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Original Research Article

Benchmarking Present and Future Performances of Coastal and Island Settlements with the Sustainable Development of Energy, Water and Environment Systems Index

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ABSTRACT

The renewable energy transition and integrated approaches are ever more important for cities in a rapidly changing climate. This research work focuses on benchmarking 11 coastal and coastal island cities based on the Sustainable Development of Energy, Water and Environment Systems Index. The coastal and coastal island cities are located in the Mediterranean Sea Basin, including on the islands of Mallorca, Sardinia, and Sicily. The method involves benchmarking present performance levels and possible future performances considering a numerical 100% renewable energy scenario in which energy usage is decoupled from carbon dioxide emissions for complete elimination of the latter. The results of present levels of benchmarked performance indicate that the top cities are Messina, Siracusa, and Palermo. Shortcomings limit all of the analysed coastal and coastal island cities from reaching an upper quartile that represents the pioneering cities among a total of 132 cities that are benchmarked with the composite indicator to date. All else being equal, the exemplary scenario enables an upward shift in performance, with 6 of the cities reaching the upper quartile of the pioneering cities. Additional analyses are conducted to estimate the local job opportunities that can be established through the realization of a renewable energy transition among the multiple other co-benefits that can be attributed to the numerical scenario. The results of the research work are expected to be beneficial in providing impetus for more sustainable coastal and coastal island cities despite the climate crisis. Perspectives for coastal settlements in Latin America, including Viña del Mar in Chile, are discussed among related opportunities in the world.

KEYWORDS

Benchmarking, Sustainable development, Renewable energy, Emissions, Decoupling, Cities.

INTRODUCTION

Addressing the challenge of the climate crisis requires significant paradigm shifts at a global level. These paradigm shifts are unprecedented when compared to the scale of the foreseeable changes [1]. The pace and speed of change, however, may be comparable to other changes humanity has or is realising. Most recently, the rapid advances that are taking place in renewable energy technologies, including reductions of 85% in the unit costs of solar photovoltaics [2], are opening new opportunities to pursue rapid decarbonisation. As one of the major outcomes, the

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First Global Stocktake under the Paris Agreement also recognised the call for tripling renewable energy capacity, doubling energy efficiency by 2030 and transitioning away from fossil fuels in consistency with the science [3]. Making progress that takes these opportunities forward requires upscaling mitigation action, including in coastal and coastal island settlements and cities.

Renewable energy-based systems in human settlements constitute a distinct solution area that provides opportunities to support paradigm shifts with more targeted action and speed towards sustainability. Particularly in island settlements, the water sector may involve additional needs for water desalination that can support an integrated approach to increase the penetration of variable renewable energy while supporting greater well-being for sustainable development, such as in the case of Porto Santo, Portugal [4]. Such directions in the scientific literature have initiated a vibrant research field for islands that can be supported with 100% renewable energy systems [5]. The density and diversity of sectors in the energy systems of islands [6] can directly support options for efficient, more integrated infrastructure across sectors with better demand flexibility. Along these lines, the scientific landscape of related studies on coastal and coastal island cities since the turn of the century is found to cluster around sustainable development, renewable energy, climate change, and modelling (Appendix 1). These clusters are utilised to structure the literature review of this paper, leading to the gap in the literature that will be addressed.

Sustainable development and renewable energy

In Duić *et al.* [7], a RenewIslands method was put forth to transform island energy systems that are dependent on fossil fuels from the mainland into 100% renewable energy systems. The method involves the integration of resource flows according to the needs and resources of islands through integration between systems, including storage in the form of desalinated water when necessary. In this pioneering study, the RenewIslands method across resources, commodities, and technologies was initially applied to the islands of Porto Santo, Corvo, and Mljet. In addition, Krajačić *et al.* [8] analysed the production and storage of hydrogen (H_2) for energy supply structures with 100% renewable energy in islands, including Malta. Other studies based on the RenewIslands method include Pfeifer *et al.* [9], in which interconnected energy systems for multiple Croatian islands were simulated. In addition, Mimica and Krajačić [10] sought to automatise the approach for smart islands and tested it with the islands of Krk and Vis. Dorotić *et al.* [11] optimised island energy systems assuming 100% variable renewable energy and electric transport with smart charging. With a focus on Singapore, Dominković and Krajačić [12] determined the optimal share of district cooling to reduce socio-economic costs. Moreover, water desalination, demand side management, and energy efficiency measures were considered to lower carbon dioxide (CO_2) emissions, primary energy supply, and particulate matter [13].

Among other studies, Groppi *et al.* [14] analysed the long-term energy transition of Favignana island in Italy, which was modelled based on a new version of H2RES. From another perspective, sector coupling options were analysed with multi-objective optimisation [15] for the same island. As another Italian island, EnergyPLAN was used for Sardinia, which was considered a smart energy system with high shares of renewable energy [16]. In the context of satisfying cooling loads, flexibility provision was found to provide additional revenue when analysed for the coastal city of Rijeka in Croatia [17]. In addition, Meschede [18] proposed increasing the utilization of solar and wind resources on the island of La Gomera in Spain based on demand response in the water supply and distribution system. Salamanca *et al.* [19] investigated an osmosis power plant that utilises the salinity gradient between a river and the Caribbean Sea.

Other studies that are triggered by integrated approaches include Liu *et al.* [20], in which the need to reduce the import of energy and water to the islands of Maldives was targeted based on solar, wind, and biomass energy resources towards a zero-input island system. Selosse *et al.* [21] investigated scenarios for the island of Réunion, including a 100% renewable energy power sector by the year 2030 based on biomass, hydropower, solar, wave and wind energy, ocean thermal energy conversion, and geothermal energy. In other renewable energy-oriented studies, Selvaggi *et al*. [22] considered the diffusion of biogas plants with flexibility of power, heat, and biomethane production in the Sicilian context based on residual biomass from agricultural by-products, ground-cover crops, and municipal organic waste. Montorsi *et al*. [23] simulated a waste-to-energy plant considering fluctuations in the amount of wastewater generation due to tourism cycles in a town in Sicily. Ocon and Bertheau [24] considered transitioning the energy system of the Philippine archipelago from diesel power plants to hybrid systems with solar photovoltaic (PV) and battery energy storage. Battery and thermal energy storage options are deemed essential across a range of studies, including those to provide benefits for the power, heating, and transport sectors in the island of Samsø in Denmark as well as the Orkney Islands in Scotland [25]. Related studies further provide insight into the energy transition, particularly the municipal planning process leading to the fossil fuel-free island of Samsø that involved a synthesis of energy and socio-technical priorities [26].

Through these and other advances for islands, the first cluster in the scientific landscape of Appendix 1 with the main node of sustainable development represents studies that are directed to aspects of development with environmental protection and the conservation of natural resources. A key subset of studies emphasises the need for an integrated approach to realise sustainable development with linkages to multiple other clusters, predominately renewable energy. Studies seek to address the problematic use of fossil fuels on islands, especially when compared to the opportunities to utilise renewable energy, including solar, wind, bioenergy, geothermal energy, wave, and/or tidal energy.

Climate change, water and environment systems

Water management, water supply, water quality, agriculture, and recycling are other aspects of the scientific literature. Such studies include a focus on water desalination utilising renewable energy with an integrated, systemic approach. Advances in renewable energy technologies with local case studies that relate to coastal or coastal island cities include a polygeneration system with geothermal and solar energy that meets the energy and water demands of 800 buildings on Pantelleria Island [27]. Calise *et al*. [28] put forth a polygeneration system based on solar and biomass to produce electricity, heating, and cooling, as well as desalinated water. In Beccali *et al*. [29], a renewable energy retrofit of a hotel building in Lampedusa Island was evaluated based on solar thermal collectors, PV with and without electrical energy storage, and retrofits for building automation. The interaction of climate change and coastal settlements can also be observed in studies that relate to the urban heat island effect, energy utilisation, and urban planning.

Other studies have focused on reducing the environmental impacts of waste management systems. Empirical data from the municipal waste management system of Palermo indicated that the current collection, transport, and disposal of waste have an ecological footprint of 6331 ha. In contrast, increasing the recycling rate from only 7% up to 37%, as well as composting and landfill methane recovery as included in an integrated waste management plan, was found to produce a net saving of 36,336 ha [30]. Siracusa and La Rosa [31] evaluated the benefit-cost ratio of using wetlands for wastewater treatment in a small town in Sicily from an emergy perspective. The treated water was proposed to be reused for agricultural irrigation where risks of desertification are prevalent. Ruiz-Orejón *et al*. [32] evaluated the accumulating amount of floating plastic debris in the coastal waters surrounding the Balearic Islands. The highest concentrations were found on the surface of coastal waters that did not correspond to more highly populated areas, which suggested impacts from hydrodynamic conditions.

Necessity for multi-sectoral approaches and benchmarking

Multi-sectoral approaches that improve livelihoods and the sustainable use of resources are essential for coastal communities [33]. Among the limited number of studies with the keyword of benchmarking, however, none of the studies focused on benchmarking multiple dimensions of sustainable development. Ioannidis *et al*. [34] compared the energy and emissions intensity as well as the diversity of energy sources in 44 different islands. Islands with opposite performances were given, including Trinidad and Tobago, which have high energy and emissions intensity and zero diversity, in contrast to Iceland, which has near-zero energy and emissions intensity and high diversity. The results suggested the need to shift to renewable energy solutions, while the benchmarking process did not consider co-benefits, such as air quality or other dimensions. Schipper *et al*. [35] developed an approach to compare the performance and long-term plans of 10 ports, including a Sustainable Integrated Condition Index, to compare policy measures to address the social, environmental, and economic aspects of sustainability. The measures were scored according to evidence-based knowledge that was obtained from available sources, while the need for a standard in key performance indicators was underlined.

In other studies, a zero energy concept based on solar, wind, and wave energy for a small island of Hong Kong that otherwise relies on fossil fuels and nuclear energy was analysed [36]. Co-located wind and wave energy was another solution that was analysed to achieve the goal of an energy-sufficient island in Spain [37]. Experimental sea energy technologies, including osmotic energy, were included in the portfolio of renewable energy options in analyses for Réunion Island [38]. In Mendoza-Vizcaino *et al*. [39], the possibility of solar and wind energy for an island in Mexico was found to reduce the price of grid electricity by 35%. This possibility was compared to various renewable energy developments in 77 other islands from 45 countries. For comparative purposes, the study did not benchmark islands based on current or future performances.

A direct focus on the aim of benchmarking cities in coastal and/or island contexts towards sustainable development based on a composite indicator is, therefore, limited. In contrast, the literature review emphasises the suitability of islands in acting as pilot sites for demonstrating the integration of multiple systems towards complete decarbonisation, which merits benchmarking studies that are dedicated to islands as well as coastal settlements from a multi-dimensional perspective. This study addresses this gap in the scientific literature by pursuing the application of the Sustainable Development of Energy, Water and Environment Systems (SDEWES) Index [40–46] to coastal and coastal island cities. This multi-dimensional index provides a benchmarking framework that can be used to support renewable energy penetration, the integration of urban and energy planning, and a decoupling of emissions from greater well-being. Existing benchmarking studies with the SDEWES Index focused on 22 port cities in the Mediterranean Sea Basin [41]. Other island cities in and outside of the Mediterranean Sea Basin that take place among the largest islands in Europe were also benchmarked.[†] Overall, benchmarking studies with the SDEWES Index involve 120 cities across the world [45], and the data inputs are openly accessible [46]. As the 121st city, the index was also applied to Çankaya municipality in Ankara, Türkiye [47]. Recently, cities that have been benchmarked with the SDEWES Index and analysed based on urban emissions scenarios in a green-growth mitigation context were compared for 8 urban areas [48] and 15 Mission Cities in Europe [49].

The present study contributes to increasing an understanding of the relative sustainability of newly benchmarked port cities and coastal settlements on islands in the Mediterranean Sea Basin area. The uniqueness of the SDEWES Index for benchmarking the selected coastal and coastal island cities arises from the multi-dimensional nature of this index in aspects of energy, water and environment systems. Moreover, the index is suitable for evaluating opportunities for decoupling energy usage from emissions through renewable energy utilisation, which is undertaken in this research work through a scenario application that extends beyond benchmarking present levels of performance. Such a future-oriented scenario for 100% renewable energy is further analysed

[†] For example, London, Birmingham, Reykjavík and Dublin are benchmarked with the SDEWES Index. Other cities that exist on islands in Europe are Copenhagen (island of Zealand), Stockholm (island of Södertörn), Heraklion (island of Crete), Funchal (island of Madeira), and Gothenburg (island of Hisingen).

based on its possible impact on the ranking results and co-benefits for local employment opportunities. These aspects provide an original research endeavour in the scope of benchmarking studies involving the SDEWES Index. The results are further discussed in the context of recent island initiatives at the European and international levels. Opportunities for co-learning among coastal cities on different continents are exemplified, including a particular focus on Viña del Mar in Chile.

METHOD

This research work provides a benchmarking study for selected coastal and coastal island cities in the Mediterranean Sea Basin based on the SDEWES Index [40–46]. The SDEWES Index is a composite indicator that enables a comparison of the performances of cities with a focus on benchmarking the sustainability of energy, water and environment systems. This composite indicator is also used to identify collaboration opportunities to address joint challenges and consider possible scenarios with a solution-oriented approach. Figure 1 summarises the scope of the SDEWES Index, which is based on 7 dimensions and 35 main indicators, some of which contain sub-indicators. Strategies that are able to target a decoupling of environmental impact and emissions from increased growth and well-being can provide opportunities to obtain simultaneous improvements across these dimensions and increase overall city performance. Possibilities for such synergetic measures that improve multiple dimensions are represented visually through the interlinking arrows in the centre of this circular representation.

Figure 1. Seven dimensions and the main indicator framework of the SDEWES Index

Figure 2 provides the cities that are selected for the present benchmarking study. In this process, coastal settlements of the Mediterranean Sea Basin are first ordered according to population from largest to smallest. Those coastal and coastal island cities that have adopted Sustainable Energy Action Plans (SEAP) or Sustainable Energy and Climate Action Plans (SECAP) [50] are identified. Once identified, cities that are already benchmarked with the SDEWES Index are eliminated from the scope of the present study, which corresponds to 16 cities along the Mediterranean Sea Basin.[‡] The relevant energy plans for the remaining cities are reviewed to ensure the necessary quantifications. Finally, the selection criterion depends on coastal cities with monitoring reports that contain quantitative data and have been adopted in the last 5 years. As observed from the map, the geographical distribution of the cities along the Mediterranean Sea Basin from west to east spans Marbella in the southwest to Trieste in the northeast. Of the 11 new coastal settlements in the sample, 6 cities are located on islands, namely Palma in the Mallorca island of the Balearic Islands, Cagliari in the island of Sardinia, and four settlements on the island of Sicily, namely Palermo, Catania, Siracusa, and Messina. Palermo was also the venue of the 13th Conference on SDEWES, the first such conference on an island [51]. Collectively, the coastal and coastal island cities from C_1 to C_{11} that are determined based on the selection criterion are Marbella [52–54], Cartagena [55], Alicante [56], Palma de Mallorca [57], Cagliari [58], Palermo [59], Catania [61], Siracusa [62], Messina [63], Salerno [64], and Trieste [66].

