Towards Smart Green Cities: Analysis of Integrated Renewable Energy Use in Smart Cities

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Abstract

This study aims to estimate and explore the experience of introducing renewable energy use in the context of the world's smart cities. In this regard, the study points out that the use of green energy is an important part of sustainable development. Environmental problems are a matter of global concern. Hence sustainable development is one of the approaches to end the harmful anthropogenic impact. The work includes quantitative assessment methods, for example, statistics, quantitative analysis, analogy, and synthesis. As a result, the analysis confirms that the effective development of a smart green city is impossible without the introduction of several renewable energy sources, the integrated use of which will reduce the likelihood of problems with the city's energy supply. Likewise, the outcome accentuates that the desire to fully switch to renewable energy sources (RES) can be accompanied by several problems as the creation of RES technologies does not always

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take the risk of abnormal situations into account. In conclusion, the research findings are recommended to be taken into consideration by researchers in the field of smart and sustainable cities development, as well as urbanists and economists for designing future smart green cities based on renewable energy sources.

Keywords: Smart green city, greening, renewable energy, green city, integrated implementation of renewable energy, sustainable development, sustainable cities, energy generation, energy efficiency, smart technologies, solar power.

Introduction

The problem of ecology is of concern to all states. Environmental pollution is a global problem that affects all of humanity. It implies a high content of chemical and biological reagents, which leads to negative consequences such as the depletion of natural resources, destruction of ecosystems, the rise in global sea level. The main goal is to make the world greener and urban areas more comfortable for citizens. A smart city is one of the concepts that help solve global problems.

With the growth of the urban population smart city concept has become widespread. People draw attention to the upcoming change in cities: Smart administration, Smart buildings, Smart grid, Smart transportation, etc., which would allow calling cities 'smart' (1). Some such urbanized areas are built from scratch (e.g., Masdar, OAE (Sankaran, 2020), Songdo, South Korea (Kuecker, 2020) or Eko Atlantic city, Nigeria (Ajibade, 2017)), others are the results of advancement and complex work on existing cities and towns (e.g. Singapore, Helsinki, Zurich, Auckland – the fourth first cities of the Smart City Rank in 2020 (IMD, 2020)).

Our society is thinking about changing the space around to improve the quality of our life and the planet as a whole. In 2015, the United Nations ("UN") put forward 17 interrelated sustainable development goals, which are aimed at achieving a better and more sustainable future for the whole world. In 2017, all UN member states adopted a 15-year plan to achieve these goals. Obviously, becoming a smart green city directly contributes to the achievement of the eleventh and the seventh SDG goals: Sustainable cities and communities, Clean Energy.

The smart city paradigm has a long changing path and, what is more, different concepts of smart cities highlight various aspects: ones emphasize the changed attitude of smart city dwellers to the urban areas and their role in it, others prioritize the role of advanced IT technologies. However, these approaches are based on the idea of implementing autonomous IT assets in urban areas, so that a city becomes more efficient and enhanced (the so-called 'smart cityism' (McQuire, 2021)). As long as energy supply is put under an additional load by the IT assets, and evolving society is concerned about environmental issues, usage of renewable energy sources in smart cities is unquestionable. Therefore, the key issue in the establishment of a smart city is to make its energy supply stable and green.

The use of renewable energy sources is the most economically profitable way to meet energy demand. With the development of technologies, the cost of renewable energy is constantly decreasing, while productivity is increasing. In many countries the unsubsidized normalized cost of electricity Levelized Cost of Energy ("LCOE"), generated by onshore wind and solar power plants, has already equaled or fallen below the cost of energy generated by most other technologies. According to the Lazard study, the LCOE of wind and solar energy varies from $30 to $60. US $ per 1 megawatt-hour (MWh, while the same figure for the cheapest fuel of traditional energy (natural gas) is around 40% higher and amounts from $42 to $78 per 1 MWh). Moreover, renewable energy sources also respond to the demand of society in a more environmentally friendly world order. Greening is one of the trends of the 21st century. The main goal of greening is the idea of a sustainable city, a holistic system where social, environmental, and economic aspects of development interact in a complex way. In recent years, international organizations have introduced several documents, the main purpose of which is to reduce harmful emissions into the environment: the IMO rules on limiting the sulfur content in bunker fuel, the Paris Agreement on Reducing the Content of Carbon Dioxide in the Atmosphere.

