. In future works about heat pumps, district energy systems, thermal energy storage, and carbon footprint calculations, the Second Law must complement the current methodologies, guidelines, and standards so that the Paris Agreement goals are met on time and on a sustainable basis by taking into account the new opportunities hinted at by the Second Law. At the same time, the *COP* values need to be improved technologically, and a closer match between the supply and demand temperatures needs to be established to minimize exergy destructions. Thermal energy storage systems must also be evaluated and designed in accordance with the Second Law, and sized and operated accordingly. Furthermore, the model presented in this article analyses exergy transfer in a TES system and identifies exergy destructions beyond a certain limit of thermal exergy use in the TES system. Such an analysis is not present in the open literature because all calculations depend on the quantity of energy (First Law), and field measurements are recorded by conventional calorimeters that solely measure the quantity of heat transferred, without accounting for the temperatures, which are essential for calculating exergy transfer. Because of this shortcoming, while such data is not available, presenting any field support was not possible. Therefore, it is recommended that future studies include exergy meters.

5. Nomenclature

a, b	Linearized performance (*COP*) factors of a heat pump
c'	Coefficient in Equation 13
c_K	Carbon factor of fuel, kg CO_2/kW_{en}-h
CO_2	Carbon dioxide emission, kg CO_2/kW_{en}-h
COP	Coefficient of performance
COPEX	Exergy-based *COP*
D_X	Demand Exergy, kW_{ex}-h
E_X	Input exergy for heat, kW_{ex}-h
E_{XS}	Input exergy for power, kW_{ex}-h
F_C	Correction factor for *COP*
k	ΔCO_2 penalty ctor for exergy destructions, kg CO_2/(kW_{ex}-h/kW_{en}-h)
P	Pump energy, kW_{en}-h
P_f	Pressure, Pa
Q	Thermal energy, kW_{en}-h
PEF	Primary energy factor
R	$\Delta CO_2/CO_2$
R_{EX}	Exergy-based renewable energy mix in the energy sector of a given region or country
T	Temperature, K
T_a	Outdoor air temperature, K
T'_p	Thermal equivalent, virtual source tem perature of a pump, K

T_{ref}	Reference environment temperature, K
T_f	Adiabatic flame temperature of the fuel, source temperature, K
T_f^*	The Carnot-Cycle-equivalent source temperature, K
X	Amount of thermal energy received from the thermal energy storage system, kW_{en}-h

Greek Symbols

η_I	First-Law efficiency
ΔCO_2	Nearly avoidable CO_2 emission responsibility, kg CO_2/kW_{en}-h
ε	Unit exergy, kW_{ex}-h/kW_{en}-h
ψ_R	REMM Efficiency
ΣCO_2	Total (or net) emission, $+\Delta CO_2+CO_2$, or $+\Delta CO_2-CO_2$.

Subscripts

app	Useful application
B	Boiler
dem	Demand
DE	District Energy
DS	District supply (Temperature)
DR	District return (Temperature)
des	Destroyed
E	Exit (Temperature) from useful application
en	Energy
eq	Heating equipment
ex	Exergy
H	Heat
HP	Heat pump
max	Maximum
R	Rational (Exergy utilization), resource
ref	Reference
res	Ambient resource
ret	Return
sup	Supply

Acronyms

ADS	Adsorption Cooling Machine
CHP	Combined Heat and power
DE	District Energy
DH	District Heating
DHW	Domestic Hot Water
EC	European Commission
EU	European Union
FPC	Flat Plate Collector
HE	Heat Exchanger
HP	Heat Pump
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilating, and Air-Conditioning
NG	Natural Gas
nZEXB	Nearly Zero Exergy Building
nZEB	Nearly Zero Energy Building
OECD	Organization for Economic Co-operation and Development
PV	Photo Voltaic
PVT	Photo Voltaic Heat (Solar Panel)
REMM	Rational Exergy Management Model
TES	Thermal energy Storage

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Consideration of an Industrial Database Format for Resource Recycling and for Matching Recyclable Resources Using Between Industries

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Abstract

As one of the strategies to mitigate climate change and increase resource use efficiency, there is a need to improve energy recovery and recycling. Then, sector-coupling methods between industries are expected to improve resource recycling efficiency. This study considered the supply of extracted steam from waste treatment plants (WTP) to neighboring factories. We focused on the fact that the company names contained characteristic terms depending on the type of industry. The target factories of the steam supply were classified into industry types by the LSTM method based on the database of company names, and we estimated spatial steam demand using developed models However, they lack of spatial energy demand data could not validate this model result. From this situation, the process database of industries for matching recyclable resources and the list of company names for estimating the location of industries would need to be developed. Therefore, it is necessary to establish a beneficial system to provide data for validation. Based on the knowledge obtained from estimating the location of industries based on the company names and estimating the distribution of industrial steam demand, we developed a database arrangement model system. In this context, trial consideration of the industrial process with Resource Description Framework (RDF) formatting was conducted to enable the data collection and retrieval of process data through a knowledge base.

***Keywords**: Recyclable resource, Circular economy, Supply-Demand Matching, RDF, Semantic Web*

1. Introduction

In the field of waste management, improvement of energy recovery and acceleration of recycling are required in terms of global warming countermeasures and the improvement of resource efficiency. The sector coupling method is currently being focused on to improve the efficiency of resource recycling and the utilization of waste materials. However, t the supply and demand of recyclable resources, cannot be considered in terms of quantity and quality. Therefore, it is necessary to determine the spatial distributions of supply and demand.

Fujii et al. [1] explained steam that steam from waste treatment plants to some industries is more efficient regarding exergy, energy and economic benefits than electricity generation. This study focuses on the industrial steam demand for recyclable resource distribution.

Maki et al. [2] estimated steam demand using geographical data on industries, the steam supply potential of waste treatment plant, and the locations of waste generation sites in Aichi Prefecture, Japan. They found that the steam supply could be transported as far as 6 km from the generation point and that the waste treatment plants had a steam generation potential of -60%. Maki et. al. [3] improved on this study and analyzed industrial augmentation areas that should be prioritized as steam supply targets from an economic perspective.

In industrial ecology, Behera et al. [4] evaluated the effects of an exhaust heat utilization network and the heat supply from a waste incineration plant in an industrial park in Ulsan, South Korea. The authors also evaluated the business processes facilitating a targeted Eco-industrial park (EIP). Dou et al. [5] [6] [7] analyzed that included the industrial scenario based on a recent industrial location map.

Most studies that have focused on the geographic distribution of recyclable resources and attempted to improve the efficiency of resource circulation based on the geographic distribution of recyclable resources have focused on recycling. Wu et. al. [8] used GIS to estimate the future generation and management of construction and other demolition waste in Shenzhen City, China. Robinson et. al. [9] used GIS to study the appropriate arrangement of recycled aggregate use based on transportation networks and population density information. Nour Madi et. al. [10] used GIS to estimate the amount of demolition waste generated, including that generated during disasters, and considered recycling sites. Wang et. al. [11] used machine learning methods to estimate spatial building resource stocks in Japan. Wiedenhofer et. al. [12] estimated resource stocks in transportation infrastructure at national level. Bai et. al. [13] used a 4D-GIS to estimate building stocks and developed a bottom-up spatio-temporal database of carbon emissions from construction and demolition in Japan. These studies have estimated the amount and potential of waste and other resources generated; however, few have attempted to understand the existing demand locations for recyclable resources. Pauliuk et al. [14] noted that industrial ecology lacks generic structures and databases, necessitating the development of databases for components and analysis methodology systems.

In this situation, we focused our research on the existence of characteristic terms in each factory industry in the steam demand target. We developed an industry classification estimation model using the LSTM (Long Short-Term memory) model from the names of each factory listed in the Nationwide Factory Directory data. This text-mining method was used by Rizwan et al. [15], Rahimi et.al. [16], Lourentzou et al. [17], Han et.al. [18], Hasan et.al. [19], Luo et.al. [20] and many other studies that analyzed geographic information data associated with SNSs and estimated their geographic distribution. Several studies in this area were reviewed by Utomo et al. [21]. However, few studies have focused on company names or analyzed industries.