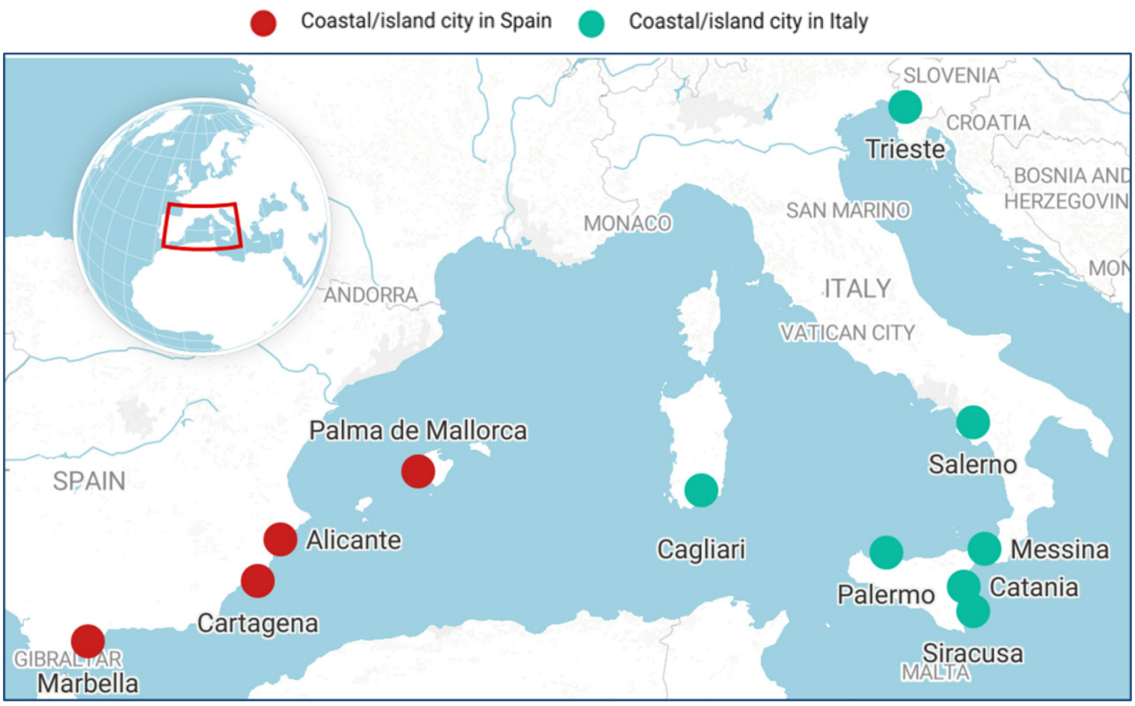

Figure 2. Geographical distribution of the cities along the Mediterranean Sea Basin

Figure 3 provides the framework of the research work that involves benchmarking with the composite indicator of the SDEWES Index and a comparison of relative performances across selected coastal and coastal island cities and their rankings. In addition, the research framework involves an analysis of a future scenario that decouples energy usage from emissions based on renewable energy and an estimation of one of the co-benefits due to job opportunities when progress towards net-zero emissions is realised. In so doing, the present research work addresses a knowledge gap in benchmarking the performances of coastal and coastal island cities and its comparison to a scenario in which energy usage is decoupled from CO_2 emissions based on the

[‡] These cities are Rome, Izmir, Barcelona, Antalya, Nice, Naples, Valencia, Thessaloniki, Genoa, Málaga, Bari, Venice, Sfax, Patras, Heraklion, and Volos based on relevant studies [40–46].

potential for advancing towards 100% renewable energy systems, particularly through solar and wind energy. The co-benefits for employment due to renewable energy technology deployment allow an additional layer of scenario analysis.

Overall, **Figure 3** includes the main steps in the framework of the present research work for the selected coastal and coastal island cities that are benchmarked in this study. First, the implementation of the benchmarking process necessitates a rigorous data compilation process with data processing to determine any outlier values prior to the normalisation of the data based on the min-max method. The normalised data entries are then aggregated according to the formulation of the SDEWES Index as elaborated in related benchmarking studies for 121 other cities [40–47]. The results of the present benchmarking study are then compared to the results of 10,000 Monte Carlo simulations with random weights that sum up to unity and confidence intervals, which are calculated at a confidence level of 95% based on the standard error of the mean. The ranking results of the newly benchmarked cities are compared to determine whether the original ranks are within the upper and lower bounds of the ranks, considering a confidence level of 95% (level of significance α value = 0.05).

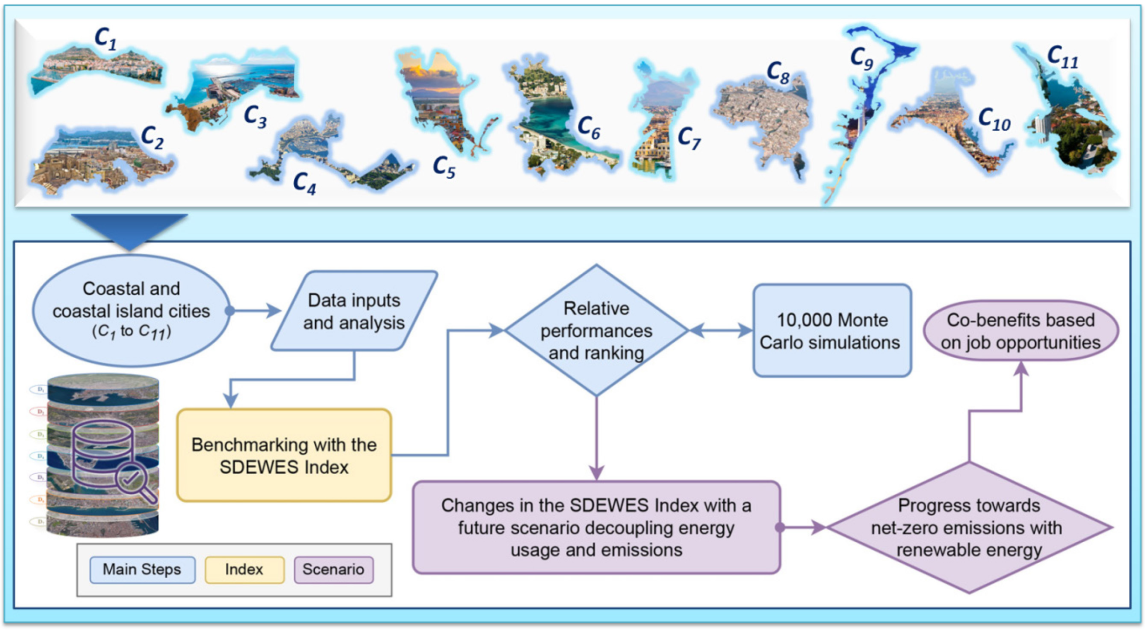

Figure 3. Method of the research work for benchmarking coastal settlements

The steps in **Figure 3** then continue with a determination of the relative performances and ranking of the benchmarked coastal settlements and island cities. In the future-oriented scenario in which energy usage is decoupled from CO_2 emissions, the endpoint of a 100% renewable energy system is applied to the benchmarked coastal settlements and island cities based on an absolute reduction of CO_2 emissions in all sectors. The possible change in ranking is discussed from the perspective of addressing structural shortcomings in the existing status of island energy systems. **Equation (1)** represents the re-calculation of the SDEWES Index values per city based on a complete reduction of CO_2 emissions based on the decarbonisation scenario with renewable energy as considered in this study, where C_j' represents the scenario values of a coastal settlement. Here, α_x represents dimension weights with a summation of unity [40]. Their default values are $\alpha_x = 0.23$ and 0.22 for dimensions D_1 and D_5 that directly relate to energy and emissions data per city, and $\alpha_x = 0.11$ for each of the other five dimensions. These default values lead to a 45% and 55% share in the weight of the dimensions in the index when split across D_1 and D_5 and the other dimensions to enable a well-rounded benchmarking of the cities in aspects of energy, water and environment systems. $I_{x\text{-}y}$ are the normalised values of the indicators that are summed for all indicators in dimensions $x = 1$ to $x = 7$. All normalised values per indicator have the same scale ranging between values of zero and ten for the minimum and maximum values, respectively. Such a normalisation process allows for comparability in relative performances across dimensions.

$$SDEWES\left(C_j'\right) = \sum_{x=1}^{7}\sum_{y=1}^{5} a_x I_{x.y}\left(C_j'\right) \tag{1}$$

Progress in mitigating climate change through measures to reach net-zero emissions can be accelerated through communicating co-benefits towards sustainable development, including employment opportunities [67] and air quality. The renewable energy scenario that is applied to the benchmarking results is compared to the number of local and regional jobs that may be generated based on a shift to renewable energy sources. Given that the 11 coastal and island cities in **Figure 2** are located in Spain and Italy, the IRENA jobs database [68] is used to obtain the number of jobs per renewable energy technology that is specific to these countries, namely solar, wind, bioenergy, geothermal, hydropower, and marine energy technologies. The IRENA statistics database [69] is used to further obtain the total electricity generation from these renewable energy sources to obtain the ratio of jobs per GWh per energy technology. For consistency, the use of renewable energy technologies for heating and cooling is excluded. Although the renewable energy potential of the coastal and island cities differ, the scenario that is based on a complete reduction of CO_2 emissions is supported by an estimation that considers the average contribution shares of renewable energy technologies at the European level [70] within a global modelling study [71].

Eq. (2) formulates the approach that is used to obtain the estimated values of one of the possible co-benefits based on employment opportunities. Here, the variable β is the total number of estimated job opportunities for a given renewable energy resource R_z based on renewable electricity generation. Within the formulation, E_I is the total energy use for urban infrastructure considering buildings and transport based on local data sources for a given coastal or island city C_j, and γ is an expected average electrification ratio for buildings and transport under a 100% renewable energy scenario [71]. Next, δ is the expected average contribution of a given renewable energy resource R_z to electricity generation, considering the 100% renewable energy scenario [70]. β^* is the ratio of the estimated job opportunities per GWh also as a function of R_z. This ratio expresses an employment multiplier taking into account the total electrical energy produced from a given renewable energy resource and the local employment that is generated by related renewable energy technologies, preferably in the same year for the relevant country. The results are summed across renewable energy resources R_z to obtain $\Sigma\beta$ in **eq. (3)** as the total number of job opportunities in an estimation of employment-related co-benefits. Here, R_z represents solar (R_1), wind (R_2), hydropower (R_3), bioenergy (R_4), geothermal (R_5), and marine (R_6) energy.

$$\beta(R_z) = \left[E_I\left(C_j\right) \times \gamma \times \delta(R_z)\right] \times \left[\beta^*(R_z)\right] \quad \{R_z = R_1, R_2, R_3, R_4, R_5, R_6\} \tag{2}$$

$$\sum\nolimits_{z=1}^{6} \beta(R_z) = \beta(R_1) + \beta(R_2) + \beta(R_3) + \beta(R_4) + \beta(R_5) + \beta(R_6) \tag{3}$$

The results are expected to be beneficial for several initiatives. At the global level, the Greening the Islands Initiative has been launched with the aim of integrating the concept of circular economies in islands. In addition, the Greening the Islands Observatory [72] contains projects and good practices from islands in the European, Asia-Pacific, and Caribbean regions. At the European level, the Smart Islands Initiative, which is based on a Smart Islands Declaration, has provided 10 action points and 7 key areas to decarbonise over 1000 islands within the European Union by the year 2030 [73]. This initiative preceded the European Mission for Climate-Neutral and Smart Cities, including cities in mainland Italy and Spain [74], which is another representation of the pioneering role of islands in decarbonisation. Under the initiative, smart islands are to increase synergies between the key areas of energy, transport, water, waste, governance, information and communication technologies, and economy with an integrated approach. A discussion of the benchmarking results and related initiatives contextualise the implications of the findings in society.

RESULTS AND DISCUSSION

The implementation of the method based on the SDEWES Index towards benchmarking 11 coastal and/or island cities in the Mediterranean Sea Basin is provided in four subsequent subsections. First, the results of the data compilations for the main indicators in the 7 dimensions are provided in Tables 1 to 7; the data for the sub-indicators are provided in Tables A1 to A10, which are in Appendix 2. Second, the normalised and aggregated values at the dimension and index level are put forth in addition to the comparison of the ranking results based on confidence intervals with a confidence level of 95%. Third, the benchmarking results for the 11 coastal and/or coastal island cities are compared through an exemplary 100% renewable energy scenario with co-benefits for employment. The fourth subsection provides an extended discussion of the results in the context of island initiatives.

Results of data compilations in the benchmarking study

Table 1 provides the data compilation for the first dimension of the SDEWES Index, namely, "Energy Usage and Climate" (D_I). The values of the benchmarked cities indicate an average energy usage of 1,400,805 MWh in buildings and 1,458,327 MWh in transport, with an average energy usage of 11.27 MWh per capita. The lowest and highest values of energy usage per capita occur in Siracusa and Cagliari, respectively. Aspects of climate indicate total degree days of 1,080 when weighted with an average seasonal coefficient of performance.

Table 1. Data inputs to the Energy Usage and Climate Dimension (D_I)

Indicators per City (C_j)	$i_{1.1}$ Energy usage of buildings [MWh]	$i_{1.2}$ Energy usage of transport [MWh]	$i_{1.3}$ Energy usage per capita [MWh/capita]	$i_{1.4}$ Total degree days factor [b]	$i_{1.5}$ Final to primary energy ratio [%]
Data Source	SEAP [a]	SEAP [a]	SEAP [a]	[76]	[77]
Marbella	911,485	669,934	13.35	1,042	66
Cartagena	930,072	1,456,557	11.04	1,080	71
Alicante	1,161,435	1,960,933	9.41	1,061	71
Palma de Mallorca	3,554,884	2,911,939	15.34	1,070	66
Cagliari	1,116,851	1,594,996	17.38	1,056	58
Palermo	2,476,143	4,114,787	10.48	1,086	79
Catania	1,235,950	1,050,209	8.49	1,094	79
Siracusa	377,011	364,154	6.08	1,119	79
Messina	924,589	429,884	6.45	1,098	79
Salerno	691,119	522,677	11.52	1,058	78
Trieste	2,029,318	965,529	14.46	1,116	78
Average (11 cities)	1,400,805	1,458,327	11.27	1,080	73

[a] Obtained or calculated from SEAP or equivalent plans based on the relevant local level references [52–66]
[b] Weighted by an average COP of 4 in the heating season and an average COP of 3.5 in the cooling season

Based on other aspects of the data compilation in D_I, local energy generation in the 11 benchmarked cities is still limited, with reliance on energy generation from outside the vicinity and on the mainland. The island cities are interconnected to the mainland power grid that allows for the usage of the primary energy factor for electricity generation at the national level [75] along with primary energy factors for solid, liquid, and gas fossil fuels as well as waste within the energy resource flow of the cities. Among the region of the cities, Andalucía reports both final energy usage and primary energy spending [53]. In the case of Italy, the primary energy factor for electricity generation varies from about 2.0 in the winter months to about 1.85 in May and June for an annual average of about 1.95 [75]. Considering the broader energy system in which the coastal and coastal island settlements are located, including the power mix and the transformation facilities, the average final to primary energy intensity ratio is about 73%.

Table 2 provides the data inputs to the main indicators of the second dimension, namely "Penetration of Energy and CO_2 Saving Measures" (D_2), while Tables A1−A3 provide the evaluations for the sub-indicators. Among the cities, the use of high-exergy resources, particularly natural gas, remains to be prevalent. Electricity supplies 82% of the building energy needs in Cartagena. Combined heat and power systems are still emerging (Table A1), including plans to integrate micro-CHP in hotel buildings in Alicante [78] and measures to increase micro-production plants undertaken in Cagliari. Renewable energy-based district energy networks are being considered in Trieste. Another approach for piloting a transition in the urban energy system is based on a 33 kW_e dish Stirling concentrated solar power unit in Palermo.

