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Benchmarking South East European Cities with the Sustainable Development of Energy, Water and Environment Systems Index

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ABSTRACT

Tools that can benchmark cities, including cities in South East Europe, are necessary to enable the comparison and diffusion of more sustainable practices for urban systems. The "Sustainable Development of Energy, Water and Environment Systems Index" provides a composite indicator for benchmarking city performance based on 7 dimensions and 35 main indicators. In this research work, the Index is applied to a new sample of 18 cities in South East Europe for which data is collected, normalized, and aggregated. Klagenfurt (3.08), Velenje (3.06) and Pécs (3.01) are found to be the top three cities in the sample while an average city receives an index score of 2.85. The results are further compared to reference averages and evaluated based on the mean simulated values of 10,000 Monte Carlo experiments. The results are interpreted in quartiles for pioneering, transitioning, solution-seeking, and challenged cities. The results are then applied within a benchmarking tool of the Index that supports policy learning to trigger collaboration between cities and further used to match cities according to a search algorithm based on index performance. In addition, the results are compared to urban hierarchy as well as development contexts and mapped onto the spatial dimension as an initial step for enabling a "Sustainable Development of Energy, Water and Environment Systems Future City Network". The paper concludes with a set of four proposed steps to enable decision-makers and urban planners in using the Sustainable Development of Energy, Water and Environment Systems Index in support of more sustainable urban systems.

KEYWORDS

Energy, Water, Environment systems, City index, Composite indicator, Urban systems.

INTRODUCTION

Urban areas are responsible for about 365 EJ or 64% of global primary energy usage and are liable for 24 Gt of CO_2 emissions, which correspond to about 70% of total Carbon dioxide (CO_2) emissions from energy-related activities [1]. In a future outlook, baseline scenarios predict that urban primary energy usage may soar to 618 EJ with an increase of 69% by the year 2050 [1]. However, scenarios that seek to limit global warming to at most 2 °C indicate that this value may be at most 432 EJ with a maximum increase of 18% [1]. Under this scenario, the urban share in global CO_2 emissions must also be reduced by at least 22% that will require the elimination of 15.2 Gt CO_2 from the baseline scenario [1]. Additional scenarios that are in line with the Paris Agreement on Climate Change [2] require values that are well below these projected levels of increases based on a rapid process of decarbonisation using renewable energy resources.

Clearly, urban systems have a central role in enabling the ability to attain a future within planetary thresholds. Urban energy systems define vibrant contexts to address the need to move towards a more sustainable, cleaner, and efficient energy future. At the same time, urban energy systems must be evaluated in a much broader context, including water and environment systems. Hence, the Sustainable Development of Energy, Water and Environment Systems (SDEWES) City Index was developed as an original composite indicator to benchmark city performance [3]. The index has the namesake of the SDEWES Center and Conference series that are dedicated to diffusing knowledge on methods, policies, and technologies for improving the sustainability of development [4]. The composite indicator has since been applied to 58 different cities around the world [3, 5, 6] as put forth in the website of the SDEWES Center [7]. In this research work, a new sample of 18 cities in South East Europe (SEE) is benchmarked based on the SDEWES Index. The results are used to identify those cities that have performances in certain quartiles as the pioneering, transitioning, solution-seeking, and challenged cities of the sample. The aim of the research work is to present the benchmarking results for the new sample and provide steps that can be used by decision-makers in those cities to improve city performance in the future.

The paper proceeds with a literature review of the existing analyses, tools and solutions to support a more sustainable SEE region. The themes of urban systems for renewable energy, transport, water, waste, and governance are used to exemplify the existing stock of knowledge. In contrast, composite indicators are suitable for combining multiple indicators to benchmark more than one entry in a common framework with numerous other entries. The paper then provides the method of applying the SDEWES Index to enable the systematic benchmarking of 18 cities in the SEE region. The aims of the research work are satisfied based on rankings, a benchmarking tool for cities, and the formulation of city pairs for the present sample. The results are further compared through 10,000 Monte Carlo experiments and evaluated according to contextual factors for urban hierarchy and development. The paper concludes with the implications of these contributions to promote more sustainable urban systems in SEE cities.

SCIENTIFIC SUPPORT FOR A MORE SUSTAINABLE SEE REGION

Analyses, tools, and solutions to support a more sustainable SEE region have been increasing rapidly. These include studies that provide scientific support for a renewable energy transition in the SEE region [8] and beyond. Among related studies, Duić *et al*. [9] developed a RenewIslands method to enable islands to plan for the integration of energy and resource flows based on local assets to increase the sustainability of development. The need for smart energy storage to utilize excess electricity production was undertaken by Krajačić *et al*. [10] to enable an energy system for Croatia that is self-sustainable based on renewable energy. Pukšec *et al*. [11] modelled the energy demand of Croatia and suggested wedges that could reduce energy demand by 40% by the year 2050 when compared to the worst case scenario. Komušanac *et al*. [12] simulated and graded scenarios for the power system of Croatia. A scenario with over 3 GW of wind power and installed PV capacity provided favourable results. Schneider *et al*. [13] found the possibility of 3% emission savings based on measures for recovering energy from Municipal Solid Waste (MSW) in Croatia.

In addition, Dedinec *et al*. [14] identified priorities for realizing the Greenhouse Gas (GHG) emissions target of Macedonia based on renewable energy. Three scenarios with various levels of ambition to reduce CO_2 emissions were analysed [15]. Ćosić *et al*. [16]

put forth scenarios towards reaching a 100% Renewable Energy System (RES) for Macedonia in the year 2050. At the regional level, Dominković *et al*. [17] modelled the energy systems of 11 countries in the SEE region. These models were combined into one energy system to evaluate scenarios that could transform the current reliance on fossil fuels to 100% renewable energy, including sustainable biomass.

Towards more sustainable urban systems

Urgent challenges that require pioneering scientific results include the need to make cities and communities smarter [18] and more sustainable [19]. In this context, sustainable cities will be a vital component for a more sustainable SEE region. Figure 1 exemplifies the present status of the stock of knowledge in providing scientific support for more sustainable urban systems within the SEE region. The directional flows in the Sankey diagram of Figure 1 represent contributions to the broader themes of urban renewable energy systems, urban transport systems, urban water systems, urban waste systems, and/or urban governance systems. Some studies and technological solutions address more than one urban theme and underline the need to merge analysis boundaries. At the same time, the application of an integrated approach to benchmark cities within the SEE region with a focus on energy, water and environment systems as applied in this research work can diffuse a systematic outlook to allow cities to seek and develop innovative urban solutions. The same outlook can be used to support a cross-sectoral approach between multiple sectors in cities.

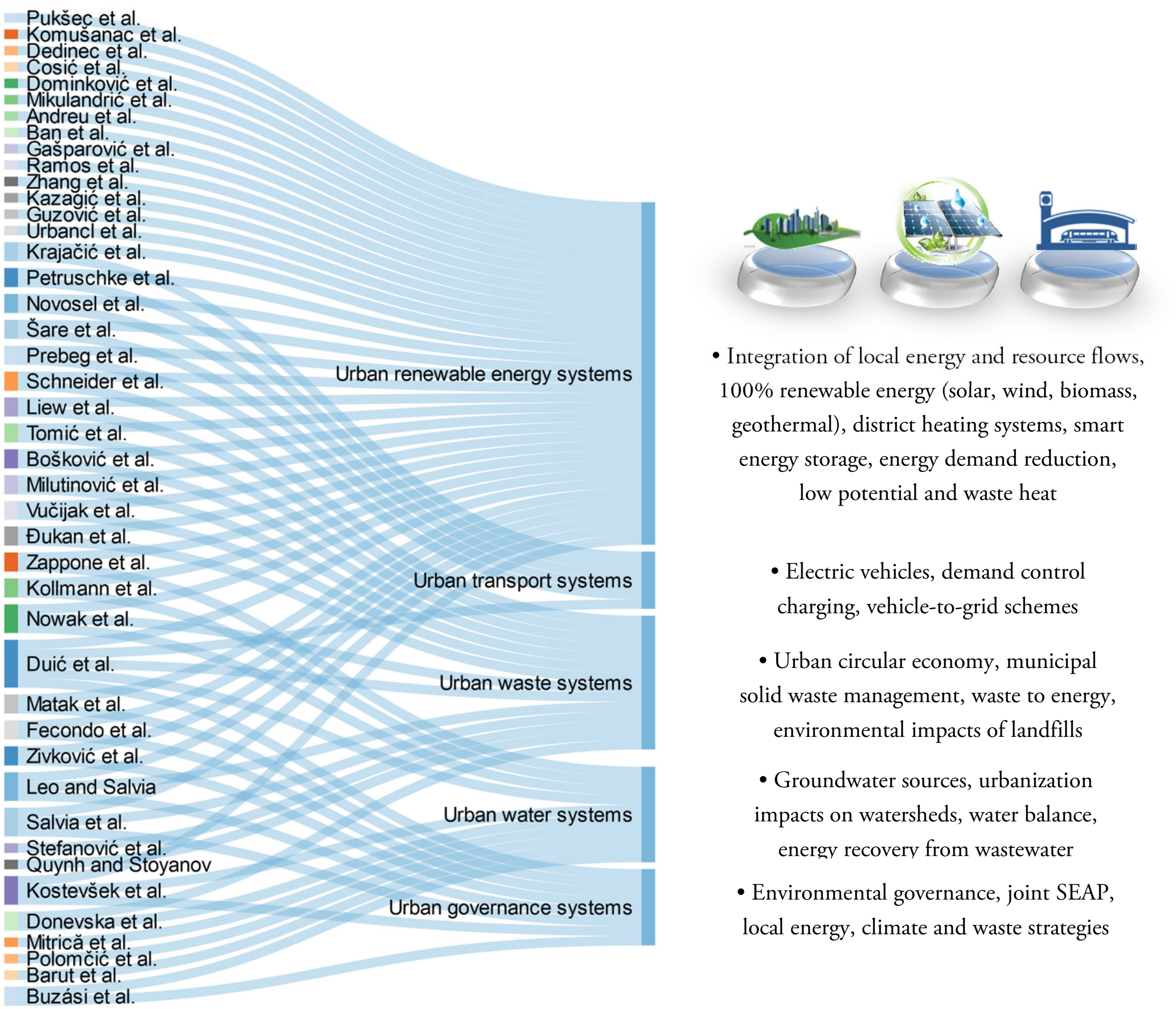

Figure 1. Exemplary research contributions to sustainable urban systems in the SEE region

Analyses of urban renewable energy systems

As represented in Figure 1, studies at the local level that have an impact on more sustainable urban energy systems include those that are focused on district heating systems. For example, Mikulandrić *et al*. [20] compared 12 cases for the district heating system of Pokupsko district in Croatia based on heat production costs. Cases that involved renewable energy options were found to provide significant cost advantages. Andreu *et al*. [21] analysed the potential for upgrading the district heating system of the city of Velika Gorica near Zagreb, Croatia, based on the use of solar energy with pit thermal seasonal storage. In another aspect of energy storage, Ban *et al*. [22] analysed case studies for the integration of Cool Thermal Energy Storage (CTES) at the building, building cluster, and district cooling system levels at the campus of the University of Zagreb.

The sustainability of a district heating system in Ormož Municipality, Slovenia was assessed by Kostevšek *et al*. [23] based on the use of various metrics to capture energy-related aspects as well as environmental, social, and economic terms. In a related aspect, Liew *et al*. [24] reviewed studies that applied total site heat integration to increase the reuse of waste and low potential heat as well as local sources of renewable energy. The authors indicated a need for the integration of industrial, urban and renewable energy systems to enable more efficient local energy sectors.

Other studies emphasized the role of local renewable energy solutions and/or indicated the implications of these solutions for cleaner energy supply to urban areas or islands. Gašparović *et al*. [25] analysed options to integrate Photovoltaic (PV) panels in campus buildings at the University of Split and the neighbouring vicinity. Ramos *et al*. [26] compared a set of scenarios based on the area that would be needed for Photovoltaic Thermal (PV-T) collectors in 10 European cities, including Rome and Bucharest. Zhang *et al*. [27] proposed a hybrid operation of a coal-fired power plant with concentrated solar power in Dubrovnik-Neretva county. Kazagić *et al*. [28] analysed a typical SEE power system based on a power utility in Sarajevo, Bosnia and Herzegovina and found the possibility of halving CO_2 emissions in 2030 under a RES scenario. Moreover, Guzović *et al*. [29] analysed the proposed application of a system involving an Organic Rankine Cycle (ORC) to utilize the energy and exergy potential of the geothermal field of Velika Ciglena in Croatia. The use of geothermal energy in Slovenia and Serbia was also undertaken by Urbancl *et al*. [30] for the case of greenhouses. Petruschke *et al*. [31] combined the RenewIslands method with an optimization approach to reduce the investment costs of a renewable energy solution for Mljet Island in Croatia.

Analyses of urban transport systems

The interrelation of urban energy and urban transport systems have been another area in which analyses and scenarios have been put forth for the SEE region. For example, Novosel *et al*. [32] established hourly curves of the transport energy demand of the four largest cities in Croatia to construct a national model to compare scenarios that involved electric vehicles. Šare *et al*. [33] found that excess electricity production in a future 100% renewable energy system for the Dubrovnik region could be reduced based on a flexible demand control charging mode for electric vehicles. Prebeg *et al*. [34] modelled the power system of Croatia between 2015 and 2050, including scenarios for the integration of renewable energy and vehicle-to-grid schemes. Aspects of these studies can support more efficient and renewable energy oriented urban energy systems.

Analyses of water and environment systems supporting South East European cities

Water and environment systems are other areas of research focus with possible connections to urban energy systems. Zappone *et al*. [35] analysed the energy usage of water and wastewater treatment plants in a metropolitan area in Italy. Polomčić *et al*. [36] modeled the groundwater sources that provide public water supply to the City of Kikinda, Serbia. Mitrică *et al*. [37] compared the amount of public water that may be supplied and demanded in scenarios for the Timiş Plain that includes the urban population of Timişoara, Romania. Barut *et al*. [38] used satellite images to assess the impact of urbanization on temporal variations in a watershed in Turkey. Nowak *et al*. [39] analyzed two municipal wastewater treatment plants in Austria that are self-sufficient in energy due to the use of Combined Heat and Power (CHP) based on biogas. Kollmann *et al*. [40] evaluated the wastewater treatment plant of the Austrian town of Freistadt as a local source of energy. Tomić *et al*. [41] analyzed scenarios to integrate waste to energy schemes in the district heating system of Zagreb to support circular economy at the urban level.

In addition, Donevska *et al*. [42] assessed the environmental impacts of planned landfills in Macedonia based on the Water Balance Method. Bošković *et al*. [43] analyzed 51 landfills in Serbia to determine the potential for CHP plants at those sites. Stefanović *et al*. [44] developed and compared four waste treatment scenarios for the city of Niš (Serbia) in which scenarios for composting and recycling of organic waste were found to have the most favorable outcomes. Milutinović *et al*. [45] compared two cities in Serbia and Bulgaria, namely the cities of Niš and Sofia, based on scenarios for different waste management systems using multi-criteria analysis. Vučijak *et al*. [46] applied the VIKOR method to evaluate waste management scenarios for Zavidovici municipality (Bosnia and Herzegovina). The VIKOR method involves the use of a strategy coefficient that represents a compromise between selections of the scenario that excels in the majority of the criteria or a single criterion to better inform decision-making processes.

Beyond the urban core area of cities, Quynh and Stoyanov [47] compared the environmental performance of ports in Bulgaria, including those of Burgas and Varna. Đukan *et al*. [48] used a bottom-up approach to estimate the biogas production potential in a rural area of Croatia in Gundinci municipality with potential implications for building upon urban-rural linkages.

