Resilience of Renewable Energy Systems

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ABSTRACT **Resilience is the ability of a system to resist unwanted influences and effects during its proper operation. The concept of resilience provides a new framework for how to "measure" the vitality/adaptability of systems and analysis systems, which faces many challenges (predictable and/or sudden changes). The resilience index of a defined energy system with the selection of the specific indicators reflects specific constraints, namely the change of individual indicators with other indicators being constant. The paper in the analysis of renewable energy systems (PV-solar and wind-based power plants) takes into consideration the following indicators: change of electricity costs, change of energy consumption of the system, change of the energy costs, change of electricity, change of concentration pollution gases for solar power plant, and change of wind power density, change of efficiency of wind power plant, change of frequency and change of electricity costs for wind power plant.**

KEYWORDS resilience, indicators, renewable energy

1 Introduction

A system is in control if it is able to minimise or eliminate unwanted variability, either in its own performance, in the environment, or in both. In order to be in control, it is necessary to know what has happened, what is happening, and what may happen, as well as knowing what to do and having the required resources to do it. A resilient system must have the ability to anticipate, perceive, and respond (Afgan, 2010). When resilience is lost or significantly decreased, a system is at high risk of shifting into a qualitatively different state. Restoring a system to its previous state can be complex, expensive, and sometimes even impossible.

Resilience provides a new framework for analysing economic, ecological, technological, and social systems in a changing world that faces many uncertainties and challenges. It represents an area of explorative research under rapid development with major policy implications for sustainable development.

Since the beginning of the 1990s, there has been a growing evolution of the principles for organisational resilience and in the understanding of the factors that determine human and organisational performance. The research group uses a different terminology and provides the term engineering resilience for the property resilience and the term ecological resilience for the stability property robustness (Afgan, 2010).

By appreciating the dynamic and cross-scale interplay between abrupt change and sources of resilience, it is obvious that the resilience of complex adaptive systems is not simply about resistance to change and conservation of existing structures. Resilience is defined as the capacity of a system to absorb disturbance and reorganise while undergoing change, so as to still retain the same essential function, structure, identity, and feedbacks (Folkea, 2006).

Resilience is the ability of any system to avoid or minimise, and recover from, the effects of adversity, under all circumstances of use. In addition, resilience can be defined in at least two more ways. The first is a measure of the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour. The second, a more traditional meaning, is a measure of resistance to the disturbance and the speed of return to the equilibrium state of a system (Afgan, 2010).

The resilience of an energy system is defined as the capacity of an energy system to withstand perturbations from e.g. climatic, economic, technological, and social causes and to rebuild and renew itself afterwards (Kainan, 2006).

The time change of the economic indicators is common to the classical evaluation of a system. Any crises of the economic system are preceded with corresponding changes in the economic indicators of the system. Qualitative measurement of the indicator changes may lead to the forecast of the economic crises, which is only one element of the potential disastrous changes of the system that affects its safety (Afgan & Carvalho, 2008).

The change of social element of complexity of the system is a property of the complex system. The social aspect of the system includes the risk of changes as health hazards and may have to deal with a compounding of complexity at different levels. It is of interest to notice that some of the social changes are inherent characteristics of the system. As an example, we can take any strike, which is the result of the economic changes of the system. A similar example can be seen if there is a sudden change in the environment, which will lead to social disturbances (Afgan, 2010). This paper is devoted to the resilience assessment of renewable energy systems (primarily PV-solar power plant and wind power plant), as a complex problem for the urban community.

2 Renewable Energy

Renewable energy continued to grow against the backdrop of increasing global energy consumption, particularly in developing countries, and a dramatic decline in oil prices during the second half of 2014. 176 countries (increased again) had defined renewable energy targets by 2016 (REN21, 2016, REN21 2017). Globally, there is a growing awareness that increased deployment of renewable energy is critical for addressing climate change, and thereby creating new economic opportunities. Renewables also are an important element of climate change adaptation, improving the resilience of existing energy systems and ensuring delivery of energy services under changing climatic conditions.

Renewable energy (all renewables) provided an estimated 19.3% of global final energy consumption in 2015. The most rapid growth, and the largest increase in capacity, occurred in the power sector, led by wind, solar PV, and hydropower. Growth has been driven by several factors, including renewable energy support policies and the increasing cost-competiveness of energy from renewable sources (REN21, 2017).

The supply of biomass for energy (heat, power, and transport) has been growing at around 2.5% per year since 2010 (REN21, 2017). The geothermal industry (for electricity and thermal energy) continues to face significant project development risk, and various efforts are underway to ameliorate such risks in developed and developing countries (REN21, 2016, REN21 2017). Geothermal energy global output was 78 TWh for power and 79 TWh for heat, in 2016 (REN21 2017). Several EU cities (e.g. Munich, Paris, Bordeaux) are expanding their geothermal district heating network. Ocean energy capacity, mostly tidal power generation, were in some form of pilot or demonstration projects.

