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Decarbonizing hard-to-abate sectors: A hybrid electrification approach for low-carbon cement production

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ABSTRACT

The decarbonization of energy-intensive industries, particularly the cement sector, is critical to achieving global climate targets. Cement production contributes approximately 7% of global CO_2 emissions, largely due to fossil fuel-powered clinker formation at around 1450 °C. Key challenges include heavy reliance on fossil-derived thermal energy, inefficient thermal energy utilization, and process emissions from calcination reactions. This research proposes an integrated decarbonization framework by electrification of the cement-making process and by incorporating green e-hydrogen, on-site wind and solar photovoltaic power generation, and a hybrid energy storage system comprising sodium-ion batteries and a molten carbonate fuel cell. Case studies across three European locations, with diverse renewable energy resources and climatic conditions demonstrate the broad applicability and effectiveness of the proposed system. The results show that a hybrid wind–solar setup could achieve up to a 45% emission reduction compared to the state-of-the-art, showing the system's significant CO_2 mitigation potential. The technologies are scalable and adaptable beyond the case study locations offering a general solution to significantly reduce CO_2 emissions from cement production. Energy system costs of $252–285/MWh for wind-based systems, $247–272/MWh for hybrid solar–wind configurations, and $249–277/MWh for solar-based systems were achieved by electrifying the cement-making process.

1. Introduction

To reach the climate goals set out by the Paris Agreement to mitigate the effects of global warming [1], the consumption of fossil fuels must be reduced [2]. Some of the heaviest polluting individual sectors are the transportation [3], steelmaking industries [4] and cement industries [5]. Electrification is an effective way to reduce emissions in all sectors through increased energy efficiency and the adoption of renewable sources of power. Sectors that cannot readily be electrified are referred to as the hard-to-abate sectors, to which steel and cement manufacturing belong, due to their high thermal energy and temperature requirements, which can currently only be met by fossil fuel combustion [6]. With new technological advancements, sectors previously deemed unfeasible to electrify can now be electrified. A RotoDynamic Heater (RDH) is able to reach temperatures required in cement making (~1700 °C) [7,8]; thus, it is time to explore the decarbonization of the cement sector.

Cement-based concrete is the world's second-most utilized material and the most extensively produced by volume, contributing 5% of global CO_2 emissions [9]. As a crucial element in the construction

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Nomenclature

Abbreviations

BESS	Battery Energy Storage System
Capex	Capital expenditure
CCUS	Carbon Capture Utilization and Storage
COE	Cost of Energy
CRF	Capital Recovery Factor
CSP	Concentrated Solar Power
DE	Two letter country code for Germany
e-fuel	Fuels produced with renewable energy
e-hydrogen	Hydrogen produced with renewable energy
EU ETS	European Union Emissions Trading Scheme
EU	European Union
FI	Two letter country code for Finland
HESS	Hybrid Energy Storage System
HOMER	Hybrid Optimization of Multiple Energy Resources
IRR	Internal Rate of Return
IT	Two letter country code for Italy
KPI	Key Performance Indicator
LCOE	Levelized Cost Of Electricity
LF	Load Following
MCEC	Molten Carbonate Electrolysis Cell
MCFC	Molten Carbonate Fuel Cell
NPC	Net Present Cost
NPV	Net Present Value
O&M	Operation and Maintenance
Opex	Operating expenditure
PV	Photovoltaic
RDH	RotoDynamic Heater
rMCC	reversible Molten Carbonate Cell
ROI	Return on Investment
SoA	State of the Art
SPECCA	Specific Primary Energy Consumption for CO_2 Avoided

Sub- & superscripts

ann	Annualized
el	Electricity-based
h	Heat-based
LHV	Lower Heating Value
nonren	Non-renewable
p	Peak
ren	Renewable
t	Time period

Variables

C	Cost
E	Electricity-based energy
f	Fraction
H	Thermal-based energy
n	Lifetime in years
r	Discount rate

sector, it is an indispensable building material for economic growth with a worldwide production of up to 30 gigatons (Gt) annually. In recent decades, growing concerns have emerged about the significant emissions of direct (CO_2, NO_2) and indirect (SO_2, NO_x, CO) greenhouse gases that are released during fuel combustion and the reactions needed to produce cement [10,11]. Among these, CO_2 is the most abundant in terms of volume. It comes from two main sources: burning of fossil fuels for heat, which accounts for 40% of CO_2 emissions, and calcination reactions during the manufacturing process, which contribute the remaining 60% of CO_2 emissions [12,13]. The three principal steps of the cement manufacturing process are raw material extraction, clinker manufacturing, and cement grinding. Clinker manufacturing is the main contributor to CO_2 emissions. Calcination, which happens inside the kiln at a temperature of approximately 1400 °C, involves the decomposition of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), producing calcium oxide (CaO), magnesium oxide (MgO), and carbon dioxide (CO_2), as shown by Eqs. (1) and (2) [14,15].

$$CaCO_3\,(s) \longrightarrow CaO\,(s) + CO_2\,(g) \qquad \Delta H = 179.4\,\mathrm{kJ\,mol^{-1}} \tag{1}$$

$$MgCO_3\,(s) \longrightarrow MgO\,(s) + CO_2\,(g) \qquad \Delta H = 117.6\,\mathrm{kJ\,mol^{-1}} \tag{2}$$

The Eqs. (1) and (2) summarize the main steps and required heat levels of the cement-making process as well as the share of energy consumption and CO_2 emissions [16]. The cement-making process is summarized in Fig. 1.

Traditionally, cement manufacturing has utilized fossil fuels to reach the required process temperatures without addressing the emissions from the calcination reactions. Improvements worth noting were the substitution of wet processing with dry processing, the introduction of preheaters, and the invention of pre-calciners, which resulted in lower fuel consumption for the cement kilns and overall less expensive processes. Nowadays, the focus on the decarbonization of the cement industry coincides with a renewed interest in reducing fossil fuel consumption. Advancements have been made with the transition to biofuel blends; however, the use of biofuels is not a sustainable worldwide solution due to the disparity of availability of biofuel produced from sustainable sources on a truly large scale [17,18]. The emissions from the calcination reactions have been reduced by some cement manufacturers by capturing part of the released CO_2 and mixing it into the cement, providing additional material strength and permanently capturing the carbon [19,20].

In Europe, the EU Emissions Trading System (EU ETS) sets a price on the emitted carbon [21]. First launched in 2005, has since grown to included more and more sectors. The price of carbon is set through market balance of supply-and-demand for emission allowances. Cement is set to fully join the EU ETS between 2026–2034 with gradual phasing out of free allowances. The Carbon Border Adjustment Mechanism is a European mechanism that sets a fair price on the carbon emitted during the production of carbon intensive goods entering the EU, which will also apply to imported cement [22]. Electrifying the cement production can provide substantial competitive advantage through reduced carbon fees, both within Europe under EU ETS and for imported cement under the Carbon Border Adjustment Mechanism.

With the introduction of emissions trading schemes, direct cost comparisons of the final cement product between electricity-based and fossil-based cement are increasingly uncertain. Fossil-based cement faces both geopolitical uncertainty in fuel prices and uncertainty from non-uniform exposure to emission pricing. As a result, the paper does not aim to assess future competitiveness. Instead, the focus is on the feasibility of the system, its potential for emissions reductions, and evaluation of energy cost under varied renewable energy generation conditions.

Overall, it is important to have general solutions that are applicable under different conditions. This paper aims to provide a set of solutions to decarbonize the cement industry under various renewable power generation conditions in three different countries through electrification of heat, a hybrid energy storage system, and carbon capture, utilization, and storage (CCUS). Different scenarios assess the viability using Key performance indicators KPI to analyze energy efficiency, economic viability, environmental impact, and technical feasibility.

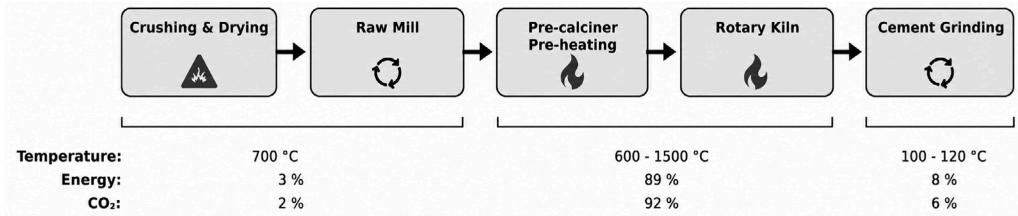

Fig. 1. Summary flow chart of the whole cement-making process.

2. Description of the system, choices, and assumptions

The major energy consumers of the whole cement production process are pre-heating and heating steps around the kiln, as seen in Fig. 1. Due to the high energy consumption of the kiln, the electrification of the kiln is a general solution that can be widely adopted with great energy efficiency, regardless of location.

In this context, the electrification concept considered in this study is based on the integration of the RotoDynamic Heater (RDH), developed by Coolbrook, which converts electrical energy into high-temperature process gas (up to 1000–1700 °C) without combustion [7].

From a process integration perspective, RDH can be incorporated into existing cement plants without fundamental redesign of the kiln system. The most relevant integration points are the precalciner, rotary kiln main burner, and raw material drying systems. In the precalciner, RDH can replace or supplement conventional fossil fuel burners by supplying high-temperature gas for calcination reactions, thereby directly reducing process-related fuel emissions. Similarly, RDH can provide high-temperature secondary air to the kiln burner, partially substituting flame-based heat transfer. Lower-temperature RDH operation (600–800 °C) can also be used for raw meal or alternative fuel drying [23].

A first industrial-scale implementation of RDH in the cement sector has been announced in collaboration with Adani Cement, targeting deployment at a commercial cement plant in India. This project represents the first full-scale demonstration of RDH integration into a cement pyro-process and aims to validate operational feasibility, heat transfer performance, and CO_2 reduction potential under real industrial conditions [24]. Initial estimates indicate significant reductions in fossil fuel consumption and associated emissions, although detailed performance data has not yet been published in peer-reviewed literature. As shown in Fig. 2, the remaining process units require an extensive degree of electrification, which in this study is designed around RDH-based heat supply [7,8].

The exact technical specifications and operating parameters of the RDH units, as well as other system components, are provided in Section 3. The overall configuration results in a 90 MW_p fully electrified cement plant. A schematic representation of the system and its main energy and material flows is presented in Fig. 2.