Analyses of governance and policy formulation in South East European cities

Governance is a cross-cutting issue for orienting urban energy, water and environment systems towards more sustainable states in the future. Matak *et al*. [49] put forth and applied an integrated approach to allow small neighboring municipalities on the island of Korčula to prepare joint Sustainable Energy Action Plans (SEAP). Fecondo *et al*. [50] put forth the results of a mechanism to support technical interventions to increase energy savings in public buildings and lighting armatures in the Province of Chieti, Italy. Zivkovic *et al*. [51] implemented a participatory approach to enable local stakeholders to define five scenarios for the heating system of the city of Niš, Serbia by the year 2030. Leo and Salvia [52, 53] put forth the results of an EU project in which SEE cities developed Local Energy and Waste Strategies. The policy formulation process involved the provision of guidance for energy efficiency, renewable energy, and waste management in 8 SEE cities, including the cities of Nitra and Skopje. Buzási *et al*. [54] analyzed the CO_2 emissions mitigation and climate adaptation measures of Budapest, including those for water management, green areas for flood control, and ventilation corridors.

Policy learning processes in cities as learning organizations

The vast array of studies that aim to support more sustainable cities in the SEE region as summarized in Figure 1 represent a valuable stock of knowledge. In contrast, barriers to policy learning among cities may still limit the spread and speed of the diffusion of related applications [55]. This limits the ability of cities to identify, learn about and implement effective approaches that take place in other cities [56]. Tools that can accelerate the diffusion of knowledge for comparing city performance, thereby increasing opportunities to adopt new solutions, are an urgent need to support SEE cities in their transition towards more sustainable urban systems.

Benchmarking can increase the opportunities that are made available for cities to evaluate present levels of progress relative to other cities and determine areas for further improvement. In particular, cities are learning organizations [57, 58] that seek continual improvement, including progress for more sustainable systems [59]. Hirvonen-Kantola *et al*. [60] had defined two main dynamics that cities utilize in their learning processes. These dynamics, namely exploration and exploitation, require access to new ideas and the use of existing competencies [61]. Marsden *et al*. [62] found that most cities, however, relied on undertakings on an ad-hoc basis, including scanning visits to other cities, especially in the case of policy learning for urban transport.

Benchmarking opportunities to support a "Science of cities"

Benchmarking cities based on the systematic use of indicators is vital for stimulating policy learning and providing analytical guidance at the local level. The use of common metrics can also support a "science of cities" to advance an understanding of strengths and weaknesses [63]. Currently, indices to benchmark the social and economic dimensions of city performance represent the most prevalent use of city level indices [63]. In particular, the majority of indices for cities are found to focus on benchmarking the quality of life or the ability of cities to attain economic and business growth [63]. Other indices address digital opportunities [64] as well as issues of safety and security in cities. For example, the Safe Cities Index has provided a benchmarking of 50 cities based on digital security, health security as well as infrastructure and personal safety [65]. In this respect, the gap in the literature for providing analytical support to benchmark urban energy, water and environment systems is addressed with the integrated approach of the SDEWES Index [3, 5-7], which also involves data that is monitored in SEAPs.

Prior to the SDEWES Index, Afgan and da Graça Carvalho [66] developed a General Index of Sustainability to evaluate options for a hybrid energy system for the generation of electricity, heat and/or hydrogen. The authors addressed the utility of multi-criteria methods to support the decision-making process. Lipošćaka *et al*. [67] applied this framework to compare scenarios for the cogeneration sector in Croatia based on 7 indicators for emissions of exhaust gases and particles, health, and social acceptance, as well as capital investment and fuel costs. Zidanšek *et al*. [68] undertook analyses of indicators that expressed environmental sustainability, the quality of life and technological development in nations. Positive correlations between quality of life indicators and Gross Domestic Product (GDP) values were found to indicate a possible replacement of the latter.

The footprint method is another branch of benchmarking studies. Galli *et al*. [69] defined a footprint family based on ecological, carbon and water footprints and proposed its use to track progress towards a One Planet Economy. Most recently, Baabou *et al*. [70] sought to provide conformity to ecological footprint comparisons at the local level. The method involved the use of monetary multi-regional input-output tables [71] and was applied to 19 coastal cities in the Mediterranean. In another aspect, De Benedetto and Klemeš [72] developed the Environmental Performance Strategy Map that combined the five footprints of carbon, water, energy, emission, and work environment into a single graphical area. The concept was further extended to obtain a Sustainable Environmental Performance Indicator (SEPI) that includes the costs of different options as applied to a plant in the agricultural chemicals sector in Denmark. The possibility of applying the combinatory approach to local communities as well as countries was discussed.

At the city level, various benchmarking studies were undertaken for world cities mostly outside of the SEE region. For example, Tan *et al*. [73] developed a framework to define a low-carbon score for cities. Stockholm received the best score among 10 major cities based on aspects including energy, carbon and urban mobility. Other studies focused largely on one domain of sustainable development. Wang *et al*. [74] compared the energy efficiency of 25 cities with an impact on global economic activity. The authors found that the European cities in the sample were more efficient than those in North America and Asia. Similarly, Hu *et al*. [75] compared five European and Asian cities to derive policy lessons for techno-social regimes.

In other studies, Deilmann *et al*. [76] compared the eco-efficiency of 116 cities in Germany based on the ratio of the economic value that was added by the city over the level of environmental damage that was caused. For buildings, Broto *et al*. [77] evaluated the energy, water usage and GHG emissions of private sector buildings in 40 cities. Van Leeuwen [78] developed a City Blueprint to assess the sustainability of urban water services based on 25 indicators. Mori *et al*. [79] compared 18 megacities based on 12 indicators for environmental, economic and social power. Wilson [80] put forth 12 indicators to benchmark integrated sustainable waste management practices, which were applied to 5 cities. For urban transport, Ahn *et al*. [81] benchmarked the energy use intensity of subway stations in Seoul, South Korea.

Aims and rationale of the research work

This research work aims to apply the SDEWES Index to a new sample of 18 SEE cities to obtain unique benchmarking results. The results are utilized in related analyses so that quartile groupings and city pairings are identified to stimulate collaboration and policy learning between cities. Based on this scope, three interconnected research questions are answered:

- What are the benchmarking results for the present sample according to the SDEWES Index?
- How may the performance of cities be compared based on quartiles and city pairings?
- What may be the policy implications of the SDEWES Index for more integrated urban systems?

A set of four steps is then proposed for decision-makers and urban planners to use the results of the SDEWES Index to trigger policy learning, collaboration and action for more sustainable cities. The results contribute to the literature with benchmarking applications for cities in the sample.

METHOD

The SDEWES City Index is a composite indicator that provides an integrated approach towards benchmarking the sustainable development of energy, water and environment systems in cities [3, 5-7]. The SDEWES Index is composed of 7 dimensions and 35 main indicators. The first three dimensions are, namely, energy consumption and climate (D_1), penetration of energy and CO_2 saving measures (D_2) and renewable energy potential and utilization (D_3). The last four dimensions are water and environmental quality (D_4), CO_2 emissions and industrial profile (D_5), city planning and social welfare (D_6), as well as R&D, innovation and sustainability policy (D_7). The indicators and the results of the previous samples are elaborated in a website of the SDEWES Center that promotes a multidisciplinary approach to sustainability [4].

Previous city samples included 22 Mediterranean port cities [3], 12 SEE cities that consisted mostly of capitals [5] and 25 world cities [6] for an overall total of 58 different cities. In this research work, 18 SEE cities are integrated as a new sample for the

SDEWES Index. These cities were not benchmarked in any kind of index previously with the exception of four cities that were included in other indices with different scopes and aims as noted in the footnote of Table 1. In addition, Tapia *et al*. [82] found that cities with relatively high to medium sensitivities to climate vulnerabilities included Rome and Budapest for the impact of heat waves on human health. The same cities further took place among cities that had vulnerabilities to pluvial and fluvial floods as well as the impact of droughts on water planning. Varna also had similar sensitivities to drought as well as the impact of pluvial and coastal flooding on the urban fabric.

Determination of the city sample

The determination of the city sample is based on a two-phased approach as a variant of multi-stage cluster sampling. In the first phase, an initial set of cities is constructed to represent the widest array of possibilities based on the most populated cities in each country of the SEE region. The SEE region includes the area that is bounded by the countries of Austria and Slovakia in the north and circumscribed by Italy, Greece, Bulgaria and Romania [83]. Turkey is also evaluated in the SEE region [84]. In the second phase, two selection criteria are used to scale-down the initial set to a practical size. First, as a criterion of data availability, cities are required to have a SEAP or an equivalent plan and/or energy statistic. Second, cities that were included in previous samples are directly excluded so that 27 cities to which the SDEWES Index has been applied [3, 5-7] are eliminated[*]. Lastly, the municipality of Izola that is closest to the town of Piran as the venue of the 2nd SEE SDEWES Conference [85] is added to increase opportunities for policy learning. Table 1 provides the 18 cities in the new sample along with the main references for the cities [86-108].

Table 1. Cities in the sample and references for SEAP or equivalent plan

City	C_j	Country	SEAP	Other plan	Reference
Bijeljina	C_1	Bosnia and Herzegovina	✓		[86]
Brașov	C_2	Romania	✓		[87]
Bratislava[a]	C_3	Slovakia	✓		[88]
Budapest[a]	C_4	Hungary	✓		[89, 90]
Burgas	C_5	Bulgaria	✓		[91]
Bursa Nilüfer	C_6	Turkey	✓		[92]
Celje	C_7	Slovenia	✓		[93]
Izola	C_8	Slovenia		✓	[94]
Klagenfurt	C_9	Austria	✓		[95]
Kranj	C_{10}	Slovenia	✓		[96]
Nitra	C_{11}	Slovakia	✓		[97, 98]
Osijek	C_{12}	Croatia	✓		[99, 100]
Pécs	C_{13}	Hungary	✓		[101]
Rome[a]	C_{14}	Italy	✓		[102]
Turin[a]	C_{15}	Italy	✓		[103-105]
Varna	C_{16}	Bulgaria	✓		[106]
Velenje	C_{17}	Slovenia	✓		[107]
Zenica	C_{18}	Bosnia and Herzegovina	✓		[108]

[a] Included in other indices with different aims, including the Digital City Index [64] and Safe Cities Index [65]

Data collection for implementation

Data sources for indices can rely on available data at the local, national or international level [63]. The application of the SDEWES Index to the 18 SEE cities required an extensive process of data collection from multiple sources. SEAPs that are prepared under the Covenant of Mayors (CoM) initiative [109] and monitoring reports

[*] Athens, Bari, Belgrade, Bucharest, Cluj-Napoca, Eskişehir, Heraklion, İstanbul, Ljubljana, Maribor, Milan, Naples, Niš, Patras, Podgorica, Pula, Rijeka, Sarajevo, Skopje, Sofia, Thessaloniki, Timișoara, Tirana, Vienna, Volos, Zadar, Zagreb

[110], including those that may be given in the context of the updated Global Covenant of Mayors for Climate and Energy [111], provided the basis to evaluate energy and CO_2 emissions related data and the set of measures for most cities. The CoM initiative represents the leading policy framework for climate mitigation in which signatories have already achieved an overall reduction of 23% in CO_2 emissions from baseline years [112]. Such a reduction received the greatest contribution from the building sector. In addition, while 7% of CoM signatories also had climate adaptation targets previously [112], the total number of signatories in the new framework has since surpassed 7,500 signatories [111]. Hence, the share of cities that have or will approve both kinds of climate action is increasing.

Table 1 provides the references for the SEAPs, the most recent monitoring reports, and/or equivalent plans. Moreover, Sustainable Energy and Climate Action Plans (SECAP) are expected to extend to climate hazards, such as extreme weather events and related adaptation actions [113]. Table 2 summarizes the data sources for all indicators in the SDEWES Index. These include datasets from the United Nations, World Health Organization and the European Environment Agency. Databases based on geographic information systems were also deployed, such as those of the Joint Research Center and International Union for Conservation of Nature.

Table 2. Dimensions and indicators of the SDEWES Index

Dimension	Indicator ($i_{x,y}$)	Unit	Source	Direction
D_1	1.1. Energy consumption of buildings	[MWh]	SEAP[a]	↓
	1.2. Energy consumption of transport	[MWh]	SEAP[a]	↓
	1.3. Energy consumption per capita	[MWh]	Calculated	↓
	1.4. Heating Degree-Days (HDD)	[Days °C]	[114]	↑
	1.5. Cooling Degree-Days (CDD)	[Days °C]	[115]	↑
D_2	2.1. Sustainable Energy Action Plan (SEAP)	Dimensionless	Table 4	↑
	2.2. Combined heat and power based DH/C	Dimensionless	Table 4	↑
	2.3. Energy savings in end-usage (buildings)	Dimensionless	Table 4	↑
	2.4. Density of public transport network	Dimensionless	Table 4	↑
	2.5. Efficient public lighting armatures	Dimensionless	Table 4	↑
D_3	3.1. Solar energy potential	[Wh/m^2/day]	[116]	↑
	3.2. Wind energy potential	[m/s]	[116, 117]	↑
	3.3. Geothermal energy potential	[mW/m^2]	[117, 118]	↑
	3.4. Renewable energy in electricity production	Dimensionless	Table 5[b]	↑
	3.5. Biofuel share in transport energy usage	Dimensionless	Table 5[b]	↑
D_4	4.1. Domestic water consumption per capita	[m^3/year]	See note[c]	↓
	4.2. Water quality index (/100)	Dimensionless	[119, 120]	↑
	4.3. Annual mean PM_{10} concentration	[μg/m^3]	[121, 122]	↓
	4.4. Ecological footprint per capita	[gha]	[71, 123]	↓
	4.5. Biocapacity per capita	[gha]	[123]	↑
D_5	5.1. CO_2 emissions of buildings	[t CO_2]	SEAP[a]	↓
	5.2. CO_2 emissions of transport	[t CO_2]	SEAP[a]	↓
	5.3. Average CO_2 intensity	[t CO_2/MWh]	Calculated	↓
	5.4. Number of CO_2 intense industries	Dimensionless	Table 7	↓
	5.5. Airport ACA level (0, 1, 2, 3)	Dimensionless	[124]	↑
D_6	6.1. Accessibility of public transport	Dimensionless	Table 8	↓
	6.2. Urban form and municipal management	Dimensionless	Table 8	↑
	6.3. Gross domestic product per capita	PPP$ national	[125]	↑
	6.4. Inequality adjusted well-being	Dimensionless	[126]	↑
	6.5. Tertiary education rate	Dimensionless	[127]	↑
D_7	7.1. R&D and innovation policy orientation	Dimensionless	Table 9	↑
	7.2. National patents in clean technologies	Dimensionless	[128]	↑
	7.3. Local public/private universities	Dimensionless	Table 9	↑
	7.4. National *h*-index (citations per paper)	Dimensionless	[129]	↑
	7.5. Reduction target for CO_2 emissions	Dimensionless	SEAP[a]	↑

[a] Calculated from SEAP or equivalent plans and statistics as referenced in Table 1
[b] Calculated based on the share of renewable energy in the energy mix from IEA statistics [130]
[c] References are based on the water footprint [131-133]

Normalized value aggregation for the composite index

The data entries for each indicator are normalized based on the Min-Max method [134] according to the desired direction of change in either increasing (↑) or decreasing (↓) functions. Eq. (1) provides the means of aggregating the normalized values of the data entries into a composite index value per city C_j. Here, $I_{x.y}$ is the normalized value of the y^{th} indicator in dimension x for a given city C_j, which represents a process that is reiterated for all data entries $i_{x.y}$. Accordingly, the double summation in eq. (1) sums the normalized values $I_{x.y}$ of indicators $y = 1$ to $y = 5$ (inner summation) in all dimensions $x = 1$ to $x = 7$ for 35 indicators:

$$\text{SDEWES}(C_j) = \left[\sum_{x=1}^{7} \sum_{y=1}^{5} \alpha_x I_{x.y}(C_j) \right] \text{ where } \sum_{x=1}^{7} \alpha_x = 1 \tag{1}$$

The results of eq. (1) for each dimension are analysed in dimension rankings and performance quartiles. Moreover, the normalized dimension values for cities C_j are compared with those for the sample average (C_{AV}) based on the ratios in eq. (2). In addition, eq. (3) is used to determine the percentage difference of the aggregated index value for cities C_j with the aggregated index value for C_{AV}, which are integrated into the presentation of the results:

$$D_x(C_j)/D_x(C_{AV}) = \sum_{y=1}^{5} \left[I_{x.y}(C_j)/I_{x.y}(C_{AV}) \right] \text{ for } x = \{1, 2, \ldots 7\} \tag{2}$$

$$\text{SDEWES}\left[\left(C_j - C_{AV} \right)/C_{AV} \right] = \sum_{x=1}^{7} \sum_{y=1}^{5} \alpha_x \left\{ \left[I_{x.y}(C_j) - I_{x.y}(C_{AV}) \right] / I_{x.y}(C_{AV}) \right\} \tag{3}$$

In eq. (1), all dimensions have five indicators and may be weighted equally. In this case, dimension weights α_x will be 0.14. In practice, α_x is 0.22 for D_1 and D_5 that directly involve energy and CO_2 emissions data from SEAP. For other dimensions that may indirectly relate to SEAP data, the values of α_x are 0.11. As indicated in the condition of eq. (1), the sum of dimension weights α_x is equal to unity and the maximum aggregated index value that is possible is 5. Weights $\alpha_{x.y}$ may also be differentiated for each indicator. In this research work, the sensitivity of the SDEWES Index to random weights $\alpha_{x.y}$ is evaluated based on 10,000 Monte Carlo experiments that are applied to the normalized values of the indicators in eq. (1). Any changes in rank are assessed based on the mean simulated values of the experiments.