Table 2. Data inputs to the Penetration of Energy and CO_2 Measures Dimension (D_2)

Indicators per City (C_j)	$i_{2.1}$ Action Plan for Energy and CO_2 Emissions	$i_{2.2}$ Combined heat and power based DH/C	$i_{2.3}$ Energy savings in end- usage (buildings)	$i_{2.4}$ Density of public transport network	$i_{2.5}$ Efficient public lighting armatures
Data Sources	[52–66] [a]	Table A1 [b]	Table A2 [c]	Table A3 [d]	[52–66] [e]
Marbella	2	0.0	1.0	1.5	1.0
Cartagena	2	0.0	1.0	1.0	1.0
Alicante	2	1.0	1.0	2.0	1.0
Palma de Mallorca	2	1.0	1.0	3.0	1.0
Cagliari	2	1.0	1.0	2.5	2.0
Palermo	2	1.0	2.0	3.0	2.0
Catania	2	0.0	2.0	2.0	1.0
Siracusa	2	0.0	1.0	1.5	2.0
Messina	2	0.0	2.0	2.0	1.0
Salerno	2	0.0	1.0	1.5	1.0
Trieste	2	1.0	1.0	1.5	2.0
Average (11 cities)	2	0.5	1.3	2.0	1.4

[a] The minimum is zero based on the samples with partial points for monitoring without an action plan
[b] Top points received by DH/C based on CHP with > 75% penetration and renewable energy (Table A1)
[c] Scored based on sub-indicators for nearly net-zero energy buildings/districts implementation (Table A2)
[d] Based on urban rail density, daily users, and decentralised options with bicycle sharing (Table A3)
[e] Penetration of LED armatures using solar energy and/or best practices obtain an extra point

In the aspect of net-zero energy buildings (Table A2), Palermo has retrofits of school buildings based on the nZEB target. Similarly, the CERtuS project in Messina has targets for near-net-zero buildings. However, net-zero energy buildings constitute less than 0.002% of the building stock in Sicily, the island of Sardinia, and the Campania, as well as the Friuli-Venezia Giulia regions in Italy. For the density of public transport (Table A3), Alicante has about 0.41 km/km^2 of urban light rail based on a tram network. In contrast, multiple cities have municipal bicycle-sharing programs as alternatives to the use of private vehicles.

Best practices in public lighting are based on the relative penetration of LED lighting in a zero-energy neighbourhood in Palermo and the LED replacement of 1,530 lighting points in Siracusa. In contrast, LED lighting is not used in Palma de Mallorca for 10,000 lighting points, which indicates additional room for improvement in this city.

Table 3 provides the data compilation for the third dimension, which focuses on "Renewable Energy Potential and Utilization" (D_3). As coastal or coastal island cities in the Mediterranean Sea Basin, the benchmarked cities have favourable solar energy potential at an annual average of 5,563 Wh/(m^{2}day), wind energy potential at an average of 4.78 m/s at a height of 50 m and geothermal energy potential of 61 mW/m^2. Among the benchmark cities, Catania has the highest installation of solar PV panels at 50,834 kW, followed by Palermo at 14,074 kW [79]. Cagliari utilises the local wind energy potential with an installed capacity of 46,321 kW [58]. Overall, however, the share of renewable energy is still below 40% in the energy mix of the electricity sector. Considering the inclusion of the transport and thermal energy sectors, the share of renewable energy is even less, which necessitates greater shares of renewable energy across all sectors. In the transport sector, the share of green energy in transport is less than 8%, based on data from Spain and Italy.

Table 3. Data inputs to the Renewable Energy Potential and Utilization Dimension (D_3)

Indicators per City (C_j)	$i_{3.1}$ Solar energy potential [Wh/(m^{2}day)] [a]	$i_{3.2}$ Wind energy potential [m/s] [a]	$i_{3.3}$ Geothermal energy potential [mW/m^2] [b]	$i_{3.4}$ Renewable energy in electricity production [%] [c]	$i_{3.5}$ Green energy in transport [%] [d]
Data Sources	[80]	[81]	[82]	[83]	[84]
Marbella	5,900	5.88	65	36.61	5.28
Cartagena	5,830	4.23	75	36.61	5.28
Alicante	5,790	4.50	75	36.61	5.28
Palma de Mallorca	5,670	4.31	65	36.61	5.28
Cagliari	5,930	5.82	65	34.01	7.24
Palermo	5,610	4.77	40	34.01	7.24
Catania	5,820	4.78	70	34.01	7.24
Siracusa	5,560	5.26	70	34.01	7.24
Messina	5,360	5.07	50	34.01	7.24
Salerno	5,320	4.02	30	34.01	7.24
Trieste	4,400	3.95	65	34.01	7.24
Average (11 cities)	5,563	4.78	61	34.96	6.53

[a] Based on coordinate entries in the PVGIS [80] or IRENA [81] databases, respectively
[b] Based on geothermal heat-flow density categories in [82] and/or local sources
[c] Based on the share of renewable energy in electricity production based on [83] and/or local sources
[d] Based on biofuel and/or electricity in transport given at least a 45% renewable share [84] or local sources

In **Table 4**, data inputs into the fourth dimension of "Water Usage and Environmental Quality" (D_4) are provided. The average of the benchmarked cities represents domestic water consumption per capita at 13.09 m^3. The average water quality level is 90.65 out of a perfect score of 100 for dissolved oxygen, pH, conductivity, nitrogen, and phosphorus. For Sicily, the water demand has been met based on desalination plants through the use of multi-stage flash and reverse osmosis at Gela as well as thermal vapour compression based multiple effect distillation at Trapani and mechanical vapour compression in Porto Empedocle [85]. Among these options, mechanical vapour compression is the most energy intense, with energy usage up to 12 kWh/m^3, while the multi-stage flash and thermal vapour compression based on multiple effect distillation plants require at most 1 and 2 kWh/m^3, respectively. Water treatment from reservoirs is planned to better manage water shortages.

In aspects of air quality, the average value of the annual mean particulate matter concentration of PM_{10} at a value of 22.54 μg/m^3 is above the guidelines of the World Health Organisation. Alicante receives the cleanest annual mean PM_{10} concentration at a value of 16.00 μg/m^{3,} while Palermo currently has the highest annual mean PM_{10} concentration at about 31.70 μg/m^3. An existing transport issue with extended traffic in the city centre is one of the reasons for the continued deterioration in air quality. Palermo has an average congestion level of 43%, with above 60% congestion in the morning and evening peak hours. As the impact of the benchmarked cities in and outside of the urban area and vicinity, the average ecological footprint per capita is 3.92 gha. In comparison, the average biocapacity is 1.08 gha per capita, which indicates an average ecological deficit of about 2.84 gha per capita as the accumulating impacts on the global environment.

Table 4. Data inputs to the Water Usage and Environmental Quality Dimension (D_4)

Indicators per City (C_j)	$i_{4.1}$ Domestic water consumption per capita [m^3] [a]	$i_{4.2}$ Water quality index [/100] [b]	$i_{4.3}$ Annual mean PM_{10} concentration [μg/m^3]	$i_{4.4}$ Ecological footprint per capita [gha]	$i_{4.5}$ Biocapacity per capita [gha]
Data Sources	[86, 87]	[88, 89]	[90]	[91, 92]	[91]
Marbella	11.73	81.83	25.00	3.81	1.33
Cartagena	11.73	81.83	21.00	3.81	1.33
Alicante	11.73	81.83	16.00	3.81	1.33
Palma de Mallorca	11.73	81.83	19.00	3.81	1.33
Cagliari	14.22	95.69	24.50	4.29	0.94
Palermo	12.72	95.69	31.70	3.76	0.94
Catania	13.93	95.69	24.20	3.76	0.94
Siracusa	14.55	95.69	25.40	3.76	0.94
Messina	13.43	95.69	21.50	3.76	0.94
Salerno	14.87	95.69	19.60	4.29	0.94
Trieste	13.31	95.69	20.00	4.29	0.94
Average (11 cities)	13.09	90.65	22.54	3.92	1.08

[a] Domestic water consumption per capita per day for 7 cities is scaled with water footprint values
[b] Based on the UN water quality index for dissolved oxygen, pH, conductivity, nitrogen, phosphorus

The data inputs of the benchmarked cities for the fifth dimension of "CO_2 Emissions and Industrial Profile" (D_5) are provided in **Table 5**. Since any of these cities are not yet neutral on CO_2 emissions, the average amount of CO_2 emissions is 551,163 tonnes of CO_2 emissions from the building sector and 395,783 tonnes of CO_2 emissions from the transport sector at the urban level. On average, the CO_2 intensity of the energy mix is 0.32 tonnes of CO_2 per MWh. Based on measures for energy planning, a 585 MW coal and gas-fired power plant on the island of Mallorca is already targeted to be phased out based on the energy transition plan for the Balearic Islands [93]. Prior to a phase-out, the island had the highest CO_2 intensity at 0.45 tonnes of CO_2 per MWh.

The island of Sardinia, on which Cagliari is located, as well as the island of Sicily, also established energy plans [94, 95]. In addition, Palermo has a plan for smart buildings and smart mobility, including measures for renewable energy and energy sharing [96]. The scheme of energy sharing is targeted to extend to the utilisation of residual energy from the industry. Currently, the island of Sicily has sources of waste heat or residual energy based on facilities for non-metallic minerals, fuel supply, and refineries, as well as the chemical and petrochemical sectors [97]. In addition to the benchmarked cities in Sicily, others based on Cartagena, Alicante, Salerno, and Trieste also have similar sources of residual energy from industry (Table A4). In the aspect of airports that serve the cities, four airports reached the mapping or reduction levels of the Airport Carbon Accreditation scheme, including Cagliari Airport.

Table 5. Data inputs to the CO_2 Emissions and Industrial Profile Dimension (D_5)

Indicators per City (C_j)	$i_{5.1}$ CO_2 emissions of buildings [t CO_2]	$i_{5.2}$ CO_2 emissions of transport [t CO_2]	$i_{5.3}$ Average CO_2 intensity [t CO_2/MWh]	$i_{5.4}$ Number of CO_2 intense industries [b]	$i_{5.5}$ Airport ACA level and measures [c]
Data Sources	[52–66] [a]	[52–66] [a]	[52–66] [a]	Table A4	[98]
Marbella	231,192	169,924	0.25	1	1
Cartagena	325,020	377,125	0.29	5	0
Alicante	349,294	589,739	0.30	2	1
Palma de Mallorca	1,820,654	756,673	0.45	2	2
Cagliari	425,976	397,566	0.30	4	1
Palermo	1,140,543	1,185,170	0.36	2	0
Catania	528,607	277,743	0.36	3	0
Siracusa	134,259	93,941	0.32	4	0
Messina	329,260	110,254	0.32	2	0
Salerno	225,194	146,563	0.33	3	0
Trieste	552,794	248,920	0.27	4	0
Average (11 cities)	551,163	395,783	0.32	2.9	0.5

[a] Calculated from SEAP or equivalent plans based on the relevant local level references [52–66]
[b] Includes sectors that require high-temperature processes (e.g. kiln heating up to 2000 °C), Table A4
[c] Scores greater than 3 require renewable energy best practices on the land side, air side and/or ground side

Table 6 provides the data inputs into the main indicators in the sixth dimension, namely "Urban Planning and Social Welfare" (D_6). Among the benchmarked cities, Alicante has the lowest waste generation per capita at 431 kg per capita, which is also close to the overall sample average of 433 kg per capita [46]. Three cities have shares of waste reuse, recycling, or composting at about 30% or higher (Table A5).

Table 6. Data inputs to the Urban Planning and Social Welfare Dimension (D_6)

Indicators per City (C_j)	$i_{6.1}$ Waste and wastewater management [a]	$i_{6.2}$ Compact urban form and green spaces [b]	$i_{6.3}$ GDP per capita [PPP USD regional]	$i_{6.4}$ Inequality-adjusted well-being [/10]	$i_{6.5}$ Tertiary education rate [%]
Data Sources	[99–102]	[103–106]	[107]	[108]	[109–111]
Marbella	4.2	2.5	26,849	7.0	32.6
Cartagena	4.2	2.3	29,988	7.0	32.9
Alicante	4.4	2.3	32,040	7.0	36.7
Palma de Mallorca	3.8	2.3	37,830	7.0	34.4
Cagliari	4.5	2.0	28,058	7.1	24.2
Palermo	4.0	2.5	23,778	7.1	19.1
Catania	3.4	2.0	23,778	7.1	19.1
Siracusa	3.8	2.0	23,778	7.1	19.1
Messina	4.2	2.3	23,778	7.1	19.1
Salerno	5.9	2.5	25,288	7.1	21.7
Trieste	4.7	2.0	41,916	7.1	27.9
Average (11 cities)	4.3	2.5	28,826	7.1	26.1

[a] Based on municipal waste management and wastewater treatment sub-indicators (Tables A5–A6)
[b] Based on compact urban form including sprawl index and green spaces sub-indicators (Table A7)

In the aspect of municipal wastewater treatment, all cities have 0% discharge of wastewater without treatment, with the exception of Catania (Table A6). Compliance with wastewater treatment criteria is upheld in all benchmarked cities, with the exception of Cagliari and Trieste, to various extents (Table A6). In the context of urban form, no cities among benchmarked cities have polycentricity, while relatively high shares of the population live in the urban core (Table A7). In contrast, land use and land use changes are documented based on Copernicus satellite images, including an exceptionally high sprawl index of 15.2% in Catania, which indicates that the built land area is growing much faster than the growth in population.

The presence of urban green areas as a provider of protection against climate change impacts, as well as better air quality, is currently best maintained in Cartagena at 86.61% (Table A7). In about 100 km of the city, three cities have protected sites that are larger than 1000 km^2, namely Marbella, Palermo, and Salerno. In aspects of social welfare, the benchmarked cities have an average of 28,826 PPP USD of gross domestic product (GDP) per capita at the regional level when adjusted using purchasing power parity (PPP) rates. Inequality-adjusted well-being is surveyed to be 7.1 out of 10, and the tertiary education rate is 26.1% for the population of 30−35 years of age, based on the relevant statistics.

Table 7 provides data inputs for the indicators in the cross-cutting seventh dimension of "Research, Development (R&D), Innovation and Sustainability Policy" (D_7). Aspects of R&D and innovation policy orientation are higher for Italian cities than Spanish cities, with similar performances in national patents in clean technologies (Tables A8−A9). The project of Palma de Mallorca (OPTi) is one of the projects in the Smart Cities Information System, while Palermo takes place in the Roadmaps for Energy project [96]. Alicante has the most universities and institutes in the local ecosystem based on two universities that are ranked in the Scimago top 1000 institutional rankings (**Table A10**).

Table 7. Data inputs to the R&D, Innovation and Sustainability Policy Dimension (D_7)

Indicators per City (C_j)	$i_{7.1}$ R&D and innovation policy orientation [a]	$i_{7.2}$ National patents in clean technologies [b]	$i_{7.3}$ Universities/ institutes in the local ecosystem [c]	$i_{7.4}$ National h-index [d]	$i_{7.5}$ Reduction target for CO_2 emissions [e]
Data Sources	[114], [115]	[116]	[117]	[118]	[50]
Marbella	1.5	2.0	0	723	20
Cartagena	1.5	2.0	2	723	21
Alicante	1.5	2.0	4	723	20
Palma de Mallorca	1.5	2.0	2	723	33
Cagliari	2.0	2.0	2	839	26
Palermo	2.0	2.0	2	839	22
Catania	2.0	2.0	2	839	22
Siracusa	2.0	2.0	0	839	39
Messina	2.0	2.0	2	839	23
Salerno	2.0	2.0	2	839	23
Trieste	2.0	2.0	2	839	20
Average (11 cities)	1.8	2.0	1.82	797	25

[a] Based on the approach for thematic priorities and R&D expenditure as a share of GDP (Table A8)
[b] Patents are limited to clean energy technology coded patents, e.g. Y02B for buildings (Table A9)
[c] Sum of universities located in the city, those in the SCImago list receive double points (Table A10)
[d] Sustainable development is a multidisciplinary field with inputs from multiple fields (fields not restricted)
[e] Linearly annualised to the same year for consistency between the percentage target reductions of cities

Based on the strength of scientific knowledge production as represented within the h-index, the average value for the benchmarked cities is 797. These knowledge assets can provide an advantage for a city to reach CO_2 mitigation targets if well-aligned with related efforts and innovation activities. Among the benchmarked cities, Palma de Mallorca declared a CO_2 neutrality target for 2050, while Siracusa had a CO_2 reduction target of 39% by the year 2020.