Moreover, some European countries have imposed a ban on the entry of vehicles with an internal combustion engine. The authorities reduce the level of harmful emissions into the atmosphere by setting such restrictions. At the same time, in contrast to traditional energy sources, renewable energy sources do not lead to greenhouse gas emissions during use. This approach is fully consistent with current trends.

Another argument in favor of RES is the fact that traditional energy sources (oil, gas, etc.) can be completely depleted, so in order not to get into a critical situation, society should gradually switch to RES.

There is a constant increase in the efficiency of RES, so we can conclude that this type of energy is a good solution for the concept of smart city.

However, renewable energy sources have their drawbacks. In many regions, solar energy production has the highest productivity in the summer and falls to low values in the winter. The hydroelectric power station has the greatest capacity in the spring, but the latter often changes from year to year. Wind energy is quite variable, both from year to year and from month to month. Renewable energy sources cannot provide uninterrupted electricity supply throughout the year if they are used separately. Therefore, for the development of a smart city, it is necessary to implement renewable energy sources concurrently. This approach can be achieved by using hybrid power plants. A hybrid energy system refers to the use of several types of renewable energy sources: solar, wind, hydro, bioenergy, etc. Thus, the sources complement each other, providing an uninterrupted power supply for the consumer, despite natural conditions and the time of year (Masera et al., 2018).

The object of the research is smart cities. The subject of the research is renewable energy in the smart city system.

The purpose of the article is to analyze the modern world practice of the integrated implementation of renewable energy sources.

This study expands the existing body of knowledge in the field of smart city establishment. It emphasizes the significance of knowledge gained to be implemented by municipalities and governance in enhancing smart cities and increasing their number. Moreover, this study might be beneficial for developers on the local and regional levels as it may provide the information on how to reach better results in innovative projects of redeveloping existing areas and establishing the new ones, or in tackling environmental issues.

Hypothesis

Modern society is aware of the environmental problems that they will have to face in the near future due to the irresponsible consumption of traditional energy sources. At the same time, as described above, the implementation of the infrastructure of smart, green cities will help us achieve at least 7 SDG goals and make the planet more environmentally friendly. The hypothesis of the study is that the effective development of a smart, green city is impossible without the introduction of several renewable energy sources, the integrated use of which will reduce the likelihood of problems with the city's energy supply.

Methodology

To achieve the objectives of this article, a review of the relevant literature and research was conducted. A search in key databases such as Web of Science, Scopus, Google Scholar was carried out to obtain suitable literature.

There was also a general internet search,using the following keywords: “smart city”, “biomass”, “renewable energy”, “greening cities” in the available headlines, excerpts or keywords. No restrictions were found on geographic locations or years in the literature. The reviewers based their analysis on publications in English, German, Russian, which made it possible to consider in more detail the problem of introducing smart cities around the world. The search result amounted to 90 works.

The review was based on the fact that the articles reflected the experience of the integrated implementation of renewable energy sources in smart cities around the world. The present paper will also refer to statistics, which will be presented in the work using the data of paper. The work also includes quantitative assessments methods, for example, statistics, quantitative analysis, analogy and synthesis.

Analysis Results

The authors chose five different cities in order to demonstrate the empirical evidence of smart green city establishment for further study of renewable energy implementation. The selection of smart cities was based on their energy use and efforts of greening. Therefore, a detailed overview of cases of San Diego (California, USA), Malaga (Andalucia, Spain), Kennedy Energy Park (Queensland, Australia), Vancouver (British Columbia, Canada), Austin (Texas, USA) is provided in further analysis.

San Diego, California

San Diego is the second-largest metropolitan area in California with the population of over 3 million people. Being a conservative place, it is still set to be a leader in the US in applying smart city technologies (Clayton, 2017). Ecological issues have prompted such interest in the reduction of greenhouse gas (“GHG”) emissions. Hence, Climate Action Plan (“CAP”) of the city of San Diego was proposed in 2015 (City of San Diego, 2015). It put forward five major strategies for greening the city. One of these strategies was to spread the usage of clean and renewable energy. According to the CAP, the city has to run on 35% of renewable energy by 2020 and shift to its entire use by 2035. That would lead to the reduction of GHG emissions by half by 2035 (City of San Diego, 2015). Due to San Diego's location solar power has the biggest capacity, though wind power, methane gas and landfill gas apply, as well. The fourth strategy of the CAP is waste management, due to the production of methane gas and landfill gas, in order to decrease GHG emissions, is set to be profitable in both cases.