Determination of city performance quartiles

Overall, the mean simulated values of the Monte Carlo experiments are used to determine cities that perform in certain quartiles. The cities that are in Q_4 at the top 25^{th} percentile are termed as "pioneering" SDEWES cities based on a high level of performance in multiple dimensions. Those cities that put forth noteworthy efforts towards obtaining above median performances but may have certain shortcomings take place in the next quartile (Q_3) as the "transitioning" SDEWES cities. Cities in Q_3 have a standing in the top 50% but below the top 25%. In contrast, those cities that are faced with greater challenges in attaining more sustainable urban systems are termed as "solution-seeking" (Q_2) and "challenged" (Q_1) SDEWES cities. The results are not to be seen as static but those that may be changed across time in a dynamic approach, particularly through city-to-city collaboration for more integrated urban systems.

City pairings and pattern identification

One of the aims of the SDEWES Index is to stimulate collaboration among cities, which is further supported based on city pairings. In this context, the performance of cities is subjugated to a search algorithm to identify those cities that may have similar levels of performance in each dimension of the Index when compared to the average. Eq. (4) indicates the condition for the search algorithm [6]. For each dimension D_x, the summation of the normalized values of the indicators $I_{x.y}$ for a city C_j is tested for being greater than or equal to the average value of the summation for an average city of the overall sample (C_{AV2}). Any given city pair P has to be either above or below the average in the same dimension across all dimensions D_1 to D_7. This condition is tested in a 76 × 76 matrix that includes over 4,000 different combinations. The process can support twinning cities [135] based on the SDEWES Index, including peer cities:

$$\sum_{y=1}^{5} I_{x.y}(C_j) \geq \sum_{y=1}^{5} I_{x.y}(C_{AV2}) \text{ for } x = \{1, 2, ...7\} \tag{4}$$

Comparison of the results to contextual factors

Rather than a single indicator, Table 2 requires a high level of performance across a gamut of indicators and dimensions for cleaner energy, better environmental quality, as well as social welfare. In this respect, all cities need to explore the means of obtaining a more efficient and cleaner status in the context of distinct urban realities. For this reason, the benchmarking results of the SDEWES Index for the present sample of 18 SEE cities and any cities in the city pairs are compared to broader contextual factors. Such contextual factors are assessed based on urban hierarchy according to population [136] and the development of the country in which the city is located. Other factors include the set of local characteristics, opportunities, and concerns [137].

Benchmarking tool and the Sustainable Development of Energy, Water and Environment Systems City Atlas

An interface that is based on the SDEWES Index was proposed to enable the benchmarking of multiple cities in reference [6]. This proposal, namely, the SDEWES Index Benchmarking Tool for Policy Learning, is applied to the results for the present sample of 18 SEE cities. The Tool can be used to support at least two typologies of policy learning. Cities with differing performances can trigger processes of exploration so that a city with a lower ranking may identify ways to reach a better ranking in any component of the index [6]. Cities with similar performances can be matched to exploit ways to address needs, problems, and/or goals jointly.

Moreover, a SDEWES Index Atlas is developed for the first time in which the results for the city sample are mapped onto the spatial dimension to compare levels of urban performance. The atlas may also be used to support a future city network for which exemplary policy implications are put forth. It is expected that both tools will increase the ease with which the results are used by urban planners and decision-makers to improve the relative sustainability of their cities.

SUSTAINABLE DEVELOPMENT OF ENERGY, WATER AND ENVIRONMENT SYSTEMS INDEX APPLICATION

This section summarizes the application of the 35 main indicators of the SDEWES Index to the new sample of 18 SEE cities. Based on original data compilations, 630 data inputs were collected for the 35 main indicators (Tables 3-9). With sub-indicators, about 990 data entries were involved. Appendix A provides the data for the sub-indicators as supplementary material.

Energy consumption and climate (D_1)

Table 3 provides the data inputs for the 18 SEE cities based on the indicators in D_1. In an average city, the building and transport sectors consume 4,371,710 MWh and

1,765,674 MWh of energy per year, respectively, which are reducing in the context of SEAPs. The realization of such reductions requires more efficient solutions as well as precautions against short and long term rebound effects [138] that may partially reduce or offset energy savings. Some cities have implemented measures for efficiency gains and user behaviour mostly on the demand side. On average, the total final energy use per capita is 13.52 MWh. Energy per capita values are known to vary according to affluence, urban density, climate and proximity to public transport, among a multiplicity of other factors [139]. In the sample, the lowest value is 6.42 MWh (Varna) and the highest value is 22.91 MWh (Kranj) per capita. As other indicators in D_1, Heating Degree Days (HDD) and Cooling Degree Days (CDD) are useful to adjust energy consumption with climate. The average HDD is 3,063 and average CDD is 1,494. Based on international climate zone definitions [140], 10 cities fall within the 5A, 5B, and 5C climate zones with 3,000 < HDD ≤ 4,000, which is followed by the 4A and 4B climate zones (CDD ≤ 2,500 and HDD ≤ 3,000). The cities on the extreme end of HDD or CDD are Klagenfurt, Kranj, and Rome, respectively.

Table 3. Data inputs to the energy consumption and climate dimension (D_1)

City (C_j)	Energy consumption of buildings [MWh][a]	Energy consumption of transport [MWh][a]	Total energy consumption per capita [MWh][a]	HDD[b]	CDD
Bijeljina	1,405,280	329,821	11.37	2,987	1,534
Brașov	1,919,368	606,006	9.34	3,778	1,232
Bratislava	6,854,194	3,131,796	21.46	3,210	1,360
Budapest	21,723,238	6,274,839	15.93	2,834	1,670
Burgas	2,190,589	208,788	11.30	2,269	2,052
Bursa Nilüfer	1,696,110	1,057,446	7.93	2,270	1,903
Celje	303,984	370,050	13.87	3,542	1,165
Izola	133,032	60,009	12.27	3,075	1,386
Klagenfurt	1,333,847	592,025	19.93	4,028	918
Kranj	968,445	250,687	22.91	4,028	918
Nitra	628,329	349,977	12.20	3,337	1,267
Osijek	1,427,712	226,987	15.35	2,607	1,813
Pécs	1,637,687	362,109	12.75	2,564	1,877
Rome	23,503,569	14,459,000	14.03	1,201	2,528
Turin	10,563,000	2,783,000	14.95	4,254	718
Varna	1,373,506	552,000	6.42	2,471	2,001
Velenje	400,302	61,196	13.90	3,542	1,165
Zenica	628,580	106,391	7.39	3,130	1,380
Average	4,371,710	1,765,674	13.52	3,063	1,494

[a] Obtained or calculated from SEAP or equivalent plans based on the references in Table 1
[b] Based on temperature differences with the base value of 18 °C for each day over the heating period

Penetration of energy and carbon dioxide saving measures (D_2)

Table 4 provides the data inputs into the indicators in D_2. All SEE cities in the sample are in the process of implementing SEAP measures or equivalent strategies to increase primary energy savings. In Table 4, cities with CHP based District Heating and Cooling (DHC) networks are further distinguished from those cities that have individual Heat Only Boilers (HOB) or only district heating. Table A1 in supplementary material provides details on the energy system characteristics. Energy systems that involve the utilization of renewable energy have central roles in enabling more sustainable urban systems. In a future outlook, some cities can be seen to have developments towards the initiation of fourth generation (4G) district heating networks. These networks have lower supply temperatures and higher efficiencies based on multiple sources [141, 142]. Bijeljina is evaluating the utilization of geothermal energy [86] and Izola has proposals to benefit from sea water for district cooling in a local future energy concept [94].

In addition, almost all cities are located in countries with national level plans for nearly Zero Energy Buildings (nZEB). The cities that have implementations of nZEB, energy-plus buildings, carbon neutral buildings and/or districts are scored accordingly. The details of nZEB related developments are given in Table A2. In other aspects of D_2, Budapest (157 km) and Rome (60 km) have the tramway and subway with the longest length, respectively (see Table A3). Based on the use of an additional sub-indicator, the density of public transport is evaluated relative to the urban area. Turin (0.75 km/km^2) and Budapest (0.37 km/km^2) have the densest schemes.

Cities with best practices in implementing efficient public lighting measures are as provided in Table 4. These include Budapest that implemented a self-sustaining public lighting system [143, 144]. Other cities improved electricity usage per light pole among which Braşov reduced this value to 550 kWh per light pole [145] and Klagenfurt saved 16 MWh per year [146].

Table 4. Data inputs to the penetration of energy and CO_2 measures dimension (D_2)

City (C_j)	SEAP[a]	Combined heat and power based DH/C[b]	Energy savings in end-usage (buildings)[c]	Density of public transport network[d]	Efficient public lighting armatures[e]
Bijeljina	2.0	1	1	1	1
Brașov	2.0	2	1	1	1
Bratislava	2.0	2	2	4	1
Budapest	2.0	2	2	5	2
Burgas	2.0	2	1	1	2
Bursa Nilüfer	2.0	0	1	3	1
Celje	2.0	2	1	1	1
Izola	1.0	1	1	1	2
Klagenfurt	2.0	2	2	1	1
Kranj	2.0	1	1	1	1
Nitra	2.0	2	1	1	1
Osijek	2.0	2	2	3	1
Pécs	2.0	2	2	3	1
Rome	2.0	1	2	4	1
Turin	2.0	2	2	6	1
Varna	2.0	2	1	1	2
Velenje	2.0	2	1	1	2
Zenica	2.0	1	1	1	1
Average	1.9	1.6	1.4	2.2	1.3

[a] Includes SEAP equivalent plans. The minimum is set at zero for comparison with previous samples
[b] Existing CHP plants receive double points compared to planned CHP or DH networks, see Table A1
[c] Scored based on sub-indicators for nZEB implementation, see Table A2
[d] Based on the length of the public transport network, number of stations and lines, and urban area see Table A3
[e] Penetration of Light-Emitting Diode (LED) armatures using solar energy and/or best practices obtain an extra point

Renewable energy potential and utilization (D_3)

Table 5 provides the data inputs for the indicators in D_3. An average city in the sample has 4,286 Wh/m^2 of solar energy potential per day on an optimally inclined plane. The average wind energy potential is 4.4 m/s at 50 meters above the ground. For geothermal energy, Bijeljina has the greatest mean heat-flow density of about 86 mW/m^2 while the average is 66 mW/m^2. The city is considering the use of geothermal wells to supply the district heating system [147]. The average share of renewable energy in electricity production is 32.9% with a dominant contribution from hydropower. The highest share is 78% (Klagenfurt) and the lowest share is 10% (Budapest and Pécs). Based on calculations of biofuels in the transport sector, six cities obtained at least a 4% share of biofuels in the transport sector. The highest in the sample is 5.9% (Klagenfurt). An additional four cities are above the average share value of 3.2%.

Table 5. Data inputs to the renewable energy potential and utilization dimension (D_3)

City (C_j)	Solar energy potential [Wh/m^2/day][a]	Wind energy potential [m/s][a]	Geothermal energy potential [mW/m^2][b]	Renewable energy in electricity production [%][c]	Biofuel share in transport [%][d]
Bijeljina	4,210	4.8	86	41	0.0
Brașov	3,870	4.0	56	34	4.0
Bratislava	3,950	5.0	65	22	4.3
Budapest	3,890	4.3	80	10	4.0
Burgas	4,590	5.9	40	17	3.8
Bursa Nilüfer	4,760	4.9	80	29	2.0
Celje	4,080	4.1	76	32	3.2
Izola	4,670	4.5	40	32	3.2
Klagenfurt	4,160	3.9	65	78	5.9
Kranj	4,010	4.0	65	32	3.2
Nitra	3,950	5.0	65	22	4.3
Osijek	4,220	4.5	86	65	1.6
Pécs	4,170	4.6	86	10	4.0
Rome	5,300	3.9	65	39	3.5
Turin	4,730	3.0	65	39	3.5
Varna	4,570	5.3	40	17	3.8
Velenje	3,980	3.8	65	32	3.2
Zenica	4,040	4.2	65	41	0.0
Average	4,286	4.4	66	32.9	3.2

[a] Based on coordinate entries in the PVGIS and SWERA databases, respectively
[b] Based on geothermal heat-flow density categories and/or reports, e.g. [117, 118]
[c] Based on the share of renewable energy in electricity production as calculated based on [130]
[d] Based on the share of biofuel in the transport sector in IEA statistics [130]

Water and environmental quality (D_4)

Table 6 provides the data inputs into the indicators in D_4. The average ground and surface water that is consumed per capita is 10.1 m^3 per year based on the water footprint method [132, 133]. On average, water quality is scored to be 88.3 out of 100 based on levels of dissolved oxygen, pH, conductivity and nutrients of nitrogen and phosphorus. Annual mean concentrations of PM_{10} in urban traffic contexts are 31.7 µg/m^3 in which the lowest value is 19.9 µg/m^3 (Izola) and the highest value is 69.8 µg/m^3 (Zenica) where the latter includes impact from the local industry. Velenje closely follows Izola for the lowest annual mean concentration of PM_{10} at 21.0 µg/m^3. The average ecological footprint per capita is 4.2 global hectares (gha), which quantifies the demand for land across six categories, including built-up land, land for various agricultural produce and land to uptake CO_2 emissions from human activities [148]. In contrast, biocapacity per capita is 2.2 gha, indicating an ecological deficit of 2.0 gha per capita. In comparison, ecological footprint per capita in Rome deviates by about 5% from the national value and represents 7% of the total ecological footprint of Italy [70]. Similar instances indicate that cities have double dynamics based on trade-offs between investments to improve eco-efficiency and citizens who may have higher resource use due to urban lifestyles

[70]. The world average is an ecological footprint of 2.7 gha and biocapacity of 1.8 gha per capita [123].