We developed an LSTM model that estimated the demand potential for steam at 200°C or lower. This model estimated industrial distribution of steam demand locations using text mining and statistical databases. The potential was estimated from the 1km mesh level, using the estimated industrial distribution based on steam demand unit data by industry. Because this research is limited, obtaining data on the demand potential of quantity and quality by industry for other recyclable resources is difficult. However, expanding the list of sample companies with their names and industrial types matched is necessary to improve accuracy. As data were not adequately collected, this study focused on developing a system to estimate industrial location. Improving the accuracy will be the focus of future studies. Data collection bias and data number problems were caused by the lack of a mechanism to collect and compile data in future studies.

2. Method

2.1 Factory type of steam demand target

In Factory name data statistics (Nationwide Factory Directory data [22] [23], the 28385 factories listed in the Kanto/Kansai region, where digital data is available, were targeted. The target industry sectors were selected based on the steam demand factory statistics (A comprehensive survey of energy consumption in industrial facilities,) [26]. However, the metal manufacturing industry, which has the largest sample size, is separate from the steel industry. The industry classifications are listed in **Table 1**.

Table.1 Steam demand target factory type [26]

① Foods (Processing)
② Foods (Ready meal)
③ Foods (Seasoning)
④ Foods (Bakery/Confectionery)
⑤ Beverages, tobacco & feed (Soft drink)
⑥ Beverages, tobacco & feed (Liquor)
⑦ Textile & Apparels
⑧ Pulp & paper products
⑨ Inorganic chemicals
⑩ Organic chemicals
⑪ Pharmaceutical
⑫ Oil and coal products
⑬ Plastic products
⑭ Rubber products
⑮ Ceramic, stone & clay products
⑯ Iron and Steel
⑰Metals
⑱Nonferrous Metals
⑲General machinery equipment
⑳Electronic parts, devices & electronic circuits
㉑Transportation equipment (automobile)
㉒Non-target

2.2. Industry Classification and Location Estimation Model from Company Name

Fig. 1 shows how to estimate the building type. It is difficult for existing factories to create such figures because of privacy issues and other reasons. Therefore, we created a figure based on a Japanese map using a public research institute affiliated with the author as the subject to illustrate a specific image of the analysis. From the textual information "研究所," it is possible to estimate that the building is an institute. Thus, specific terms are considered to characterize specific industries. We apply this characteristic to identify the type of industry for companies through text analysis. We aim to develop a system that estimates the spatial distribution of steam demand by integrating it into lists containing address data.

"研究所 " is characteristic name for Research institute by Japanese

- The industry sectors also includes characteristic words for different industries.
- For example, including "Chem", "Chemical" are chemical industries, "Medicine", "Medical" are medical industries.

Map application data is included "Name" and "Location". We would estimate target factories data-base by using these data.

Ex. National Institute for Environmental Studies

<Reference>https://www.google.com/maps/d/viewer

Fig. 1. Concept image
(ex., National Institute for Environmental Studies)

In this study, we developed an industry-classification model based on factory names using LSTM. The Deep Learning Toolbox and Text Analytics Toolbox in MATLAB R2022b were used for the analysis.

We developed an industry classification model using the LSTM model with word coding based on the text data of the target factory names. The analysis was conducted on a dataset in which 80% of the factories in each industry were randomly selected from the 22 targeted industries for the learning data. We examined two approaches to analysis: one using stop words and one that did not. Here, stop-words mean terms without meaning in text analysis, such as the Japanese symbol “㈱” meaning “ company limited.” The removal of such terms is known as stop-word processing.

For estimation at the national level, we developed a model to classify the manufacturing industry among corporations based on Phonebook data [24]. Phonebook data is a list of corporations registered in the Phonebook for each prefecture and contains data on nearly 10 million corporations nationwide. This database classified industrial categories as “manufacturing” or others, which we named “non-target.” We developed a model that combines manufacturing industry data for all prefectures and uses 5% of the manufacturing industries and the same number of non-target companies as the learning data.

The two models were then integrated. We developed a two-stage industry classification model using LSTM with word coding, as shown **Fig. 2**, and developed industry unit data for industries with steam demand below 200°C. Spatial industry and steam demand estimations were conducted at the national level. In this study, we estimate industry types based on company names. Based on these results, we developed a system to estimate steam demand by estimating the industry type and location. Therefore, we used the word-encoding method for text analysis, with a maximum of 10 words. After time-series data conversion, estimation was performed using a classification model set as a single-layer 80-perceptron LSTM. Because of limited training data and the inability to randomly sample industries within Japan, improving the accuracy of models may not always improve the accuracy of the spatial distribution estimation. Improving analytical accuracy, including problems with data collection, remains a challenge for future research.

Cross-validation analysis was also performed for each category to compare and evaluate the applicability of this study. We analyzed the trends in the sample size and correct rates based on cross-validation for each category.

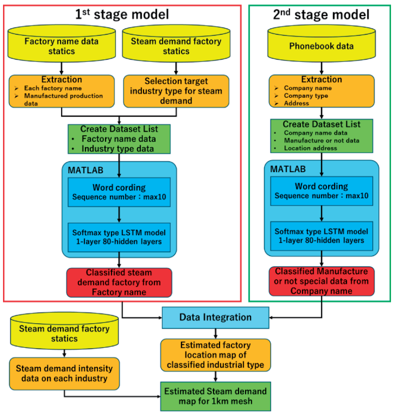

Fig. 2. Spatial Estimation Algorithm

3. Result

3.1. Industry Classification Model Results

We developed a model that could estimate industry types from company names with a correct response rate of about 70–80% for 22 industries (**Fig. 3.**).

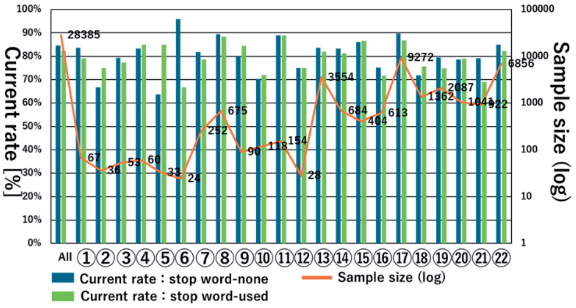

Fig 3. Results of the Industry Classification Model

Table 2 presents the cross-validation results. These results confirm that stop-word processing had no significant effect in cross-validation either. Table 2 shows that industries with larger sample sizes had higher correct rates.

The highest accuracy obtained through cross-validation was approximately 60%, indicating that further improvements in accuracy are possible by advancing the model. However, the lack of data on many industries is problematic.

Table 2. Result of cross-validation for LSTM

	validation sample	Current rate stop word-none	Current rate stop word-used
①	14	35.7%	28.6%
②	8	25.0%	37.5%
③	11	9.1%	9.1%
④	12	25.0%	25.0%
⑤	7	14.3%	28.6%
⑥	5	80.0%	60.0%
⑦	51	29.4%	39.2%
⑧	135	60.0%	58.5%
⑨	18	11.1%	22.2%
⑩	23	8.7%	8.7%
⑪	31	48.4%	54.8%
⑫	6	0.0%	0.0%
⑬	696	45.0%	52.9%
⑭	137	46.0%	45.3%
⑮	80	42.5%	47.5%
⑯	114	27.2%	23.7%
⑰	1663	63.1%	50.4%
⑱	262	19.8%	30.9%
⑲	401	24.9%	21.9%
⑳	199	22.6%	29.6%
㉑	173	28.9%	23.7%
㉒	1338	40.4%	36.6%
Total	5384	44.7%	41.4%

3.2. Results of the manufacturing classification model from the company name

Fig. 4 shows the results of the manufacturing classification. Each point represents a prefecture. The larger the number of factories, the higher the percentage of correct answers.