Subsequently, Siracusa is one of the municipalities that adopted a Climate Energy Declaration based on the scientific findings and the necessity for limiting global warming to 1.5 °C [112, 113].

Results of the normalisation, aggregation and uncertainly analyses

The data inputs in the compilation process are searched for outliers. Winsorisation is not necessary since the data inputs in each of the 35 main indicators contributed to values of skewness less than 2.0 and kurtosis less than 3.5. The data inputs are, therefore, directly normalised according to the min-max method with minimum and maximum values that are harmonised with those of other cities in the benchmarking studies of the SDEWES Index. Table 8 summarises the average value of the cities that are benchmarked with the SDEWES Index prior to and after the inclusion of the newly benchmarked 11 coastal or coastal island cities. From Table 8, the average values increase by at most 1.918% in dimensions D_1, D_3, and D_5, while the average values decrease in dimensions D_2, D_4, D_6, and D_7 by at most −1.721%. These same dimensions represent the areas of relative strengths and weaknesses in the cities that are benchmarked in the present study. Overall, the new average values for a total of 132 cities are represented by the grey dashed lines in Figures 4−10.

Table 8. Average values without and with the inclusion of the newly benchmarking cities

Average	D_1	D_2	D_3	D_4	D_5	D_6	D_7
120 cities	33.255	31.901	21.851	30.016	29.426	25.479	20.921
132 cities [a]	33.572	31.352	22.270	29.860	29.591	25.414	20.863
% Change	0.953	−1.721	1.918	−0.520	0.561	−0.255	−0.277

[a] Includes 11 new cities, and Çankaya benchmarked as a case study for urban system integration [47]

In the context of D_1, Figure 4 provides the normalised values for the 11 newly benchmarked cities. Siracusa receives the highest sum of normalised values at a value of 40.413 out of a perfect score of 50.000. Advantages in multiple indicators, including energy usage per capita, appear to be influential in allowing Siracusa to obtain such a performance based on the results in Figure 4. The normalised values for the indicator on the total degree days have relatively less variance across the urban areas in Figure 4, given that all of the newly benchmarked cities belong to the common Mediterranean climate zone. Only two cities remain below the average value in D_1, namely Palma de Mallorca and Cagliari.

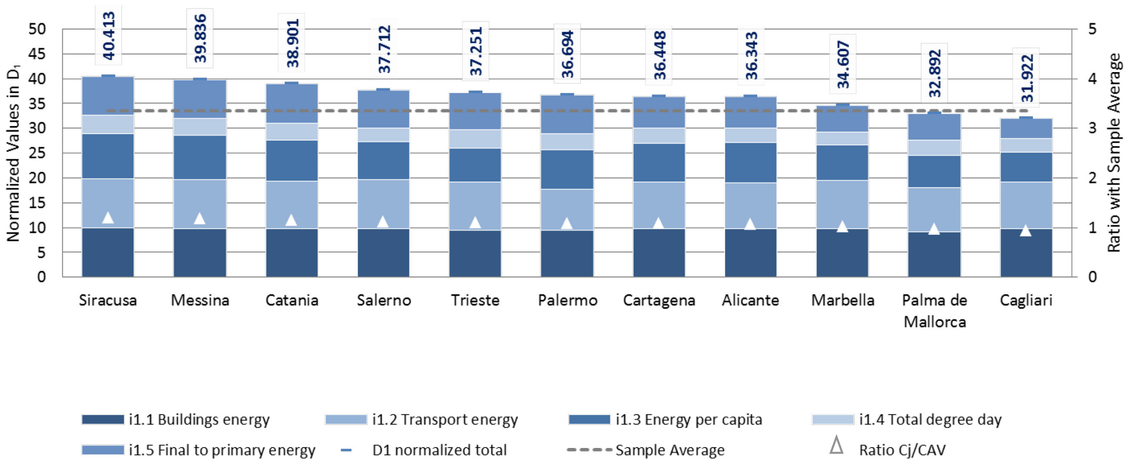

Figure 4. Sum of normalised values for the indicators in D_1

Figure 5 provides the normalised values of the data inputs into D_2, indicating that the cities of Palermo, Cagliari, and Trieste are the top three cities in this dimension. The plans of these cities to initiate district heating and/or cooling networks or micro-CHP, as well as projects for net-zero energy school buildings, are influential in differentiating the approach of these cities over others. In some cities, the use of natural gas boilers remains prevalent without plans for significant change (Tables A1 and A2). None of the cities receive the maximum dimension value of 50.000 in D_2, and 9 cities remain below the average value across the 132 cities. Despite transport-related shortcomings, Palermo and Palma de Mallorca receive relatively higher normalised values for the density of public transport than other cities in Figure 5 based on light rail options, which would have some favourable impacts on performance if this had not been the case. As 7 cities have inefficient public lighting infrastructure, normalised values in this indicator disfavour these cities.

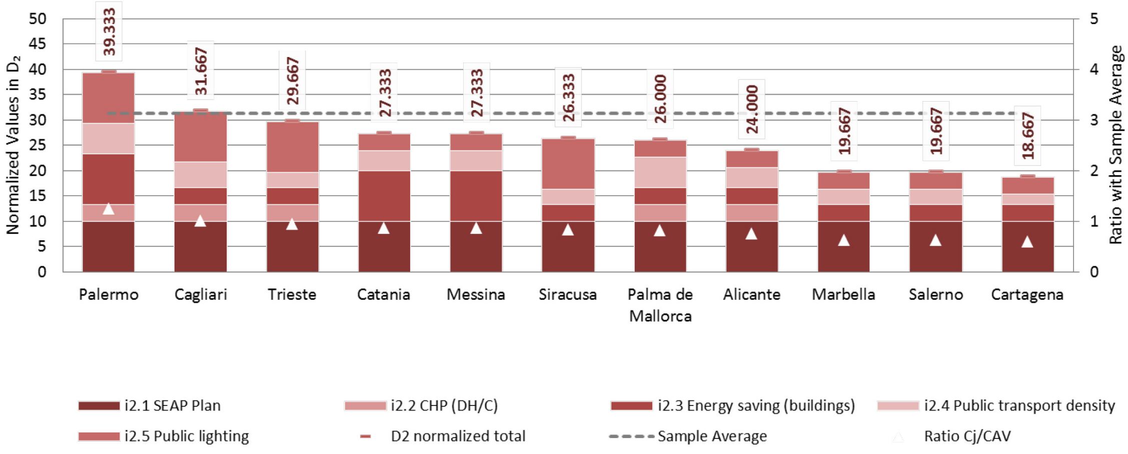

Figure 5. Sum of normalised values for the indicators in D_2

The results in **Figure 6** indicate that significant progress remains to be captured for the coastal or coastal island cities to utilise their favourable renewable energy potential. The island city of Reykjavík, benchmarked in reference **[46]**, had 100% renewable energy in the electricity mix. In contrast, the urban settlements in the present study have limited local energy generation and rely on interconnections to the national electricity grid with up to 36.61% of renewable energy.

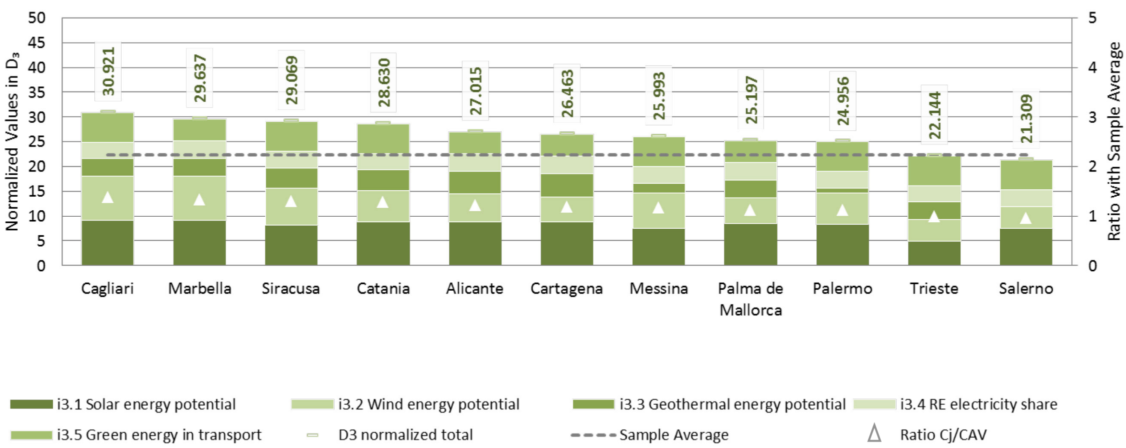

Figure 6. Sum of normalised values for the indicators in D_3

In other cities, shares of green energy in transport reach above 12.04% in Stockholm and higher in the Brazilian cities of Rio de Janeiro and São Paulo, which are winsorised as outliers **[46]**.

In comparison, those in the newly benchmarked urban areas remain less than 8.00%, which is further reflected in the normalised values in **Figure 6**. Despite these shortcomings in D_3, Cagliari, Marbella, and Siracusa are able to obtain the highest dimension values among the cities in the present study in aspects of renewable energy potential and utilisation with a top value of 30.921 out of a possible 50.000.

The normalised values in **Figure 7** indicate that all of the 11 coastal or coastal island cities perform close to the average value of the 132 cities. Among the newly benchmarked cities, Messina, Alicante, and Trieste receive about a 1.015 above-average ratio that is marked as the ratio of the values of C_j over C_{AV} in **Figure 7**. This performance may be explained based on relatively lower domestic water consumption per capita in Messina and Trieste, lower annual mean PM_{10} concentration in Alicante, and other aspects. The relatively high annual mean concentration of PM_{10} in Palermo, including impacts due to traffic congestion, affects reducing the performance of this city in this dimension. In contrast, ecological footprint per capita is the second lowest in Palermo and other Sicilian cities, so a higher normalised value is received under this indicator. The cities of Cagliari, Salerno, and Trieste have a higher ecological footprint per capita and, thus, lower normalised values for this indicator. The normalised value of biocapacity per capita is not favourable considering the values of the other benchmarked cities.

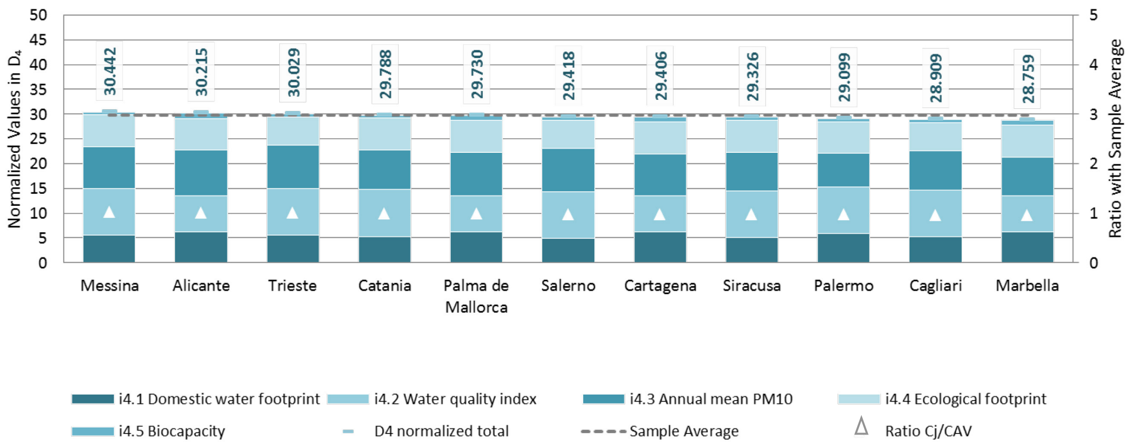

Figure 7. Sum of normalised values for the indicators in D_4

Figure 8 provides the normalised values of the indicators in D_5, where some of the cities, including Marbella, Alicante, and Messina, have favourable performances in this dimension with above-average performances. While the average value for D_5 across the 132 cities is 29.591, Marbella receives a sum of 36.320, which is a ratio of 1.227 with this average value. The average CO_2 intensity of the energy mix is among the indicators that support a relatively better position of Marbella in this dimension. In addition, Marbella, Alicante, and Messina are among the cities that have relatively low or absent energy-intensive industries in the urban vicinity. In Palma de Mallorca, however, the relatively high average CO_2 intensity has given this city the lowest normalised value for this indicator among the 11 cities in **Figure 8**. At the same time, the city plans to phase out the coal-based power plant by 2025 [119] in the next years, and the airport of Palma de Mallorca is accredited for reducing CO_2 emissions.

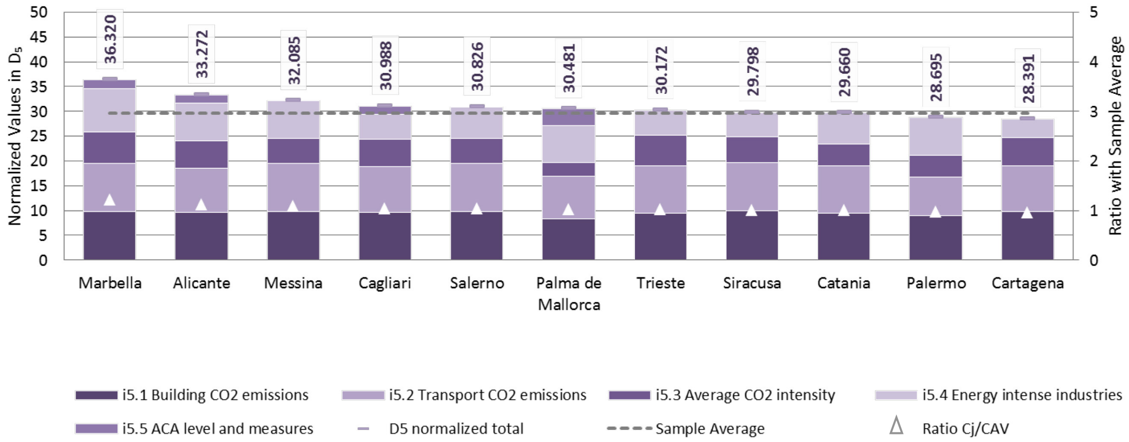

Figure 8. Sum of normalised values for the indicators in D_5

Figure 9 presents the results of the normalised values for the indicators in D_6. Accordingly, the cities of Alicante, Salerno, and Palma de Mallorca are able to obtain the highest positions in this dimension. In contrast, the lowest sum of the normalised values for D_6 is obtained by Catania, which includes the impact from the 9% share of urban wastewater that is discharged without being treated. The relatively lower tertiary education rates in the Sicilian cities of Messina, Palermo, Siracusa, and Catania, when compared to a best practice value as high as 62.4% in Incheon [46], have affected limiting the performance of these cities in D_6. Overall, 6 of the newly benchmarked cities are able to surpass the 132-cities average value that remains at 25.414 for D_6 based on a comparison of the average values (see Table 8). Of the newly benchmarked cities, 5 cities receive below average performances by a ratio as low as 0.823.