Table 6. Data inputs to the water and environmental quality dimension (D_4)

City (C_j)	Domestic water consumption per capita [m^3]	Water quality index [/100][a]	Average air quality PM_{10} [$\mu g/m^3$][b]	Ecological footprint per capita [gha]	Biocapacity per capita [gha]
Bijeljina	10.5	90.9	22.6	3.1	1.6
Brașov	7.7	70.7	24.3	2.7	2.3
Bratislava	8.0	70.7	27.1	4.1	2.7
Budapest	7.0	91.8	29.0	2.9	2.2
Burgas	13.8	95.5	35.7	3.3	2.9
Bursa Nilüfer	8.3	72.3	36.9	3.3	1.5
Celje	10.1	97.6	29.5	5.8	2.4
Izola	10.1	97.6	19.9	5.8	2.4
Klagenfurt	9.2	75.9	23.0	6.1	3.1
Kranj	10.1	97.6	24.6	5.8	2.4
Nitra	8.0	70.7	26.4	4.1	2.7
Osijek	9.7	90.4	33.2	3.9	2.8
Pécs	7.0	91.8	30.5	2.9	2.2
Rome	14.0	95.7	27.9	4.6	1.1
Turin	14.0	95.7	39.0	4.6	1.1
Varna	13.8	95.5	51.0	3.3	2.9
Velenje	10.1	97.6	21.0	5.8	2.4
Zenica	10.5	90.9	69.8	3.1	1.6
Average	10.1	88.3	31.7	4.2	2.2

[a] From UN water quality index [119, 120] for dissolved oxygen, pH, conductivity, nitrogen, phosphorus
[b] Based on WHO Air Pollution in Cities or EEA databases except for Bijeljina [149] and Zenica [150]

Carbon dioxide emissions and industrial profile (D_5)

Based on Table 7, the average CO_2 emissions of buildings in the cities are 1,122,711 tonnes while it is 460,070 tonnes for transport. The average CO_2 intensity is 0.27 tonnes per MWh. The lowest value is 0.15 tonnes of CO_2 (Burgas) and the highest value is 0.36 tonnes of CO_2 emissions (Brașov) per MWh. Surveys of energy intense industries are conducted based on sectoral reports, including those for important clusters of the chemical industry in Europe [151]. Overall, Bratislava, Burgas and Zenica have the greatest presence of energy intense industries, including iron and steel and petroleum products. Based on Table A4, an average city receives a score of 1.6 industries. Six airports that service the cities in the sample received Airport Carbon Accreditation (ACA) for reducing CO_2 emissions per passenger based on energy savings on the supply and demand sides. Overall, accredited airports reduced CO_2 emissions per passenger by about 14.8% in the years 2015 and 2016 [152-153], which exemplifies absolute decoupling [154] based on a 6.5% decline in total airport CO_2 emissions for Scope 1 and 2 CO_2 emissions despite an 8.9% growth in passenger traffic. Ljubljana Airport that services at least two cities in the sample (Celje and Kranj) is accredited for reducing airport CO_2 emissions [124]. Leonardo da Vinci-Fiumicino Airport that services Rome has a CHP unit that covers 90% of the reduced electricity and heating demands and partially cooling loads. In addition, a smart grid project that involves photovoltaic and micro-mini wind turbines is completed [155]. Electrical energy per passenger reduced to 3.8 kWh from 4.8 kWh between 2010 and 2015 for a 22% reduction [156].

Table 7. Data inputs to the CO_2 emissions and industrial profile dimension (D_5)

City (C_j)	CO_2 emissions of buildings [t CO_2][a]	CO_2 emissions of transport [t CO_2][a]	Average CO_2 intensity [t CO_2/MWh]	Number of CO_2 intense industries[b]	Airport ACA level
Bijeljina	362,791	85,428	0.26	1	0
Brașov	761,994	153,459	0.36	4	0
Bratislava	1,593,575	816,733	0.24	5	0
Budapest	6,984,132	1,693,915	0.31	3	3
Burgas	308,854	55,126	0.15	4	0
Bursa Nilüfer	404,236	285,127	0.25	3	0
Celje	114,970	96,303	0.31	2	2
Izola	30,597	15,422	0.24	0	0
Klagenfurt	395,872	183,528	0.30	1	0
Kranj	309,713	59,413	0.30	0	2
Nitra	132,652	90,286	0.23	2	0
Osijek	352,147	66,226	0.25	1	0
Pécs	462,960	99,760	0.28	1	0
Rome	4,491,482	3,688,549	0.22	1	3[c]
Turin	2,737,000	713,000	0.26	4	0
Varna	408,460	137,856	0.24	2	0
Velenje	147,488	13,081	0.35	1	2
Zenica	209,874	28,048	0.32	5	0
Average	1,122,711	460,070	0.27	2.22	0.67

[a] Calculated from SEAP or equivalent plans based on references in Table 1
[b] Includes sectors that require high-temperature processes (e.g. kiln heating up to 2,000 °C), see Table A4
[c] The ACA level of 3+ (carbon neutrality) is not further distinguished for the purposes of this study

City planning and social welfare (D_6)

Table 8 provides the data inputs into D_6. For example, the average price of a one-way public transport ticket is EUR 1.0. Four cities provide further data on the modal share of journeys to work. Bratislava has the highest share of journeys to work with public transport (87%) while the average is 46% among reporting cities [157]. The average score for compact urban form and protected sites is 1.9. In total, over 200 green areas were surveyed to score urban park intensity and protected green corridors based on the World Database on Protected Areas [158]. In contrast, a higher mean percentage of impermeable surfaces in urban areas can increase the impact of heat waves and the risks of flooding due to extreme weather events. For example, the share of sealed surfaces was 36.6% in Klagenfurt and 62.9% in Budapest and Turin [159]. Table A5 also provides the number of reserves with special protection status and an area greater than 15 km^2, the protected wetlands, and national parks within a 100 km radius of the city center.

In other aspects of D_6, seven cities have predominately monocentric urban forms while twelve cities are characterized to have polycentric urban forms. For example, Burgas and Varna have continuous urban fabric in centralized locations in the city [160]. D_6 further includes an assessment of cities under the Urban Waste Water Treatment Directive [161] for compliance with Biochemical (BOD) and Chemical Oxygen Demand (COD) as well as Total Suspended Solids (TSS). In the aspect of waste and waste management, the average amount of municipal solid waste per capita in the sample is 406 kg. As a best practice, Celje uses municipal waste, sludge, and landfill gas in CHP units in waste to energy schemes (see Table A1 and A5). In addition, recycling rates in Slovenia are one of the highest rates in Europe at 55% [162]. In contrast, the solid waste of Nitra is landfilled 50 km away from the city while only 10% of the waste is recycled [163]. Such aspects are differentiated under the scorings for municipal management.

In aspects of social welfare, the average GDP per capita is 25,852 international dollars adjusted for purchasing power parity. The lowest values are in Bijeljina and

Zenica and the highest value is in Klagenfurt. As an assessment of social welfare beyond GDP per capita, inequality adjusted well-being scores have a low of 6.0 (Bursa Nilüfer) and a high of 7.7 (Klagenfurt) out of a possible score of 10. The well-being scores represent satisfaction with daily experience based on the views of the population that may be thriving, struggling or suffering [126]. The average tertiary education rate that also supports social welfare is 27.3%. In addition to the pervasiveness of tertiary education, Pécs and Turin from the present city sample have been recognized as a "learning city" based on commitments to improve quality, excellence, and inclusiveness in education as a pillar of sustainable development [164, 165].

Table 8. Data inputs to the city planning and social welfare dimension (D_6)

City (C_j)	Accessibility of public transport [EUR][a]	Urban form and municipal management[b]	GDP per capita [PPP$ national]	Inequality adjusted well-being [/10]	National tertiary education rate [%]
Bijeljina	0.87	1.0	10,427.0	6.2	18.0
Brașov	0.44	2.0	21,635.0	6.6	21.8
Bratislava	0.90	2.3	28,327.0	6.5	23.7
Budapest	1.13	2.0	25,069.0	6.9	29.9
Burgas	0.51	2.0	17,208.0	6.5	26.9
Bursa Nilüfer	0.76	2.0	19,788.0	6.0	22.0
Celje	1.30	2.2	30,403.0	6.8	39.2
Izola	1.30	2.3	30,403.0	6.8	39.2
Klagenfurt	2.10	2.0	47,682.0	7.7	26.3
Kranj	1.00	1.7	30,403.0	6.8	39.2
Nitra	0.72	2.0	28,327.0	6.5	23.7
Osijek	1.46	1.7	21,635.0	6.2	23.7
Pécs	1.16	1.7	25,069.0	6.9	29.9
Rome	1.50	2.7	35,463.0	7.1	21.7
Turin	1.50	2.0	35,463.0	7.1	21.7
Varna	0.51	2.0	17,208.0	6.5	26.9
Velenje	0.00	1.7	30,403.0	6.8	39.2
Zenica	0.51	1.0	10,427.0	6.2	18.0
Average	1.0	1.9	25,852.2	6.7	27.3

[a] Based on the price of a one-way public transport ticket
[b] Based on the average score of compact urban form, green space, and municipal management (Table A5)

Research and development, innovation and sustainability policy (D_7)

For D_7, Table 9 provides the main data inputs and Tables A6-A8 provide those of the sub-indicators. The average score for Research and Development (R&D) and innovation policy orientation is 2.0 based on R&D spending and priorities in funding. Based on the national level, 3 cities have thematic calls and priorities in the areas of energy and environment, namely Klagenfurt, Osijek, and Bursa Nilüfer. Klagenfurt has the highest number of patents (20,145) with green patent codes while Osijek has the highest share of green patents (2.82%) in total patents. Both aspects are used to determine the final score based on Table A7. As local knowledge institutions, Budapest has the highest number of universities in the local innovation system and the most academic institutions in the Scimago rankings. For cities with available data in Urban Audit, the number of tertiary students (ISCED 5 and 6) range between 9,725 (Burgas) and 154,235 students (Budapest) [157]. The knowledge production capacity based on the average *h*-index is 281. The average CO_2 emissions target is a 25% reduction with the highest target set at 40% (Klagenfurt). Such targets are essential to allow cities in spearheading local climate action towards attaining climate neutrality by mid-century in support of Articles 2 and 4 of the Paris Agreement [2, 166].

Table 9. Data inputs to the R&D, innovation and sustainability policy dimension (D_7)

City (C_j)	R&D and innovation policy orientation[a]	National patents in clean technologies[b]	Universities in the local ecosystem[c]	National h-index[c]	Reduction target for CO_2 emissions
Bijeljina	1.0	1.5	2	61	31
Brașov	1.5	1.0	4	187	32
Bratislava	1.5	1.0	11	195	20
Budapest	1.5	1.5	24	329	21
Burgas	2.0	1.0	2	184	25
Bursa Nilüfer	2.5	1.0	4	296	20
Celje	2.5	1.0	3	204	21
Izola	2.5	1.0	2	204	20
Klagenfurt	3.0	2.0	3	487	40
Kranj	2.5	1.0	1	204	21
Nitra	1.5	1.0	4	195	21
Osijek	2.5	1.5	2	194	22
Pécs	1.5	1.5	2	329	34
Rome	2.0	2.0	13	766	20
Turin	2.0	2.0	5	766	30
Varna	2.0	1.0	5	184	25
Velenje	2.5	1.0	1	204	23
Zenica	1.0	1.5	1	61	20
Average	2.0	1.3	5	281	25

[a] Based on the approach for thematic priorities and R&D expenditure as a share of GDP, see Table A6
[b] Patents are limited to clean energy technology coded patents, e.g. Y02B for buildings etc., see Table A7
[c] Sum of universities located in the city. Those in the Scimago list receive double points, see Table A8
[d] Sustainable development is a multidisciplinary field with inputs from multiple fields (fields not restricted)

RESULTS AND DISCUSSION

The data inputs for the new sample of 18 SEE cities as given in Tables 3-9 are normalized according to the direction of the indicators in Table 2 and aggregated into the SDEWES Index based on eq. (1). In this process, the range of the indicators for the 18 new cities is compared with those for the previous city samples of Mediterranean port cities [3], SEE cities [5], and world cities [6]. In 34 of the 35 indicators in the index, the range of the previous city samples had a defining role in the minimum and maximum values. In these cases, the minimum and maximum values of the present sample were within the previous range. In the indicator for PM_{10}, one city in the present sample was an outlier and received the value of zero according to the winsorization method [167]. In this method, outliers are assigned either a value of 1 or 0 as the highest or lowest possible values according to the direction of the specific indicator. Thus, the normalized values of the new sample are compatible with those of the previous samples.

The normalized values of the indicators per dimension are provided in Figures 2-8 that are also used within the SDEWES Index Benchmarking Tool (see Figure 10 in subsequent sections for a screenshot). The SDEWES Index Benchmarking Tool has functionalities for comparing the overall performance of cities and dimension performance. The Benchmarking Tool for the present sample of 18 SEE cities is provided as a downloadable Appendix B of this manuscript.

Results for energy consumption and climate

The stacked bar chart of Figure 2 provides the normalized values of the indicators in D_1 for the 18 SEE cities in the sample. The labels indicate the total unweighted score for D_1 prior to the aggregation in eq. (1). Accordingly, Varna (3.81), Zenica (3.73), Brașov (2.69) and Bursa Nilüfer (3.65) are the top performing cities in D_1 based on normalized values that are in the top 25% of values (Q_4). This performance is followed by those of Burgas and Bijeljina. The sample average C_{AV} is 3.37, which is given as the last stacked bar in Figure 2 and extended with a dotted line as a reference value. The ratios of the total D_1 values for each city C_j over C_{AV} is given in the triangular markings that range between 1.13 and 0.70. Cities that minimize energy usage in buildings and transport relative to both population and climate have a better performance in D_1.

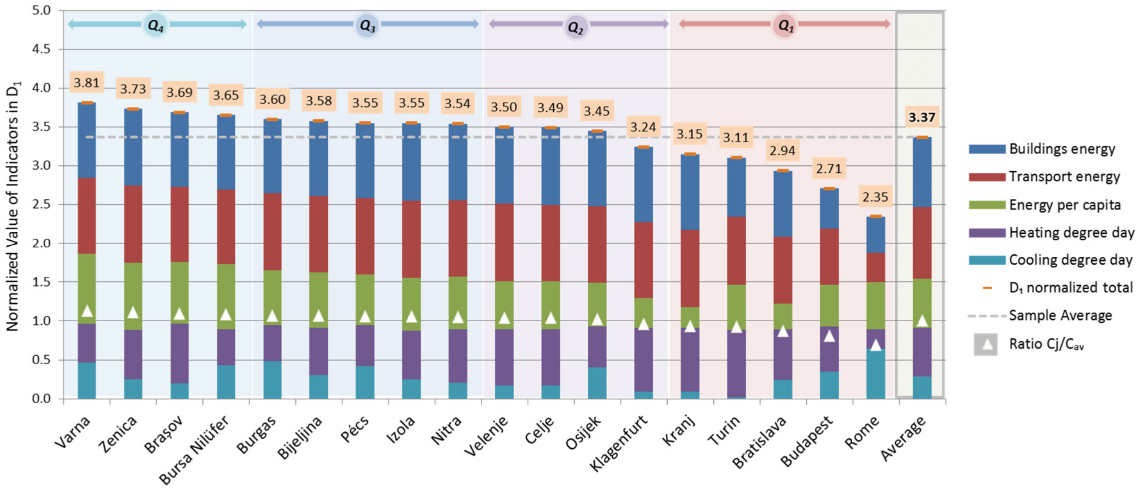

Figure 2. Normalized values of the indicators in D_1

Results for penetration of energy and carbon dioxide saving measures

Figure 3 presents the normalized values of the indicators in D_2 for the 18 SEE cities in the sample. Based on multiple aspects of energy and CO_2 saving measures, Budapest (4.57), Turin (4.08) and Bratislava (3.72) receive the highest scores in this dimension. Osijek and Pécs (3.54) closely follow the performance of these cities and also take place among the cities in Q_4. In comparison to others, these cities put forth best practises in adopting an integrated approach to optimize the energy system from both the supply and demand sides. These best practices include diffusing CHP based DH/C networks, implementing pilot nZEB projects, and/or connecting multiple modes of public transport towards a more energy efficient city. These include urban rail systems, including light rail trams that can provide a 6% reduction in the CO_2 emissions from urban mobility alongside other benefits for traffic flow and air quality [168]. At the same time, such infrastructure may also need to be protected from climate vulnerabilities, including segments of the public transport network that may be located in floodplains [169].