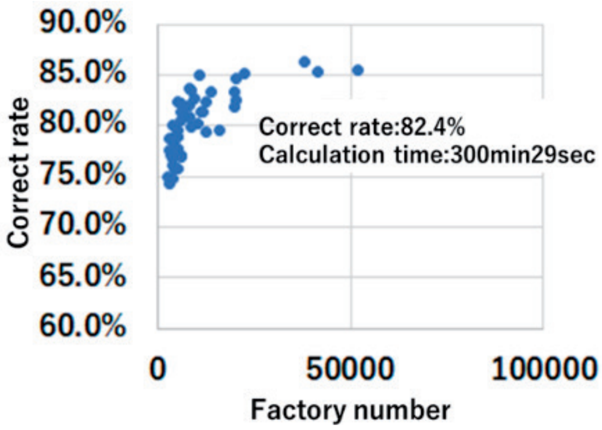

Fig. 4. Results of manufacturing classification model

3.3. Estimation of factory locations using a two-stage model

Based on these results, they estimate the spatial distribution of industries, as shown in **Fig. 5**. These figures are estimated for nationwide Japan, but because of the difficulty of description, Aichi and Yamaguchi prefectures are chosen for this report; each point in **Fig. 5** shows factory locations, and each color shows industrial types. If any point data were classified as non-manufacturing companies, they were eliminated from the map. Then, **Fig. 5** shows the estimated factory locations.

In Aichi Prefecture, many factories are distributed around the large population center of Nagoya, while in Yamaguchi Prefecture, many factories are located along the coast of the Seto-Nai Sea. It is thought that the results for Aichi Prefecture are affected by a large number of small factories located in areas with high population density. The Phonebook data lists factories without limiting their size, thus including small factories in the data. However, in some cases, factory names such as “rice cake (餅)” were classified as plastic product industries even though they were considered food processing industries by human thinking; this is thought to be caused by the lack of databases.

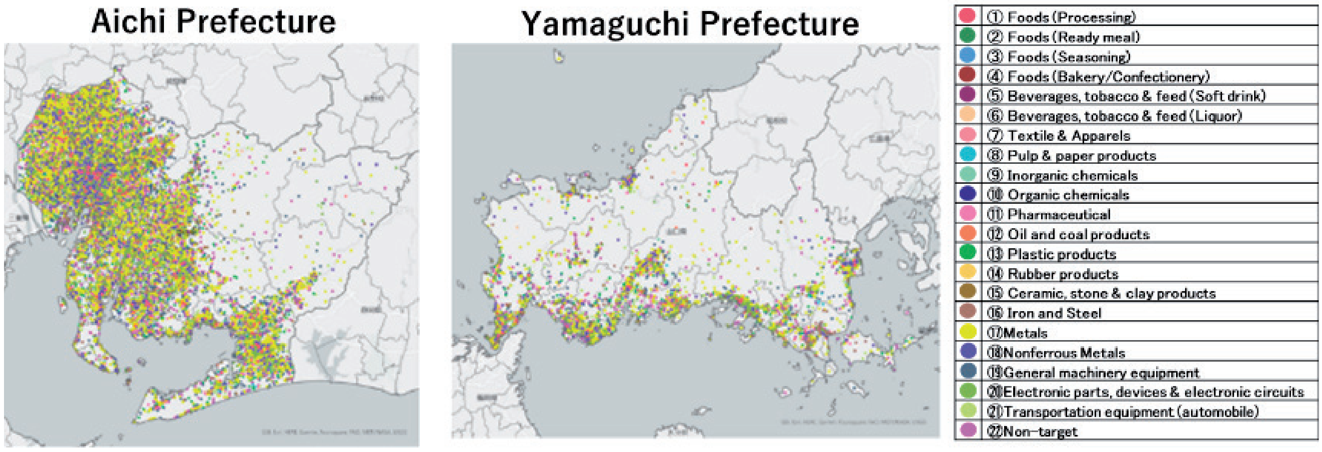

Fig. 5. Estimated results of industry distribution in Aichi and Yamaguchi Prefectures

3.4. Results of spatial estimation of steam demand

Fig. 6. was obtained in Aichi and Yamaguchi prefectures using steam demand unit data per office based on Reference [25]. Offices are typically tend to be located in highly populated areas. In Aichi Prefecture, it is estimated that a large amount of steam demand exists in the neighborhoods of cities, including inland areas. However, in Yamaguchi Prefecture, steam demand is concentrated near ports on the coast, and there are no large steam demand points in the inland area. In this context, we can develop a system to estimate the spatial steam demand based on company names.

However, this study did not sufficiently analyze the differences in the scale of the facilities. Using an average intensity value is considered to result in overestimating the heat demand; this was caused by using per-office intensity. Therefore, a future challenge is to proceed with estimates based on the building area and shipment value of manufactured goods.

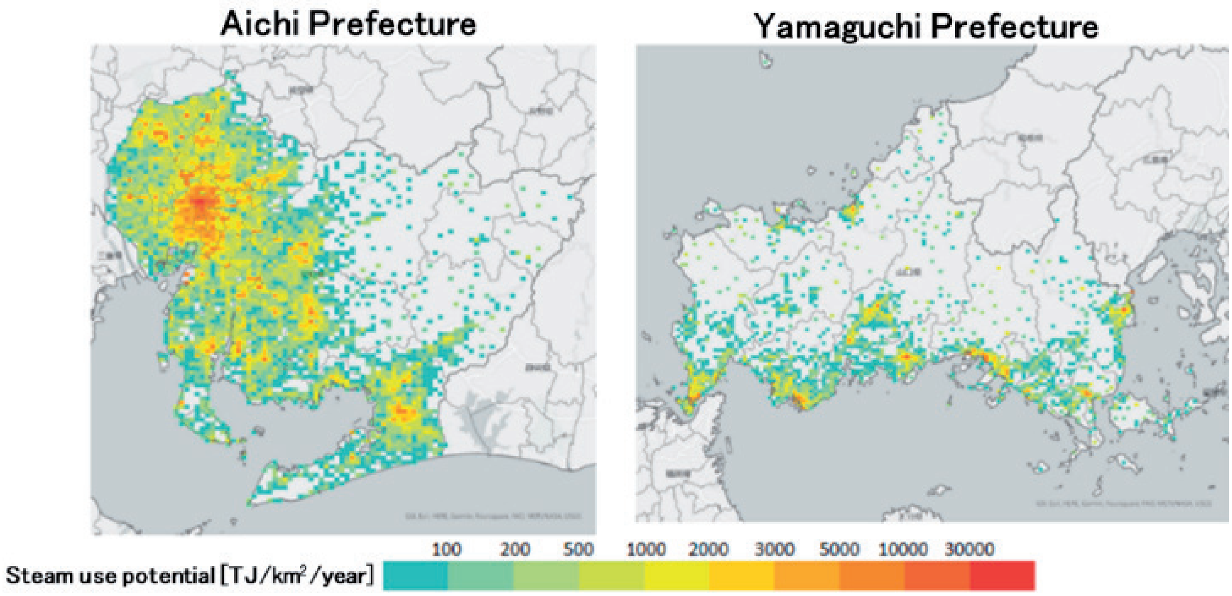

Fig. 6. Estimated results of the spatial distribution of steam demand in Aichi and Yamaguchi Prefectures

4. Conclusion

In this study, we considered the format structure of a database required for the supply-demand matching that utilizes recyclable resources.

We developed a model to classify industries based on factory names. This model was extended to Phonebook data, and a model was developed to classify manufacturing industries from corporations nationwide. By integrating the above two models, we estimated the location of factories that use steam and the estimated steam demand using the steam demand intensity of each industry.