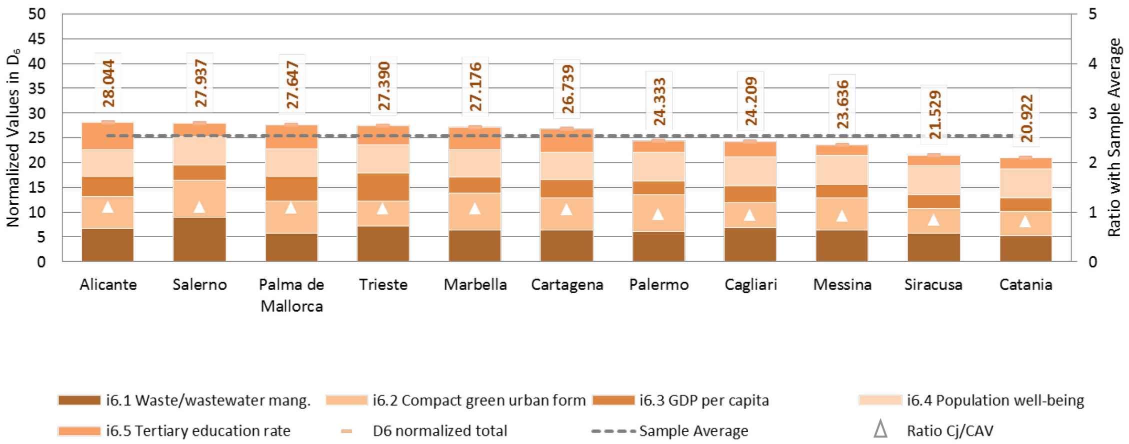

Figure 9. Sum of normalised values for the indicators in D_6

The sum of the normalised values for dimension D_7 is put forth within the scope of **Figure 10**, in which the cities of Siracusa, Cagliari, and Messina are able to obtain higher values. In the case of Siracusa, the more ambitious CO_2 mitigation target that the Climate Emergency Declaration follows enables the city to obtain a higher performance than the next best-performing city, namely Cagliari. In contrast, this city has other advantages when compared to Siracusa, which is based on universities in the local ecosystem and is surpassed only by Alicante among the newly benchmarked cities. The last 4 cities have below-average performances in D_7, namely Palma de Mallorca, Alicante, Cartagena, and Marbella, with a ratio as low as 0.822 with the average value.

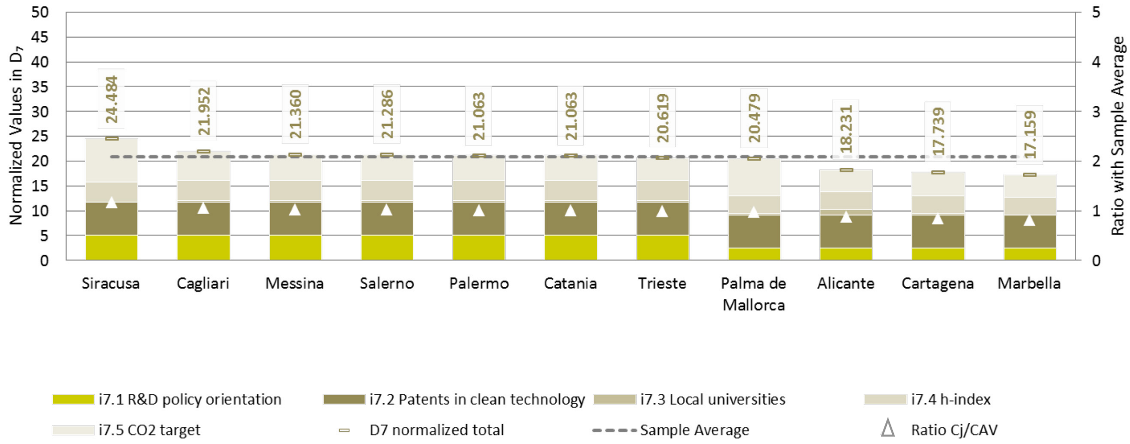

Figure 10. Sum of normalised values for the indicators in D_7

Table 9 summarises the aggregated sum of dimension values according to the formulation of the SDEWES Index [40–46] for the coastal and coastal island cities. These urban areas are ordered according to their aggregated index values in descending order that corresponds to rank positions from the top to the lowest rank among the 11 newly benchmarked cities. The marks (↑) or (↓) signify dimensions in which the cities receive above or below-average performances. According to Table 9, the top 3 cities among the newly benchmarked cities are Messina (*SDEWES* = 30.385), Siracusa (*SDEWES* = 30.232), and Palermo (*SDEWES* = 30.019). These cities, located on the island of Sicily, are differentiated based on energy and water usage, air quality, and CO_2 emissions, among multiple other aspects.

Table 9. Dimension and index values for the newly benchmarked cities

City C_j	D_1	D_2	D_3	D_4	D_5	D_6	D_7	Index [a]	ΔM_j [%]
Messina	39.836 (↑)	27.333 (↓)	25.993 (↑)	30.442 (↑)	32.085 (↑)	23.636 (↓)	21.360 (↑)	30.385	4.083
Siracusa	40.413 (↑)	26.333 (↓)	29.069 (↑)	29.326 (↓)	29.798 (↑)	21.529 (↓)	24.484 (↑)	30.232	3.559
Palermo	36.694 (↑)	39.333 (↑)	24.956 (↑)	29.099 (↓)	28.695 (↓)	24.333 (↓)	21.063 (↑)	30.019	2.829
Alicante	36.343 (↑)	24.000 (↓)	27.015 (↑)	30.215 (↑)	33.272 (↑)	28.044 (↑)	18.231 (↓)	29.704	1.750
Catania	38.901 (↑)	27.333 (↓)	28.630 (↑)	29.788 (↓)	29.660 (↑)	20.922 (↓)	21.063 (↑)	29.524	1.134
Trieste	37.251 (↑)	29.667 (↓)	22.144 (↓)	30.029 (↑)	30.172 (↑)	27.390 (↑)	20.619 (↓)	29.489	1.014
Marbella	34.607 (↑)	19.667 (↓)	29.637 (↑)	28.759 (↓)	36.320 (↑)	27.176 (↑)	17.159 (↓)	29.414	0.757
Cagliari	31.922 (↓)	31.667 (↑)	30.921 (↑)	28.909 (↓)	30.988 (↑)	24.209 (↓)	21.952 (↑)	29.302	0.373
Salerno	37.712 (↑)	19.667 (↓)	21.309 (↓)	29.418 (↓)	30.826 (↑)	27.937 (↑)	21.286 (↑)	28.613	−1.987
Palma	32.892 (↓)	26.000 (↓)	25.197 (↑)	29.730 (↓)	30.481 (↑)	27.647 (↑)	20.479 (↓)	28.467	−2.487
Cartagena	36.448 (↑)	18.667 (↓)	26.463 (↑)	29.406 (↓)	28.391 (↓)	26.739 (↑)	17.739 (↓)	27.720	−5.046

[a] The median index value for 132 cities is 29.193, with an equal number of cities above and below this value

In contrast, the city of Catania, also located in Sicily, is ranked 5th (*SDEWES* = 29.524), with one of the shortcomings being in D_6 based on urban water management. The rank 4 is taken by Alicante (*SDEWES* = 29.704), in which 5 dimensions have above-average performances. The lowest rank among the newly benchmarked coastal and coastal island cities is observed for Cartagena (*SDEWES* = 27.720), in which the city has 4 dimensions that are below the average dimension values when compared to the average of all cities.

In **Table 9**, the last two columns represent the index values for the benchmarked performances and the comparison of these values for the newly analysed 11 cities with the median index value for all 132 cities. The top index value of *SDEWES* = 30.385 for Messina, for example, is the summation of the dimension values $D_1 - D_7$ in **Table 9** with default weights prior to the scenario application in **eq. (1)**. This benchmarked index value is 4.083% above the median index value for all other cities. These percentage values that are marked as ΔM_j are further elaborated in **Figure 11** in which the vertical axis of index rank is plotted against the percentage differences with the median value as ΔM_j. Based on **Figure 11**, none of the newly benchmarked cities are positioned in the top 25% of the benchmarked cities that contain the pioneering cities. However, the index values of 8 of the cities in **Table 9** enable them to take place in the next quartile, which contains cities with index performances in the upper 25% to 50% of cities, as marked with the red circular markings. The remaining 3 cities in **Table 9** have a relative positioning in the quartile immediately after the median value as marked with the green triangular markings. According to the performance definitions **[45]**, these quartiles represent the transitioning and solution-seeking cities, respectively, as further grouped in **Figure 11**. The values of ΔM_j range between 4.083% for Messina and −5.046% for Cartagena.

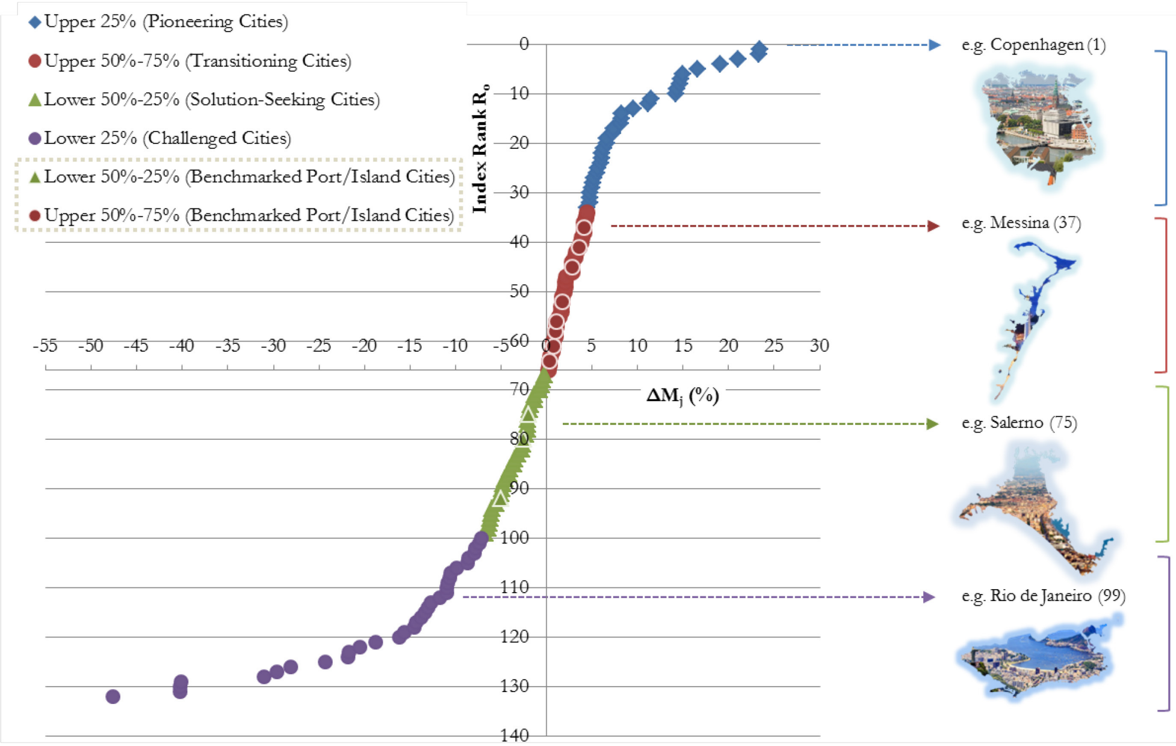

Figure 11. Analysis of the benchmarking results according to index performance

The relative positioning of the newly benchmarked cities is further compared in the context of uncertainty analyses. The ordering of cities, as provided in **Table 9**, remains stable based on the mean values of 10,000 Monte Carlo simulations, with the exception of the exchange in rank between the two adjacent cities of Trieste (original rank 6) and Marbella (original rank 7). Cagliari has the highest standard error of the mean, with a standard deviation of 2.482 for the rank positions in the 10,000 Monte Carlo simulations. Cartagena has the lowest standard error of the mean, considering a standard deviation of 0.870 for the rank positions in the Monte Carlo simulations. Overall, the rank positions of the cities based on the SDEWES Index, as given in **Table 9**, are within the upper and lower bounds of the rank positions with confidence intervals at a confidence level of 95% with a level of significance (α) equal to 0.05. This situation provides complete coverage of the highest and lowest ranks. **Figure 12** provides the ranking of the 11 newly benchmarked cities according to the mean values of 10,000 Monte Carlo simulations and corresponding confidence intervals at a confidence level of 95%.

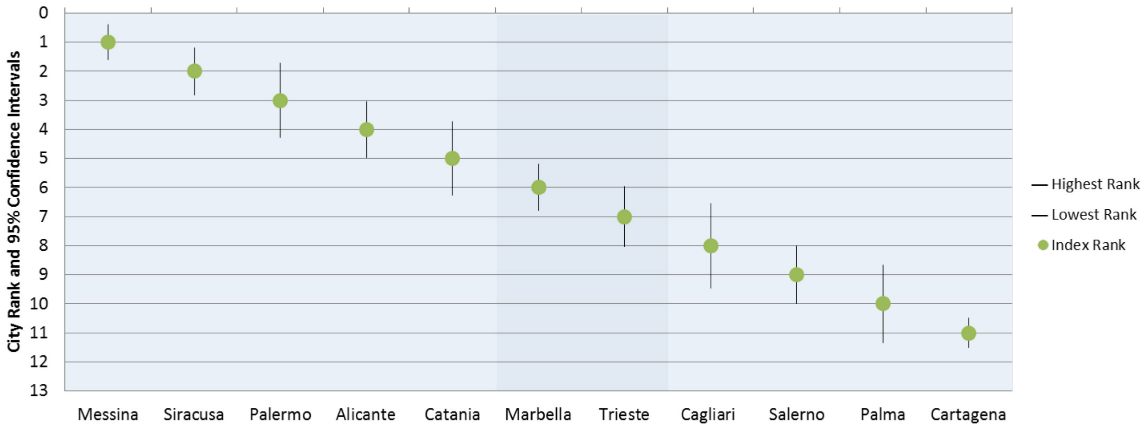

Figure 12. Ranking results of the Monte Carlo simulations and confidence intervals

Comparison of the benchmarked results with a renewable energy scenario

One of the most persistent shortcomings of the newly benchmarked cities is the reliance on fossil fuels despite the presence of favourable renewable energy resources. **Figure 13** provides exemplary Sankey diagrams for the present energy and CO_2 emission flows in the three coastal cities of Messina, Trieste, and Cartagena. These diagrams clearly put forth the existing situation in which there is no indication of any decoupling between energy usage and CO_2 emissions due to the reliance on fossil fuels in the energy mix, including transport. Such a problematic issue on the supply side is further exacerbated with the use of natural gas, which is a high-quality, high-exergy resource for low-exergy demands in residential buildings. In fact, the natural gas network that was introduced on the island of Sicily **[60]** remains one of the infrastructural barriers to the greater penetration of renewable energy on the island. From another perspective, the persistent problems that are common to the benchmarked cities are representative of the significant opportunities to realise progress toward sustainable energy systems based on a transition to renewable energy resources. Solutions that enable higher shares of renewable energy across various sectors of the energy system also provide the opportunity to decouple energy usage from CO_2 emissions with additional possibilities to obtain multiple co-benefits, including those for environmental quality, lower demands on limited water resources, and human well-being.

Currently, options for a renewable energy transition include concepts for a net-zero energy island in Sicily based on the utilization of solar, wind, and geothermal energy **[120]**, water desalination based on wave energy **[121]**, and offshore renewable energy platforms that produce hydrogen to be used in public transport **[122]**. The energy roadmap for Palermo under the Roadmap4Energy project **[96]** also puts forth strategic objectives for energy sharing and the utilisation of waste heat. Already, the Pan-European Thermal Atlas of Heat Roadmap Europe **[97]** indicates a theoretically available sum of 1.33 PJ of waste heat in the urban vicinity about 12 km from Palermo. Moreover, the coastal and coastal island cities have ample opportunities to displace the use of fossil fuels based on multiple uses of land and offshore sources of renewable energy. In this context, four main strategies can be identified to accelerate progress towards reaching net-zero emissions: (1) increasing the share of electricity in transport,

(2) increasing the share of renewables in the energy mix, (3) reducing energy demand and increasing demand flexibility, including in the water sector, and (4) eliminating the use of natural gas for low exergy demands as important steps towards decarbonisation.