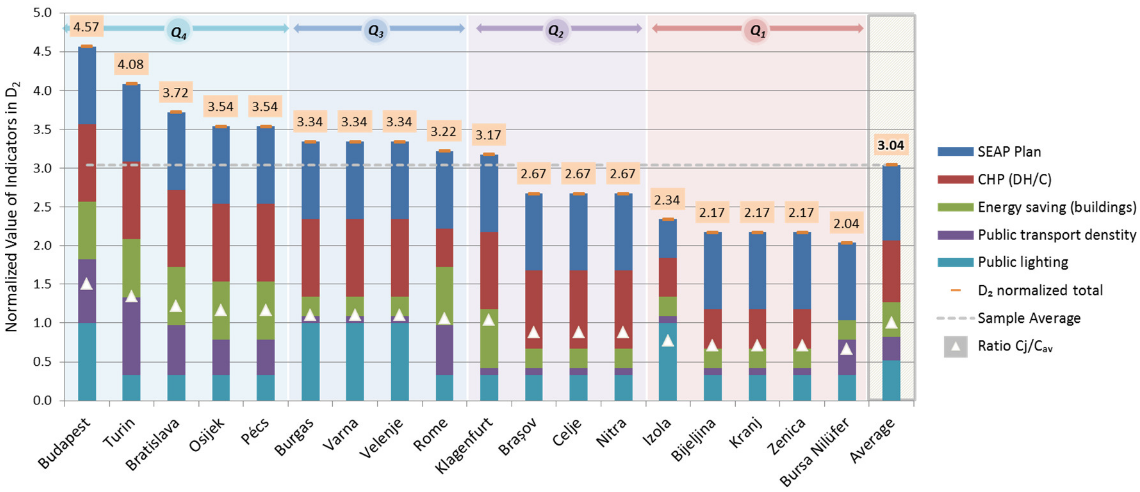

Figure 3. Normalized values of the indicators in D_2

Moreover, as indicated in Table A1, the energy system of Budapest is based on a CHP system with a power-to-heat ratio of 0.5 and about a 30% savings in primary energy [170]. Turin has three combined-cycle CHP plants for 1,200 MW_e of electrical power and 740 MW_t of thermal power in cogeneration mode [171]. Other cities have best practices mostly on the supply side and include Varna that has a biomass boiler with an ORC that provides for 3.8 MW_t of heat recovery [172]. In contrast, the opportunity to use excess heat is currently not utilized in these cities, including those from industry in Braşov [173] and Osijek [174]. Rome is planning to transition to a CHP based DH network that will have up to 50% input from biofuels [102].

In another aspect, the cities that receive top scores in Figure 3 also have nZEB related implementations. For example, as indicated in Table A2, Budapest has a residential complex that has an nZEB status [175] while Rome and Turin have sites for climate neutral urban districts [176]. Cities in which high exergy resources are mostly being used to meet the low exergy demands of space heating and cooling [177] are disadvantaged in D_2. Comparisons such as these are useful for policy learning across cities for saving both energy and exergy. For example, some cities, such as Bursa Nilüfer, rely on individual heating of buildings based on high exergy resources. The city can better utilize lower exergy energy resources in the future.

Results for renewable energy potential and utilization

In Figure 4, the normalized values of the indicators in D_3 for the 18 SEE cities in the sample indicate that Klagenfurt (2.59) has the highest performance across multiple indicators for renewable energy potential and its utilization, which is rewarded in D_3. Based on the indicators in Table 2, Klagenfurt may have a relatively lower renewable energy potential than some of the other cities but has the highest shares in renewable energy utilization. Rome (2.29), Osijek (2.27), Bursa Nilüfer (2.19), and Burgas (2.14) also perform in the top 25% of values for D_3.

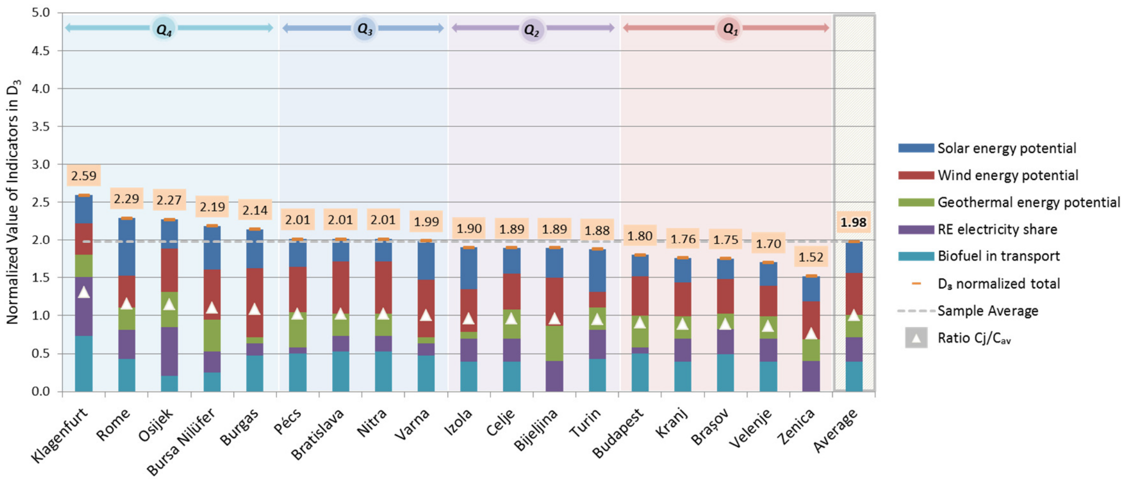

Figure 4. Normalized values of the indicators in D_3

As best practices, cities in D_3 integrate the local renewable energy potential into the power grid and thermal energy networks. These best practices may be initiated in pilot districts that may then be up-scaled to the larger city level. For example, the energy concept of Pécs is based on local straw and woodchips as locally available biomass to generate 35 MW_e and 70 MW_t of electrical and thermal power, respectively [178]. In addition, Nitra (2.01) in Q_3 uses geothermal energy to supply about 40% of the 24,167 MW_t of thermal power in the DH network [179].

Other cities may have a favourable performance in renewable energy potential but lack the utilization of these resources. Bijeljina (1.89) that has the highest geothermal energy potential in the sample is planning to integrate geothermal energy into the coal-based district heating system [147]. The use of this local renewable energy resource in the supply structure of the city may also improve its performance in multiple dimensions beyond D_3, including D_2 and D_5.

Results for water and environmental quality

Based on the normalized values in Figure 5, Budapest (3.38) and Pécs (3.35) have the highest performance in D_4 among the 18 SEE cities in the sample. Such a result indicates that both cities have a holistic approach to water and environmental quality and are able to obtain related advantages, including better air quality. Bijeljina, Braşov and Izola are other cities that perform in the top 25% of values in D_4. Other cities with lower performances in D_4, such as Celje (2.86), have relatively high water quality but obtain a less favourable outcome in the other indicators, such as ecological footprint per capita. In contrast, cities that take place in the lowest 25% of values in D_4 have certain shortcomings in more than one indicator. For example, Zenica (2.46) is given to have the worst air quality among the cities in the sample. Hence, the ability to reach top performance in D_4 necessitates a consistent performance across multiple indicators, including water consumption, water quality, minimized air pollution, and ecological footprint.

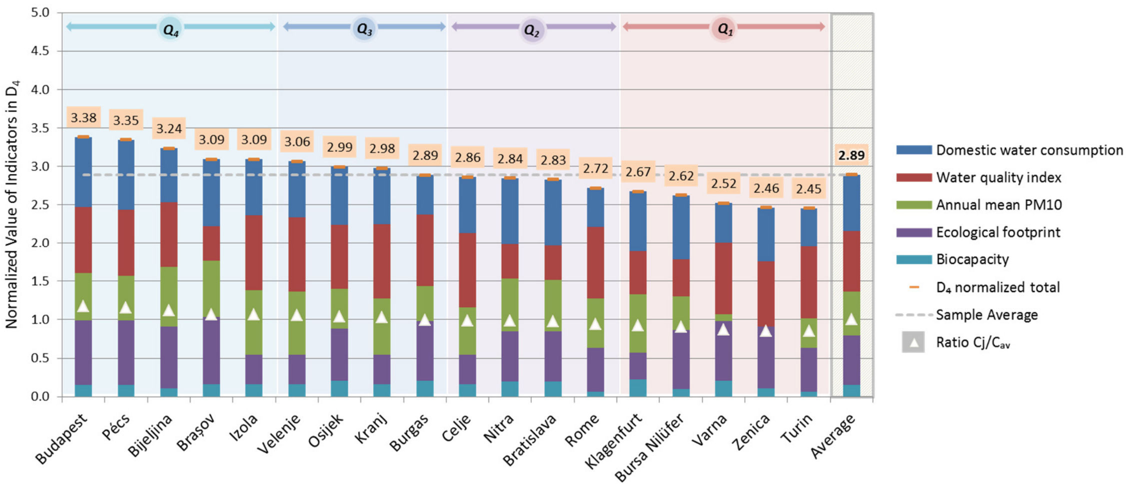

Figure 5. Normalized values of the indicators in D_4

Results for carbon dioxide emissions and industrial profile

Figure 6 provides the normalized values of the indicators in D_5 for the 18 SEE cities in the sample. Kranj (4.02) has the best performance in the related indicators for CO_2 emissions and industrial profile. Velenje (3.78), Celje (3.75), and Izola (3.74) are the next best performing cities in D_5 with performances in Q_4. Among these cities, Izola has no direct energy intense industry although the Port of Koper is nearby. In contrast, the performances of Bratislava (2.87) and Zenica (2.85) that take place among cities that perform below the D_5 average are limited due to the presence of energy intense industries, which places a greater need for CO_2 mitigation. Cities that excel in D_5 reduce CO_2 emissions relative to energy usage, minimize the presence of energy intense industries and reduce the CO_2 emissions impact of the airport servicing the city. Currently, CO_2 reductions in the building sector are surpassed by those in public and private transport. For example, Nitra that takes place in the quartile of Q_3 achieved a 13.2% reduction in residential buildings when compared to its baseline while 75% of the measures for this sector are still ongoing [98]. An energy systems approach will further expedite improvements in D_5.

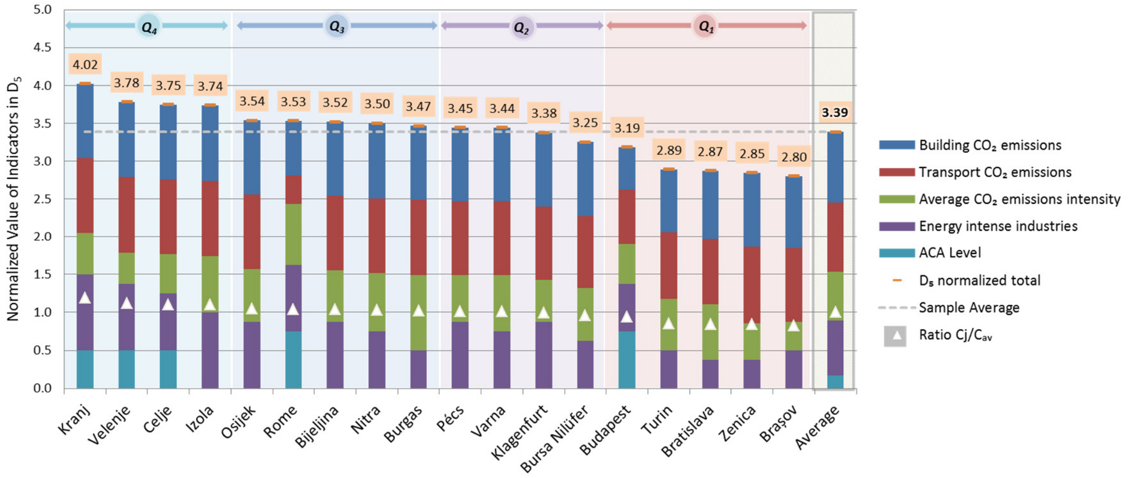

Figure 6. Normalized values of the indicators in D_5

Results for city planning and social welfare

In Figure 7, the normalized values of the indicators in D_6 indicate that Izola (3.09), Velenje (3.09) and Klagenfurt (3.08) are the best performing cities for city planning and social welfare. Celje (3.04) and Rome (2.97) are other cities with advantages in multiple indicators under D_6. Relative to the other cities in the present sample, a performance in the top 25% of values can be explained by the efforts of these cities for compact urban form while preserving urban green spaces and protecting surrounding areas. Favourable socio-economic indicators, including GDP per capita and/or the tertiary education rate are other factors that further enhance the performance of these cities in D_6. Best practices from the top performing cities in D_6 include those of Klagenfurt that has the most distinct profile of green corridors with 1 nature reserve, 2 Ramsar wetland sites, and 1 national park (see Table A7). Celje has a waste to energy scheme to increase the valorisation of municipal waste. In aspects of social welfare, Slovenian cities have the highest tertiary education rate. Cities can improve their level of performance in D_6 by increasing measures that address city planning, municipal management, and social welfare.

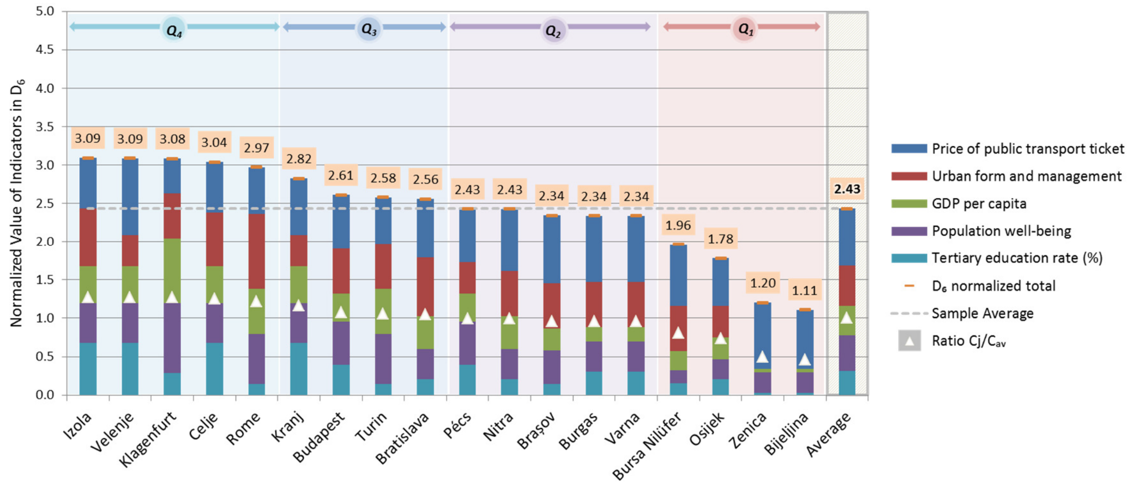

Figure 7. Normalized values of the indicators in D_6

Results for research and development, innovation and sustainability policy

Figure 8 puts forth the normalized values of the indicators in D_7. Here, Klagenfurt (2.91), Rome (2.46), Turin (2.42), Budapest (2.15) and Osijek (1.88) take place as the cities with the best performance in R&D, innovation, and sustainability policy among the cities in the sample. These cities have assets in being able to combine a strong knowledge production and technology development capability with an ambitious CO_2 emissions reduction target. Such an asset, including patents in clean technologies, is essential to support the contextual framework in which cities work to realize CO_2 emission reduction targets. In contrast, cities in quartiles other than Q_4 have certain limitations and perform below the average value (C_{AV}) of 1.76 in D_7. For example, Nitra (1.26), Bijeljina (1.25) and Zenica (0.97) do not possess the same advantages that may place a greater need for knowledge transfer to these cities. The best practices in D_7 emphasize that cities can build capacities to be hubs of sustainable innovation. City partnerships may also give impetus to more solution-oriented sustainability research [180].