As a result, we developed a model that can estimate the location of factories that are considered to have steam demand from nationwide corporations listed in the Phonebook data by text mining using the LSTM method. Using the steam demand intensity, we can estimate the amount of steam demand per 1 km mesh. The LSTM-based model achieved a certain level of accuracy, but further improvements were possible through the multilayering of the LSTM and hyperparameter tuning. However, there is a problem with the industry classification model in that the data from the main source does not comprehensively cover factories. However, some industries are not sufficiently classified. Although this study considers steam utilization, the model applies to other underutilized resources, if data are available. However, the lack of such data remains an issue.

5. Future works for the Necessity of data collection

Although it is possible to improve the accuracy rate by improving the LSTM model compared to the current data, the fundamental problems of bias in the limited data and the lack of data for validating the final factory location remain. Therefore, it is assumed that the advancement of classification models may not solve engineering problems because it is not beneficial to generalize data disclosure to the industrial side due to the inclusion of company secrets and technologies. However, the generalization and collection of industrial process data could increase the possibility of sector coupling among companies, thereby increasing the efficiency of recycling resource utilization. Therefore, it is necessary to consider a format that can promote sector coupling to utilize recyclable resources by increasing the number of samples and their types, as well as expanding the database.

In this situation, it is proposed to construct a data format in a knowledge base using an RDF [26], which is considered an easier way to build a relational database. RDF is also used for searches using search engines on the Internet. This technology is known as the Semantic Web. This technology can be used to estimate a knowledge base, such as the RDF described above, using the metadata on the HP; this makes it possible to search for recyclable-resource-use suggestions in a simplified way. **Fig. 7** shows an image of a connection based on several industrial processes using an RDF. In the Semantic Web field, methods for measuring the distance between knowledge bases such as RDF have been studied [27]. Because it is based on a semantic approach, the processes can be classified according to a linguistic database and thus can be presented without showing secret information about individual companies. Based on this technical background, we would like to explore expanding the sample data by developing data collection methods that utilize Semantic Web technologies.

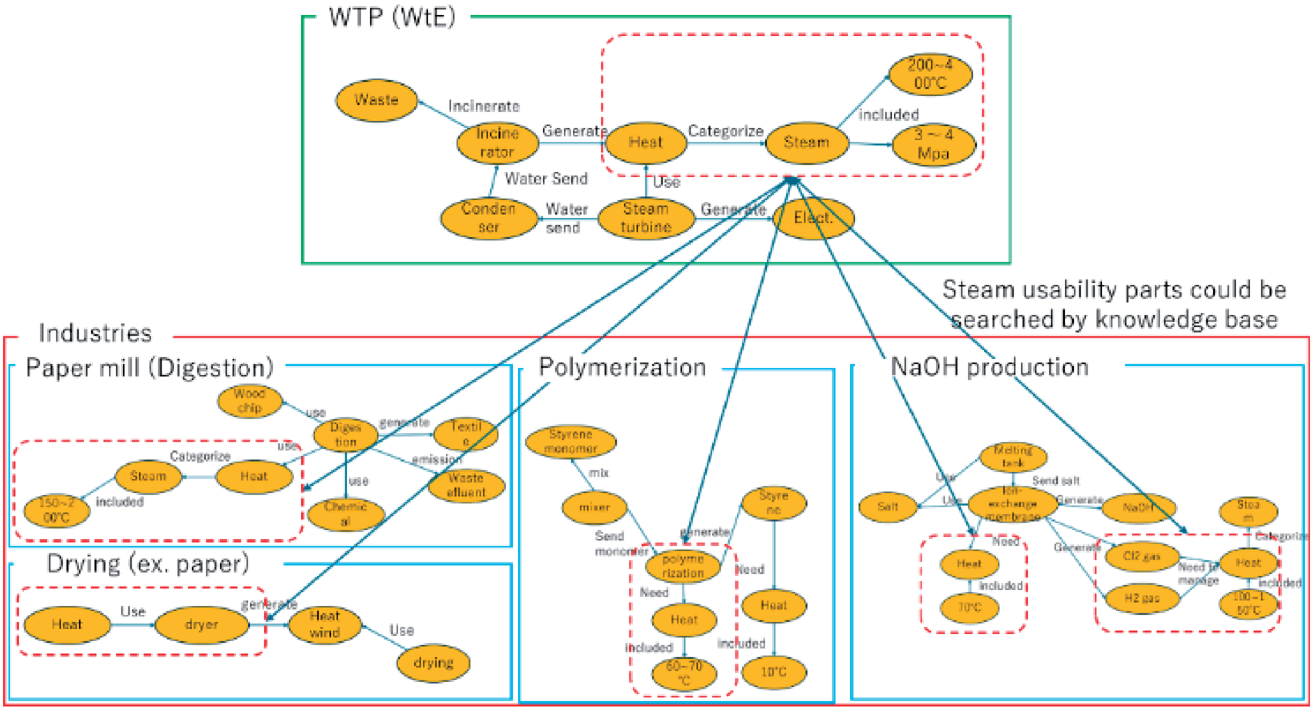

Fig. 7. Example of utilization of recyclable resources by the RDF description of industrial processes

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Navigating Marine Propulsion: Trends, Challenges, and Emerging Technologies

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Abstract

This study presents a comprehensive bibliometric analysis of marine propulsion research to investigate its historical development, current landscape, and future directions. Through the analysis of scientific literature retrieved from the Scopus database, the study employs Biblioshiny and VOSviewer software for data visualization and trend exploration. The analysis uncovers key research trajectories, dominant thematic areas, influential keywords, and leading contributing countries. The results reveal a growing global focus on sustainable and energy-efficient propulsion technologies, with particular attention to electric and hybrid systems. However, the adoption of clean propulsion alternatives remains constrained by technological limitations and economic feasibility, indicating that electric propulsion is still in a relatively nascent stage within the maritime sector. As the maritime industry advances toward decarbonization, this study highlights the untapped potential of alternative propulsion systems, including the relatively underexplored domain of pneumatic propulsion.

Keywords*: Pneumatic propulsion, compressed air energy storage, Maritime, Bibliometric analysis, Sustainable transportation.*

1. Introduction

Maritime transportation plays a vital role in global trade and economic development, serving as the backbone of international commerce. Maritime transport facilitates the movement of approximately 80% of international goods by volume [1]. It plays a central role in connecting economies, enabling the exchange of raw materials, energy resources, manufactured products, and food supplies across continents. One of the key advantages of maritime transport is its cost-efficiency, especially for bulk cargo and long-distance shipments. Ships can carry massive quantities of goods in a single voyage, reducing per-unit transportation costs and lowering environmental impact compared to other modes of transport [2]. Additionally, maritime transport is generally more fuel-efficient and offers greater cargo capacity, making it ideal for global logistics. The extensive network of ports and shipping routes also enhances global accessibility and supply chain resilience, underlining the strategic importance of maritime transport in today's interconnected world. Maritime transport, due to its ability to carry large volumes of cargo in a single voyage, generally results in a lower environmental impact per unit of goods transported. Although it contributes to CO_2 emissions, these emissions are significantly lower when compared to road or air transport on a per-ton-kilometer basis, making maritime transport a relatively more environmentally friendly option [3]. The lower carbon footprint is indicative of reduced fuel consumption, which further enhances its sustainability credentials [4]. However, despite these advantages, maritime transport also presents several drawbacks. Environmental concerns persist, particularly regarding air quality in coastal and port areas, where emissions from ships contribute to localized pollution [5]. Additionally, maritime transport is considerably slower than other modes, such as air transport, with shipping routes often taking several days or even weeks to complete, whereas air freight can accomplish the same in less than a day. Furthermore, maritime operations are highly dependent on weather conditions; adverse events such as storms, hurricanes, or rough seas can lead to significant delays or even accidents [6]. Safety remains another critical issue, as maritime transport is susceptible to operational risks including collisions, grounding, and human error. While modern navigation and safety technologies have improved overall reliability, the inherent risks of maritime operations remain a concern [7].