In order to reduce emissions through electrification, the electricity must come from renewable sources, such as solar or wind. As many cement plants are located on the outskirts of cities, access to a strong grid may not be guaranteed. To reduce costs, renewable power generation consisting of wind and solar power is built alongside the cement plant, as they have the lowest levelized cost of electricity (LCOE) [25,26]. A grid connection exists to provide some power balancing during times of low renewable power generation. A fully off-grid renewable based system is researched by Salmi et al. [27], where baseload electricity generation is provided to data centers from wind, solar PV, and batteries. A LCOE of approximately 100 €/MWh is obtained for a fully off-grid system. This system would work with cement production; however, additional investments would have to be made for CCUS to reach comparable emission reduction as the proposed system.

To assist with the intermittency of renewable power generation, a hybrid battery energy storage system (BESS) is deployed. As the main battery, a sodium-ion (Na-ion) battery was chosen due to its high efficiency and lower projected cost than lithium-ion (Li-ion) [28]. Additionally, lithium resources are unevenly distributed, with the largest reserves found in Bolivia, Chile, Argentina, China, and Australia [29,30]. Sodium batteries have the benefit of not requiring scarce minerals [31,32], with the potential of obtaining most of the required materials in higher concentrations in the often discarded brine from desalination plants [32]. This would bring further opportunities to water-deprived regions, which often coincide with the financially disadvantaged regions of the world.

To complement the Na-ion battery, a reversible molten carbonate cell system (rMCC) is deployed alongside the sodium-ion battery with a dual purpose: to assist with longer-term energy storage, producing hydrogen, as well as to capture the carbon from the calcination reaction occurring in the kiln. The reversibility of MCCs permits them to act as an electrolyzer during renewable energy's generation period and as a fuel cell for the rest of the time. Molten Carbonate Fuel Cells (MCFCs) generate electricity by reacting CO_2 and O_2 with hydrogen or methane. Reversible MCFCs can also function as Molten Carbonate Electrolysis Cells (MCECs), primarily producing hydrogen by electrolyzing water vapor and CO_2 at high temperatures. The reactions reported in Table 1 represent idealized electrochemical processes. In practice, integration with cement plant flue gases requires pretreatment to remove impurities (e.g., SOx, particulates, trace metals) that could impair performance. Since the operational temperature is in the 600–700 °C range, these systems can achieve higher efficiency in terms of electricity consumption for hydrogen production compared to low-temperature electrolyzers.

It has been observed that molten carbonate fuel cells can reduce CO_2 emissions in cement production processes by capturing CO_2 directly from high-temperature, high-CO_2 waste streams and concentrating it for further storage or utilization [33,34]. The SPECCA (Specific Primary Energy Consumption for CO_2 Avoided) index of Molten Carbonate Fuel Cells has been evaluated at 0.3 $MJ_{LHV}/kgCO_2$ [35].

This reversible functionality allows for flexible operational modes that meet the cement industry's dual need for carbon capture and energy generation or storage. Furthermore, the captured CO_2 can be directly reintegrated into industrial processes on-site or utilized in downstream chemical applications [36].

Currently, nearly all CO_2 utilization is for enhanced oil recovery, where captured CO_2 is injected into oil fields to increase oil production. However, it is the authors' ambition and hope that a more sustainable application can be found. One promising avenue is mineral carbonation, where captured CO_2 is transformed into stable carbonates, such as calcium or magnesium carbonates. Due to its potential use in construction materials like concrete, magnesium carbonate represents an ideal candidate for CCUS. Its production not only ensures the permanent sequestration of CO_2 but also contributes to a circular economy by generating products that can be reintegrated into the construction industry [37].

Magnesium chloride ($MgCl_2$) was selected as the starting material for carbonation due to its high solubility, availability (as an abundant by-product of water desalination [38]), and compatibility with efficient CO_2 mineralization processes. However, we acknowledge that carbonation of $MgCl_2$ does not occur spontaneously with CO_2 under mild

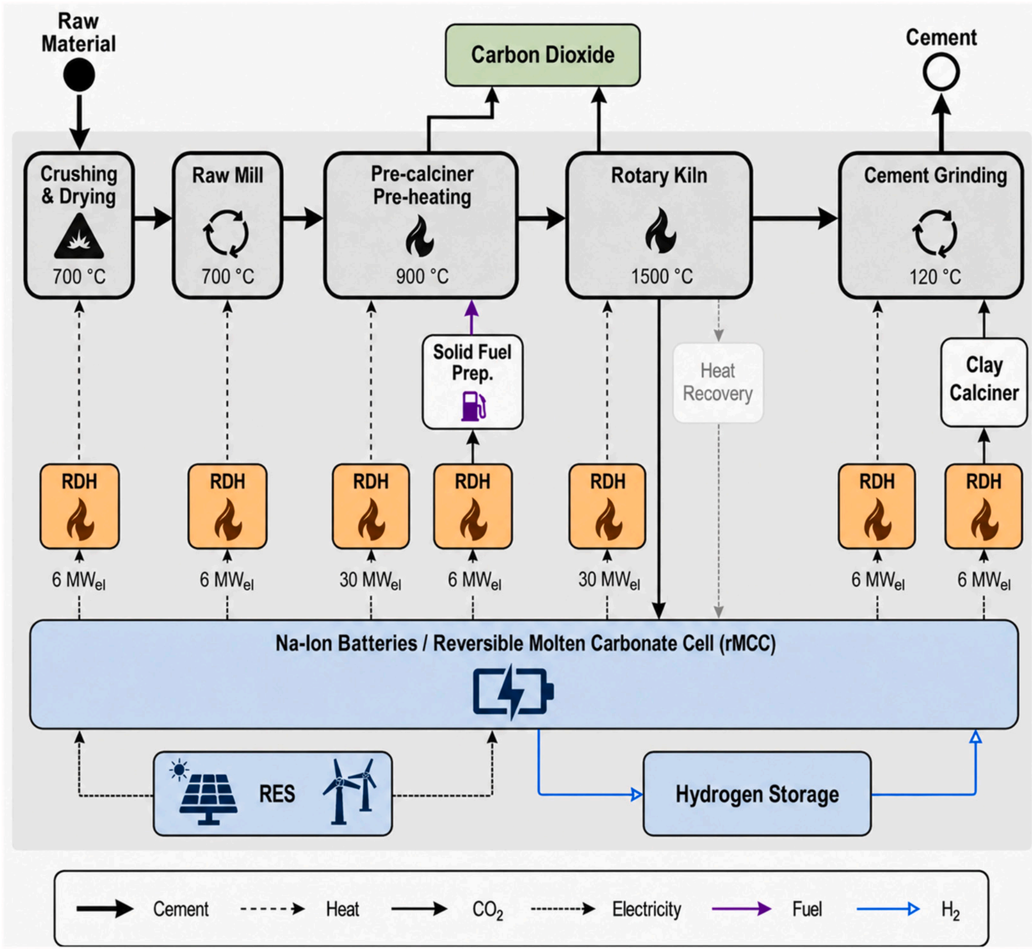

Fig. 2. Process scheme of the whole cement-making system with temperature requirements of each process and required heaters and the energy flows.

Table 1
Ideal electrochemical and chemical reactions of an rMCC system.

	Fuel Cell Mode (MCFC)	Electrolysis Mode (MCEC)
Fuel electrode	$H_2 + CO_3^{2-} \longrightarrow H_2O + CO_2 + 2e^-$ $CH_4 + H_2O \longrightarrow CO_2 + 4H_2$ $CO_2 + H_2 \longleftrightarrow H_2O + CO$	$H_2O + CO_2 + 2e^- \longrightarrow H_2 + CO_3^{2-}$ $CO_2 + H_2 \longleftrightarrow H_2O + CO$
Oxidant electrode	$CO_2 + 0.5\,O_2 + 2e^- \longrightarrow CO_3^{2-}$	$CO_3^{2-} \longrightarrow CO_2 + 0.5\,O_2 + 2e^-$

conditions, as the displacement of hydrochloric acid (HCl) is thermodynamically unfavorable without alkaline additives or controlled pH. Therefore, this pathway is presented as exploratory rather than techno-economically optimized, and Ca-based carbonation routes remain more directly relevant for cement decarbonization. Unlike magnesium silicates, which require energy intensive pretreatment to extract reactive Mg^{2+}, $MgCl_2$ dissolves readily in aqueous solutions, enabling rapid reaction kinetics with CO_2 [39]. Additionally, $MgCl_2$ is abundantly found in industrial wastewater streams such as desalination brines [38], those generated in rare earth extraction [40], and those produced from oil and gas extraction [41], making it a cost-effective and sustainable feedstock.

The carbonation of $MgCl_2$ leads to the formation of hydrated magnesium carbonates, such as nesquehonite ($MgCO_3{\cdot}3H_2O$). This process typically occurs with CO_2 being sparged into a magnesium chloride solution at near-ambient temperatures (20 ± 2 °C). The reaction proceeds rapidly, with carbonate deposition completed within approximately 10 min [39]. Hydrated magnesium carbonates exhibit high purity, and their thermodynamic stability under slightly alkaline conditions ensures long-term sequestration of CO_2, mitigating the risk of re-release. Furthermore, they can be processed into magnesite ($MgCO_3$) or calcined to magnesium oxide (MgO) for Portland cement production [42].

Moreover, the captured CO_2 can be utilized for the production of lithium and potassium carbonates [43,44], which are commonly used as efficient electrolytes in molten carbonate cells [45]. This approach could provide not only a sustainable pathway for CO_2 utilization but also supports the eco-friendly production of the system itself, contributing to a more circular and sustainable energy infrastructure.

The integration of CCUS in the cement industry could also be expanded by leveraging CO_2 in the production of synthetic fuels and chemicals. Recent advances in CO_2 electroreduction and thermochemical conversion have shown promise in converting captured CO_2 into valuable hydrocarbons, which can serve as renewable feedstocks in chemical industries or as alternative fuels [46].

The load profile is set at 90 MW_{el}. The model focuses on electrifying the heating processes in cement production. According to Arellano et al. [47], the kiln, which requires the highest temperature level, is operated continuously with a maximum power consumption decrease of 10%. With the consideration of a BESS, the system demand can be approximated as being continuous. The secondary heaters in adjacent processes offer great power flexibility with the load being variable between 0%–100%, which provides a great opportunity for demand response according to daily availability of renewable power. These secondary heaters and other processes consume less than 10% of overall energy and produce less than 10% of overall emissions [48]. The load was scaled according to the heat requirements of the system and the sizes of the RDHs to operate at full load.