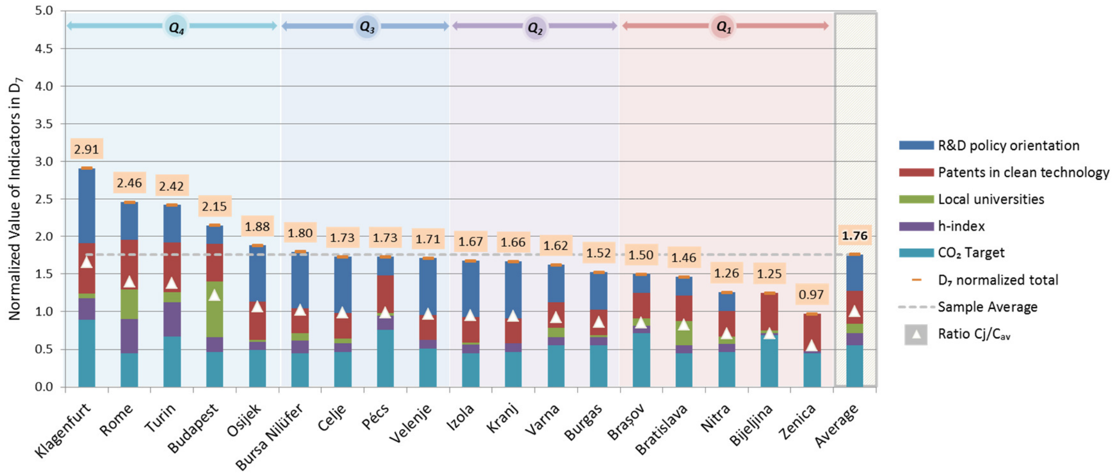

Figure 8. Normalized values of the indicators in D_7

Results of the Sustainable Development of Energy, Water and Environment Systems Index for South East European cities

Table 10 provides the results of the SDEWES Index when the normalized values are aggregated based on eq. (1). The top three cities in the present sample are Klagenfurt (SDEWES = 3.08), Velenje (3.06) and Pécs (3.01). As referred from Figures 2-8, these top cities consistently have the highest value in the most number of dimensions and/or exceed the average with a greater difference in multiple dimensions. The average city in the sample receives a score of SDEWES (C_j) = 2.85. The results in Table 10 allow a comparative approach to benchmark cities and underline the need to adopt well-rounded policy efforts to increase the sustainable development of energy, water and environment systems in cities across multiple dimensions. Weaknesses in certain dimensions may also be used to identify areas of strategic intervention for improvement. The percentage difference with the sample average is further provided as a basis of comparison. For example, Klagenfurt has a performance at 8.1% above the sample average based on eq. (3). In contrast, the lowest performing city, namely Zenica, is found to perform about 15.8% below average when compared to the sample average.

Table 10. Ranking of the SEE sample based on the SDEWES Index

City (C_j)	Index	Rank	% ΔC_{AV}	City (C_j)	Index	Rank	% ΔC_{AV}
Klagenfurt	3.08	1	8.09	Kranj	2.86	10	0.37
Velenje	3.06	2	7.39	Turin	2.83	11	−0.68
Pécs	3.01	3	5.63	Rome	2.82	12	−1.03
Izola	2.97	4	4.23	Nitra	2.81	13	−1.38
Celje	2.96	5	3.88	Bursa Nilüfer	2.72	14	−4.54
Osijek	2.94	6	3.18	Brașov	2.70	15	−5.24
Burgas	2.94	7	3.18	Bratislava	2.69	16	−5.60
Varna	2.93	8	2.83	Bijeljina	2.66	17	−6.65
Budapest	2.91	9	2.13	Zenica	2.40	18	−15.77
				Average	2.85	-	0.00

Comparison of the results based on Monte Carlo experiments

In addition to the results in Table 10, the normalized values of the indicators are subjugated to random weights based on 10,000 Monte Carlo experiments. Accordingly, indicator weights are generated randomly and applied within the context of eq. (1) for all cities in the sample.

Figure 9 provides the box plot of the experiments in which the cities in the sample are ordered based on mean simulated values. The original rankings in Table 10 is upheld in the rankings in Figure 9, which indicates that the mean simulated values of the Monte Carlo experiments for cities C_j are in conformity with the ranking of the results of the SDEWES Index based on eq. (1). The mean simulated values are also used to sub-divide the index results into quartiles so that cities performing above or below the median ($\tilde{x}$) value of SDEWES = 2.89 are characterized to be in the top or bottom 50% of observations. In particular, cities with index values above 2.96 (Q_4), 2.89 (Q_3) or 2.74 (Q_2) or equal to or less than 2.74 (Q_1) are included in the associated quartiles in Figure 9. These quartiles are attributed to contain the pioneering (Q_4), transitioning (Q_3), solution-seeking (Q_2) and challenged cities (Q_1) of the present sample.

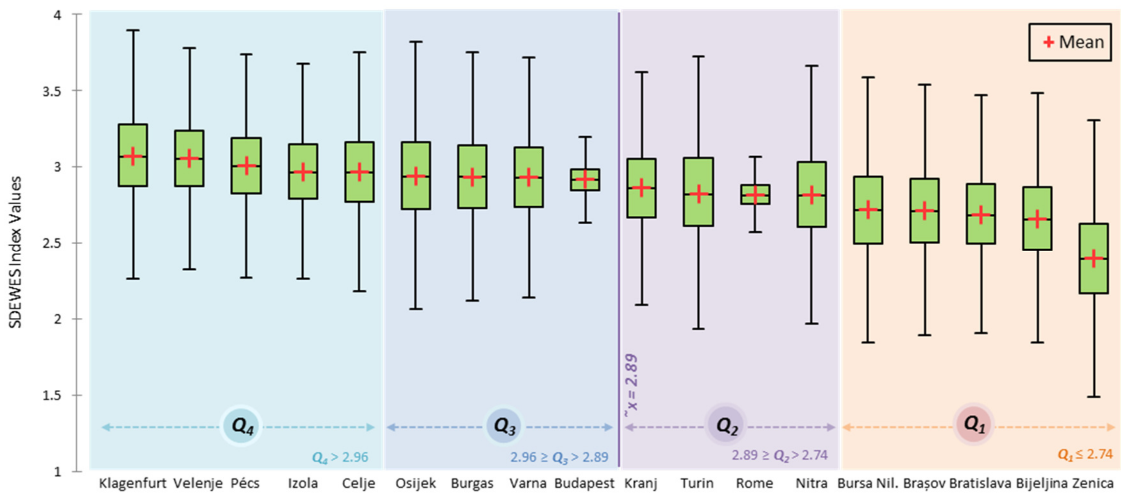

Figure 9. Results of the 10,000 Monte Carlo experiments

<u>The pioneering cities of the sample</u>. Based on Figure 9, five cities are identified to take place in the top 25% within Q_4 as the pioneering cities of the sample. These cities, namely, Klagenfurt, Velenje, Pécs, Izola and Celje, can each provide best practices in more than one dimension. For example, Klagenfurt has one of the highest renewable energy shares in the electricity mix in D_3.

<u>The transitioning cities of the sample</u>. The next four cities, namely Osijek, Burgas, Varna and Budapest, are cities that have certain strengths in specific dimensions. For example, Budapest has commendable levels of performance in D_2 and D_4. In some of the other dimensions, the city may require a transition to attain higher levels of performance, including in D_3. While cities in Q_3 have an above median performance, there are still opportunities to improve to reach Q_4.

<u>The solution-seeking cities of the sample</u>. The cities in Q_2 are identified to be those that need to seek more urban solutions to balance levels of performance across the SDEWES Index. In the present sample, these cities are Kranj, Turin, Rome and Nitra. For example, Turin and Rome both have advantages in D_7 while their performance in the other dimensions is more varied. The measures that these cities are implementing can be diversified, including aspects of air quality.

The challenged cities of the sample. The five cities in Q_1, namely Bursa Nilüfer, Brașov, Bratislava, Bijeljina and Zenica have multiple challenges that require policy attention, including issues of energy and development. With the exception of Bratislava, these cities also need to strengthen energy and CO_2 mitigation measures relative to the other cities in the sample. An example for Bursa Nilüfer is provided based on the SDEWES Index Benchmarking Tool.

Sustainable Development of Energy, Water and Environment Systems Index Benchmarking Tool

Figure 10 applies the SDEWES Index Benchmarking Tool that is first developed in [6] to the results of the present sample. This tool may be used to compare two cities based on the overall performance across all dimensions (top section) and/or to the sample for a particular dimension (bottom section). In Figure 10, Bursa Nilüfer (ranked 14 in the SDEWES Index) is compared with Budapest (ranked 9). The two cities that are five rankings apart have different patterns in nearing or exceeding the sample average. In addition, dimension D_2 is selected to benchmark the cities with the SEE sample to indicate domains in which policy gaps may exist. For example, Bursa Nilüfer that is ranked 18 in D_2 uses mostly natural gas, which is a high exergy resource, for space heating and cooling in buildings. In contrast, the city may utilize the geothermal energy potential that is currently used sparingly in the tourism sector [92] to heat local residential buildings in an eco-district concept in the future. The city is currently designated as a replicator city under the Smart Cities Light House projects that focus on energy and transport measures [92, 181]. In the other dimensions, Bursa Nilüfer can be paired with cities that may have similar or different performances according to policy learning objectives.

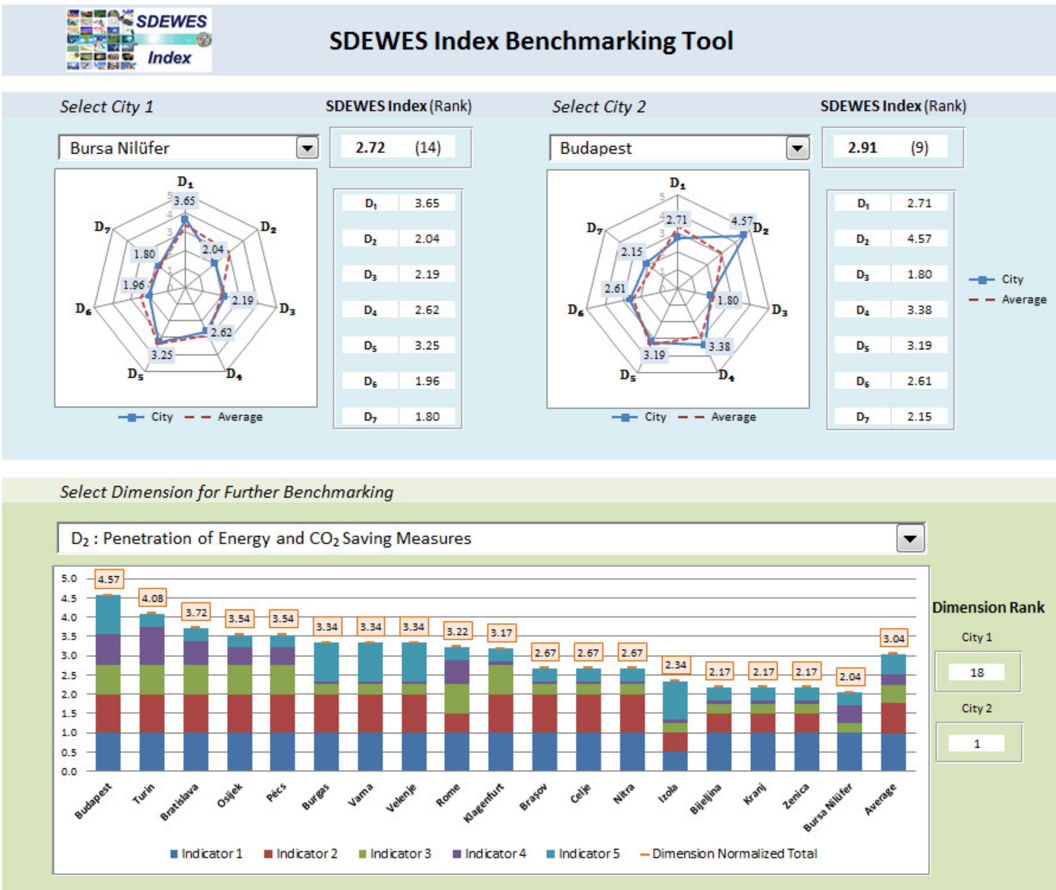

Figure 10. SDEWES Index Benchmarking Tool for Policy Learning

Interactions with the radar and bar charts can be used to compare the potential for strategic interventions towards more innovative urban systems. For example, Klagenfurt that is ranked first has the highest CO_2 reduction target for the year 2030 at a 40% reduction from the base year [95]. The city can better reach its target by mobilizing its R&D and innovation competence so that the waste of one system becomes the input of another. In another aspect, Izola (ranked 4) plans to deploy sea-water based cooling [94]. A partnership model that involves cooperating institutions and the transfer of knowledge from local examples, such as a resort in Piran that used the technology [182], can enable Izola to improve its ranking in the SDEWES Index. The ability to improve multiple indicators of the SDEWES Index at the same time will be possible with well-designed solutions. In addition, any use of bioenergy sources that meets sustainability criteria must be below emission limit values [183] that will increase benefits for public health.

Identification of city pairs for policy learning

Based on eq. (4), Table 11 exemplifies the use of the search algorithm to find cities with similar dimension performances. Cities from the previous two samples are added to diversify the overall possibilities. Among a total of 76 cities to which the index is applied to date, 8 common patterns that involve 8 cities from the present sample and 17 cities from the previous samples are found. Table 11 marks the common patterns for the city pairs based on values that are at or above (↑) or below (↓) the overall sample averages in the 7 dimensions of the SDEWES Index. In various combinations, the first 4 city pairs have above average performance in at least 4 dimensions. The last 4 city pairs have below average performance in at least 4 dimensions.

Table 11 can be used to mobilize policy learning opportunities in a targeted way to improve the performance of the cities. For example, the city pair of P_1 that contains Budapest from the present sample has an above average performance in D_2, D_4, D_5, D_6 and D_7. In contrast, the city pair of P_5 in which Bursa Nilüfer from the present sample takes part has below average performances in the same dimensions except for D_5. The decision makers in these cities can observe that exchanges across the cities in complementary aspects may provide opportunities to find best practices. In addition, Zenica (present sample), Cluj-Napoca and Skopje (previous samples) perform below average in all dimensions except D_1. Based on common areas of need, this city pair P_8 can address such issues and seek best practices from cities that have a higher performance in these dimensions.

Table 11. Identification of cities with common patterns

P_R	City in new sample	City in previous samples [3, 5-7]	Pattern						
			D_1	D_2	D_3	D_4	D_5	D_6	D_7
P_1	Budapest	Zagreb, Espoo	↓	↑	↓	↑	↑	↑	↑
P_2	Rome	Naples	↓	↑	↑	↓	↑	↑	↑
P_3	Izola	Ohrid, Zadar	↑	↓	↓	↑	↑	↑	↓
P_4	Braşov	Podgorica, Niš, Timişoara, Rijeka	↑	↓	↓	↑	↓	↓	↓
P_5	Bursa Nilüfer	Kalamariá, Seferihisar, Bornova	↑	↓	↑	↓	↑	↓	↓
P_6	Bijelina	Sarajevo	↑	↓	↓	↑	↑	↓	↓
P_7	Turin	Incheon, Nagoya	↓	↑	↓	↓	↓	↑	↑
P_8	Zenica	Cluj-Napoca, Skopje	↑	↓	↓	↓	↓	↓	↓
		Average (C_{AV2})	3.19	3.20	2.17	2.87	3.10	2.52	1.94

Overall, the SDEWES Index can provide the basis for a network of cities that can exchange experiences based on dimension performance. Cities that have opposite outcomes when compared to the average may also provide opportunities for exchanging experiences in relative strengths and weaknesses. For example, the two city pairs in Table 11 that involve Rome (P_2) and Braşov (P_5) from the present sample have opposite outcomes in each dimension of the SDEWES Index. In addition, in D_7, while R&D, innovation and sustainability policy is an area of strength for the city pair involving Rome, it is a weakness for the city pair involving Braşov. Knowledge transfer from the city pair involving Rome to the city pair involving Braşov may initiate city-to-city cooperation.