To create an incentive for citizens several policies have been implemented: money compensation is given for certain amounts of solar energy production, there is no taxation for producing renewable energy for householders, furthermore, citizens get compensation for the energy they send back to the grid (Wheeland, 2016). San Diego Gas & Electric ("SDG&E"), local utility, supports the needs of the city and offers 50% or 100% renewable energy (it provides natural gas, renewable energy and unspecified sources) for residential, non-residential and municipal customers (San Diego Gas & Electric, 2016). The SDG&E-created program of supplying 100% of renewable energy is called EcoChoice. It provides solar power from facilities of a general size of 99 MW (San Diego Gas & Electric, 2016).

CAP's authors made a comparison with the year of 1990, assuming that by 2020 GHG level would be at the same level as in 1990, and by 2035 – 40% lower. The 2010 baseline for the CAP is 12,984,993 Metric Tons of CO2 which was intended to be the maximum amount of GHG in 2010. Already in 1995 there were first 'green' movements: City's Green Building Demonstration Project was presented, and 33.3MW of solar power was produced in the region by the year of 2005 (City of San Diego, 2005). Nevertheless, electricity from coal and hydro power was presented in San Diego's grid until the end of 2000s, from nuclear power – until 2012.

To understand the results of the CAP and smart city establishment projects we should consider the dynamics of solar and wind power usage and GHG reduction. In the Solar Siting Survey (December 2018) approximately 100 technical photovoltaic sites were identified, which produced over 490 MWac of electricity (Clean Coalition, 2018). The City of San Diego 2020 Climate Action Plan Annual Report Appendix shows the change of percentage of renewables in San Diego's grid (Figure 1). Starting from 2010 the major rise in renewables use has been observed, at the same time witnessing a slight decrease of 1% in 2018. Appearance of solar, wind power, biomass and biofuel in recent years remains roughly the same: solar and wind power vary between 20-21% each, while biomass and biofuel contribute to 1–2% of the whole supply (San Diego Gas & Electricity, 2016, 2017, 2018).

Year	Renewables in SDG&E Electricity Supply
2010	11%
2011	16%
2012	19%
2013	24%
2014	32%
2015	36%
2016	43%
2017	44%
2018	43%

Figure 1 Renewables in SDG&E electricity supply.
Source: https://www.sandiego.gov/sites/default/files/cap-2020-annual-report-appendix.pdf

The number of photovoltaic sites increases every year, which makes a higher percentage of renewable energy in the grid. According to that, the GHG emissions are set to decrease. Indeed, as was proposed in the CAP, by the time of 2019 there has been a 25% reduction of GHG emission from the 2010 baseline (Figure 2). This result occurred even more profitable than it was expected in the CAP: in 2019 GHG emissions were 9.6 million MT CO2e – to 9.8 million MT CO2e in 2020 planned in the CAP (City of San Diego, 2015). The empirical results of the mid-deadline of 2020 could be seen in the nearest future. Therefore, as long as the Climate Action Plan of San Diego remains successful, with the 100% usage of renewable energy in 2035 GHG emissions would decrease in half (approximately 6 million MT CO2e).

Using solar and wind power as main sources of renewable energy San Diego still needs other types of renewable energy to cover its goals of becoming the smart green city. San Diego's plan of wide-spreading solar power mostly relates to the electricity supply, while other energy-intensive sectors of urban processes rely on other types, for example, the transportation system requires mainly biofuel, or methane gas and landfill gas should be produced in waste management to lower GHG emissions.

Hence, the establishment of a smart green city could not be obtained without the complex use of different energy sources. San Diego maintains the title of a smart green city and provides an example of "smart" administration and regulation - an appealing, for customers, system of photovoltaic construction installation that allowed the city to boost solar power.