The capture of waste heat from hot cement and high-temperature molten carbonate cells was considered; however, due to simulation limitations that preclude explicit modeling of heat recovery systems, a detailed discussion of applicable technologies and techniques for improving overall plant energy efficiency is provided in the supplementary material. Nevertheless, it is important to note that the integration of heat recovery systems would systematically enhance overall process performance by reducing both power and total energy consumption. As a result, the relative differences between the analyzed scenarios are not expected to change significantly when heat recovery is implemented, since all configurations would benefit comparably from such efficiency improvements. Furthermore, while the inclusion of heat capture improves energy efficiency and may contribute to cost reductions, its exclusion from the present modeling framework does not inherently increase carbon emissions, provided that the electricity supply from the grid is carbon-neutral.

Multiple different fuels and technologies could have significantly reduced the emissions from the cement industry. Other technologies and potential solutions were considered and are discussed in the supplementary material. Ultimately, while they were not modeled in this study, under certain conditions, they may be suitable solutions and should be studied further. For instance, Jana and De highlight environmental sustainability through CO_2 reduction and efficient biomass utilization [49]. Ecosystem-level considerations are addressed only indirectly within broader environmental metrics. This paper focuses on a general, widely applicable solution that is not reliant on a specific set of conditions to be met to be adoptable. The proposed system is further discussed in Section 3.

The proposed system design is novel and is therefore most suitable as a greenfield project to accommodate for the new on-site or close proximity renewable power generation capacity, energy storage, and to secure a strong grid connection. Retrofit deployment at currently existing sites is constrained by long investment cycles and substantial capital tied to existing operations and legacy assets. Additionally, down-time can impose significant economic penalties. Furthermore, cement plants are highly site-specific, with system design, location, local factors and operational practices contributing to significant uncertainty in retrofit cost. For these reasons retrofit costs are not assessed and should be evaluated on a case-by-case basis.

3. Modeling and parameters

The study employed the Hybrid Optimization of Multiple Energy Resources (HOMER) simulation tool. The modeling tool has already been deemed viable for the optimization of hybrid energy systems in a wide range of technical and economic scenarios [50].

Developed by the National Renewable Energy Laboratory in the United States, it allows users to define system constraints, input component-specific techno-economic parameters, and assign values within a decision variable space [51]. The tool simulates thousands of potential configurations and identifies the optimal system design that meets the electrical load at the lowest cost. Optimization is based on key performance indicators such as the Cost of Energy (COE) and the Net Present Cost (NPC), while ensuring all technical constraints are satisfied [52]. The core working principle of the simulation model is illustrated in Fig. 3.

The HOMER tool can perform techno-economic optimization and sensitivity analysis of hybrid energy systems by using various inputs, including techno-economic parameters of system components, resource data, and electrical load data. It identifies the most feasible and optimal solution, balancing both economic and environmental performance. It was selected due to its ability to efficiently model complex energy systems, providing reliable insights into system design and operation. Its flexibility in handling various renewable energy sources and financial scenarios makes it a valuable tool for making informed, data-driven decisions.

3.1. Location selection

This study examines three locations: Bremen (Germany, DE), Tampere (Finland, FI), and Rome (Italy, IT), selected to represent diverse European climates and renewable energy potentials. Each location exemplifies different renewable energy dominance based on climate: Rome in the south of Europe favors solar power; Tampere in the north relies primarily on wind power due to limited solar availability during winter; and Bremen, situated between these extremes, can leverage both solar and wind energy efficiently. This climatic and geographical diversity underscores the need for tailored energy strategies that optimize resource availability and sustainability across varying conditions within Europe.

The average temperature, solar radiation, and wind speeds are listed in Table 2 to characterize the renewable power generation potential and conditions in each location. It is important to note the seasonal differences as the provided values are annual averages, and how, for example, seasonal swings in solar power availability may influence operation during different stages of the year.

3.2. Scenarios

Four different scenarios for how the energy and power are obtained and stored are considered for all of the locations, with three different dispatch strategies. The scenarios consist of a grid-only case, which acts as the reference scenario, where all of the electricity for the electric kiln is obtained from the grid with current average electricity prices and emission factors. The grid-only scenario represents the fully electrified cement production system supplied entirely by grid electricity and should not be interpreted as the grid electricity tariff alone. Then, the energy supply is diversified by adding either wind power (Wind–Battery–H_2-Grid) or solar PV (PV–Battery–H_2-Grid) to our proposed hybrid energy storage system (HESS). For the fourth and final scenario, both wind power and solar PV are combined with the HESS (Wind–PV–Battery–H_2-Grid). With the different dispatch strategies, a total of 12 optimized scenarios were simulated per location, yielding a total of 36 scenarios.

Ray et al. highlight that renewable energy-based polygeneration systems, when integrated with local resources, significantly enhance land-use efficiency while simultaneously minimizing greenhouse gas emissions and energy costs [54]. The hybridization of multiple renewable sources enhances resource efficiency and optimizes land utilization, making such systems more suitable for decentralized and land-constrained applications.

The simulations aimed to find optimum system sizing and reduce overall system and energy costs while meeting electricity demand. The studied dispatch strategies for the BESS are load following, cyclic charging, and combined dispatch. Using the power directly from renewable energy sources is prioritized in all dispatch strategies. When there is insufficient power generation and the load cannot be met with instantaneous generation, the power must be obtained from either the hybrid energy storage system or the grid. An elaborate explanation of the different dispatch strategies can be found in the supplementary material. The final ratio of installed capacities is a result of simulations and is discussed in the results section.

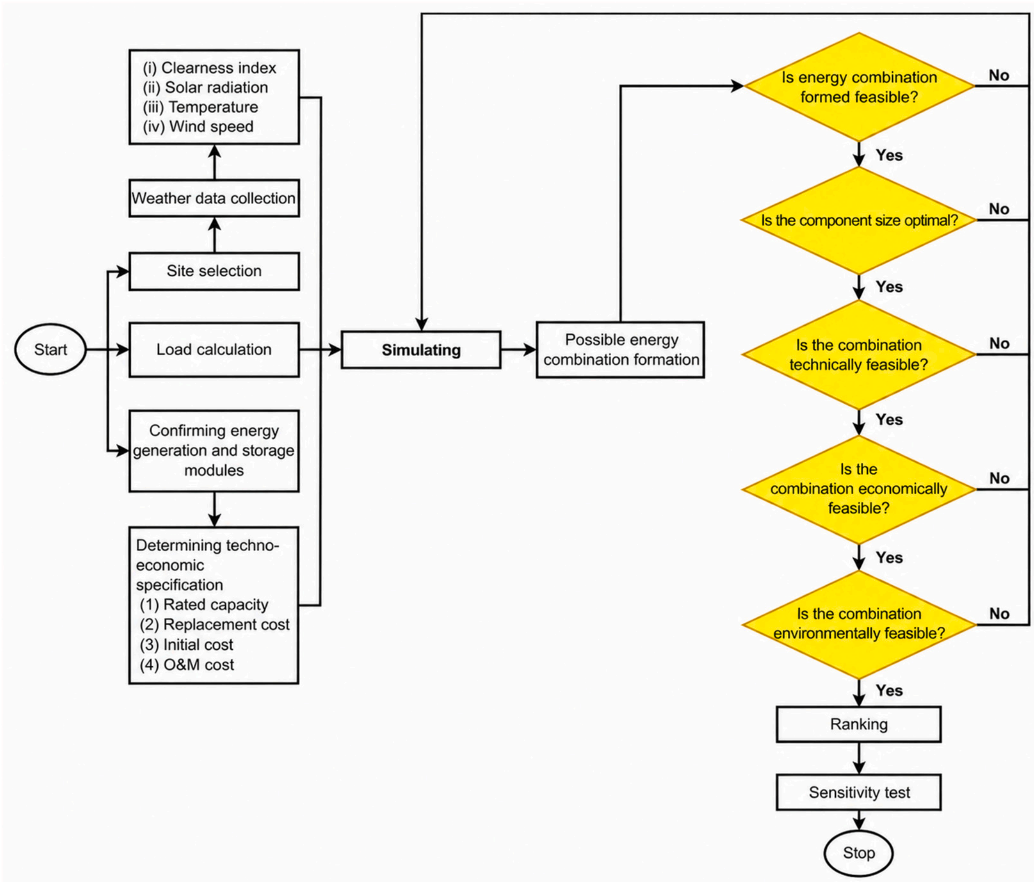

Fig. 3. Working principle of the simulation tool.

Table 2
Comparison of key weather parameters for energy planning in Bremen (DE), Rome (IT), and Tampere (FI). All provided data is from the year 2024 [53].

Parameter	Bremen (DE)	Rome (IT)	Tampere (FI)
Average temp (°C)	6.5	15.3	2.2
Average solar radiation (kWh/m^2/day)	3.7	4.7	1.8
Average wind speed @150 m (m/s)	8.4	7.1	9.7

3.3. Assessment criteria

The simulation results were assessed based on several key performance indicators, including energy efficiency, economic viability, environmental impact, and technical feasibility. The economic evaluation focused on the COE and NPC, while technical and environmental aspects were represented by the renewable fraction (f_{ren}) and CO_2 emissions.

The COE is a widely used metric for evaluating the economic feasibility of hybrid energy systems, reflecting the average cost per unit of electricity generated over the system's lifetime [55]. It is calculated as:

$$COE = \frac{\sum_{t=1}^{n} \frac{CAPEX_0 + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{3}$$

where $CAPEX_0$ is the initial capital expenditure, $OPEX_t$ is the operational expenditure in year t, E_t is the total electricity generated in year t (kWh), r is the discount rate, and n is the project lifetime in years.

The definition of COE from Homer should be clarified. In this study, the COE is obtained from HOMER and represents the average cost of supplying one unit of electrical load ($/kWh). While it includes annualized CAPEX, O&M and fuel costs similar to LCOE, they are not equivalent. HOMER's COE represents the cost of the whole system instead of only focusing on generation-side costs as in LCOE.

The NPC represents the total present value of all system costs incurred over its lifetime, including capital, operation and maintenance (O&M), and replacement costs:

$$C_{NPC} = \frac{C_{\text{ann,total}}}{\text{CRF}(I,n)} \tag{4}$$

$$CRF(I,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

where $C_{\text{ann,total}}$ is the total annualized cost (USD/year), i is the real annual interest rate, n is the project lifetime (years), and CRF(i,n) is the capital recovery factor, used to convert present costs into uniform annual equivalents [56].