Some of the city pairs are in relative geographic proximity or in the same country, such as Rome (present sample) and Naples (previous sample) in pair P_2. Another example is Bijelina (present sample) and Sarajevo (previous sample). Most of the cities, however, are separated by distance but relatively nearer in city function. These include Izola (present sample), Ohrid and Zadar (previous sample) as smaller historical cities (P_3). Another example is Turin (present sample), Incheon and Nagoya (previous samples), which are powerful industrial cities (P_7). These results indicate that city pairs can extend well beyond borders or geographic proximity.

Evaluation of the results in contexts of urban hierarchy and development

In Figure 11, the results of the SDEWES Index are compared to contextual factors that may exceed the control of cities, such as urban population size (horizontal axis) and the development setting (vertical axis). The latter is assessed based on the Human Development Index (HDI) [184] of the country in which the city is located. The size and colours of the data markers in the bubble chart represent the quartile of the city's performance in the SDEWES Index. In addition, SEE cities that are in the present sample (solid colours) are differentiated from cities in previous samples (patterned lighter colours). The city labels contain pair numbers whenever relevant.

Figure 11 indicates that cities in a particular quartile of performance in the SDEWES Index can have a seemingly diverse background of urban hierarchy and development settings. Cities that perform within quartiles Q_4 and Q_3 (blue and green coloured markers), such as Klagenfurt, Pécs, Budapest and Varna, may be given as examples. For this reason, local decision-making choices and strategic approaches have important roles in determining the performance of cities in the SDEWES Index. In this respect, the SDEWES Index can be used to empower cities to search for opportunities to pursue more sustainable pathways for their urban futures while exploring chances to collaborate with other cities to jointly address common urban challenges.

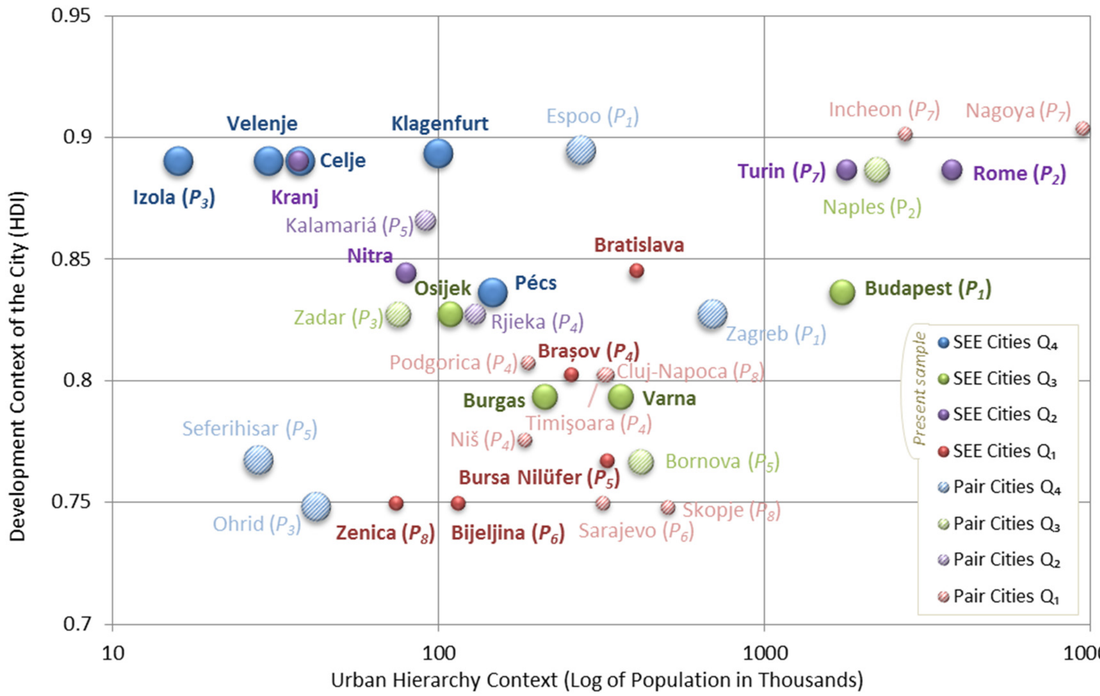

Figure 11. Comparison of results to urban hierarchy and development contexts

Mapping of a Sustainable Development of Energy, Water and Environment Systems Future City Network

The synergistic use of the benchmarking tools that are put forth in this paper for the present SEE sample and the identification of city pairs across all other samples provide a spectrum of possible uses of the SDEWES Index in support of more sustainable urban systems. The results of the SDEWES Index for the present SEE sample are also mapped on the spatial dimension as provided in Figure 12. Here, the SEE cities in the sample have different levels of performance based on the dimensions of the SDEWES Index. The existing levels of performance may be improved in the future based on the rapid implementation of actions that are already foreseen in the context of SEAP, SECAPs as well as Sustainable Urban Mobility Plans [185]. In addition, these actions should be supported by newly devised actions based on a unique process of policy learning from other cities. In the time dimension, improvements need to take place to raise the average value of the SDEWES Index for the SEE region and individual cities. The circular inset in Figure 12 provides the current average scores for the cities in the present SEE sample.

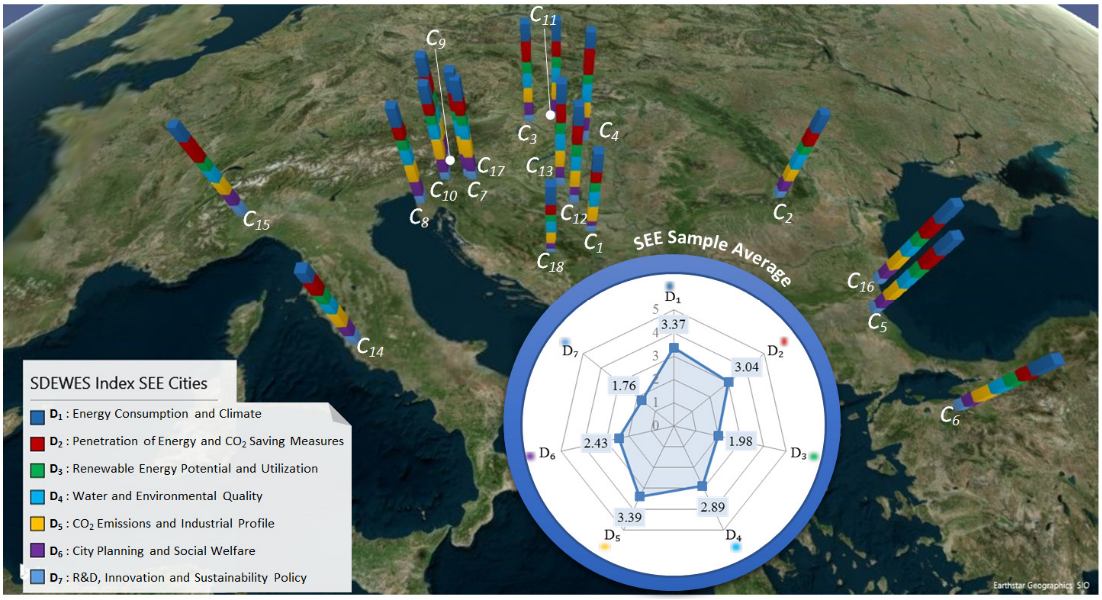

Figure 12. Mapping of the results of the SDEWES Index for the present SEE sample

Table 12 provides an overview of exemplary policy implications for urban systems based on the SDEWES Index. These policy implications also reinforce the necessity for implementing a cross-sectoral approach to attain smarter energy systems [186] at the urban level. Cities provide a vibrant context for realizing the opportunity of increasing efficiencies "by using waste from one system as an input in another" [187]. For example, local maps as developed in the Stratego project in support of heating and cooling plans include those of four cities in the present sample, namely, Braşov, Osijek, Rome and Turin [188]. As summarized in Table 13, the results of these analyses indicate the quantity of waste heat that may be extracted from urban wastewater and the availability of wood and straw resources that are less than 30 km from the city [188]. Locally available biomass resources must still be considered for use in efficient energy system configurations that may extend to an outlook based on the quality of energy (exergy) [189-191] so that the potential of displacing CO_2 emissions is maximized. Carbon capture and storage may also be used to further contribute to halving anthropogenic CO_2 emissions every decade [192].

The co-location of energy and water utilities to better benefit from distributed energy generation opportunities and to lower both energy and water requirements is another rising trend [193]. In addition, automated demand response in the urban context may extend to wastewater infrastructure, particularly in the sludge processing equipment [194]. Monetary savings from load shifting may be invested into the energy-water infrastructure. In the context of the sharing economy, the sharing of waste heat in an open district heating network, including waste heat of any data centers, is beginning to be promoted by local authorities [195]. The production of hydrogen gas from renewable electricity is also one of the key technologies for diffusing the use of intermittent energy sources [196] and has pilot demonstrations in the urban context [197]. Most importantly, the role of cities in deploying renewable energy as a means of contributing to the need to double zero-carbon shares in the energy system every 5.5 years is paramount for scenarios with a fair chance of compliance with 1.5 °C targets [192]. Renewable energy solutions and net-zero targets at the district level [198] can support multiple climate mitigation as well as climate adaptation goals. Improvements in urban form can minimize travel distances and reduce climate risks, including through an increase in permeable surfaces [199]. Despite potential changes in precipitation patterns due to global climate change, harvested rainwater and reclaimed water can be effectively maximized to reduce water demand [200].

Table 12. Exemplary policy implications for urban energy, water and environment systems

Exemplary cross-sectoral approaches	Electricity/Gas	Heating/Cooling	Building	Transport	Industry	Utilities
Diffusion of urban renewable energy solutions in all sectors	✓	✓	✓	✓	✓	✓
Incl. renewable energy and electrofuels in public/private transport	✓			✓		✓
Incl. the production of hydrogen gas from renewable energy sources	✓	✓	✓	✓	✓	✓
Increased opportunities for sharing waste heat in urban areas		✓	✓		✓	✓
Demand response, including in wastewater infrastructure	✓	✓	✓	✓	✓	✓
Material, energy, and water substitution within urban waste hierarchy	✓	✓	✓	✓	✓	✓
Co-location of energy and water utilities for resource exchanges	✓	✓	✓			✓
Improvements in urban planning to reduce climate risks	✓	✓	✓	✓	✓	✓

Table 13. Quantity of waste heat from wastewater and biomass resources based on [188]

Waste heat and biomass availabilities	Rome	Turin	Braşov	Osijek
Available heat from sewage water [TJ/year]	2,430	1,767	178	62
Available wood < 30 km [TJ/year]	454	565	1,944	968
Available straw < 30 km [TJ/year]	1,948	2,030	785	2,351

It is evident that global CO_2 emissions must peak no later than the year 2020 and rapidly decrease thereafter to reach net-zero emissions by mid-century [166, 192]. In this planetary necessity, cities are deemed as the leading actors in enabling the ability to "bend the curve" by 2020 [201] that requires a faster pace in mobilizing renewable energy and energy efficiency solutions to attain earlier reductions [202]. This mobilization will also require an integrated perspective for urban energy, water and environment systems without which the ability of cities in climate action will be compromised. The SDEWES Index that is put forth as a benchmarking tool has the potential to support cities in related endeavours and to raise awareness on chances to improve performance. The framework of the SDEWES Index and the results for the city samples has also been communicated with city managers who are responsible for energy and/or urban sustainability in their municipalities as well as CoM contact points, receiving positive feedback. Most of the cities were included in any kind of index for the first time and appreciated the chance to be compared to other cities with a common set of indicators in a benchmarking approach. The managers were also active in identifying possible ways to improve performance.

In a potential SDEWES Future City Network, decision-makers in the SEE cities can use the results of the SDEWES Index in four main steps. First, decision-makers should evaluate the overall score and dimension performance of the specific city. Second, possible solutions that are expected to improve the value of more than one indicator at the same time should be considered. Third, decision-makers should identify cities with which to strengthen or initiate collaborative efforts. Throughout these steps, urban decision-makers may further benefit from associated tools, including the SDEWES Index Benchmarking Tool for Policy Learning and the city pairs that are identified based on a search algorithm. Fourth, decision-makers should take action to increase the sustainable development of energy, water and environment systems in their cities. Periodically, the impact of the measures on city performance must be re-evaluated.

CONCLUSIONS

Urban systems will continue to have critical roles in determining the ability to address the global sustainability challenge by providing innovative urban solutions and approaches. In this context, the SDEWES Index can contribute to triggering action and collaboration in the path towards more integrated energy, water and environment systems for sustainable development. The application of the SDEWES Index to a new sample of 18 SEE cities in this research work increases the opportunities for such policy learning. The results indicate that the top three cities in the sample are Klagenfurt (3.08), Velenje (3.06) and Pécs (3.01), all of which perform above average in multiple dimensions. In addition, cities with similar challenges in and beyond the SEE region based on similar performance patterns are identified to stimulate policy learning.

The results of the SDEWES Index for the 18 cities in the present sample should not provide a static perspective of benchmarking standings since there is a dynamic potential to improve in the future. Even the 5 cities that are positioned in the top 25th percentile (Q_4) of values with a pioneering SDEWES city status in the present sample require future improvements, particularly through the synergy of cross-sector approaches. Such improvements will be possible based on additional investments according to the needs and resources of the city, including human and financial resources. Cities are in the best position to evaluate and act upon such opportunities in light of the benchmarking results, including the diffusion of urban renewable energy solutions.

In a forward-looking perspective, the SDEWES Index, its benchmarking tool and city pairings can be an effective tool to stimulate policy learning in SEE cities towards more sustainable urban systems. In this way, the index contributes to the existing stock of knowledge in aspects of renewable energy, transport, water, and waste in cities based on an integrated benchmarking approach and application. The SDEWES Index can be used to mobilize a network of cities, preferably as a SDEWES Future City Network, to collaborate in realizing the sustainable development of urban systems in the SEE region and beyond. The main steps that decision-makers and urban planners can pursue in using the results of the SDEWES Index are:

- Evaluate the overall score and dimension performance of a specific city: In this first step, decision-makers should evaluate the results of the SDEWES Index for their city. The overall score and dimension performance will provide an integrated perspective for evaluating aspects of energy, water and environment systems in the pursuit of more sustainable urban systems. Strengths in one dimension, such as R&D capabilities, may also be used to support dimensions in which there may be weaknesses to generate new urban solutions. The interactive use of radar charts and bar charts in the SDEWES Index Benchmarking Tool for policy learning will support the city level evaluation process;

- Consider solutions that will improve the value of multiple indicators: The integrated perspective that is put forth by the SDEWES Index aims to support the planning of integrated solutions. Decision-makers and urban planners can build upon this perspective to consider solutions that can address multiple indicators at the same time, particularly those that can curb CO_2 emissions and improve environmental quality simultaneously. The opportunity to increase the resource efficiency of the urban system with a combined outlook on the underlying energy, water and environment system [203] will provide the main synergetic approach to allow cities to improve values of the SDEWES Index. These include integrating renewable energy solutions in the urban energy system, utilizing sources of waste heat, diffusing demand response across urban sectors, including in wastewater treatment plants, and enhancing compact urban form;
- Identify cities with which to strengthen or initiate collaborative efforts: Given the urgency for increasing the pace with which cities make progress towards urban systems that are more sustainable, city-to-city collaboration is a necessity rather than an option. At the same time, determining the cities with which to collaborate requires a systematic diffusion of knowledge and benchmarking outcomes. Decision-makers can also refer to the results of the SDEWES Index when a search algorithm is applied to identify city pairs that have the same series of above or below average performances across all dimensions while the benchmarking tool can be used to compare two selected cities;
- Take action to increase the sustainability of development and re-evaluate: The ability of cities to better ensure the intergenerational availability and quality of resources depends upon the success of measures towards more efficient, cleaner, and integrated urban systems. For this reason, cities need to turn any contextual factors into opportunities to make this possible while targeting increases in SDEWES Index values. The monitoring results will be used to re-evaluate the benchmarking results across time.