Austin, Texas

Austin is the capital of the state of Texas. This city is one of the cleanest metropolitan areas in Texas and also ranks 12th in the United States in

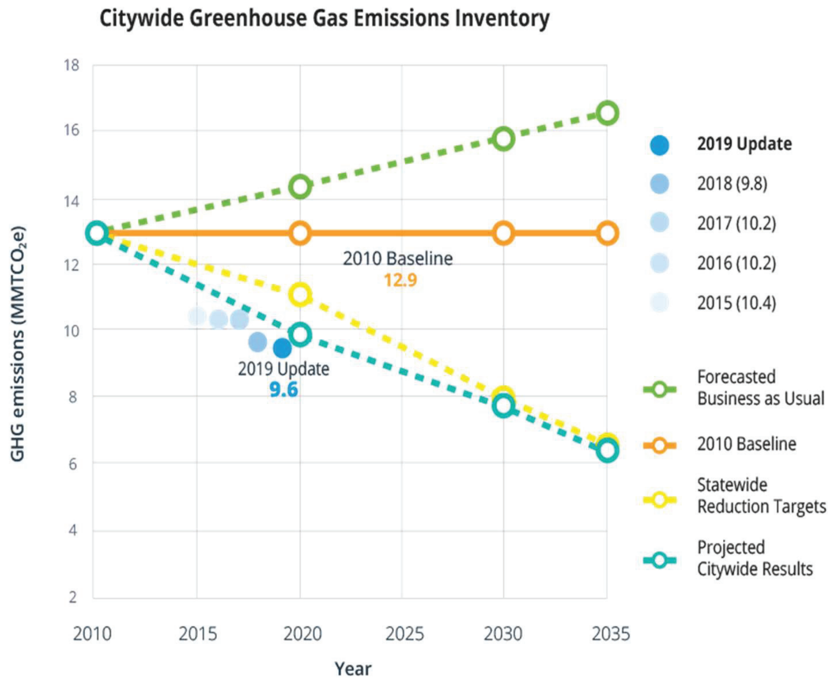

Figure 2 Citywide greenhouse gas emissions inventory.
Source: https://www.sandiego.gov/2020cap

terms of sustainability. Austin has built a reputation for being an environmentally sustainable, green, progressive and innovative city not only locally but internationally. Austin is known for its active citizens concerned on many issues of sustainability and fairness. This is evidenced by the active involvement of Austinites in the sustainable development and environmental justice movements. The role that active citizens play in sustainable development movements, as exemplified by Austin, is fundamental to the city's sustainable success, progress and growth.

In 2012, as part of Austin Energy's GreenChoice program and Austin's Climate Protection Plan, enterprises in the city, from libraries and entertainment centers to police stations and fire stations, were converted to renewable energy.

Most of Austin's renewable energy comes from a wind farm in western Texas. Solar energy is developing in the city too. Austin residents who are unable to install solar panels on their homes for some reason can invest in a community solar pool. Although about 200 days a year are sunny in Austin, solar energy provides a small amount of energy to the grid and is only a supplement to other forms of energy (wind, hydropower, biomass). Nationwide, 1 megawatt of solar power supplies power to 164 homes. According to this criterion, by 2025 Austin Energy's solar capacity will provide electricity to almost 156,000 local homes. About 5% of the city's energy comes from hydroelectric power plants on the Austin lake and rivers. Moreover, anaerobic digesters are already in operation in the city to convert vegetable, animal waste from farms, as well as food and household waste from garbage into energy.

At the moment, the Austin Energy City Utilities Company, which is responsible for the power system in the city, has set itself quite aggressive goals:

1. Providing by 2025 at least 55% of renewable energy sources.
2. Switch to 65% renewable energy sources by the end of 2027.
3. Equipping the utility service area with solar panels with a total capacity of at least 950 megawatts by 2025.
4. Zero CO2 emissions by 2035 (Joe Biden campaign the company)

In February 2021 abnormal frosts (about −20 degrees Celsius) were recorded in Texas, which led to freezing of renewable energy equipment. Texas' power equipment was not prepared for such frosts, as electricity consumption peaks in the summer. Thus, about 4 million people were left without water and electricity.

There is an opinion that Texas' commitment to renewable energy is to blame for the current situation, but this is the wrong point of view. Gas stations and nuclear power plants were also disconnected from the power grid due to outages. Thus, it can be concluded (which is confirmed by the Governor of Texas, Greg Abbott) that this problem arose due to the state's undeveloped electrical system, whose infrastructure was not oriented to such cold weather.

The implementation of solar and wind power enables the creation of additional workplaces, enhancement of buildings' energy efficiency.