Considering the techno-economic assumptions adopted in Table 3, the economic performance of the systems is primarily governed by capital-related expenditures associated with renewable generation, energy storage and power conversion technologies. Annual O&M costs are comparatively low, ranging from approximately 1%–5% of the corresponding capital investment for most components. Consequently, the NPC is expected to be dominated by investment (70%–85%) and replacement costs (10%–15%), whereas the contribution of O&M costs (below 5%) remains comparatively limited.

The renewable fraction (f_{ren}) is another key factor for decision-making. It represents the share of electricity based on renewable sources. In this paper, nuclear and biofuels are not considered renewable. When calculating the reduction of emissions compared to SoA, the carbon neutral nature of these sources of electricity is correctly reflected.

The renewable fraction is calculated using:

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \tag{6}$$

where E_{nonren} and H_{nonren} represent non-renewable electric and thermal energy production, respectively. E_{served} is the total electric load served, and H_{served} is the total thermal energy delivered. The variable f_{ren} denotes the renewable fraction as a percentage.

The scenarios that rank the highest (i.e., most favorable) are those with the lowest COE and NPC, a high f_{ren}, and low overall CO_2 emissions.

The new proposed energy system revolves around the RDH, which has become commercially available during 2025 [7,8]. The main assumptions for operation and modeling are as follows: the peak power consumption of the largest RDH unit is 30 $\mathrm{MW_{el}}$, the efficiency of converting electricity to heat is 95%, investment and operational costs are comparable to similarly sized steam turbines due to similar construction and operation, and the RDH is operated at peak power 24/7/365, excluding maintenance periods. As RDH cost data are not publicly available, estimates were made based on discussion with a representative from Coolbrook. The approximation is deemed reasonable due to similarities in scale, power requirements, and similar operating conditions as well as both being rotary machinery. Additional uncertainties arise from the early commercialization stage of technology with future price changes being likely. To account for these uncertainties in RDH cost, a system-level Capex sensitivity analysis has been performed in Fig. 14, which should more than compensate for the uncertainties in RDH costs and other technologies. Additionally, it is typical for the energy costs to dominate energy-heavy industries, such as cement production, as discussed in Section 4.5.

The system load was evaluated at a constant 90 $\mathrm{MW_{el}}$ based on the power consumption of the different heaters seen in Fig. 2. The parameters used in other parts of the system modeling are shown in Table 3. The electricity price used for the countries consists of the average electricity price for the respective countries for the year 2024 [57], together with country-specific distribution costs [58,59].

While the cost breakdown in the results emphasizes the energy capacity component ($/kWh), it is important to note that the power-related costs are implicitly included in the overall system analysis. Specifically, the COE and NPC outputs account for the total system cost, which includes both energy and power components, such as battery sizing (kWh), inverter capacity (kW), and other associated costs. These elements are factored into the simulation and optimization process, even if not individually itemized. Therefore, although the results present $/kWh as a summary metric, it reflects a comprehensive system-level cost, including the influence of both energy and power requirements.

3.4. Grid emission factors

The carbon emissions associated with imported electricity are calculated using annual average grid carbon intensity factors representative of each country. Average annual grid emission factors are employed rather than hourly values because HOMER performs techno-economic optimization using annual resource datasets and average electricity prices. Thus, emissions from grid electricity are calculated using the activity-based approach recommended by the IPCC as Eq. (7) [70].

$$CO_{2,\mathrm{grid}} = E_{\mathrm{grid}} \times EF_{\mathrm{grid}} \tag{7}$$

Table 3
Techno-economic specifications of the modules.

Components	Specifications	Reference
Solar PV module	– Type: Generic flat plate – Lifetime: 20 years Derating Factor: 87% Capex: 862 $/kWp for >1 MW system; 1076.9 $/kWp for <1MW system – Replacement cost: same as Capex Opex: 1% of system Capex/year	[60]
Battery	– LFP: Capex 280 $/kWh, – Na-ion: Capex 355 $/kWh, – Opex: 1% of system Capex/year – Replacement Cost: 215-377 $/kWh	[61]
Wind turbine	– Model: V136 4MW – Rated Power: 8 MW – Capex: 1325 $/kW – Opex: 45 $/kW/year – Lifetime: 27 years	[62]
Water cost	−3.2 $/m^3	[60]
rMCC system	– Lifetime: 40 000 h/5 years – BoP Capex: 4200 $/kW – Replacement Cost: 1327 $/kW – Specific power production: 1.4 kWh/Nm^3 H_2 (fuel cell mode) –Specific power consumption: 2.3 kWh/Nm^3 H_2 (Electrolysis mode)	[63–66]
Electricity cost	Including transmission/distribution costs: – Germany: 122.7 $/MWh –Italy: 148.1 $/MWh – Finland: 89.1 $/MWh	[60,67]
Compressor cost	– Capex: 1600 k$ – Opex: 2% of Capex	[68]
Rotodynamic Heater	– Capex 785 $/kW (adjusted for inflation from 2008 to 2025) – Opex typically 2%–5%/year or around $40/kW/year – Efficiency 95% Estimates based on equivalent size steam turbine	[69]

Where E_{grid} is the electricity imported from the grid in MWh, EF_{grid} is the country-specific annual average emission factor in $\mathrm{kgCO_{2,eq}}$/MWh and CO_2,grid is the CO_2 emissions associated with imported grid electricity in kgCO2eq. The adopted emission factors were 371 kg $\mathrm{kgCO_{2,eq}}$/MWh for Germany [71] and 255 $\mathrm{kgCO_{2,eq}}$/MWh for Italy [72].

For Finland, a lower emissions factor is considered. According to Fingrid, the national TSO, the average annual electricity carbon intensity is approximately 38 $\mathrm{gCO_2}$/kWh in 2023 [73].

The emissions from each system are compared to the State of the Art (SoA) cement plant, calculated as the sum of emissions from on-site fuel combustion, emissions generated by combustion reactions in the kiln, and emissions from electricity production. This serves as the reference case representing current industrial emissions. The comparison highlights the relative reduction or increase in CO_2 emissions achieved by each configuration.

4. Results

The study evaluates various combinations with three distinct energy dispatch strategies, assessing key techno-economic factors. The analysis was based on three cities in Europe: Rome (IT), Bremen (DE), and Tampere (FI). The case-specific analysis is followed by a variation of renewable fraction (f_{ren}) and its effects on COE and an assessment of the power share in the different systems. The exemplary operation graph

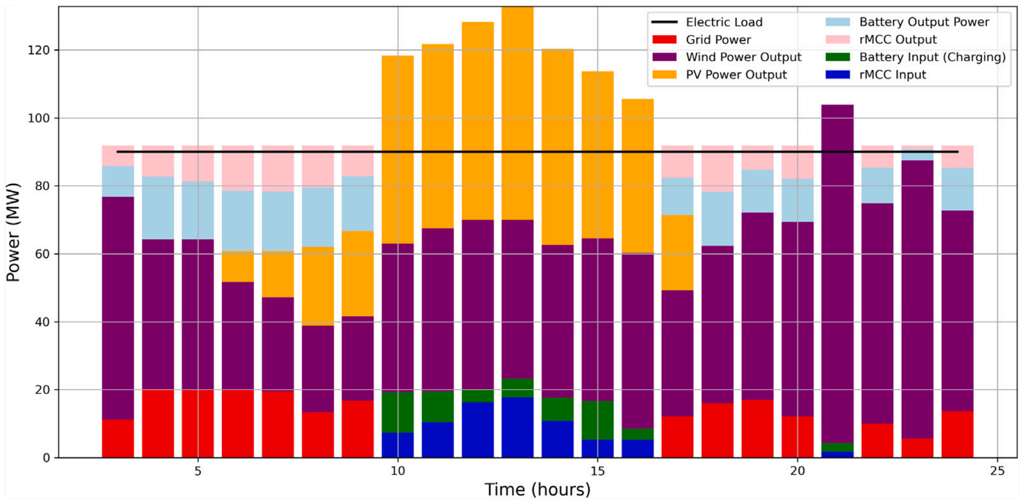

Fig. 4. Sample Wind–PV–Battery–H_2-Grid profile for a sample day (24.10.2024) from Germany with energy output from different components, where positive power is power consumption.

for the case of Germany is shown in Fig. 4 to showcase the various components of the cement plant working together. When wind or solar power is available, they are used directly in the cement plant supported by Na-ion batteries when the power demand is not met. Any surplus electricity is utilized first to charge the Na-ion batteries and second to produce hydrogen (H_2) through water electrolysis in molten carbonate cells (MCEC). Although there are conversion losses, the overall amount of energy generated from hydrogen storage remains significant. It is important to notice that the primary use of the hydrogen and the connected technologies is to perform CCUS for the carbon released from the calcination reactions.

When both renewable power generation and storage systems are insufficient to meet load requirements, grid power is used as a backup to ensure a stable energy supply. This approach demonstrates the potential to significantly reduce grid dependency in the industrial energy sector and supports the development of sustainable energy systems for hard-to-abate industries. The results from the different country cases highlight that, in all scenarios, load following was deemed the best energy dispatch strategy for all countries, and the scenarios follow the same principles as aforementioned in Fig. 4. Other dispatch strategies were considered; however, since load following was deemed the best performing dispatch strategy across all countries and scenarios, the analysis has been left in the supplementary material in order to not shift the focus away from the proposed system.

4.1. Rome (IT) — Solar power-dominated system

The energy produced by PV systems in Italy has observed a steadily rising trend, growing from 18.86 TWh produced annually in 2012 to 30.70 TWh in 2023 [74]. Generally speaking, solar PV has been more attractive than wind power in Italy, which can be observed from the installed generation capacities of 37 GW of installed solar PV capacity in 2024 [75] and 12 GW of wind power in 2023 [76]. In the modeled scenarios, by using only wind power, approximately 55.4% of total energy was met with renewable power with a COE of $285/MWh. The PV-based system managed to meet 71.5% of total energy demand with solar power with a COE of $265/MWh. The combined system of solar and wind power obtained a COE of $261/MWh and NPC of 128.4 $M with an energy share of 91.6% from renewable power sources. The COE of the hybrid PV and wind scenario is 2% lower than the standalone PV-based system and 9% lower than the wind-based system. The higher renewable share of the hybrid PV and wind system significantly reduces the emissions during electricity production by 45% compared to the SoA.

Table 4
COE, NPC and renewable fraction for the different scenarios for the case of Italy.