Future directions of the research work have involved scenario analysis for assessing future opportunities to improve the integration of energy, water and environment systems in the urban context. In this respect, improvements in rank positions or the average city score given the adoption of a related set of measures is assessed. Such improvements are relevant to all cities, including those in the transitioning SDEWES city status. The cities in the solution-seeking or challenged SDEWES city quartile may also shift current trends with relatively stronger effort. The results of the present SEE sample will be useful in analysing the diverse profile of cities in these possible future scenarios in combination with other city samples from around the world. At the same time, existing optimization and planning tools should be applied on a case-by-case basis to evaluate the applicability of possible scenarios at the local level. In this respect, the SDEWES Index may provide a mobilizing mechanism to support the pursuit of cities to strive for more sustainable urban systems as one of the most dynamic contexts for realizing change.

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APPENDICES

Appendix A (supplementary material)

Tables A1-A8 present data for the sub-indicators of the main indicators of the SDEWES Index.

Appendix B (Sustainable Development of Energy, Water and Environment Systems Index Benchmarking Tool)

The SDEWES Index Benchmarking Tool is uploaded as a Mendeley Dataset in association with the present manuscript at: http://dx.doi.org/10.17632/cv2bp78gmx.1.

NOMENCLATURE

C	specific city in the sample
D	dimensions of the SDEWES Index (D_1-D_7)
D_1	energy consumption and climate dimension
D_2	penetration of energy and CO_2 saving measures dimension
D_3	renewable energy potential and utilization dimension
D_4	water and environmental quality dimension
D_5	CO_2 emissions and industrial profile dimension
D_6	city planning and social welfare dimension
D_7	R&D, innovation and sustainability policy dimension
I	normalized values of the indicators in the SDEWES Index
i	data inputs into the indicators prior to the Min-Max method
max	maximum value among all cities for a given indicator
min	minimum value among all cities for a given indicator
P	specific city pair based on the search algorithm [eq. (4)]
Q	quartile of performance in the dimensions or overall index

Greek symbols

α	weights of the dimensions of the SDEWES Index [eq. (1)]

Subscripts

AV	present sample average [used in eqs. (2) and (3)]
$AV2$	overall sample average [used in eq. (4)]
j	number of the city in the sample
x	dimension number, dimensionless
y	indicator number in the dimension

Abbreviations

ACA	Airport Carbon Accreditation
CDD	Cooling Degree Day
CHP	Combined Heat and Power
CoM	Covenant of Mayors
DH/C	District Heating and/or Cooling
EEA	European Environment Agency
GHG	Greenhouse Gas
HDD	Heating Degree Day
IEA	International Energy Agency
IUCN	International Union for Conservation of Nature
JRC	Joint Research Center
MSW	Municipal Solid Waste

PM_{10}	Particulate matter up to 10 micrometers in diameter
ORC	Organic Rankine Cycle
RES	Renewable Energy Systems
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)
SEE	South East Europe
SWERA	Solar and Wind Energy Resource Assessment
UN	United Nations
WHO	World Health Organization

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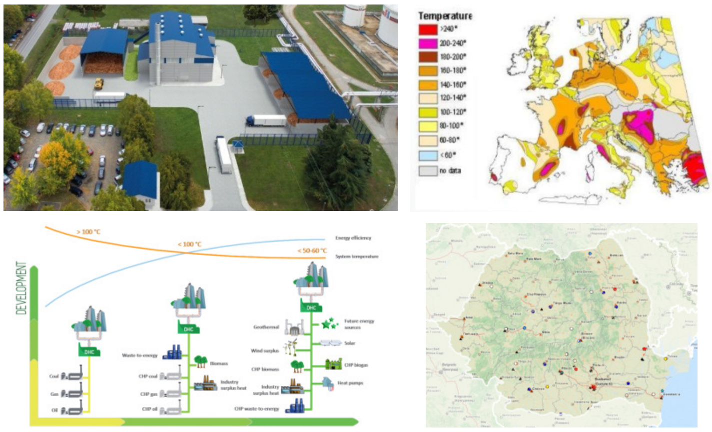
APPENDIX A. SUPPLEMENTARY MATERIAL

Table A1. Energy system characteristics based on original compilations[a, b]



City (C_j)	HOB/electric, HVAC or DH only	CHP based DH/C	Geo-thermal/solar, GHSP, seawater HP	Integration of other sources (waste heat)	
Bijeljina	✓		P		Ongoing project to integrate geothermal energy into the coal based district heating system (BGT1) [86]
Brașov		✓			SEAP measure is realized based on high efficiency CHP with 42 MW of power and 38 MW of heat [87, 204]
Bratislava		✓			PPC Bratislava CCGT CHP has design capacity of 218 MW_e; most buildings are connected to the DH network [88]
Budapest		✓			SEAP measure for high-efficiency CHP with power-to-heat ratio of 0.514 is realized as the largest CHP in Hungary [170]
Burgas		✓			CHP plant with gas reciprocating engines with capacities of 17.82 MW_e and 18.59 MW_t [91]
Bursa Nilüfer	✓				Individual heating of buildings dominate; low temperature geothermal energy is used in some touristic facilities [92]
Celje		✓			Municipal waste and sludge is used in CHP with an additional landfill gas unit [205, 206], the General Hospital plans to install CHP [93]
Izola	✓		P		Micro district heating systems are considered as future concepts, including Sea-to-City hydrothermal energy project [94]
Klagenfurt		✓			1 CHP fired by oil and NG (279 GWh_t and 68 GWh_e) and 1 CHP supplied by biomass (120 GWh_t and 40 GWh_e) [207]
Kranj	✓	P			Planned SEAP measure for the rehabilitation of the DH system with CHP units with power output of 37.2 MW [96]
Nitra			✓		DH system of 20 km for 24,167 MW_t of installed capacity and 40% covered by geothermal energy (Temp: 100/50°C) [179]
Osijek		✓			TE-TO CHP has power capacity of 89 MW_e and heat supply capacity of 139 MW_t while 3 MW_e and 10 MW_t biomass is planned [208]
Pécs		✓			Heat generating capacity of 70 MW_t and power capacity of 35 MW_e is based on biomass [178]
Rome	✓	P			Planned CHP with DH with bio-fuels up to 50% of the energy input and estimated potential of saving 25,000 tonnes of CO_2 per year [102]
Turin		✓			Three combined-cycle CHP plants for 1,200 MW_e of electrical power and 740 MW_t of thermal power in cogeneration mode [171]
Varna		✓			Biomass boiler from local sawmills plus auxiliary boilers and ORC produce 30 GWh of heat and 5 GWh of electricity [172]
Velenje		✓			77% share of DH from the coal-lignite thermal power plant in Šoštanj (256 MW_e); pilot district cooling absorption system (970 kW) [107]
Zenica	✓	P			45% is supplied with DH, 55% is individual heat system while a modern CHP infrastructure is planned [209]

[a] Data is further checked based on [210], the letter P indicates planned systems, the CO_2 emission benefits of the respective energy systems are further assessed under D_5
[b] Pictures from the top inset of Table A1 are based on [205, 118, 141, 173], respectively

Table A2. Sub-indicators for nZEB implementations in cities

C_j	National nZEB plan[a]	nZEB definition from [211]			nZEB implementation and/energy plus / carbon neutral buildings/district targets
		New buildings	Existing buildings	Minimum RE share	
Bijeljina					N/A
Brașov	✓				N/A
Bratislava	✓				EU-GUGLE site for nearly-zero energy buildings [212]
Budapest	✓(*)				Passive house residential complex and others [175]
Burgas	✓(*)	✓			N/A
Bursa Nilüfer					N/A
Celje	✓				N/A
Izola	✓				N/A
Klagenfurt	✓	✓	✓	Proposed	Villach offices & apartment [213]
Kranj	✓				N/A
Nitra	✓				N/A
Osijek	✓				Energy independent home near river Drava [214]
Pécs	✓(*)				Building with Saint-Gobain trophy ranking [175]
Rome	✓				EU-CLUE site for climate neutral urban districts [212]
Turin	✓				EU-CLUE site for climate neutral urban districts [212]
Varna	✓(*)	✓			N/A
Velenje	✓				N/A
Zenica					N/A

[a] (*) To be approved (Bulgaria) or under development (Hungary) [215]

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

C_j	Bus/ trolley bus lines	Status of tramway			Status of subway/metro			Total length urban rail [km]	Total urban area [km^2]	Urban rail density [km/km^2]	Municipal bicycle sharing	Overall score[a]
		Stations (number)	Lines	Length [km]	Stations (number)	Lines	Length [km]					
Bijeljina	✓							0	734	0.00		1
Brașov	✓							0	74	0.00	✓	1
Bratislava	✓	152	8	39.6				39.6	368	0.11	✓	4
Budapest	✓	556	33	156.9	52	4	38.2	195.1	525	0.37	✓	5
Burgas	✓							0	254	0.00	✓	1
Bursa Nilüfer	✓	23	2	9	38	2	39	48	1036	0.05		3
Celje	✓							0	23	0.00		1
Izola	✓							0	29	0.00		1
Klagenfurt	✓							0	120	0.00	✓	1
Kranj	✓							0	148	0.00		1
Nitra	✓							0	100	0.00	✓	1
Osijek	✓	20	2	12				12	169	0.07		3
Pécs	✓	-	3	16.8				16.8	163	0.10		3
Rome	✓	192	6	40	73	3	60	100	1285	0.08	✓	4
Turin	✓	-	11	84	21	1	13.2	97.2	130	0.75	✓	6
Varna	✓							0	154	0.00		1
Velenje	✓							0	13	0.00	✓	1
Zenica	✓							0	559	0.00		1

[a] Cities that have tramways or subways are further evaluated based on urban rail density, scores higher than 3 are given to densities above 0.10 km/km^2 and/or multiple modes

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

Presence of energy intensive industries in the cities	Bijeljina	Brașov	Bratislava	Budapest	Burgas	Bursa Nilüfer	Celje	Izola	Klagenfurt	Kranj	Nitra	Osijek	Pécs	Rome	Turin	Varna	Velenje	Zenica
Basic chemicals and chemical products		2	1	1	1	1	1				1			1	1	1		1
Basic precious and non-ferrous metals		1													1		1	1
Cement, lime and plaster industry		1				1												1
Ceramic products industry				1	1	1						1	1					
Iron and steel industry	1		2	1							1			1	2			2
Pulp, paper and paperboard industry					1		1		1									
Refined petroleum products industry			2		1											1		

[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 receive a binary value of 2

Table A5. Sub-indicators for urban form, green spaces, green corridors and municipal management

Urban form and municipal management	Bijeljina	Brașov	Bratislava	Budapest	Burgas	Bursa Nilüfer	Celje	Izola	Klagenfurt	Kranj	Nitra	Osijek	Pécs	Rome	Turin	Varna	Velenje	Zenica
Compact urban form (1-3)[a]	1	2	2	2	2	2	2	3	2	2	2	2	2	3	2	2	2	1
Monocentric urban form	✓				✓	✓		✓			✓					✓		
Polycentric urban form		✓	✓	✓			✓		✓	✓		✓	✓	✓	✓		✓	✓
Population density[b] [/km^2]	209	1,070	3,300	2,600	839	9,100	2,149	554	810	1,413	801	638	963	3,500	4,100	2,311	2,012	206
Urban green space (1-3)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓
Urban green park intensity[c]	1	1	2	2	2	2	1	2	1	1	2	1	1	2	2	2	1	1
Share of impermeable surfaces in the city [159]	-	63.2	50.5	62.9	-	-	-	-	36.6	-	56.9	50.3	-	44.1	62.9	50.1	-	-
Green corridor quality (1-3)	1	3	3	2	2	2	2	2	3	2	2	2	2	3	2	2	2	1
Reserve		2	3	1	2		3	2	1	2	2	2	2	4	2	3	2	
RAMSAR[d]		1	2	1	2	2		1	2	1		1	1	4				
National park		1		1		1			1						1			
Wastewater management[e]	N/A		✓	✓		N/A	✓	✓	✓	✓	✓	✓	✓	N/A	N/A		✓	N/A
Municipal waste per capita [kg]	311	313	329	377	419	400	449	449	560	449	329	393	377	486	486	419	449	311
Waste valorisation best practices[f]							✓											
Average category score	1.0	2.0	2.3	2.0	2.0	2.0	2.2	2.0	2.0	1.7	2.0	1.7	1.7	3.0	2.0	2.0	1.7	1.0

[a] Scored 1 to 3 based on both satellite images and population density with 3 being the most vivid example of compact urban form
[b] Based on Demographia World Urban Areas [216]
[c] The best practice score of 3 is given to cities with more than 40% of green area [217]
[d] Number of protected wetlands is attained based on the GIS of [218]
[e] Checked for compliance with Article 3, 4 and 5 of the Urban Waste Water Treatment Directive [161]
[f] Scored 1 for diversion measures, 2 for waste to energy schemes and 3 for regional best practices

Table A6. Sub-indicators for benchmarking R&D and innovation policy orientation

R&D and innovation policy orientation[a]	AT	BA	BG	HR	HU	IT	RO	SI	SK	TR
R&D funding approach score	3	1	2	3	1	2	2	2	1	3
General(no thematic focus)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Thematic focus (calls)	✓			✓						✓
Energy environment priority	✓		✓	✓		✓	✓	✓		✓
R&D expenditure score	3	1	2	2	2	2	1	3	2	2
GERD/GDP (percentage)	3.00	0.33	0.65	0.81	1.37	1.29	0.39	2.39	0.89	1.01
Average category score	3.0	1.0	2.0	2.5	1.5	2.0	1.5	2.5	1.5	2.5

[a] The policy scan involves R&D funding institutions, support mechanisms, and country reports from JRC [219], OECD [220] and UNESCO [221] statistics

Table A7. Sub-indicators for benchmarking national patents in clean technologies

National patents in clean technologies[a]	AT	BA	BG	HR	HU	IT	RO	SI	SK	TR
Total Y02 or Y04 patents	20,145	6	704	482	1,696	10,712	1,391	656	605	1,012
Building technologies (Y02B)	4,104	3	40	81	276	1,595	127	137	84	142
Energy generation (Y02E)	9,428	3	577	331	1,002	4,896	930	421	400	718
Transportation (Y02T)	5,743	0	72	42	336	3,926	283	70	96	112
Capture and storage (Y02C)	402	0	14	14	43	146	31	10	13	27
Smart grid (Y04S)	468	0	1	14	39	149	20	18	12	13
Y02 or Y04 patent score (1-3)	2	1	1	1	1	2	1	1	1	1
Percentage of total patents [%]	2.17	2.78	1.89	2.82	2.73	2.23	1.97	2.11	1.95	1.63
Total percentage score (1-3)	2	2	1	2	2	2	1	1	1	1
Average category score	2.0	1.5	1.0	1.5	1.5	2.0	1.0	1.0	1.0	1.0

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

Table A8. Number of public, private, and Scimago ranked universities

Universities in local innovation system	Bijeljina	Brașov	Bratislava	Budapest	Burgas	Bursa Nilüfer	Celje	Izola	Klagenfurt	Kranj	Nitra	Osijek	Pécs	Rome	Turin	Varna	Velenje	Zenica
Number of universities	2	3	8	10	2	3	3	1	2	1	2	1	1	9	3	5	1	1
Public/polytechnic	0	2	6	7	0	2	0	1	2	0	2	1	1	5	3	4	0	1
Private universities/colleges	2	1	2	3	2	1	3	0	0	1	0	0	0	4	0	1	1	0
Scimago Ranked[a]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Located in the city	0	1	3	14	0	1	0	1	1	0	2	1	1	4	2	0	0	0
Located in the country	1	19	9	23	6	60	6	6	18	6	9	10	23	64	64	6	6	1
Concentration in city [%]	0.0	5.3	33.3	60.9	0.0	1.7	0.0	16.7	5.6	0.0	22.2	10.0	4.3	6.3	3.1	0.0	0.0	0.0
University weighted score	2	4	11	24	2	4	3	2	3	1	4	2	2	13	5	5	1	1

[a] Based on top 1000 institutional rankings including universities and research institutes in [222]