Malaga

Malaga is one of the smartest cities of Spain. Abetted by sunny weather, the city and it's neighborhoods create a great opportunity for the construction of wind and solar power plants. ENDESA, a Spanish energy company, noticed this fact. Led by Endesa, another 25 companies and research organizations participated. (Carillo-Aparicio, 2013)

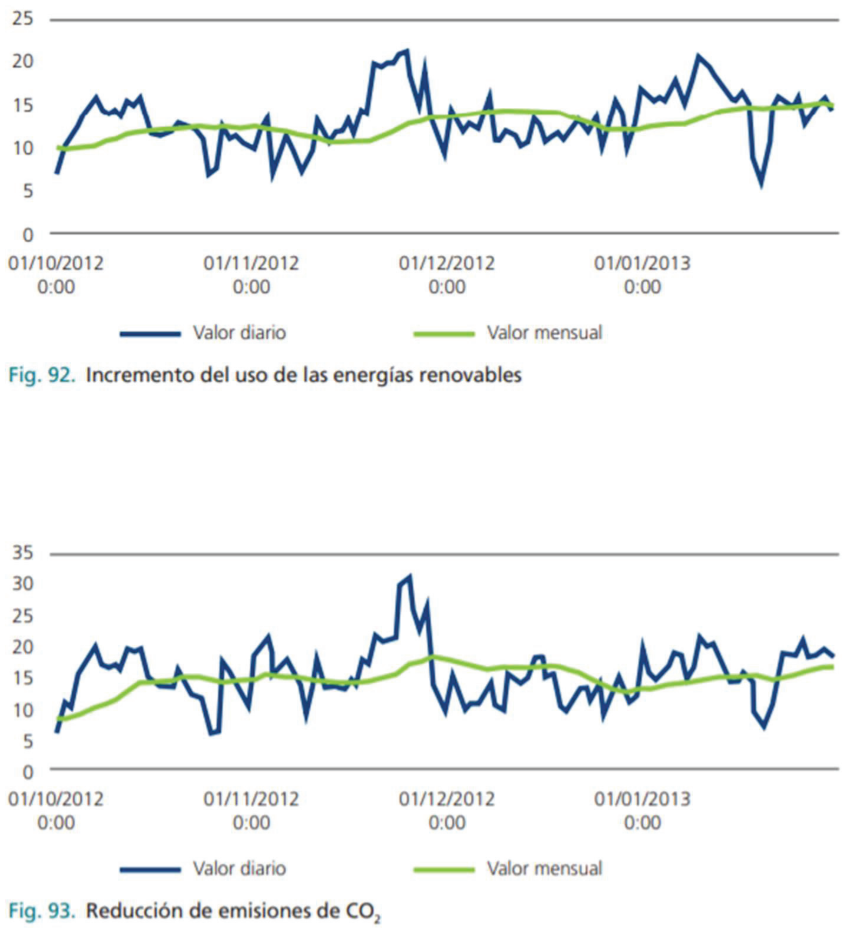

Figure 3 Reduction of CO2.
Source: https://www.ingenieros.es//files//Proyectos_1/Smartcity%20Malaga_ESP.pdf

The goals of this project were:

1. to create an advanced measurement infrastructure ("AMI")
2. to create buildings with energy-efficient facilities and a fleet of energy vehicles using V2G technology. (Carillo-Aparicio, 2013)

To implement this project, 12,000 smart meters were introduced, 69 street lights were replaced with LED ones,72 MV/LV substations connected by PLC, with a total of 40 km MV lines connected, 12.94 MW of MV generation and 43.25 kW of LV generation.

The main result of this project is the reduction of CO2 emissions (Endesa, 2013). This system helped to decrease 4,500 million tons of CO2, up the 20% reduction (Pascual, 2014). There is also 25% of energy consumption saving urban residents' energy consumption was reduced by 42% by using internal energy efficiency kits. It allowed the residents to manage their expenses from anywhere in the world using a smartphone (Ayuntamiento de Málaga, 2013).

Thus, this project is progress in the field of sustainable development. The Smart city Malaga project is an example for many countries through the introduction of electric vehicles and the optimization of energy use.

Kennedy Energy Park, Australia

The problem of RES is their instability. By using multiple energy sources together, new capacity and reliability metrics can be achieved. One possibility is to use solar and wind energy together. Solar energy increases in the morning when the wind subsides, and in the evening when the sun sets, the wind begins to increase and can steadily produce energy at night. Kennedy Energy Park (KEP) is the world's first solar, wind and energy storage project, which confirms the effectiveness of such an integrated approach (Kennedy energy Park, 2018).