System	COE ($/MWh)	NPC (M$)	Renewable fraction (%)
Grid only	291	140.8	19.6 [77]
Wind–Battery–H_2-Grid	285	130.9	55.4
PV–Battery–H_2-Grid	265	129.8	71.5
Wind–PV–Battery–H_2-Grid	261	128.4	91.6

Table 5
Energy balance for the different energy scenarios for the case of Italy.

System	Self-generated energy (GWh/y)	Excess Energy (MWh/y)	Curtailment (%)
Grid only	–	–	–
Wind–Battery–H_2-Grid	794.3	392	<0.1
PV–Battery–H_2-Grid	799.3	390	<0.1
Wind–PV–Battery–H_2-Grid	796.2	8 123	1.02

The COE and NPC are compared in Fig. 5 (left). It can be observed that the scenarios that are not dependent on the grid have lower cost. Similarly, the CO_2 emissions in Fig. 5 (right) show that a significant reduction in CO_2 emissions can be achieved by adopting local renewable power generation. Therefore, decoupling from the reliance of the grid reduces both system cost and emissions.

While Italy is considered a solar power-dominant country, overall lower system costs are obtained by combining solar with wind power generation. More detailed cost comparisons and energy data are found in Table 4 and 5.

The energy balance between various scenarios for Italy can be seen in Table 5. Due to an available grid connection, little of the renewable power is curtailed.

In the case of Italy, not only is adopting a renewable power-based system more attractive financially, it is also beneficial in terms of reducing emissions, as seen in Table 6. According to the analysis, the PV–wind-based hybrid system significantly reduces emissions.

The payback period, Internal Rate of Return (IRR), Return on Investment, and NPV are compared in Fig. 6. The grid-only case offers lowest payback period, highest IRR and highest ROI of any of the cases, however, with the highest emissions in Fig. 5. When considering emissions

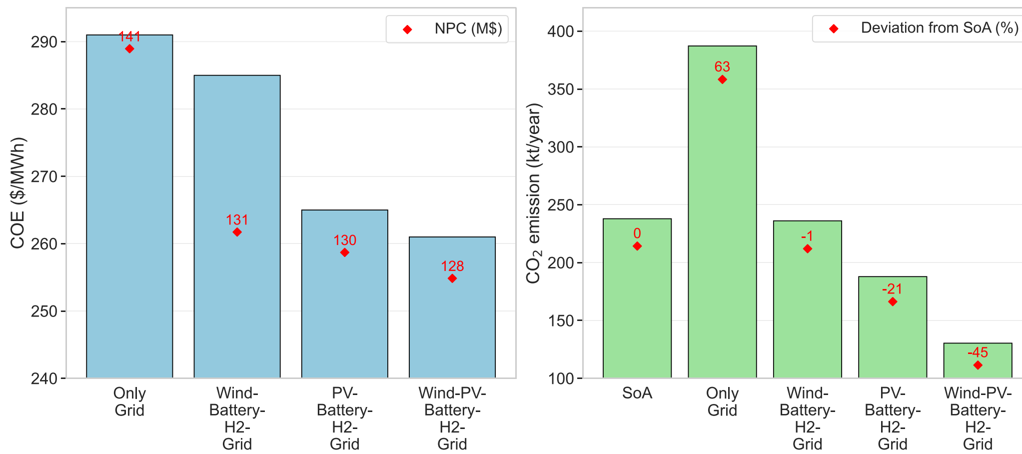

Fig. 5. COE and NPC comparison (left) with renewable fraction and CO2 emissions (right) for Italy.

Table 6
CO_2 emission assessment result for Italy.

System	[a]Total CO_2 emissions (kt/y)	rMCC captured CO_2 (kt/y)	[b]Final CO_2 emissions (kt/y)	Final CO_2 emissions deviation from SoA (%)
State of the art (SoA)	237.9	–	237.9	0
Grid only	387.6	–	387.6	+63
Wind–Battery–H_2-Grid	250.7	14.6	236.1	−1
PV–Battery–H_2-Grid	207.7	19.8	187.9	−21
Wind–PV–Battery–H_2-Grid	157.2	26.8	130.4	−45

[a] Including direct emissions from the cement plant and those from electricity generation.
[b] Emissions after subtracting the CO_2 captured by the rMCC system from the total emissions.

trading that would still be applicable to grid-consumed electricity, it can be expected that the grid-only case becomes less appealing.

The three scenarios with installed renewable capacity offer significantly higher NPV. Compared with the PV-only configuration, the hybrid wind–PV system exhibits higher IRR and ROI values while simultaneously achieving the largest CO_2 emission reduction. The improved economic performance can be attributed to the complementary generation characteristics of wind and solar resources, which contribute to a more balanced and efficient utilization of renewable energy.

The PV–Battery–H_2-Grid scenario, surprisingly, offered the lowest ROI and IRR, considering the high irradiation resources of solar PV and comparatively lower investment cost compared to wind power. The payback periods are comparable between the three cases with associated renewable installations.

4.2. Bremen (DE) — Hybrid system

In the German case study (Fig. 7), the "Grid Only" configuration incurs the highest COE at $286/MWh and an NPC of 137.7 $M. In contrast, the Wind–PV–Battery–Grid delivers the lowest COE at $272/MWh and an NPC of 129.2 $M. Furthermore, this configuration achieves an energy mix of 93.2% from renewables where PV and wind contribute 37.3% and 55.9%, respectively. The COE and NPC of the wind-based system is $280/MWh and 133.9 $M. The corresponding values for the PV-based system are $277/MWh and 130.3 $M. The reductions in COE are 4%, 3% and 2% for the hybrid, PV-only, and wind-only scenarios respectively. In the case of Germany, while the COE does decrease with the adoption of renewable sources of power, the main benefit is seen in the reduction of CO_2 emissions. Adopting the modeled renewable power-based system configurations leads to carbon emission reductions of between 14%–47%.

Similarly to the Italian case, lower COE and NPC costs are achieved by adopting renewable power and the proposed hybrid energy storage system as seen in Tables 7 and 8.

Table 7
COE, NPC and renewable fraction for the different scenarios for the case of Germany.

System	COE ($/MWh)	NPC (M$)	Renewable fraction (%)
Grid only	286	137.7	21.6 [77]
Wind–Battery–H_2-Grid	280	133.9	69.2
PV–Battery–H_2-Grid	277	130.3	67.3
Wind–PV–Battery–H_2-Grid	272	129.2	93.2

Table 8
Energy balance for the different energy scenarios for the case of Germany.

System	Self-generated energy (GWh/y)	Excess energy (MWh/y)	Curtailment (%)
Grid only	–	–	–
Wind–Battery–H_2-Grid	788.4	389	<0.1
PV–Battery–H_2-Grid	796.6	361	<0.1
Wind–PV–Battery–H_2-Grid	804.2	9 185	1.14

Although the average grid electricity price in Germany is approximately 20% lower than in Italy, the corresponding difference in the grid-only COE remains relatively small. This is because the COE represents a levelized metric that accounts for the total annualized system cost over the project lifetime. Therefore, differences in electricity prices are partly moderated by common capital, replacement, and O&M costs, resulting in a marginal variation in the grid-only COE between the two countries.

The energy balance between different scenarios for Germany can be seen in Table 8.

Further, significant emissions reductions can be achieved from adopting the proposed systems as seen in Table 9.

Similarly to the Italy case (Fig. 6), the trends in the measured KPIs in Germany in Fig. 8 follow each other. The Wind–Battery–H_2-Grid scenario offers highest NPV, ROI and IRR out of the scenarios

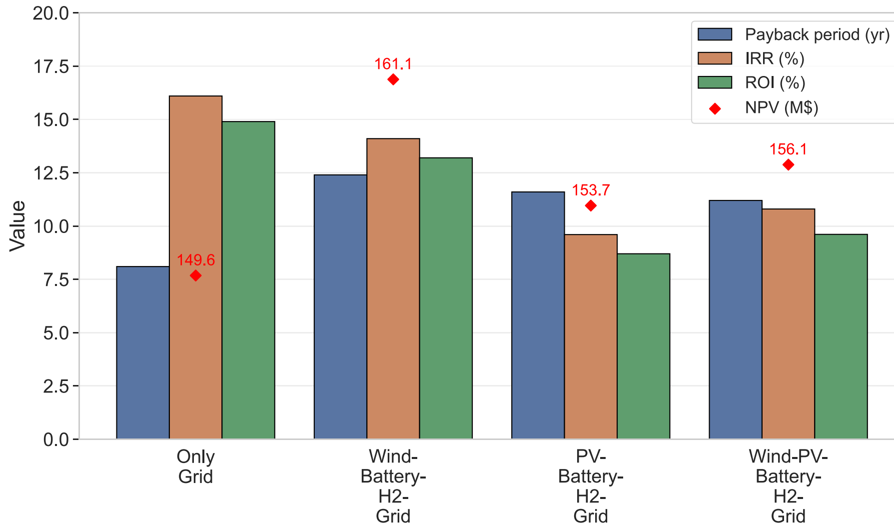

Fig. 6. Payback period, IRR, ROI and NPV comparison for Italy.

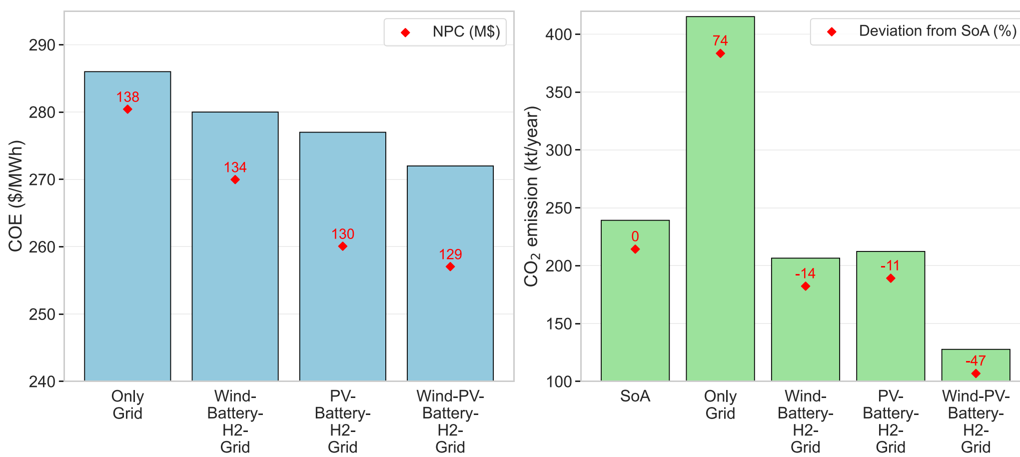

Fig. 7. COE and NPC comparison (left) with renewable fraction and CO_2 emissions (right) for Germany.