The history of marine propulsion has evolved significantly over the centuries, reflecting advances in engineering and the changing demands of global navigation. Early ships relied solely on human power, using paddles or oars, before wind power became dominant with the widespread use of sails in ancient civilizations. The Age of Sail marked a period of significant exploration and trade expansion. The Industrial Revolution introduced steam propulsion, revolutionizing maritime transport by allowing ships to travel independently of wind conditions. Steam engines, initially powered by coal and later by oil, led to the development of more reliable and faster vessels. In the 20th century, diesel engines became the primary mode of propulsion due to their greater efficiency and power. More recently, the maritime industry has begun exploring alternative propulsion technologies, including liquefied natural gas (LNG), electric and hybrid systems, and even wind-assisted propulsion, as part of efforts to reduce environmental impact and enhance energy efficiency [8].

Diesel engines have become the dominant mode of propulsion in modern maritime transport due to their high efficiency, durability, and reliability over long distances.

The main characteristic of diesel engines is their fuel efficiency, which allows ships to travel vast distances with relatively low fuel consumption compared to steam or gasoline engines [9].

Additionally, diesel engines offer high torque at low speeds, making them well-suited for the heavy-duty demands of marine vessels. However, diesel engines also present several disadvantages, as they are significant contributors to air pollution, emitting nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter, which affect both human health and the environment [10]. Furthermore, the reliance on fossil fuels raises concerns about greenhouse gas emissions and long-term sustainability. In response, the maritime industry is increasingly exploring cleaner alternatives and emission control technologies to mitigate the environmental impact of diesel propulsion systems.

One of these responses is the utilization of electrical propulsion systems, which are increasingly being adopted in the maritime industry as a cleaner and more sustainable alternative to conventional diesel engines [11]. One of the primary advantages of electric propulsion is its significant reduction in greenhouse gas emissions and air pollutants, making it an environmentally friendly option, especially in emission-controlled areas and coastal zones. Electric systems also operate more quietly and with less vibration, enhancing onboard comfort and reducing noise pollution in marine ecosystems. Furthermore, electric propulsion allows for greater flexibility in ship design and improved energy efficiency, particularly when integrated with renewable energy sources or hybrid configurations. However, the widespread adoption of electric propulsion faces several challenges. The current limitations in battery energy density and storage capacity restrict its use to short-distance or smaller vessels, such as ferries and tugboats. Additionally, the high initial investment cost and the need for supporting infrastructure, such as charging stations and grid upgrades at ports, remain significant barriers.

Pneumatic propulsion in maritime applications has recently evolved as a niche system for propulsion of maritime vessels. Pneumatic propulsion involves the use of compressed air to generate thrust, typically through the expansion of high-pressure air in a turbine or piston system. These systems can offer high responsiveness and precise control, which is particularly useful in vessels with predetermined routes and schedules [12]. Pneumatic propulsion can reduce reliance on fossil fuels when integrated with renewable energy sources to compress air, contributing to lower emissions. It also eliminates risks associated with fuel combustion, such as fires or spills, enhancing operational safety. In the context of maritime transportation, bibliometric analysis is especially valuable for several reasons. First, it enables the monitoring of developments in areas such as ship propulsion technologies, environmental regulations, port management, and logistics. It also highlights emerging topics like green shipping, digitalization, or autonomous vessels, guiding research priorities and funding decisions. Additionally, bibliometric tools can identify influential authors, institutions, and journals, fostering collaboration and knowledge sharing across disciplines. Numerous studies have been conducted on maritime transport, focusing on maritime tourism research [13] and maritime transport resilience [14]. Some also carried out bibliometric studies on alternative marine fuel [15], maritime inspection [16], and green shipping [17].

This paper examines the evolution of marine propulsion research using a comprehensive bibliometric framework grounded in science mapping and innovation transition theory. Through the systematic analysis of scholarly literature, the study identifies dominant research trajectories, thematic clusters, and keywords' evolution that have shaped marine propulsion development across different periods. The analysis is further used to interpret how technological priorities have shifted in response to environmental regulation, energy efficiency requirements, and sustainability imperatives. Accordingly, the paper critically evaluates the extent to which current propulsion pathways, particularly electric and hybrid systems, address the limitations of conventional diesel technologies. The study also explores under-investigated propulsion concepts, such as pneumatic propulsion, as part of an emerging sustainability-oriented transition in marine transport.

2. Methodology

For the bibliometric analysis, Scopus database is used to extract the data, which is imported into Biblioshiny and VOSviewer for visualization. Scopus is selected as the primary database because it is a widely recognized and comprehensive source of peer-reviewed literature, covering journals, conference proceedings, and books, while offering advanced analytical tools that enable systematic monitoring and evaluation of global research output across disciplines, thereby reducing the risk of overlooking relevant international studies. In addition, no exclusions are applied with respect to document types or subject area filters, ensuring an inclusive and unbiased retrieval of the relevant literature. The following search query is considered to include all publications related to marine propulsion:

((TITLE-ABS-KEY(Propulsion) AND TITLE-ABS-KEY (Ship* OR Boat* OR Maritime OR Marine* OR Ferry OR Ferries)) AND (LIMIT-TO (LANGUAGE, "English")))

Scopus is also used directly to analyze and visualize three key aspects: related subject areas, annual scientific production, and number of publications per country. Biblioshiny is responsible for presenting an overview of the bibliometric analysis and analyzing the most occurring keywords in this field. Keyword analysis undergoes data cleaning to remove highly occurring, obvious words that may hinder the visualization of crucial areas. Additionally, the keywords are further analyzed through VOSviewer, which in turn creates thematic clusters that help identify the key areas in marine propulsion and the most related keywords.

3. Results and Discussion

3.1 Overview

According to the search query presented in the previous section, 689 documents related to marine propulsion were published during the period of 1925-2025, as shown in Fig. 1. In the current bibliometric analysis, the timespan was kept as the default to include all research publications in this field and observe the variation in scientific production over time. The average annual growth rate is relatively low, accounting for 1.62%. The total number of authors who contributed to marine propulsion is 917, where 108 of them are authors of single-authored documents. However, the single-authored documents accounted for 412, representing around 60% of the total number of publications. Additionally, international co-authorships are considered low, with a percentage of 8.8%. This shows that this field of study is highly affected by various factors, particularly the location and transportation sector in the investigated region/country. Consequently, this highlights that many of these studies are related to case studies focused on particular regions rather than general research.


Timespan 1925:2025
Sources 239
Documents 689
Annual Growth Rate 1.62 %
Authors 917
Authors of single-authored docs 108
International Co-Authorship 8.853 %
Co-Authors per Doc 2.12
Author's Keywords (DE) 834
References 0
Document Average Age 17.8
Average citations per doc 6.02

Fig. 1. Main information

The analysis of subject areas in marine propulsion research reveals a strong dominance of the Engineering field, which accounts for 91.4% of the total documents. This overwhelming focus indicates that most studies in this domain are technical in nature, emphasizing design, development, and optimization of propulsion systems. Energy is the second most represented area, comprising 16%, reflecting the growing interest in fuel efficiency, alternative fuels, and sustainable energy solutions within maritime transportation. Environmental Science (8.9%) and Social Sciences (8%) follow, highlighting increasing attention toward environmental impacts and societal dimensions of marine propulsion. Other contributing disciplines include Mathematics (4.9%), Earth and Planetary Sciences (4.8%), and Computer Science (4.4%), suggesting interdisciplinary involvement in modelling, simulations, and digital innovations. The presence of other areas (7.8%) further underscores the breadth of research, though the core remains firmly rooted in engineering and energy-related studies. Fig. 2 shows the number of publications related to each subject area in marine propulsion publications.