KEP is located in Flinders Share in central north Queensland, Australia. The project is owned by Windlab and Eurus and is funded by: CEFC ($94 million), and received an $18 million grant from ARENA (Vorrath, 2017). The facility was approved in 2016, construction began in 2017, and it was put into operation in 2019. Kennedy Energy Park includes 43 Mw of wind, 15 Mw of solar panel, and 2–4 Mw of battery power. The location of the object is determined by the high level of solar radiation and wind intensity, which allows it to constantly produce electricity. The complementary nature of wind and solar resources in Kennedy is shown in Figures 4–5 (Windlab, 2018).

In 2016, the ARENA Commission presented a Report from AECOM, which explored the potential for co-location of wind and solar power plants in Australia. Each existing wind farm was supposed to have its own hypothetical solar one.The report calculated the total power factor of the project. Power factors ranged from 45% to 61%, with Alinta being the most efficient wind farm in the study. In the case of Kennedy Energy Park, it is projected to achieve a combined capacity factor of 73%, far exceeding the next best project (AECOM, 2016).

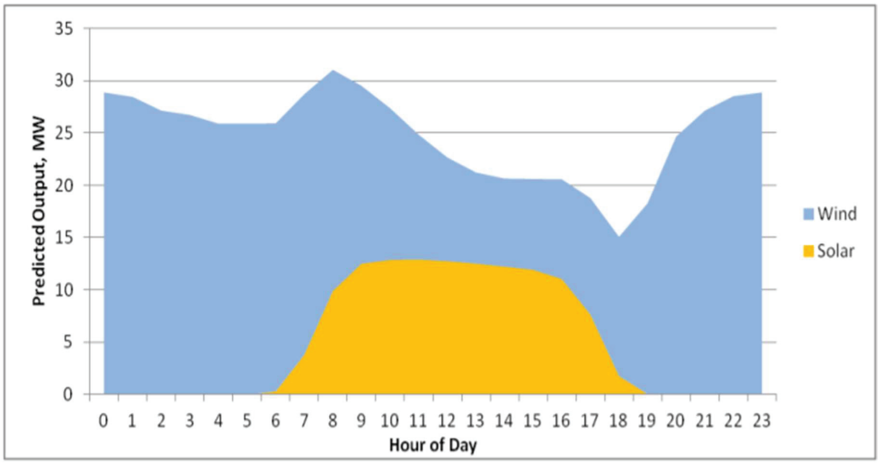

Figure 4 Diurnal profiles of the wind and solar generation at Kennedy.
Source: https://kennedyenergypark.com.au/knowledge-sharing/

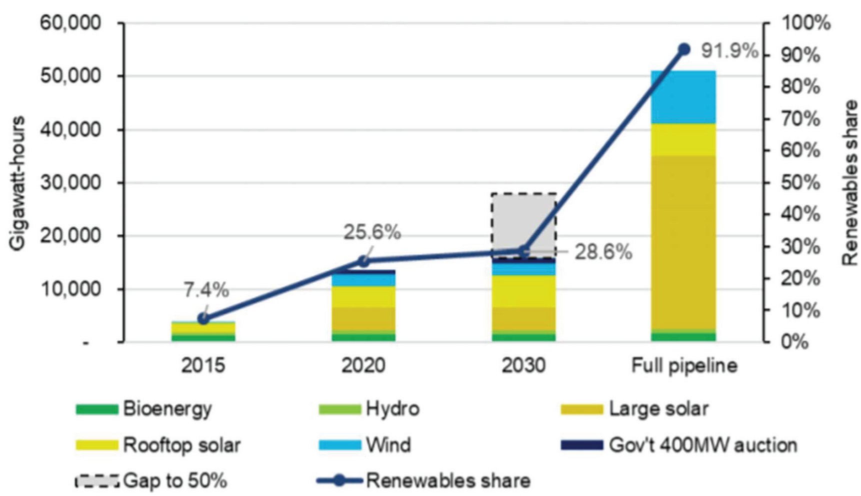

Figure 5 QLD renewable energy power generation and share of consumption.
Source: http://greenmarkets.com.au/images/uploads/GEM%20Reports/Industry%20Reports/Renewable_Energy_Across_Qld_Regions.pdf

Overall, the consumption of renewable energy in Queensland grows rapidly, as the number of renewable energy projects is also increasing. Based on the projects under construction and the expected results of the absorption of solar energy, an increase in the consumption of electricity generated from renewable energy sources is projected: from the share of RES 7.4% in 2015 to 25.6% in 2020.