Table 9
CO_2 emission assessment result for Germany.

System	[a]Total CO_2 emissions (kt/y)	rMCC captured CO_2 (kt/y)	[b]Final CO_2 emissions (kt/y)	Final CO_2 emissions deviation from SoA (%)
State of the art (SoA)	239.2	–	239.2	0
Grid only	415.2	–	415.2	+74
Wind–Battery–H_2-Grid	222.0	15.5	206.5	−14
PV–Battery–H_2-Grid	227.3	15.0	212.3	−11
Wind–PV–Battery–H_2-Grid	155.0	27.3	127.7	−47

[a] Including direct emissions from the cement plant and those from electricity generation.
[b] Emissions after subtracting the CO_2 captured by the rMCC system from the total emissions.

with renewable installations with a marginally higher payback period. It is useful to compare the results to Fig. 7 and the emissions. The Wind–PV–Battery–Grid scenario offers significant emissions reductions compared to other cases, which can be an economic advantage with emissions trading. The NPV is also higher for the hybrid Wind–PV case than with solar PV alone, which differs from the Finland case (Fig. 10).

4.3. Tampere (FI) — Wind power dominant system

In the Finnish case study (Fig. 9), renewable-integrated configurations deliver significant improvements compared to the grid-only setup. The grid-only configuration has a COE of 277 $/MWh and an NPC of 133.6 M$, with a renewable fraction of 50.8%. It is worth noting that around 39% of the grid electricity comes from nuclear and 12% from biofuels, however, are not considered as a renewable source of electricity despite being considered carbon neutral [78]. As a result, the grid renewable fraction does not directly reflect the emission intensity of the electricity. The reduction in emissions includes the carbon intensity of the electricity and correctly reflects the sources of electricity. The wind- and solar-based systems show moderate improvements to f_{ren}. PV–Battery–Grid has a COE of $249/MWh, an NPC of 123.8 $M, and a f_{ren} of 47.5%, while Wind–Battery–Grid achieves a COE of $252/MWh, an NPC of 131.2 $M, with a f_{ren} of 78.8%. The lowest cost system was found to be the hybrid wind and PV system which achieved a COE of $247/MWh, an NPC of 125.6 $M, and a f_{ren} of 81.2%. The detailed results are shown in Fig. 9 and Tables 10 and 11.

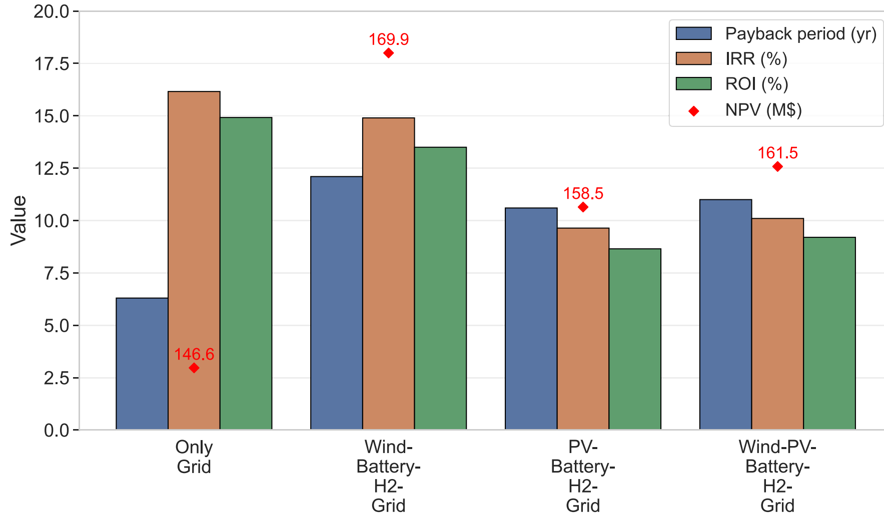

Fig. 8. Payback period, IRR, ROI and NPV comparison for Germany.

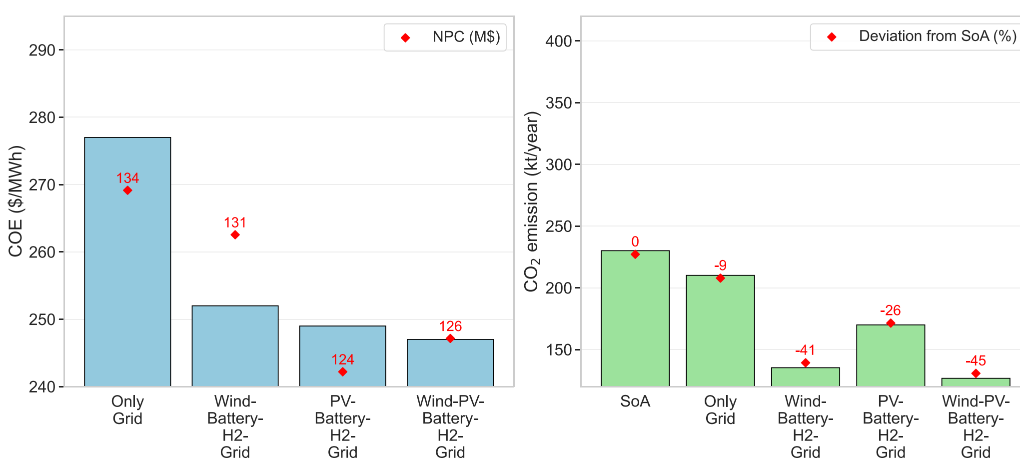

Fig. 9. COE and NPC comparison (left) with renewable fraction and CO_2 emissions (right) for Finland.

Finland does not see much benefit from the large-scale implementation of solar power due to overall poor and imbalanced irradiation conditions. The summers are characterized by an extensive period of long days with the sun barely setting, followed by the polar winter where irradiation is non-existent for several months with the additional risk of solar panels being covered in snow. As a result, a system that requires a fixed amount of energy year-round does not benefit from highly seasonally intermittent renewable power generation. Thus, the system must be built around wind power and electricity storage. Solar power does complement wind power seasonally; hybrid plants that share common power electronics infrastructure may be considered [79]. The seasonal differences in wind power generation in Finland is highlighted in the work by Salmelin et al. [80].

The energy balance between different scenarios for Finland can be seen in Table 11.

Due to poor irradiation conditions, solar does not contribute much in terms of reducing emissions. The modeled wind-based system sees a reduction of 41% of CO_2 emissions compared to the hybrid wind–PV system which sees a reduction of 45% in emissions compared to the SoA. In addition, due to the high seasonality of solar power, much of the electricity during winter would have to come from the grid. If the grid electricity is low in carbon intensity this can be acceptable; however, in grids that are still utilizing a lot of fossil fuels, the results would be significantly different in terms of emissions. Detailed emissions data can be found in Table 12.

An economic analysis of the payback period, IRR, ROI, and NPV for Finland can be seen in Fig. 10. The results of this graph coincide

Table 10
COE, NPC and renewable fraction for the different scenarios for the case of Finland.

System	COE ($/MWh)	NPC (M$)	Renewable fraction (%)
Grid only	277	133.6	50.8 [77]
Wind–Battery–H_2-Grid	252	131.2	78.8
PV–Battery–H_2-Grid	249	123.8	47.5
Wind–PV–Battery–H_2-Grid	247	125.6	81.2

Table 11
Energy balance for the different energy scenarios for the case of Finland.

System	Self-generated energy (GWh/y)	Excess energy (MWh/y)	Curtailment (%)
Grid only	–	–	–
Wind–Battery–H_2-Grid	788.4	341	<0.1
PV–Battery–H_2-Grid	788.5	105	<0.1
Wind–PV–Battery–H_2-Grid	791.6	8 268	1.04

Table 12
CO_2 emission assessment result for Finland.

System	[a]Total CO_2 emissions (kt/y)	rMCC captured CO_2 (kt/y)	[b]Final CO_2 emissions (kt/y)	Final CO_2 deviation from SoA (%)
State of the art (SoA)	230.1	–	230.1	0
Grid only	210.2	–	210.2	−9
Wind–Battery–H_2-Grid	151.8	16.5	135.3	−41
PV–Battery–H_2-Grid	175.0	5.0	170.0	−26
Wind–PV–Battery–H_2-Grid	150.1	23.5	126.7	−45

[a] Including direct emissions from the cement plant and those from electricity generation.
[b] Emissions after subtracting the CO_2 captured by the rMCC system from the total emissions.

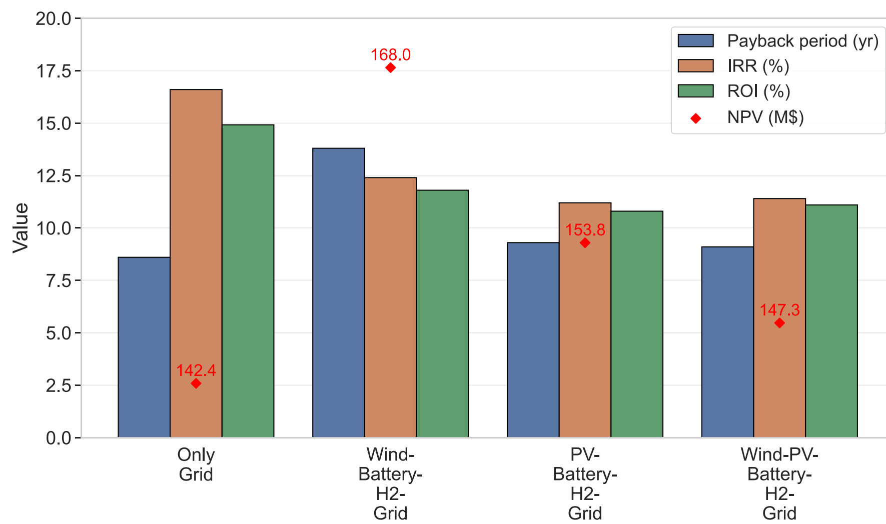

Fig. 10. Payback period, IRR, ROI and NPV comparison for Finland.

with the analysis made for Italy (Fig. 6) and Germany (Fig. 8). Main difference, apart from scale, is in the NPV between the PV and Wind–PV scenarios. Both scenarios offer comparable payback periods, IRR, and ROI, while PV–Battery–H_2-Grid offering significantly higher NPV. It is worth noting that in this scenario, during winter, solar PV production is at a minimum in Finland due to low irradiance and potential snow covering the panels. As a result, while the PV based scenario seems more favorable, it leaves the operation dependent on grid energy for many months in the year. As the grid electricity is mostly carbon neutral, from the emissions avoided perspective it can be a valid option, however, more subject to market volatility.