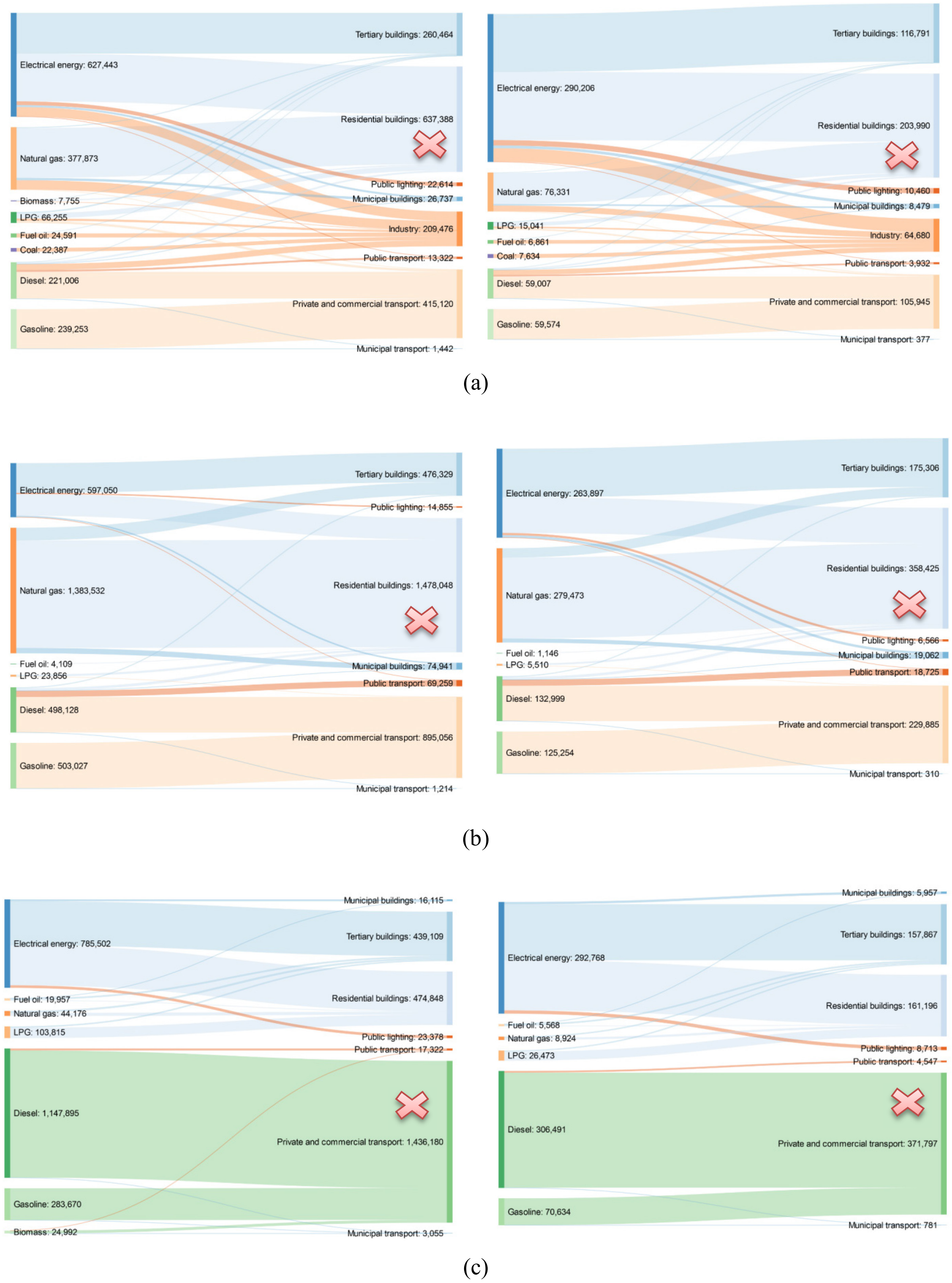

Figure 13. Sankey diagrams for energy (left, MWh) and CO_2 emissions (right, tonnes) for Messina (a), Trieste (b), and Cartagena (c); based on data in [63], [66] and [55]

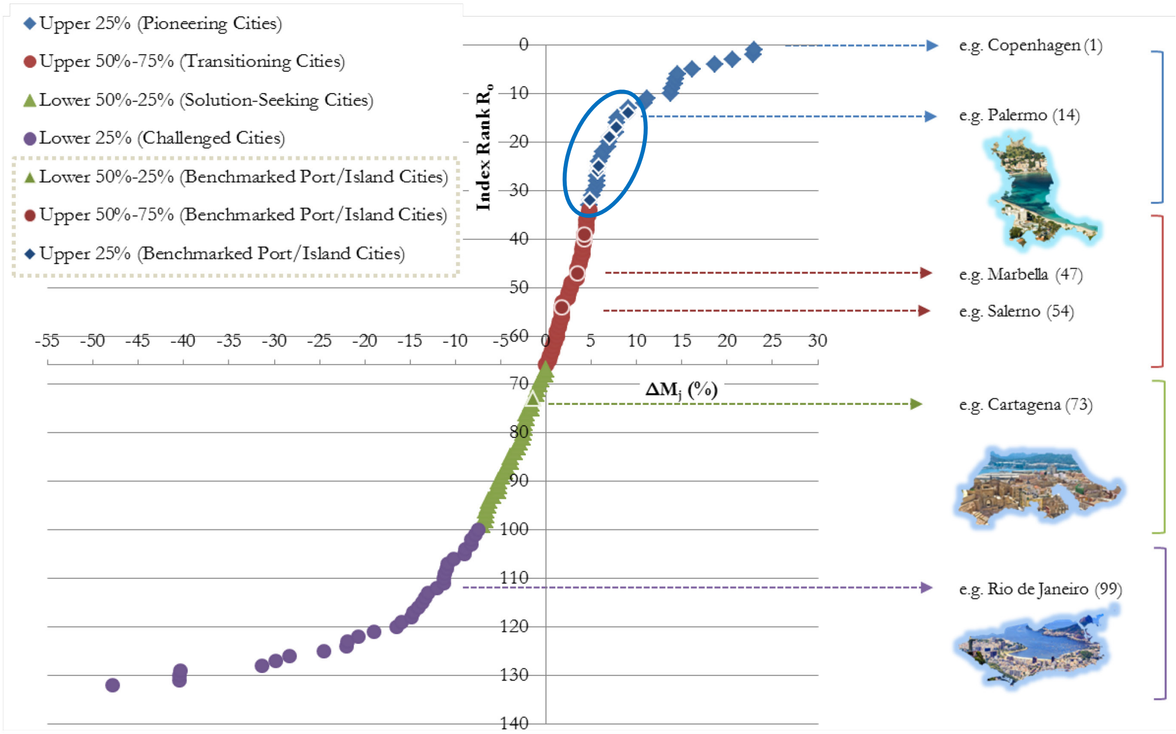

Figure 14. Depiction of the upward shift in performance with a renewable energy scenario

Figure 14 provides a view of the changes in the SDEWES Index when the results for the newly benchmarked cities are re-calculated, considering that these same cities will be frontrunners in transitioning to renewable energy to reach net-zero emissions. For example, in 2022, the islands of Sicily and Sardinia received 208 MW and 137 MW of new solar photovoltaic installations, respectively [123]. There were also 113 MW of new wind energy installations in Sicily, while significantly less in Sardinia. In addition, 42 municipalities in Italy reached 100% renewable energy municipalities, including the power sector [123]. The potential impact of a pathway that allows the 11 benchmarked cities to reach renewable energy systems and net-zero CO_2 emissions is represented in the SDEWES Index by allowing these cities to receive the best possible normalised value of 10.000 in indicators on CO_2 emissions under D_5. Since the aim of the scenario is to represent a decoupling between energy usage and CO_2 emissions, all else is taken equally. In reality, there will be multiple co-benefits for other indicators within the scope of the SDEWES Index that are not further quantified in this scenario despite their importance. Even in this base situation, the attainment of the best possible values in indicators on CO_2 emissions enables 6 of the newly benchmarked cities to take place among the top 25% of cities among the pioneering cities (the blue diamond markings that take place within the blue ellipse area). Such an upward shift in index performance with corresponding improvements in rankings is also valid for the remaining newly benchmarked cities, as observed in **Figure 14**, including Cartagena.

Figure 15 further quantifies the improvements in the ranking results based on the considered scenario where lower rank values signify a higher performance. Among the cities that have achieved the most progress in index performance and ranking based on the 100% renewable energy scenario with net-zero emissions is Palma de Mallorca, which has a rank of 32 among all 132 cities. Such an improvement allows this city to jump exactly two quartiles from the lower 50%−25% quartile to the upper 25% among the pioneering cities. The first three cities also contained an exchange of rank, with Palermo, originally ranked third, now being able to receive the top rank among the newly benchmarked cities. Prior to the 100% renewable energy scenario for net-zero emissions, Messina held the top rank, which is second rank based on Figure 15. In the overall ranking of the 132 cities, Palermo and Messina receive ranks of 14 and 17, respectively.

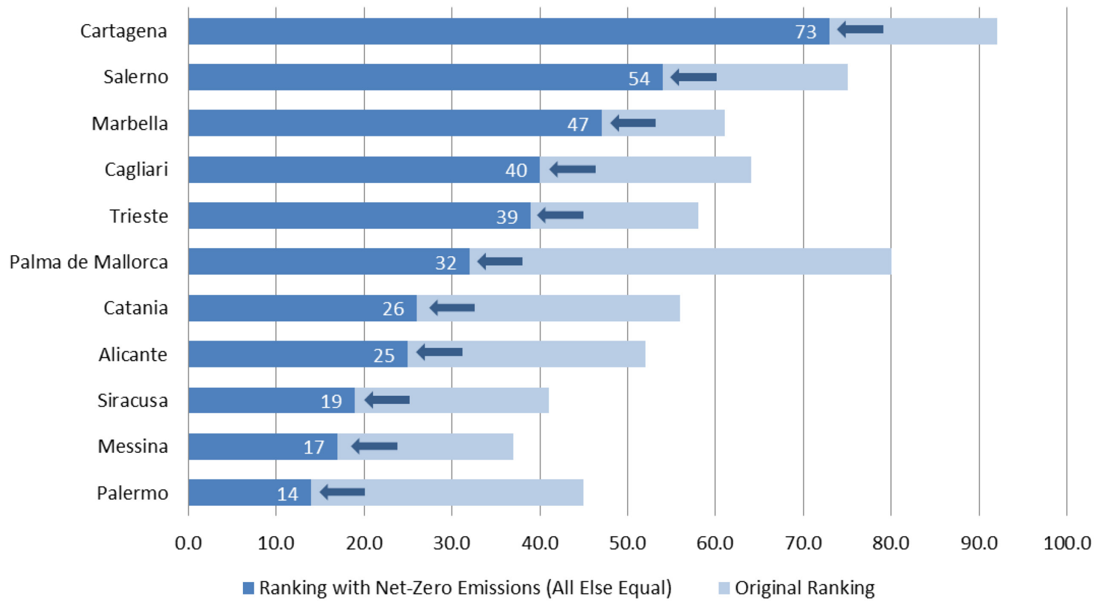

Figure 15. Improvements in rank based on the net-zero emissions scenario (dimensionless)

Co-benefits of renewable energy on local job opportunities

The co-benefits of the scenario for local job opportunities in each city are calculated based on eq. (2) and eq. (3) in the method of the research work. In the context of considering that all else is equal for the scenario, the values of E_I per city C_j are based on the data compilations for the energy indicators under D_I in Table 1. Opportunities for increasing energy savings can enable conditions that are closer to this simplification despite population growth in cities. Statistics on local job opportunities per GWh in each category of renewable energy technologies are based on the values in Table 10.

Table 10. Statistics for employment opportunities in the renewable energy scenario

Renewable energy technology	Number of jobs [× 1000] [68]		Electricity generation [GWh] [69]		Local jobs per GWh, β*		Renewable energy scenario share [%] [c]
	Italy	Spain	Italy	Spain	Italy	Spain	
Solar [a]	14.98	36.60	25,051	27,098	0.60	1.35	62.2
Wind	8.14	23.93	20,927	62,061	0.39	0.39	32.0
Hydropower	9.96	9.89	45,388	29,626	0.22	0.33	3.8
Bioenergy [b]	8.10	1.70	19,071	6,943	0.42	0.24	1.5
Geothermal	1.09	0.90	5,914	0	0.18	0.00	0.2
Marine	0.00	0.35	0	19	0.00	0.00 [d]	0.3 [e]

[a] Includes photovoltaic and concentrated solar power technologies, excluding solar heating and cooling
[b] Includes the number of jobs and electricity generation from biogas and municipal/industrial waste only
[c] Based on the shares in a 100% renewable energy scenario for Europe [70] in a global modelling study [71]
[d] The local jobs per GWh value for marine energy in Spain is excluded from Table 10 as an outlier value
[e] This share is added in this study considering summation inaccuracy due to rounding and coastal options

The year of the statistics for the number of jobs by renewable energy technology [68] considers the time lag in the most recent statistics for renewable energy production in GWh from [69] for consistency when obtaining variable β*. The values of two other coefficients in eq. (2) are based on the results of a 100% renewable energy scenario for Europe [70] within a global modelling study across the energy, transport, and desalination sectors [71]. In Europe, the share of electricity in the overall renewable energy mix is modelled to be 66% with a complete electrification of the transport sector. Such a finding is taken as the value of γ for the electrification ratio in eq. (2). Within this share, the amount of electricity generation for the energy, transport, and desalination sectors is driven mainly by contribution from solar energy that is followed by wind energy and about a 5.5% contribution from hydropower, bioenergy, geothermal, and marine energy. The last column of Table 10 provides the specific percentages that are also used as the coefficient δ in eq. (2).

The summation of the product of the relevant values for each category of renewable energy technology per benchmarked city C_j under the scenario is provided in Figure 16. These results underline the significant employment opportunities that can be captured with a transition to renewable energy technologies. Given the assumptions of the scenario, Palma de Mallorca and Palermo are estimated to obtain the highest employment benefits with 4,945 and 2,866 jobs, respectively. The amount of renewable energy that is involved in the scenario values in these two cities is about 1.1 times higher in Palermo, while β^* ratios are different. Palma de Mallorca benefits from about 1.35 jobs per GWh, and Palermo benefits from about 0.60 jobs per GWh in the context of Spain and Italy, respectively, based on Table 10. Such values that are based on recent statistics are higher than in previous years considering progress [68]. Comparatively, the values are within the range of local employment in other studies [124] with potential ahead. Across the 11 different coastal and coastal island settlements, there is potential for generating an estimated 18,062 jobs in the renewable energy sector based on the scenario of this study.

Coastal and Coastal Island Settlements	Bioenergy	Geothermal	Hydropower	Marine	Solar	Wind	Total Estimated Jobs from Renewable Energy
Marbella	5	0	15	0	1,023	150	1,193
Cartagena	7	0	25	0	1,693	249	1,975
Alicante	10	0	33	0	2,234	328	2,605
Palma de Mallorca	19	0	63	0	4,240	623	4,945
Cagliari	14	1	19	0	843	282	1,159
Palermo	36	2	46	0	2,085	698	2,866
Catania	11	1	15	0	667	223	917
Siracusa	4	0	5	0	220	74	302
Messina	6	0	8	0	367	123	504
Salerno	6	0	8	0	349	117	480
Trieste	14	1	18	0	813	272	1,117

Figure 16. Estimated co-benefits for local job opportunities under the scenario

Discussions in the context of sustainable island initiatives

The results of this research work are aligned with the action points in the Smart Islands Declaration and the aim of decarbonising over 1000 European islands by 2030. Table 11 provides a comparison of the 10 action points that are declared within the Smart Islands Initiative [73] and the dimensions of the SDEWES Index. As an original composite indicator to benchmark cities, characteristics that may be even more specific to the socio-economic and geographical context of coastal or coastal island cities are not targeted directly. Even so, there are certain correspondences between the action points of the Smart Islands Declaration and the dimensions of the SDEWES Index. Such correspondence is strengthened based on a focus on sustainable development and an integrated approach across energy, water and environment systems. In addition, the action point that is related to the need to provide "new and innovative jobs locally" [73] is addressed with a focus on the job opportunities that are possible through a renewable energy transition, as emphasised in the scenario-related analyses of this research work. Other synergistic options based on circular economy, eco-tourism, cultural tourism, and local R&D and innovation are also possible. Collective financing schemes, as emphasised in the Declaration, can be used to support progress for decarbonisation alongside a quadruple helix R&D and innovation model [125].