Kennedy Energy Park is an experimental project. Over the entire period of the project's existence, the following goals are expected to be achieved:

1. Queensland has achieved a 50% renewable electricity target for 2030 (Windlab, 2018)
2. Reduction of CO2 emissions by 3 million tons.
3. Construction of up to 1200 MW of renewable energy generation in Australia
4. Providing electricity from renewable energy to more than 800,000 homes

Such actions are a huge step in sustainable energy production. Solar-wind hybrid technologies can be used in countries located in Eurasia and Africa and are close to the equator where there is a large amount of solar radiation, a fairly arid climate and flat areas predominate for more convenient placement of solar panels and wind turbines.

Thus, this project combines both the technologies implemented in the city functions, and reasonable management of natural resources and the environment. The existence of Kennedy Energy Park, a smart green project, supports the hypothesis of this study, as it specifically illustrates the complementarity of two types of renewable energy.

Vancouver

Canada is a resource-rich country, but moreover, the government is engaged in the introduction of RES in various cities, especially smart ones.

Vancouver is the 8th largest city in Canada and since its inception, residents have already consumed 59 million gigajoules of energy annually in 2015, resulting in 2.8 million tons of CO2 equivalent (City of Vancouver, 2015). The government was concerned about the environmental situation in the city and in 2015 a decision was made to create a 100% clean city using renewable energy sources, so 2 main goals were set by 2050:

1. Getting 100% of energy through the use of renewable sources
2. Reduction of greenhouse gas emissions by 80% compared to 2007 (City of Vancouver, 2015).

The government focused on the development of the city's transport system and the creation of smart buildings, which in the future will use only clean energy sources, that is, provide residents with electricity, heating, and

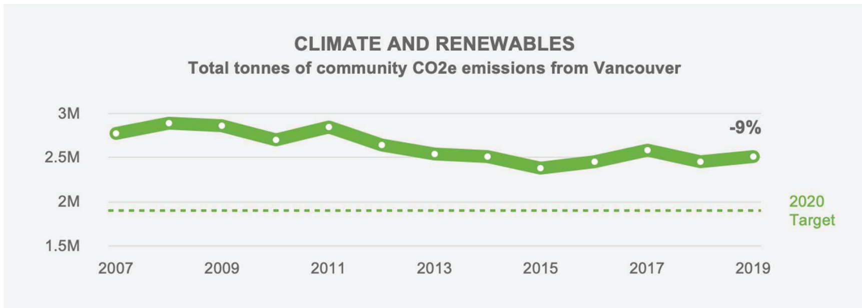

Figure 6 CO2 community emissions in Vancouver.
Source: https://vancouver.ca/green-vancouver/climate-and-renewables.aspx#climate-progress

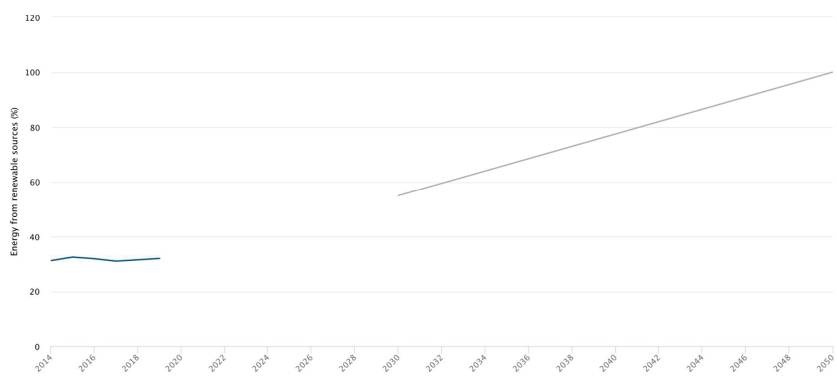

Figure 7 Energy from renewable sources from 2014 to 2050.
Source: https://opendata.vancouver.ca/pages/indicator/?q=cardid%3D77

cooling. Also, to successfully achieve the set goals, the city government has developed three strategies (City of Vancouver, 2015):

1. Environmental: Greenest City 2020 Action Plan
2. Economic: Vancouver Economic Action Strategy
3. Social: Healthy City Strategy

Also by 2020, which was an interim reporting year, a goal was set to reduce greenhouse gas emissions by 33%, but for 2019, emissions were reduced only by 9% compared to 2007 (Figures 6–7).