The economic performance is primarily influenced by the initial capital investment, which dominates the overall life-cycle cost of the system. In comparison, O&M costs contribute a smaller fraction because the considered renewable technologies and storage systems are characterized by relatively low annual maintenance requirements. Therefore, differences in economic factors among the investigated scenarios are mainly driven by variations in capital expenditures, replacement costs and also electricity purchase costs. The O&M costs have lower impact on these economic factors.

4.4. Installed capacities and power share

A comparative analysis reveals that configurations with Na-ion batteries and H_2 storage consistently outperform those using alternative storage technologies, such as Li-ion batteries, in terms of techno-economic feasibility. Na-ion batteries prove to be more cost-effective due to lower projected investment costs while receiving comparable performance to Li-ion batteries. Na-ion batteries are projected to decrease in cost further, as their commercialization is still in its infancy compared to Li-ion batteries. The lower cost comes mainly from Na-ion batteries consisting of widely available materials such as table salt. Na-ion batteries are favored in all analyzed scenarios. The results emphasize that integrating renewables with Na-ion batteries and H_2 storage achieves the optimal balance by minimizing costs, maximizing renewable energy use, and significantly reducing emissions. The technologies are widely available and do not require any specific set of geographically-tied requirements to be adopted. The provided sets of technologies and strategies to decarbonize the cement industry present a promising and sustainable energy strategy for the whole of Europe, aligning economic efficiency with environmental objectives.

These findings highlight the potential of renewable-integrated, load-following systems to enhance hydrogen production efficiency and reduce operational costs. The results emphasize the importance of combining PV, wind, and Na-ion storage to achieve sustainable and economically viable energy solutions. The different capacities for renewable power generation, grid sizing, and energy storage are shown in Tables 13 and 14.

The results demonstrate the optimum capacity to achieve the best performance according to previously listed KPIs. The biggest share of PV and wind power are obtained in Italy and Finland, respectively. In hybrid systems, the ratio of PV to wind power was optimized. Additionally, the contribution from storage and grid is also significant for the combinations. The produced hydrogen is used to generate electricity during peak demand periods.

The optimal power share for each country is shown in Fig. 11, in which renewable energy sources account for the maximum share in each country scenario where the COE was found to be the lowest. While the optimal energy combination varies by location, integrating renewables with storage and grid power consistently proves to be an economically and environmentally sustainable solution for meeting industrial energy demand.

Grid power remains a valuable asset to cover demand during longer periods of weak renewable power generation. Even in a mostly off-grid

Table 13
Installed renewable power generation and grid capacities for each country in every scenario.

	PV (MW)			Wind (MW)			Grid (MWh)		
Country	IT	DE	FI	IT	DE	FI	IT	DE	FI
Wind–Battery–Grid	–	–	–	363	352	398	59 264	46 592	44 259
PV–Battery–Grid	496	421	308	–	–	–	33 542	52 522	63 412
Wind–PV–Battery–Grid	347	228	155	299	263	309	23 853	32 583	25 385

Table 14
Installed energy storage capacities for each country in every scenario with optimal dispatch strategy.

	Na-ion (MWh)			H_2 (MWh)			Dispatch strategy
Country	IT	DE	FI	IT	DE	FI	
Wind–Battery–Grid	388	402	407	157	147	176	LF
PV–Battery–Grid	422	416	326	184	75	104	LF
Wind–PV–Battery–Grid	492	499	490	199	187	180	LF

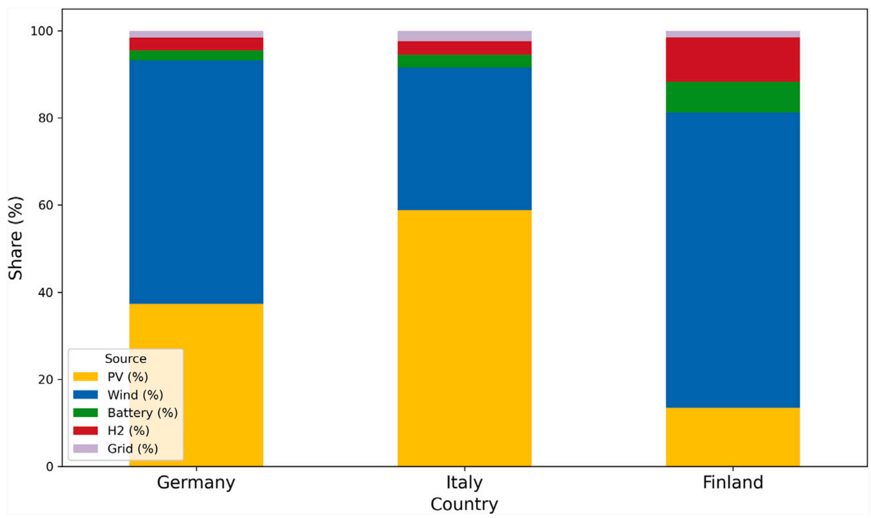

Fig. 11. Source of the power used by the cement plant for the three countries studied with the hybrid power generation wind–PV–battery–grid setup.

system, a weak grid connection can still be a valuable asset despite peak power demand being much higher. It allows for the cement plant to utilize cheap grid electricity that would otherwise be curtailed or to participate in the electricity markets through ancillary services, providing additional power and flexibility to the grid for an additional source of revenue [81].

4.5. Variation of renewable fraction and impact on cost of energy assessment

The variation of COE with f_{ren} for the hybrid PV–wind scenario of each country is shown in Fig. 12. The figure illustrates that the COE is lowest when the f_{ren} is in the 70%–90% range with a slight increase when approaching 100%. Exact f_{ren} values were identified using Fig. 12. For plotting purposes, the simulations were first recorded at 10% intervals. After identification of the regions of lowest COE, through a manual iterative process, the f_{ren} associated with the lowest COE is found. Across three case studies, Germany achieves the lowest COE at a f_{ren} of 93.2% with a PV–wind–grid energy combination. In contrast, Finland's optimal COE occurs at a lower f_{ren} of 78.8%, relying on a wind–grid configuration.

Fig. 12 indicates that Bremen (DE) achieves its minimum COE at a f_{ren} close to 93%. A similar trend is observed for Rome (IT), where the optimum occurs at approximately 90% renewable penetration, although the sensitivity of the COE to increasing renewable penetration differs among locations. These differences arise from variations in local renewable resources and system configurations. In contrast, Tampere (FI) exhibits a flatter response due to its distinct resource characteristics and technology mix. If the power generation for the cement plant were dispersed over a larger geographical area and transmitted to the plant using the common grid, then it would be possible to reach higher f_{ren} as the power generation profiles transition from more intermittent profiles to more base-load-like profiles. The same idea can also be applied to dispersed solar power in regions where solar power is the dominant source of renewable power.

A sensitivity analysis of the effect of grid price on the highest potential case for reducing carbon emissions (PV–Wind–Battery–Grid) is evaluated in Fig. 13. A 10% decrease or 10% increase in electricity cost, across all cases, resulted in a change of roughly -2% and +1%, respectively. It can be concluded that due to the low overall share of the electricity coming from the grid, a change in the electricity price does not have significant effect on the final COE. It is important to note that a percentual change in the grid electricity price experiences greater change in Germany than in Finland, for instance. For context, the average electricity price for households in 2025 in Italy, Germany, and Finland was 330 €/MWh, 400 €/MWh, and 191 €/MWh, respectively [82]. Although industrial consumers can secure lower prices through power purchasing agreements, this comparison illustrates the advantage relative to prevailing market rates.

A sensitivity analysis of the effect of Capex on the COE is performed in Fig. 14. The effect of a change in Capex has much lower influence on the overall COE compared to the grid electricity costs. This is often the case in high energy demand industries, where Opex dominates overall costs. Overall, varying Capex has low effect on the final COE across all countries.

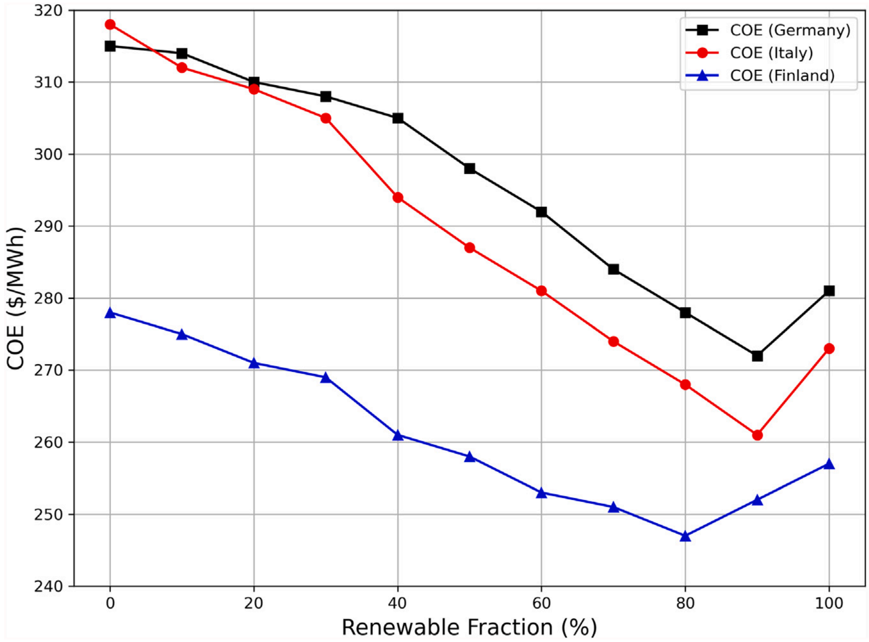

Fig. 12. Cost of electricity as a function of renewable fraction in Germany, Italy, and Finland.