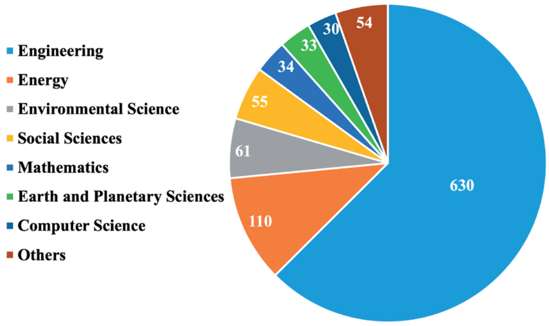

Fig. 2. Related subject areas

3.2 Research trends

The publication trend in marine propulsion research shows a slow start, with only a single document published as early as 1925. Following this, the research activity remained minimal until the mid-1980s, with no more than a few publications per year (as seen in Fig. 3). Starting from 1974, when another document appeared, the number of publications began to gradually increase. The field saw modest growth during the 1980s and early 1990s, with notable increases in 1994 (11 documents) and 1995 (30 documents), marking the beginning of more sustained academic interest. From the mid-1990s onward, the number of publications rose more consistently, peaking intermittently in certain years such as 1997 (33 documents) and 2005 (32 documents). The period between 2000 and 2010 saw steady outputs, fluctuating between 15 and 27 publications annually. A slight dip occurred between 2008 and 2014, but interest picked up again post-2015. The most significant growth occurred in the last few years, with notable peaks in 2021 (37 documents) and 2023 (34 documents), indicating a renewed and intensified focus on marine propulsion, likely driven by emerging technologies and global sustainability goals. Overall, the data reflect a long-term upward trend, particularly accelerating over the past three decades.

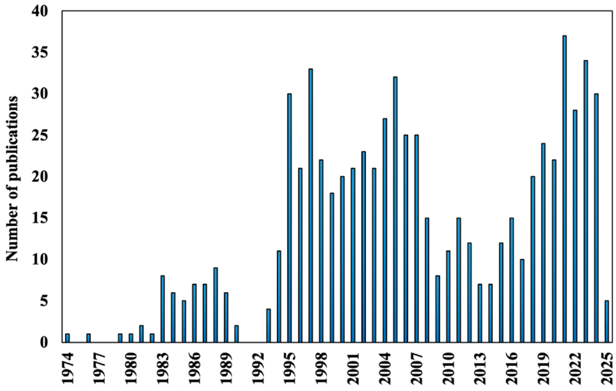

Fig. 3. Annual scientific production

3.3 Keywords analysis

Figs. 4a and 4b present word clouds illustrating the most frequently occurring keywords in marine propulsion literature, based on Indexed Keywords (Keywords Plus) and Authors' Keywords, respectively. These visualizations help identify the central themes and evolving areas of interest in the field. For better clarity and visual balance, certain highly common or overly generic terms were excluded: "ship propulsion" was removed from the indexed keywords, while "vessel," "catamaran," "ferry," and "passenger ship" were excluded from the authors' keywords. This exclusion was applied solely at the visualization stage and was guided by the need to prevent dominant terms from overshadowing more specific and informative keywords. As these generic terms broadly describe the domain rather than distinct research directions, their inclusion would reduce the interpretability of the word clouds and potentially mask emerging or specialized topics, without affecting the underlying clustering or quantitative analysis. Each word cloud is limited to the top 50 keywords, focusing on the most relevant and insightful terms used in marine propulsion research.

The indexed keywords in Fig. 4a show a clear focus on traditional and technical aspects of marine propulsion. Terms like “ferry boats” (184 occurrences), “ships” (156), “ship design” (128), “passenger ship” (127), and “shipbuilding” (115) dominate the landscape, reflecting the field’s core concern with vessel design, construction, and operation. Other frequently occurring terms include “hulls (ship),” “catamaran,” and “vessel,” which point toward structural and typological considerations. Propulsion-specific terms such as “diesel engines,” “ship propellers,” “electric propulsion,” “diesel propulsion,” and “propulsion unit” highlight the variety of propulsion technologies under investigation. The presence of keywords like “energy efficiency,” “fuel cells,” and “marine engineering” also indicates a research interest in optimizing energy use and exploring sustainable alternatives in propulsion systems.

Authors’ keywords in Fig. 4b provide more insight into emerging and innovative themes within marine propulsion. “Hydrogen” (17 occurrences) appears as the most common term, underlining increasing attention toward clean fuel technologies. Other notable terms include “shipbuilding,” “design,” “hybrid propulsion,” and “electric propulsion,” which reflect the trends observed in the indexed keywords but also emphasize technological evolution. Keywords like “energy management,” “fuel cell,” “energy storage system,” “battery,” and “life cycle assessment” demonstrate the authors’ focus on energy optimization and environmental impact assessment. The presence of terms such as “alternative fuels,” “Flettner rotor,” and “gas turbine” indicates a shift toward exploring a wider range of propulsion innovations beyond conventional systems.

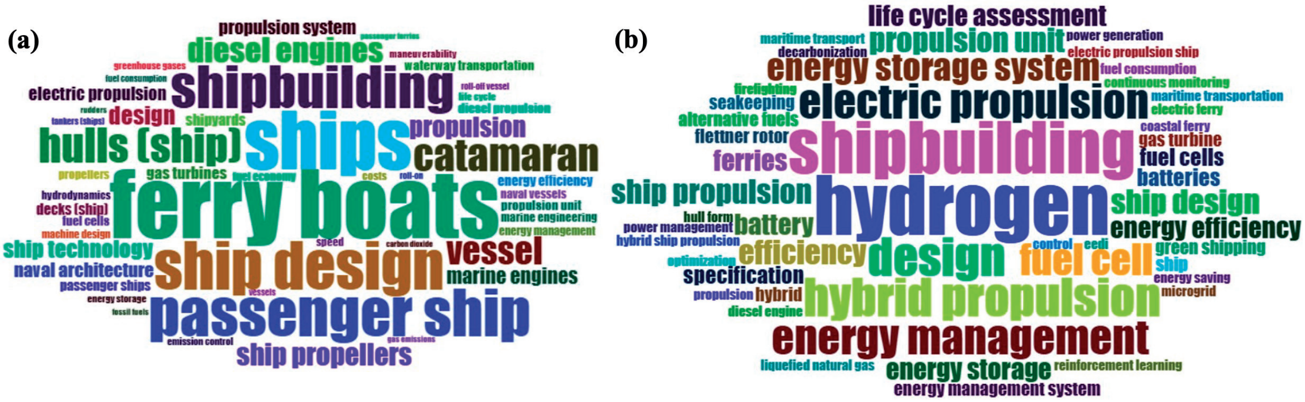

Fig. 4. Word cloud of most occurring keywords: (a) keywords plus and (b) authors’ keywords

The trends of the most occurring keywords over time, both indexed and authors, are presented in Fig. 5a and Fig. 5b, respectively. These figures highlight recent developments, focusing on the period from 2000 onward. The same keyword exclusions applied in Fig. 4 have also been considered here to improve clarity. From Fig. 5b, it is evident that terms such as “shipbuilding” and “design,” which were among the most common keywords before 2000, have not shown significant growth in recent years. In contrast, the keyword “hydrogen” began appearing after 2018 and has since risen to become the most frequently used term, underscoring the growing interest in sustainable and alternative fuel technologies. Similarly, keywords like “hybrid propulsion,” “energy management,” and “energy storage system” have emerged around the same period, although with lower frequencies compared to “hydrogen”.