The main source of energy in Vancouver is solar energy, for example, 52 solar panels were installed on the roof of the Vancouver Public Library, which currently is provided lighting for the floors of the building. Also at the time of the start of the project, 31 billion dollars were invested in the city (2010–2014) (Clean Energy Canada, 2018).

However, it should be noted that the government has made some improvements in the construction of clean houses, CO2 emissions have been reduced by 43% despite these successes, the government must work more to reach the 2050 targets. In 2019, the amount of energy obtained from renewable energy sources was 32%.

This actively demonstrates that Vancouver is currently a promising city and project, but the government should consider how to improve the effectiveness of strategies to successfully achieve these goals.

Thus, we understand that the Vancouver authorities must use renewable energy sources other than solar energy to achieve their goals. That is, our hypothesis is confirmed.

Conclusion

The research results in literacy analyses and the systematization of modern approaches to smart sustainable cities proves the hypothesis that the smart sustainable city concept is a prospective concept of urban development and the most promising approaches are based on the principles of smart-green integration. RES, oriented on SDG7 and SDG 11, is the driver of smart sustainable development in all worls as it was presented on the cases from EU (Spain), USA, Canada and Australia.

The study proved on the cases that the effective development of a smart, green city is impossible without the introduction of several renewable energy sources, the integrated use of which will reduce the likelihood of problems with the city's energy supply.

Likewise, the outcome accentuates that the desire to fully switch to renewable energy sources (RES). can be accompanied by several problems as the creation of RES technologies does not always take the risk of abnormal situations into account. In conclusion, the research findings are recommended to be taken into consideration by researchers in the field of smart and sustainable cities development, as well as urbanists and economists for designing future smart green cities based on renewable energy sources.

The Covid-19 pandemic in 2020 and 2021, proves the efficiency of the smart city concept, because cities with developed smart city concepts navigated the pandemic COVID-19 more effectively than others. So a smart city could be an efficient base for the development of urban health and sustainable city concepts in the future.

The findings provide evidence that the research results could be implemented around the world in the design of concepts of smart sustainable cities and for the future development of theoretical approaches to smart sustainable city concepts.

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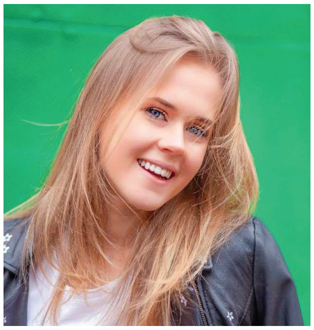
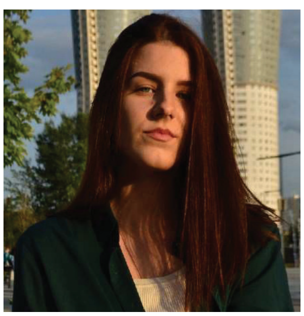
Biographies

Natalia Vukovic is an Associate Professor in the Department of World Economy of Faculty of World Economy and International Affairs at National Research University Higher School of Economics (Moscow, Russia), where she research the topic of Renewable Energy Sources, Sustainable Cities and Sustainability. She took her Ph.D. degree in Russian Academy of Science in 2007. From 2016 she is invited professor in Belgrade Banking Academy in the field of Green Economy. Natalia participated in many international sustainable projects in China and Europe.

Uliana Koriugina is a student of the HSE University, Moscow, Russia. She majors in urban planning. Her research interests include city development, urban energy consumption, smart cities, and urban sociology.



Daria Illarionova is a student of the HSE University, "World Economy" Bachelor's programme. It is important for her to develop an eco-friendly infrastructure. She claims that ecology is the future. She works for a marketing agency. Also considers green energy not only as a benefit for the world, but also for success in commercial activities.



Daria Pankratova is a graduate of the HSE University in Moscow. She studies supply chain management. Her professional interests include green logistics, logistics of return flows, and greening of urban space. She sees her role in developing logistics support projects of infrastructure facilities in the field of renewable energy.

Polina Kiseleva is a student of the HSE University in Moscow, Russia. Polina majors in world Economy and International Affairs, her second language is German. Her professional interests include renewable energy prospects, zero waste lifestyle and ecology. Author believes that one person can change the whole world for the better.

Alina Gontareva is a graduate of the HSE University in Moscow. She studied economics in the oil and gas sector of Russia. Her professional interests include economics in the oil and gas sector, trends of green energy, renewables, and prospects for developing urban space. Alina works in KPMG Moscow as an auditor.