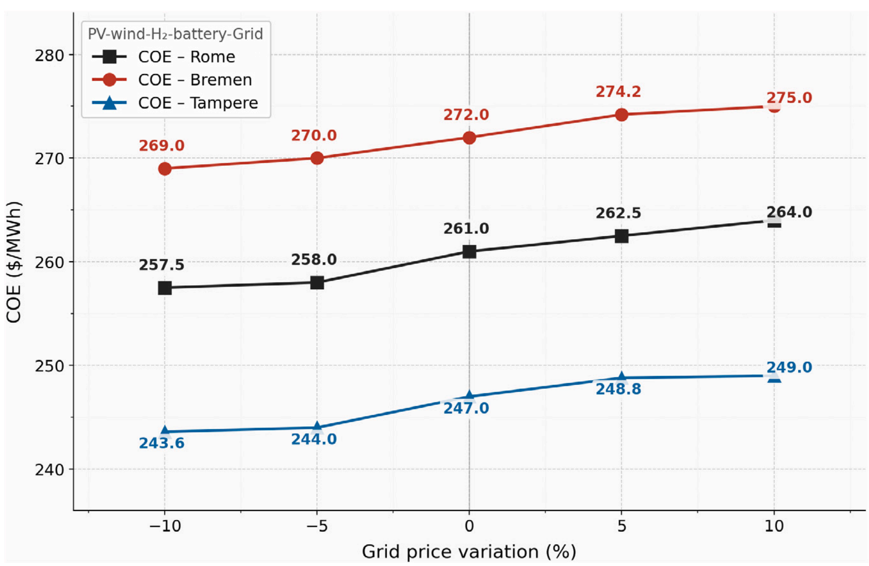

Fig. 13. Sensitivity analysis of the effect of grid price on the COE ranging from −10% of average price to +10%.

5. Discussion

The three configurations analyzed, combining PV and/or wind power with a HESS, demonstrate a notable capability for carbon capture, utilization, and storage, enabled by the integration of rMCCs in the hybrid storage system. The results highlight that the system minimizes costs and achieves a high CO_2 capture rate from cement production, varying across the 3 case studies (Italy, Germany, and Finland).

The COE and NPC of the renewable-based energy systems are approximately 0.5%–9% (for Italy), 2%–3% (Germany) and 12%–14% (for Finland) lower compared to the grid only system. The minimum NPC is also lower for the renewable systems. The NPC for the renewable combinations is in the range of 125.6–133.9 M$ which is lower than that of the grid system. The HESS combined with PV-, wind-, or PV–wind power generation, significantly reduces overall costs.

The hybrid renewable power generation setup (Wind–PV–Battery–Grid), shows the best capture rate in all the 3 locations, around 45% reduction in the total CO_2 emissions. Additionally, the combination of Na-ion batteries with rMCC (and hydrogen storage) allows integration of more intermittent renewable sources in the mix, without any negative impact on the cost and reliability. On the contrary, as shown in Fig. 11 and presented in Tables 4, 7, and 10, the increased renewable fraction overall leads to about a 10% decrease in the COE and NPC for the case studies.

Due to the large renewable generation capacity found on site and the needs of the electrical grid, the plant should be installed near other sources of power generation. When the rest of the grid is in need of power, the BESS can be discharged to provide power to the grid in different electricity markets through ancillary services. When there is significant power generation, the cement plant may charge its own batteries without stressing the long-distance transmission lines.

The implementation of rMCCs for CO_2 capture in cement plants has demonstrated significant emission reductions. In Table 15, the percentage of emission reduction is highlighted for each hybridization

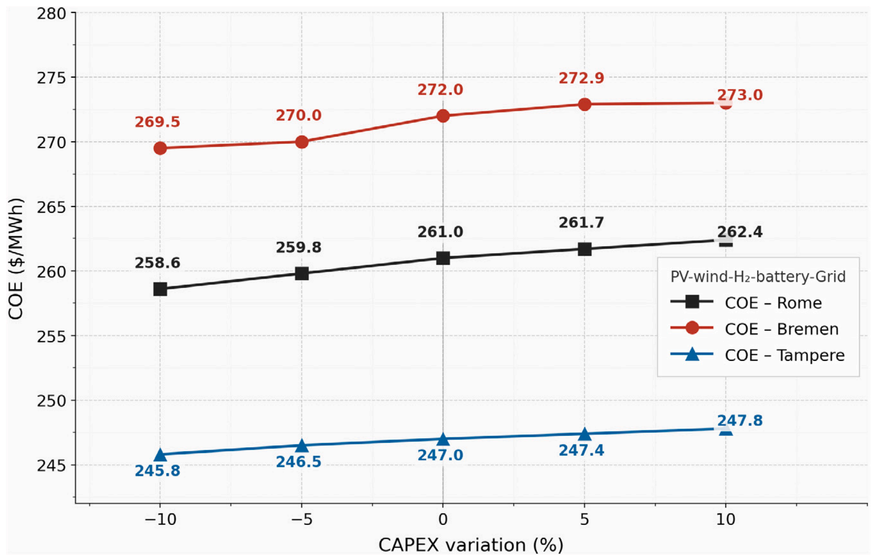

Fig. 14. Sensitivity analysis of the effect of overall CAPEX on the COE ranging from −10% to +10%.

Table 15
rMCC-linked emission reduction percentages for each hybridization case analyzed.

System	Italy	Germany	Finland
Wind–Battery–H_2-Grid	5.8%	7.0%	10.9%
PV–Battery–H_2-Grid	9.5%	6.6%	2.9%
Wind–PV–Battery–H_2-Grid	17.0%	17.6%	15.6%

case analyzed in this study, calculated specifically as the difference between the total emissions in that scenario and the emissions that would have occurred if different electrolysis-fuel cell systems had been considered in the system, allowing for a direct comparison of its impact on decarbonization.

However, the overall impact becomes even more pronounced when assessing the fully integrated energy system, where rMCCs contribute not only to carbon capture but also to efficient H_2-based energy conversion. The values in the table demonstrate how system integration and proper sizing influence the overall CO_2 reduction potential, reinforcing the role of rMCCs as a scalable solution for emission mitigation in cement production.

While heat capture could not be accurately modeled in HOMER, the cement plant could benefit from sector coupling with a local district heating system, which exists in most cities in Finland. The otherwise wasted heat could be a source of additional efficiency improvements or an additional source of revenue to the cement plant if sold, for example, to district heating networks. The implementation of heat capture in the cement plant has been extensively discussed in the Supplementary Information material.

While three different countries are compared, it is important to note that this work does not seek to highlight the competitive advantage of one country or climate type over another. Actually, this work focuses on showing that the proposed cement plant is adoptable in varied sets of climates powered by different renewable sources in different amounts.

Sources of renewable energy other than wind and solar should be considered according to local availability. Only wind and solar power were considered in this present study, as they are not geographically restricted and can be widely adopted. If geothermal, tidal, or hydropower are locally available, they should be considered as additional sources of renewable power. As the power demand of the cement plant is constant, utilizing nuclear power could also be an option worth considering; however, there are environmental and political issues associated with nuclear power. In the future, modular nuclear power could be an improvement over large-scale centralized nuclear reactors which often face uncertainties and delays that balloon costs [83].

The location of the cement plant should be planned such that it is located near other sites of power generation. As it is a significant load on the grid, locating it far from other sites of power generation will require the use of long-distance transmission lines which can stress the grid. At times of lower power generation, the renewable power generation in the cement plant can support the power demand of the grid at a time when the transmission lines are not overloaded through ancillary services. When the other large sources of renewable power generation are producing large amounts of energy, the cement plant with its large energy reserves is able to store a significant capacity of cheap, otherwise possibly curtailed renewable energy, again, without stressing the long-distance transmission lines.

Having off-grid power generation behind the load allows for a reduction of the variable costs by neglecting the distribution cost altogether. This directly leads to a saving of between 20–50 €/MWh in the case of Finland [58]. The final distribution costs vary by country. In addition, generating one's own power removes the tax component, which can also be significant depending on the location. This is a strong motivator for renewable power generation to be located on-site as opposed to far from the site of consumption, relying on the transmission grid.

The remaining emissions from the modeled plant are a result of the grid electricity still utilizing varying levels of fossil fuels. In order to make the cement industry carbon-neutral, the grid electricity must also be zero-carbon. Despite this, the proposed system can be adopted and emissions significantly reduced. As the different grids transition to cleaner sources of power, the cement plant's emissions will also drop significantly without causing significant stress to the grid due to its own share of power generation and storage, only utilizing grid energy for balancing. In addition, due to the grid connection, the cement plant could participate in different electricity markets by offering some of its power generation and storage to support normal grid operation.

6. Conclusion

The cement industry contributes greatly to climate change through the use of fossil fuels to reach high temperatures, as well as through the emissions from the calcination reactions occurring during cement manufacturing. This paper proposes a novel cement processing system that utilizes an electrified kiln together with local renewable-based power generation, with on-site hybrid energy storage systems. The hybrid storage system consists of Na-ion batteries with a reversible Molten Carbonate Cell with the dual purpose of longer-term energy storage as well as carbon capture from the chemical reaction occurring in the kiln. When compared to the state-of-the-art configuration, the hybrid system demonstrated the potential to reduce overall CO_2 emissions from cement production by 45% in Italy, 47% in Germany, and 45% in Finland. The remaining emissions from the cement industry come from the electricity supplied by the grid. As power grids transition to renewable energy, these emissions will gradually decrease. Once the grid is fully powered by zero-carbon energy, cement production can be considered carbon neutral. While the proposed system can eliminate direct emissions from cement manufacturing, achieving full decarbonization depends on using renewable electricity from the grid.

System sizing and cost optimization was conducted using on site-specific renewable energy profiles, indicating costs of energy of $249–277/MWh for solar-based systems, $252–285/MWh for wind-based systems, and $247–272/MWh for hybrid solar–wind configurations. The lowest cost of electricity and most significant emissions reductions were achieved with the hybrid solar–wind systems, regardless of location. The proposed systems, constructed using widely available technologies without geographical constraints for each location, have the potential to fully displace the use of fossil fuels in the cement-making process and make the whole process virtually carbon neutral, with a system that can be globally adopted without regional constraints.

CRediT authorship contribution statement

Naime Ahmadi: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Sayan Das:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Ahmad Reshad Delawary:** Writing – original draft, Visualization. **Simone Mataloni:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Lukas Richter:** Writing – original draft, Visualization. **Markus Salmelin:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Luigi Jacopo Santa Maria:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis. **Jakob Smith:** Writing – review & editing, Writing – original draft. **Stefano Passerini:** Writing – review & editing, Supervision, Funding acquisition. **Roberto Scipioni:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.energy.2026.142090.

Data availability

Data will be made available on request.

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