Table 11. Comparison with the Action Points of the Smart Islands Declaration

Action Point Summaries [73]	SDEWES Index Dimension(s)	Main Correspondence
1. Mitigation and adaptation to climate change and resilience	D_1, D_5 (mitigation) D_6 (resilience)	Energy and CO_2 emission savings, green spaces in urban areas, urban planning
2. Smart technologies to ensure the optimal management and use of resources and infrastructures	D_2, D_7	Measures, technologies, R&D and innovation for energy and emission savings
3. Moving away from fossil fuels by tapping significant potentials in renewables and energy efficiency	D_1 to D_7	Energy efficiency, renewable energy, air quality, well-being
4. Introducing sustainable island mobility, including electric mobility	D_2, D_3	Green energy in transport and the share of renewable energy in the electricity mix
5. Preserving distinctive natural and cultural capital	D_4, D_6	Environmental quality and biocapacity (direct), increase in well-being with ecotourism and cultural tourism (indirect)
6. Reducing water scarcity by applying non-conventional and smart water resources management	D_4	Reduction in water consumption per capita and improvement in water quality
7. Becoming zero-waste territories by moving to a circular economy	D_4, D_6	Reduction in waste per capita, increase in recycling, reuse and composting, lowering of ecological footprint
8. Diversifying local economies based on intrinsic characteristics to create new and innovative jobs	D_6, D_7	Increase in GDP per capita, inequality-adjusted well-being and other jobs based on local R&D and innovation
9. Strengthening social inclusion, education and empowerment	D_6, D_7	Increase in tertiary education, citizen-centred quadruple helix models [125] of R&D and innovation for smart cities and islands
10. Alternative yearlong, sustainable and responsible tourism, both inland, coastal and maritime	D_6, D_7	Increase in GDP per capita and well-being with a greater need for renewable energy to sustain annual activities

Strategies across the energy, transport, waste, and water sectors are gaining speed, particularly in islands [4], and related progress will improve the values of multiple indicators across the dimensions of the SDEWES Index. In comparison to the Greening the Islands Observatory [72] of the Greening the Islands Initiative [126], most of the available good practices continue to target sectors, as summarised in Table 12. At the same time, implementations that directly represent cross-sectoral perspectives are emerging, including water desalination with solar energy. In accordance with the aims of the initiative, there is room for improvement also in enabling islands to become living laboratories for more integrated approaches, including the circular economy.

Table 12. Good practices as identified in the Greening the Islands Observatory [72]

Sectors	Island(s)	Practice/Implementation
← Energy →	St Helena, South Atlantic Ocean	Solar and wind energy for self-sufficiency
	El Hierro, Canary Islands, Spain	11.5 MW_e wind turbines with pumped hydro storage
	Ta'o Island, American Samoa	1.4 MW_e solar and 6 MW_e energy storage microgrid
	Osaka, Japan	Wave energy for electricity and water
	Sicily (Palermo), Italy	Cover system for photovoltaic systems for safety and durability from natural fibres
	Vanuatu Islands	Refrigeration powered by solar photovoltaic systems
	Mauritius	Solar-assisted heat pumps
	Seychelles	Investment in renewable and energy efficiency
	La Reunion, France	9 MW_e solar panels with battery storage in agricultural sites, 1.5 MW_e solar panels above fishing pools
← Water →	Capriate San Gervasio, Bergamo, Italy	Zero emissions biofactory model with microalgae
	Great Camanoe, British Virgin Islands	Solar energy-driven water desalination
	Chumbe Island, Zanzibar/Tanzania	Zero-pollution water and sanitation technologies near a coral reef sanctuary
	Gran Canaria, Canary Islands, Spain	Eliminating brine discharges of desalination plants
	Water Saving Challenge [a]	Practices to save 25% of water usage, retrofit in water system and conservation
Mobility	Malta	Electromobility with solar energy at Malta port
	Stockholm, Sweden	Retrofitting the existing ferry into an electric ferry
	Helgoland, Germany	Fuel shift in mainland ferry connection

[a] Represents a multi-country initiative that involves islands in France, Greece, Croatia, and Ireland

Currently, the good practices in Table 12 involve solar, wind, wave, and bioenergy, energy storage, desalination technologies, water conservation, and electromobility. The importance of eliminating the brine discharges of desalination plants and protecting marine water resources is further represented among the implementations. In the context of the present study, the newly benchmarked coastal and coastal island cities provide additional good practices, including net-zero energy buildings and building integrated PV installations in cultural buildings in Palermo, including an initial flexible array of 20 kW_e solar PV panels on the roof of the Teatro Crystal. In aspects of regulatory tools and governance, the target of reaching decarbonization with renewable energy in the Balearic Islands (the location of Palma de Mallorca) is supported by the Law on Climate Change and Energy Transition [127]. The Law stipulates that emissions are to be reduced by 90% by the year 2050 based on 100% renewable energy and increases in energy efficiency with binding targets at the local level. In addition to measures for the power sector, new diesel and all new fossil fuel vehicles will be banned from the years 2025 and 2035 onward, respectively. Some public concerns about the issue of waste being imported for waste-to-energy may be addressed with accelerated solar and wind investments.

In addition to the Balearic Islands, the islands of Samsø in Denmark, Graciosa in Portugal, Gotland in Sweden, and Wight in the United Kingdom, as well as coastal cities on other islands, including Copenhagen and Edinburgh, have adopted targets for climate neutrality with 100% renewable energy [128]. In the race against time to limit global warming to as close as possible to an average increase in mean surface temperature of 1.5 °C above pre-industrial levels, coastal and coastal island cities have responsibilities not only to mitigate CO_2 emissions for the sake of the global climate similar to all cities but also to protect themselves against additional climate impacts. The striking differences between the impacts of 1.5 °C and 2.0 °C of global warming on sustainable development include an additional 10 million people who will be directly exposed to flooding in coastal cities due to sea level rise and extreme weather events for a total of up to 79 million people [129]. Moreover, up to 360 million more people will be exposed to lower crop yields, and an extra 2.2 billion people will be exposed to heat waves around the world, which will cause 8% more water stress [129]. Impacts on ecosystems are extremely severe, with 99% of coral reefs at risk of being bleached [33] and a conservative estimate of 1 million animal and plant species being threatened with extinction [130]. Already, multiple tipping points in the global climate are on the verge of irreversible change [131]. In short, the climate crisis represents an existential threat to civilization with irreversible damage on ecological balances. All means are necessary to provide additional impetus to implementing effective solutions, including in coastal and coastal island cities.

Similar comparisons can provide related perspectives for coastal settlements in Latin America, including Viña del Mar, which was the venue of the 4th Latin American Conference on SDEWES [132]. At the national level, the government recognises the importance of renewable energy, which is estimated to have a total potential of more than 1800 GW, with about 1180 GW coming from solar PV [133]. This value is about 70 times the recently installed capacity. Based on the National Green Hydrogen Strategy of Chile [133], there is an ambition to produce green hydrogen in at least two hydrogen valleys with a production capacity of about 200 kilotons per year by 2025. In addition, there is a target to produce the cheapest green hydrogen on the planet with a cost of less than 1.5 USD per kg of green hydrogen by 2030 [133]. Based on the examples of the 11 coastal and coastal island settlements in this study, there are plenty of reasons why coastal settlements in Chile, such as Viña del Mar, can also pursue renewable energy scenarios. With proper energy planning [134], the region can eventually support the green hydrogen strategy of the country, advance in making progress towards climate neutrality in Chile [135], and demonstrate promising opportunities for accelerating the energy transition in Latin America. Other promising pathways in Latin America include limitations on fossil-fuel-based electricity generation in Mexico as mandated by a national energy bill [136]. In addition, a transition strategy indicates ways to attain a 75% share of renewable electricity generation towards a defossilised, renewable energy system, including optimal capacity combinations of bioenergy, wind, and solar PV capacities [136]. Globally, jobs in the renewable energy sector have reached 13.7 million in 2022 [137] and progress to triple renewable energy by 2030 will increase co-benefits for people and the planet.

In an outlook towards future possibilities for benchmarking, one of the limitations of the present research work is that the data inputs into the SDEWES Index are based on published sources of data within an extensive compilation process due to the distributed but harmonised data sources. Across the dimensions, the data sources also include those from geographic information systems and even remote sensing. Digitalisation trends and new initiatives can be used to benefit the multi-parameter data compilation processes, especially when data inputs into the SDEWES Index are linked to integrated platforms. For example, a Digital Earth Viewer aims to represent multiple heterogeneous data sources, including both mixed observational and simulation data [138]. The flagship European initiative of Destination Earth also seeks to develop an accurate digital model to monitor, simulate, and predict aspects related to environmental data, climate change data, data for renewable energy and energy efficiency, and other domains [139]. These advances provide opportunities to support the applications of the SDEWES Index.

CONCLUSIONS

This research work that puts forth a benchmarking study for 11 coastal and coastal island cities in the Mediterranean Sea Basin based on the SDEWES Index can be used to support pathways for the energy transition. The benchmarking of these cities indicates the relative levels of performances across multiple dimensions that relate to the sustainable development of energy, water and environment systems. In comparison to other cities that have been benchmarked with the SDEWES Index to date, none of the 11 coastal and coastal island cities are able to take place in the upper 25% of cities that represent the pioneering cities with favourable performances across the dimensions of this composite indicator [45]. Instead, the highest present levels of performances are obtained by Messina, Siracusa, and Palermo, which take place in the next quartile and represent the transitioning cities due to certain limitations of less favourable performances in some of the dimensions.

Beyond present performance levels and challenges to sustainable development in the coastal and coastal island cities, a complete decoupling between energy usage and CO_2 emissions is considered based on a 100% renewable energy scenario. All else being equal, the scenario involves an elimination of CO_2 emissions as an exemplary situation. Even in the case that related co-benefits are not integrated into the results, the scenario is able to raise the ranking of the cities upward, with 6 of the coastal and coastal island cities shifting to the upper quartile as pioneering cities among the 132 cities that are now benchmarked with the SDEWES Index. The top cities in the scope of the scenario application are Palermo, Siracusa, and Messina, which represent a major shift in ranking due to better performances. These shifts in improvement were also not observed during the uncertainty analyses with 10,000 Monte Carlo simulations.

The opportunity for coastal and coastal island cities to take bold steps in the renewable energy transition is envisioned in various initiatives, most prominently the Smart Islands Initiative and Greening the Islands Initiative. In addition to the results of the scenario within the context of the composite indicator, an analysis for estimating the local job opportunities due to the shift to renewable energy is undertaken for each of the 11 coastal and coastal island cities. In contrast to the current dominance of fossil fuels with limited job opportunities, up to 4,945 local jobs are estimated for the renewable energy transition in Palma de Mallorca and 2,866 local jobs in Palermo. Across the 11 different coastal and coastal island settlements, it is possible to generate over 18 thousand local jobs in the renewable energy sector, according to the scenario. Overall, an integrated framework for evaluating the sustainable development of energy, water and environment systems, including contributions from the SDEWES Index, will be beneficial in providing additional impetus in guiding coastal and coastal island cities and settlements towards renewable energy systems in critical times to address the climate crisis worldwide.

ACKNOWLEDGMENTS

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NOMENCLATURE

C	specific city in the sample
C'	scenario version of a specific city
D	dimensions of the SDEWES Index (D_1–D_7)
D_1	Energy Usage and Climate Dimension
D_2	Penetration of Energy and CO_2 Saving Measures Dimension

D_3	Renewable Energy Potential and Utilisation Dimension	
D_4	Water Usage and Environmental Quality Dimension	
D_5	CO_2 Emissions and Industrial Profile Dimension	
D_6	Urban Planning and Social Welfare Dimension	
D_7	R&D, Innovation and Sustainability Policy Dimension	
E_I	total energy use for urban infrastructure in C_j	[GWh]
i	data inputs into the indicators of the SDEWES Index	
I	normalised values of the indicators in the SDEWES Index	
R_z	given renewable energy resource as represented by z	

Greek letters

α	weights of dimensions in the SDEWES Index	[-]
β	estimated job opportunities per R_z for electricity generation	[number of jobs]
β^*	ratio of the estimated job opportunities as a function of R_z	[jobs per GWh]
γ	expected average electrification ratio for buildings and transport	[-]
δ	expected average contribution of R_z to electricity generation	[GWh]
ΔM	median value of the SDEWES Index for 132 cities	[-]
$\Sigma\beta$	total expected local jobs as employment co-benefits for all R_z	[number of jobs]

Subscripts and superscripts

AV	present sample average (used in Figures 4−10)
j	number of the city in the sample (j = 1 to j = 11 for new cities)
x	dimension number in the index
y	indicator number in the dimension
z	solar, wind, hydropower, bioenergy, geothermal, marine

Abbreviations

ACA	Airport Carbon Accreditation
BOD	Biochemical Oxygen Demand
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
COP	Coefficient of Performance
DH/C	District Heating and/or Cooling
GDP	Gross Domestic Product
GERD	Gross Domestic Expenditure on R&D
IRENA	International Renewable Energy Agency
PM_{10}	Particulate Matter up to 10 micrometres in diameter
PPP	Purchasing Power Parity
PV	Photovoltaic
R&D	Research and Development
SDEWES	Sustainable Development of Energy, Water and Environment Systems
SEAP	Sustainable Energy Action Plan(s)
SECAP	Sustainable Energy and Climate Action Plan(s)
TSS	Total Dissolved Solids

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APPENDIX 1

The scientific landscape is compared based on the linkages between the keywords of all related scientific publications for a 22-year timespan since the turn of the century (2000−2022).[§] Based on the clustering algorithm of VOSviewer [140], four main nodes are the centre points of clusters within the scientific landscape, as observed in Figure A1. These nodes are centred based on keywords for sustainable development, renewable energy, climate change, and islands. The size of the nodes represents the frequency of the co-occurring keywords, while the relative proximity represents the strength of the co-occurrences.