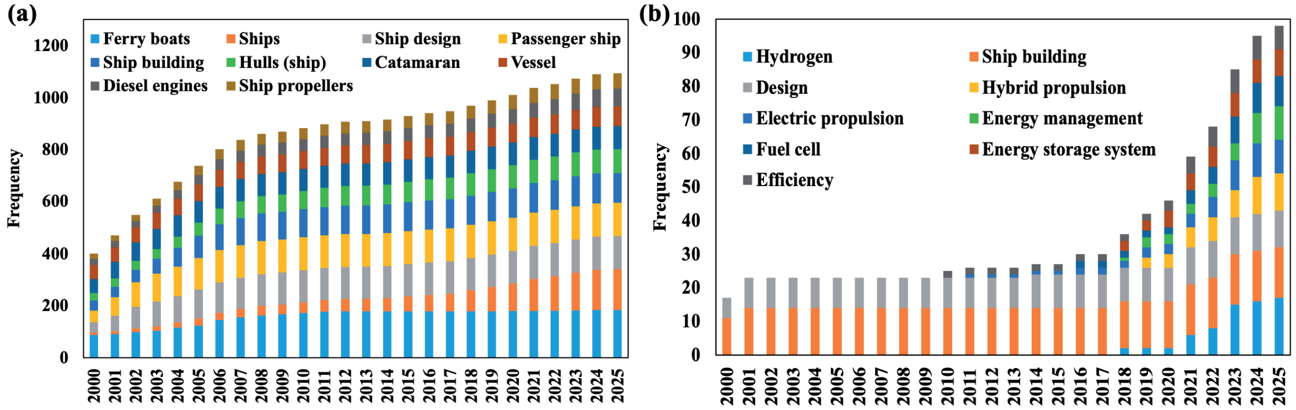

Fig. 5. Cumulative keywords occurrence over time: (a) keywords plus and (b) authors’ keywords

Fig. 6, generated using VOSviewer, illustrates the thematic clustering of keywords within the marine propulsion research field. A minimum occurrence threshold of five was set to filter the dataset, resulting in 260 keywords being visualized out of a total of 3,930. Six thematic clusters are identified, represented by the colors red, green, dark blue, yellow, light blue, and purple. However, the analysis focuses on the first four clusters as they represent the most significant groupings in terms of density and relevance. The red cluster revolves around clean and energy-efficient propulsion technologies, with dominant keywords such as electric propulsion, fuel cells, hydrogen, and energy management, indicating a strong emphasis on sustainable and low-emission systems. The green cluster centers on hydrodynamic design and performance, with keywords like ship propulsion, hulls, propulsion, and efficiency. The presence of such keywords suggests that a significant portion of the research is focused on optimizing vessel movement through fluid mechanics and structural design.

The dark blue cluster is primarily related to traditional propulsion systems and shipbuilding practices, featuring terms such as diesel engines, marine engines, shipbuilding, and gas turbines, reflecting the conventional engineering and mechanical aspects of marine propulsion. Lastly, the yellow cluster highlights topics around vessel types and onboard systems, with keywords like ship design, passenger ship, catamaran, and propulsion unit, pointing to studies concerned with different vessel configurations and their technical specifications.

Figs. 7a and 7b show the thematic evolution of keywords in marine propulsion research. The thematic evolution shows a clear shift from traditional vessel design and ferry operations (1925–2000) toward system-level optimization and propulsion technologies (2001–2010), and then to environmental impacts and alternative energy systems (2011–2020). In the most recent period (2021–2025), research strongly converges on sustainability-driven themes, including hybrid and hydrogen propulsion, batteries, energy storage, life-cycle assessment, and energy efficiency. This progression reflects a transition from performance- and cost-oriented engineering to decarbonization, emissions reduction, and holistic sustainability assessment in marine propulsion.

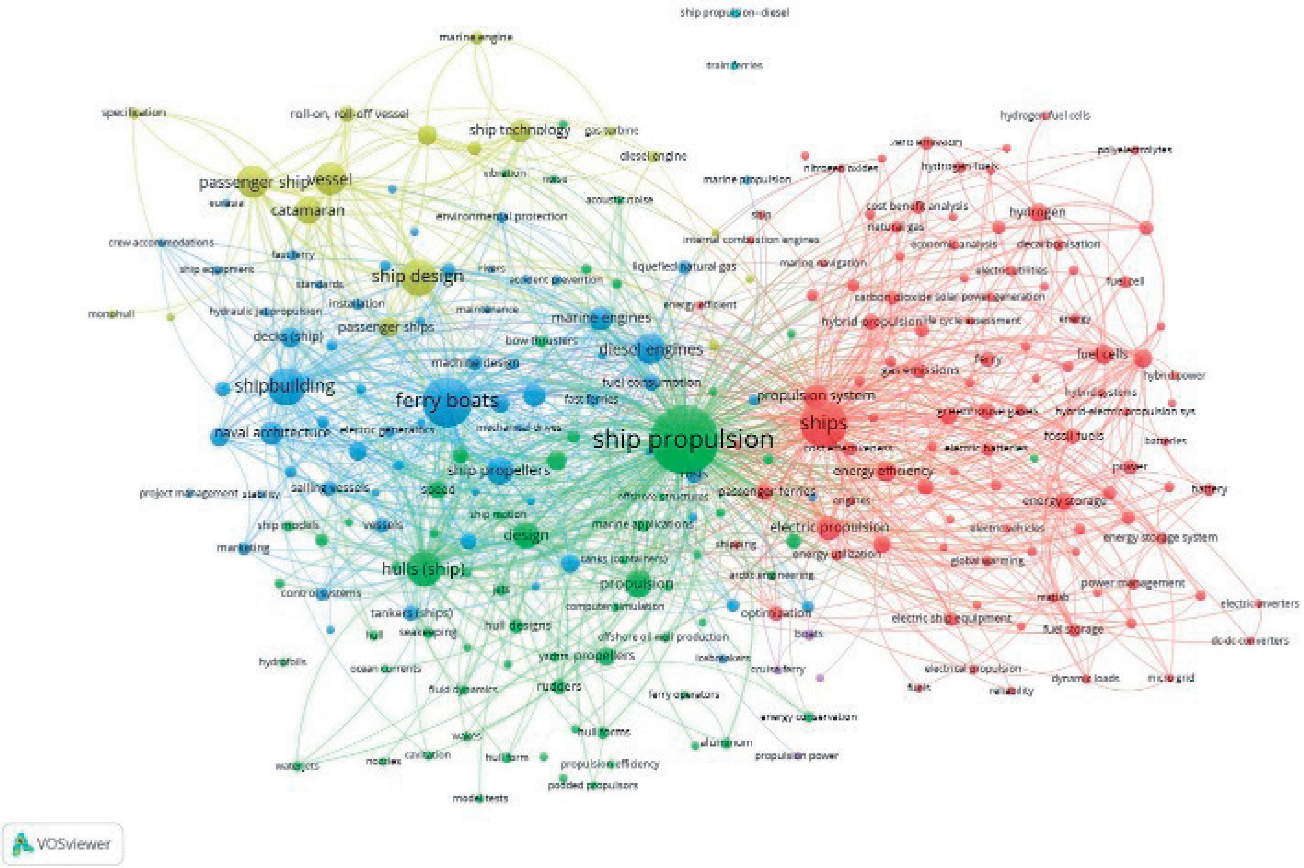

Fig. 6. Thematic clusters of keywords within the marine propulsion research field