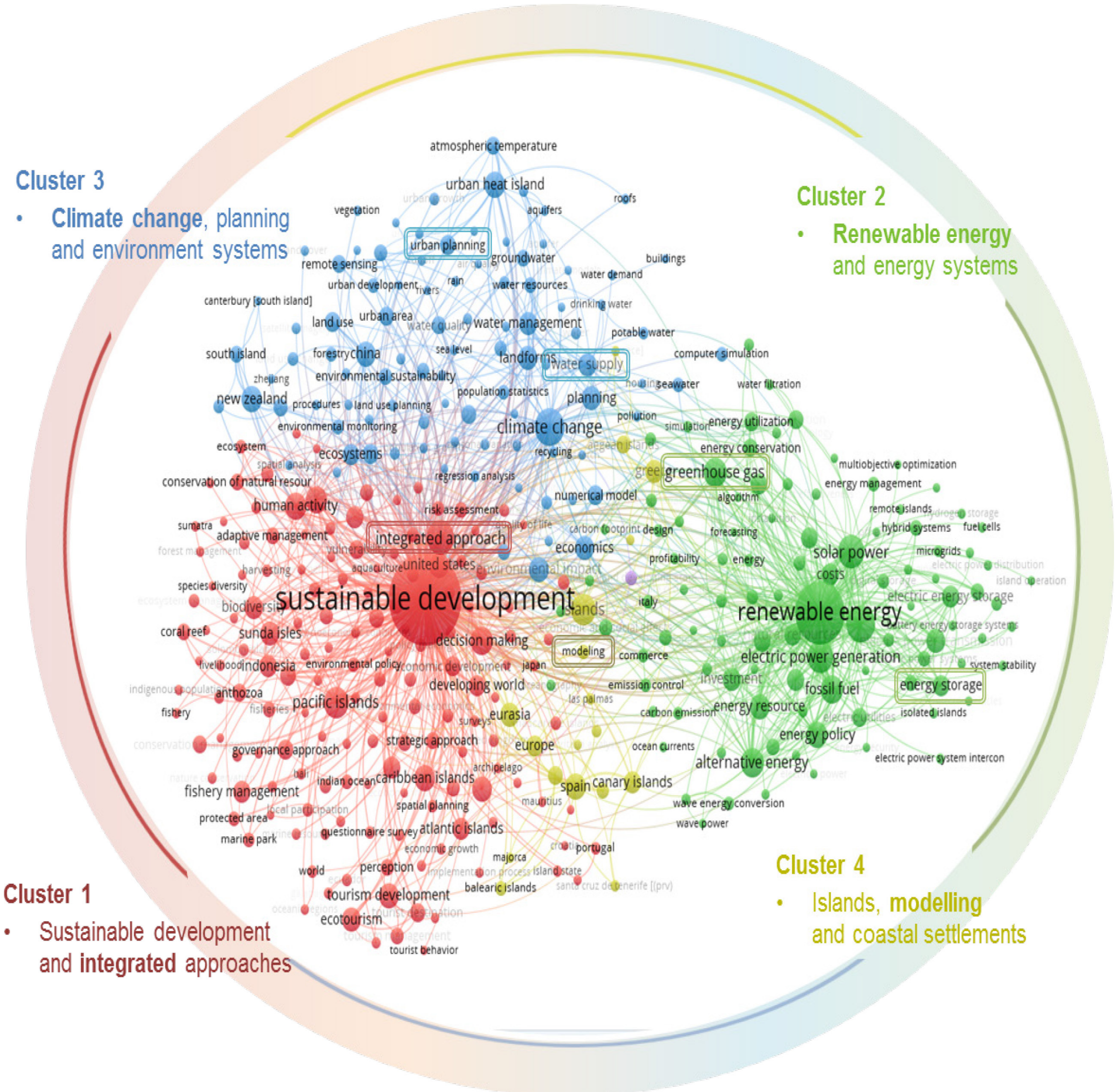

Figure A1. Depiction of the scientific research landscape (2000-2022)

[§] The search query is based on related keyword terms and the context of islands, coastal settlement, island and city as well as port and city that are searched by author and index keywords. Publications with island in the title are also included while excluding keywords that can involve the word island in other contexts, such as heat island. The advanced search query in Scopus is KEY ("sustainable development" OR sustainability OR "renewable energ*" OR "sustainable energy supply" OR "integrated approach") AND (KEY(island OR "coastal settlement") OR KEY (island AND city) OR KEY (port AND city)) OR TITLE (island) AND NOT ("heat island") AND NOT ("floating island") for the publication type of articles, reviews, book chapters and editorials that are published during the years 2000−2022. Clusters are coloured differently although there are numerous linkages between the various keywords in the different clusters.

APPENDIX 2

Table A1. Energy system characteristics based on original compilations

City (C_j)	Heat-only boiler/ electric HVAC or DH-only	CHP based DH/C	Geothermal/ solar integration, GHSP, seawater HP	Integration of other sources (waste heat)	
Marbella	✓				Buildings utilise electricity for all energy needs; SEAP targets an increase of solar thermal, particularly in public buildings [a]
Cartagena	✓				Electricity supplies 82% of building energy needs. Local electricity production is less than 10%, mostly from solar PV
Alicante	✓	P			Micro-CHP is identified to reduce the energy use of hotel buildings; it is also used in a local greenhouse and swimming pool
Palma de Mallorca	✓		P		The island of Mallorca has a 585 MW coal and gas-fired power plant that will be phased out based on the energy transition plan
Cagliari	✓	P			The SEAP of Cagliari includes a measure to "increase of micro-production plants (wind, PV, solar thermal, CHP) [b]
Palermo	✓	P	✓		UNIPA has concentrated solar power applications (33 kW Dish Stirling) that are unique in an urban setting with grid connection [c]
Catania	✓				SEAP of Catania indicates that cogeneration is not present [61]; Catania has 50,834 kW of solar PV and 1027 kW of biogas
Siracusa	✓				Siracusa SmaRt includes alternative energy generation measures; alternative wastewater purification is tested in suburbs
Messina	✓				Natural gas and electricity have a 35% and 60% share in the final energy use of buildings, mainly with separate production [d]
Salerno	✓				24 MW_p PV park is located on Monti di Eboli; SEAP measures involve cogeneration for a public swimming pool
Trieste	✓	P			SEAP includes consideration of CHP and district energy networks, including biogas cogeneration in the wastewater treatment plant

[a] In addition, the Andalucía region is not self-sufficient in electricity production, with a 34% renewable energy share and further relies on the Spanish electricity grid [53]

[b] The energy plan for Sardinia also includes the measure for the "integration of the electrical system with the thermal system in public buildings through the provision of high-efficiency micro-cogeneration systems fuelled by methane, for an aggregate power of 3 MWe" and the "implementation of high efficiency diffused cogeneration supplied with methane and bioenergy (the latter mainly locally sourced) in the agro-industrial sectors and the energy districts for a minimum cumulative electric power of 10 MW_e" [94]. Sardinia has about a 40% share of renewable energy production and is connected to mainland Italy [94].

[c] Sicily has 3018 GWh and 1714 GWh contributions from wind and solar energy, that is, 25% of total net electricity production [60].

[d] The Department of Energy in Sicily indicates the authorisation of 177 MW of cogeneration using renewable energy sources [60].

Table A2. Sub-indicators for nZEB implementations in cities

City (C_j)	National nZEB Plan	Scope of nZEB definition			nZEB implementation and/energy plus / carbon-neutral buildings/district targets
		New buildings	Existing buildings	Minimum RE share	
Marbella	✓	✓		✓	□ N/A
Cartagena	✓	✓		✓	□ N/A
Alicante	✓	✓		✓	□ N/A
Palma de Mallorca	✓	✓		✓	□ N/A with project for Platja de Palma with possible bidirectional solar DH/C grid
Cagliari	✓	✓	✓	✓	□ N/A [a]
Palermo	✓	✓	✓	✓	□ nZEB school building retrofits with smart buildings targeted in the R4E project [a]
Catania	✓	✓	✓	✓	□ Progetto Botticelli is an nZEB with 88 kWh/m^{2}y primary energy demand [a]
Siracusa	✓	✓	✓	✓	□ N/A [a]
Messina	✓	✓	✓	✓	□ CERtuS project has aimed for near net-zero buildings in Messina [63] [a]
Salerno	✓	✓	✓	✓	□ N/A [a]
Trieste	✓	✓	✓	✓	□ N/A [a]

[a] In addition, the share of any NZEB buildings to total buildings in the region is categorised as less than 0.002% [141]

Table A3. Sub-indicators for the density of the public transport system

City (C_j) [a]	Bus/ trolley bus lines	Trams length [km]	Subway/metro length [km]	Total length urban rail [km][b]	Total urban area [km^2]	Urban rail density [km/km^2]	Daily ridership per km (by metro)	Municipal bicycle sharing		
								Program	Stations	Bicycles
Marbella	✓			0.0	114.3	0.00		✓		200
Cartagena	✓			0.0	558 [b]	0.00				
Alicante	✓	52.03		52.0	127	0.41				
Palma de Mallorca	✓		15.6	15.6	168	0.09	3208	✓	33	445
Cagliari	✓	12		12.0	85.45	0.14		✓		50
Palermo	✓	17		17.0	176	0.10		✓	37	400
Catania	✓		8.8	8.8	246	0.04		P		
Siracusa	✓			0.0	207.78	0.00		✓		
Messina	✓	7.7		7.7	213.23	0.04				
Salerno	✓			0.0	58.96	0.00		✓		
Trieste	✓			0.0	84.49	0.00		✓		

[a] Cities that have tramways or subways are further evaluated based on urban rail density; [b] given as total area while not distinguished as the urban area

Table A4. Evaluation of energy-intensive industries in the cities [a, b]

Presence of energy-intensive industries in the cities	Marbella	Cartagena	Alicante	Palma de Mallorca	Cagliari	Palermo	Catania	Siracusa	Messina	Salerno	Trieste
Basic chemicals and chemical products		2		1			1	2			
Basic precious and non-ferrous metals					1				1	1	
Cement, lime and plaster industry		1	2			2				2	2
Ceramic products industry	1			1	1		1		1		
Iron and steel industry											2
Pulp, paper and paperboard industry							1				
Refined petroleum products industry		2			2			2			

[a] The presence of at least one large enterprise/factory in the sector receives a binary value of 1; [b] The presence of clustered industries in the sector receives a binary value of 2

Table A5. Sub-indicators for municipal waste management

City (C_j)	Waste per capita [kg/capita]	Reuse, recycling or composting [%]	Total scoring waste management [a]
Marbella	511	13.6	1.2
Cartagena	454	10.2	1.2
Alicante	431	15.7	1.4
Palma de Mallorca	727	18.8	0.8
Cagliari	592	29.2	1.5
Palermo	525	9.8	1.0
Catania	682	10.9	0.7
Siracusa	528	2.8	0.8
Messina	482	12.2	1.2
Salerno	453	59.6	2.9
Trieste	456	39.4	2.2
Average (120 Sample) [46]	433	26.8	2.0

[a] Sum of ratios over the average values of 433 kg per capita minus the top score and 26.8% for the integrated sample

Table A6. Sub-indicators for municipal wastewater treatment

City (C_j)	Discharge without treatment [%] [102]	Percentage of compliance [× 100%] [a]			Scoring coverage [b]	Scoring compliance [c]	Total
		BOD	COD	TSS			
Marbella	0	1.00	1.00	1.00	2.00	1.00	3.00
Cartagena	0	1.00	1.00	1.00	2.00	1.00	3.00
Alicante	0	1.00	1.00	NR	2.00	1.00	3.00
Palma de Mallorca	0	1.00	1.00	1.00	2.00	1.00	3.00
Cagliari	0	0.99	0.99	0.99	2.00	0.99	2.99
Palermo	0	1.00	1.00	1.00	2.00	1.00	3.00
Catania	9	1.00	1.00	1.00	1.73	1.00	2.73
Siracusa	0	1.00	1.00	1.00	2.00	1.00	3.00
Messina	0	1.00	1.00	1.00	2.00	1.00	3.00
Salerno	0	1.00	1.00	1.00	2.00	1.00	3.00
Trieste	0	0.28	1.00	0.28	2.00	0.52	2.52
Average (11 Cities)	0.82	0.93	1.00	0.93	1.98	0.96	2.93

[a] When there is more than one plant, percentage compliance is weighted by the total wastewater load of the urban area
[b] Coverage scoring includes a penalty multiplier for any discharge without treatment subtracted from the top score
[c] Compliance scoring is the average of the relevant criteria for BOD, COD and/or TSS divided by 100

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Table A7. Sub-indicators for compact urban form and green areas

Urban form and municipal management	Marbella	Cartagena	Alicante	Palma de Mallorca	Cagliari	Palermo	Catania	Siracusa	Messina	Salerno	Trieste
Compact urban form (1−3) [a]	2	2	2	2	2	2	1	2	2	2	2
• *Polycentricity* (*core areas*) [103]											
• *Population core areas* [%] [103]	73.32					69.03	45.71				
• *Sprawl index* [%] [103]						5.3	15.2				
Urban green space (1−3)	3	3	3	3	2	3	3	3	3	3	3
• *Urban park intensity*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
• *Percentage of green areas* [%] [104]	80.99	86.61	71.61	69.57	25.87	62.06	65.34	82.37	82.3	67.4	65.47
• *Impermeable surfaces* [%]			38.96					31.94			
• *Green area per capita* [m^2]						44.52	35.05				
Green corridor quality (1−3)	2.5	2	2	2	2	2.5	2	1	2	2.5	1
• *Natural reserves* [105]	2	4	4	1	4	5	2	0	0	2	1
• *RAMSAR* [106]	1	3	3	1	2	0	0	2	0	1	3
• *National parks* [105]	0	0	0	0	0	0	0	0	1	1	0
• *Total number evaluation*	3	7	7	2	6	5	2	2	1	4	4
• *Total area* [km^2]	1892	585	388	651	263	1009	773	17	642	2523	109
Average category score	2.5	2.3	2.3	2.3	2.0	2.5	2.0	2.0	2.3	2.5	2.0

[a] Scored so that polycentricity, a high share of the population living in core urban areas, and a sprawl index far less than 0 receive the top score; additional reports are taken into account

[b] The best practice score of 3 is given to cities with about a 40% or more share of green areas and/or less than 30% share of impermeable surfaces based on data availability

Table A8. Sub-indicators for benchmarking R&D and innovation policy orientation

R&D and innovation policy orientation [a]	ES	IT
R&D funding approach score	1	2
• *General (no thematic focus)*	✓	✓
• *Thematic focus (calls)*		
• *Energy environment / smart cities priority*		✓
R&D expenditure score	2	2
• *GERD/GDP (Percentage)*	1.22	1.34
Smart city demonstration site [b]	✓	✓
Average category score	1.5	2.0

[a] The policy scan involves R&D funding institutions, support mechanisms, JRC RIO country reports [114], OECD/UNESCO statistics [110], other reports as relevant
[b] Palma de Mallorca is a demonstration site based on SCIS, while Palermo is involved in the EU Roadmap4Energy project [96]; other cities in the country excluded

Table A9. Sub-indicators for benchmarking national patents in clean technologies

National patents in clean technologies	ES	IT
Total Y02 or Y04 patents [a]	21,699	10,712
• *Building technologies (Y02B)*	3,139	1,595
• *Energy generation(Y02E)*	12,535	4,896
• *Transportation (Y02T)*	5,179	3,926
• *Capture and storage (Y02C)*	469	146
• *Smart grid (Y04S)*	377	149
Y02 or Y04 patent score (1−3)	2	2
Percentage of total patents [%]	2.29	2.23
Total percentage score (1−3)	2	2
Average category score	2.0	2.0

[a] For countries in which the total patents number exceeds the output limit of the database, the total is estimated from the total of sub-codes

Table A10. Number of public, private, and Scimago Ranked universities

Universities and research institutes in the local innovation system	Marbella	Cartagena	Alicante	Palma de Mallorca	Cagliari	Palermo	Catania	Siracusa	Messina	Salerno	Trieste
Number of universities/institutes	0	1	2	1	1	1	1	0	1	1	1
Public/polytechnic	0	1	2	1	1	1	1	0	1	1	1
Private universities/colleges	0	0	0	0	0	0	0	0	0	0	0
Scimago Ranked [a]		✓	✓	✓	✓	✓	✓		✓	✓	✓
Located in the city	0	1	2	1	1	1	1	0	1	1	1
Located in the country	59	59	59	59	62	62	62	62	62	62	62
Concentration in city [%]	0.0	1.7	3.4	1.7	1.6	1.6	1.6	0.0	1.6	1.6	1.6
University weighted score	0	2	4	2	2	2	2	0	2	2	2

[a] Based on top 1000 institutional rankings, including universities and research institutes

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