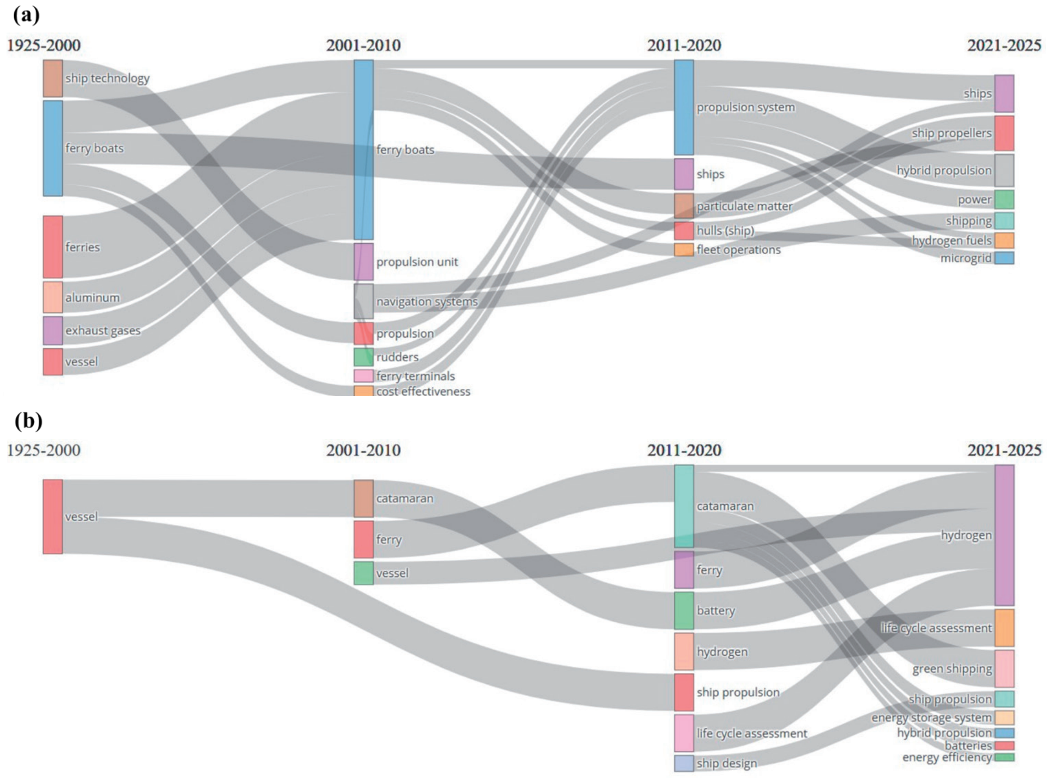

Fig. 7. Thematic evolution within the marine propulsion research field: (a) keywords plus and (b) authors' keywords

3.4 Countries contribution

Fig. 8 presents the top ten contributing countries in marine propulsion research, based on the number of publications. Italy leads the list with a notable margin, contributing 65 publications, which reflects its strong maritime industry and research focus on propulsion technologies. The United States follows with 39 publications, indicating active involvement, likely driven by both academic and naval interests. The United Kingdom and Norway contribute 25 and 24 publications respectively, aligning with their long-standing maritime heritage and investment in marine innovation. Notably, most contributions come from Europe, as 8 out of the top 10 countries, namely Italy, United Kingdom, Norway, Germany, Finland, Poland, Denmark, and the Netherlands, highlighting the continent's dominant role in advancing research and development in marine propulsion.

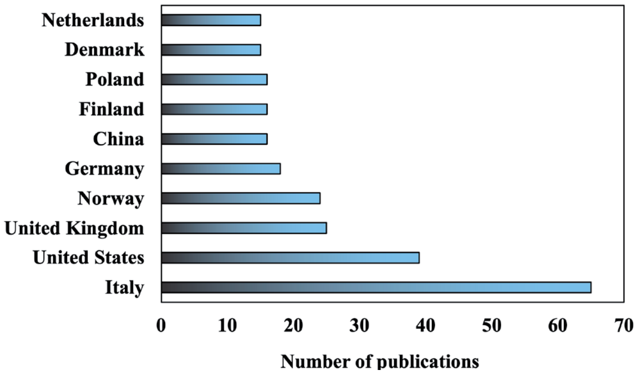

Fig. 8. Countries' contribution to the scientific production

4. Sustainable Transition in Marine Propulsion

4.1 Current limitations and challenges

One of the significant gaps in both academic research and practical applications within maritime transportation lies in the continued reliance on diesel-based propulsion systems. Despite their widespread use, these systems are known to contribute heavily to environmental pollution, emitting greenhouse gases and other harmful pollutants. Based on the conducted bibliometric analysis, it is evident that researchers and stakeholders are increasingly turning their attention toward environmentally benign alternatives that align with global sustainability goals. Among these, electric propulsion has emerged as a prominent area of interest, offering the potential for cleaner operation and reduced emissions. However, despite this growing attention, electric propulsion technology in the maritime sector still lacks strong and conclusive evidence to prove its feasibility as a full replacement for traditional diesel engines. Multiple economic and technological challenges have hindered their widespread adoption, including high initial investment costs, limitations in battery energy density, and the need for specialized infrastructure. Given these challenges, it is essential to explore other innovative and sustainable propulsion options, such as pneumatic propulsion, which utilizes compressed air to generate thrust.

4.2 Pneumatic propulsion

Compressed air energy storage (CAES) plays an important role in pneumatic propulsion by enabling energy to be stored in the form of pressurized air and later converting it directly into mechanical motion. In such systems, electrical or mechanical energy is first used to compress air into tanks, effectively storing energy without the chemical degradation associated with batteries. This direct conversion from stored pressure to motion allows pneumatic propulsion systems to be mechanically simple, responsive, and capable of high-power output over short durations [18].

The utilization of CAES in pneumatic propulsion is particularly attractive in applications where cleanliness, safety, and rapid energy discharge are priorities. Compressed air is non-flammable and produces no exhaust emissions at the point of use, thus pneumatic propulsion is well-suited for maritime applications.

In [19], the performance of pneumatic propulsion was evaluated alongside electric propulsion systems powered by electrochemical batteries. A life cycle analysis was also conducted to assess the environmental benefits, particularly regarding carbon dioxide emissions. The results revealed that pneumatic propulsion not only matched, but in some aspects, outperformed electric systems, providing approximately 6% more thrust and achieving an annual carbon footprint reduction of 307 kg CO_2. These findings highlight the practical advantages of pneumatic systems, especially for applications like ferryboats, where routes are consistent in both distance and direction, making them well-suited for the operational characteristics of compressed air propulsion.

Another recent study proposed a pneumatic propulsion system as a sustainable alternative to replace a diesel-powered ferry operating in Finland [12]. The research examined all essential components of the system, including air motors, compressors, storage tanks, heat exchangers, and auxiliary energy sources like battery banks and electric chargers. The proposed setup, designed to match the ferry's daily energy requirement of 3.58 GJ, featured eight 60 kW air motors and a 50 m^3 compressed air tank at 150 bar, recharged using a 132 kW compressor within 6.2 hours. Compared to the diesel system, which consumes over 55,000 liters of fuel annually, the pneumatic configuration demonstrated substantial environmental and economic advantages, including projected savings of approximately $73,000 and 120 tons of CO_2 emissions per year, with an estimated payback period of 8.1 years.

5. Conclusion

In conclusion, the bibliometric analysis highlights a clear shift in marine propulsion research toward more sustainable and environmentally friendly solutions. The increased occurrence of keywords such as "electric propulsion," "energy efficiency," "fuel cells," and "hydrogen" reflects a growing academic and industrial interest in cleaner technologies. However, despite the gradual appearance of electric propulsion systems, the analysis suggests that the maritime sector still lacks a comprehensive and unified strategy for transitioning to fully sustainable propulsion methods. Electric propulsion, although promising, remains relatively immature within the industry and is likely to face a range of challenges, particularly related to technological readiness, high implementation costs, limited infrastructure, and concerns about long-term reliability. These obstacles indicate the need for further development and support before such systems can be widely adopted. Given these limitations, it is essential to explore alternative propulsion technologies that offer environmental benefits while potentially overcoming the barriers associated with electric systems. One such emerging solution is pneumatic propulsion, which relies on compressed air to generate thrust. Although still in its early stages and not yet extensively tested in real-world maritime applications, pneumatic propulsion has demonstrated considerable potential in initial studies. Its feasibility, low emissions, and possible cost-effectiveness make it a compelling area for further investigation. Encouraging deeper research and development into such innovative technologies could diversify the portfolio of sustainable options available for the maritime industry and accelerate the transition toward cleaner and more resilient propulsion systems.

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