Hydropower is still giant among its peers. Global hydropower capacity reached over 1,000 GW (REN21, 2016, REN21 2017). Solar PV is starting to play a substantial role in electricity generation in some countries as rapidly decreasing costs have made unsubsidised solar PV-generated electricity cost-competitive with fossil fuels in an increasing number of locations around the world. The CSP (Concentrating Solar-thermal Power) market remains less established than most other renewable energy markets. Wind power is the cheapest option for new power generation. Wind generated more than 20% of electricity in several countries: Denmark (37%), Ireland, and Portugal. 11 out of the 28 Member States had a wind penetration rate of more than 10% (Nghiem & Mbistrova, 2017).

In recognition of the importance of renewable energy and energy efficiency for sustainable development, the United Nations General Assembly declared 2014 the first year of a decade of Sustainable Energy for All (SE4ALL). SE4ALL aims to double the share of renewable energy in the global energy mix from a baseline share of 18% in 2010 to 36% in 2030 (United Nations Decade of Sustainable Energy for All 2014-2024, 2015; Tracking Progress, 2015; Our Objectives, 2015).

New global investment in renewable power and fuels (not including hydropower >50 MW) was USD 241.6 billion in 2016, as estimated by Bloomberg New Energy Finance (REN21, 2017). Renewables outpaced fossil fuels for the sixth year running in terms of net investment in power capacity additions with 9.8 million jobs in 2016 (REN21 2017).

Stronger position in terms of taking responsibility for climate change by the USA during two mandates of President Obama has resulted in the signing of the Paris Agreement of 2013, which opens new perspectives for RES, especially in developing countries. It remains to be seen what lies ahead of us.

3 Renewable Energy and the Environment

Each renewable energy source has its own particularities (hydropower, biomass, wind energy, solar energy, geothermal energy, tidal energy, wave energy, Ocean Thermal Energy Conversion - OTEC). This also relates to environment and landscapes. The focus here will be on only some specifics on wind energy and PV-solar energy.

3.1 Wind Energy

Wind turbines have some negative as well as positive impacts on the environment. The possible negative impacts of wind turbines are: visual impact, noise, fatal accidents involving birds and bats, shadow effect, and pollution during manufacturing and installing the wind turbines, as well as land use, electromagnetic interference, marine mammals, etc. Each wind energy plant must complete an environmental assessment impact and monitoring measures. A number of studies have concluded that these impacts are minor or easy to avoid.

TYPE	ENERCON E-70	NORDEX N80	REPOWER 5M	VESTAS V90/3 MW
Hub height (m)	57 / 64 / 85 / 98 / 113	60 / 80 / 100; 115 (lattice)	100 / 120 onshore	80 / 105
Rated power (kW)	2300	2500	5000	3000
Tower construction	Concrete, tubular steel	Conical tubular steel, lattice	Conical tubular steel	Conical tubular steel
Tower weight (t)	140 / 232 / 336 / 1171	115 / 193 / 281 / 205		175 / 275
Nacelle weight (t)	66	86	290	70
Cut-in wind speed (m/s)	2,5	4	3,5	4
Cut-out wind speed (m/s)	28-34	25	25	25
Rotor diameter (m)	71	80	126	90
Swept area (m²)	3959	5026	12 469	6362
Rotor speed (rpm)	6-21,5	10,9-19,1	6,9-12,1	8,6-18,4
Blade weight (kg)	6000	8700	19 000	6600

TABLE 3.1 Characteristics of wind turbines *(Johnsen, Baars, & Ellinghaus, 2007)*

Wind turbines (windmills) have been a feature of the landscape of Europe for more than 800 years. Wind turbines are highly visible elements with rotating blades in the landscape. Table 3.1 shows the main gabarit (dimensions) characteristics of some types of wind turbines that can be found on the market.

In flat areas, wind turbines are often placed in a simple geometrical layout, while in hilly areas the turbines follow the altitude contours of the landscape and therefore they have a better layout. Big wind turbines with low blade rotation speed, and similar size and type, fit better in the surroundings than a greater number of small turbines with higher rotation speed, in terms of their visual effect as an environmental factor. Large wind turbines produce the same amount of energy as large number of wind turbines with decreased power. There may be economic advantages to this, such as lower maintenance costs. In the first half of 2016, approx. 71% of the wind turbines erected in Germany had a hub height of more than 120 m (Ender & Neddermann, 2016).

Large modern wind turbines have become very quiet. Birds do collide with high-voltage power lines, towers, cars, windows of buildings. In Denmark there are several examples of birds nesting in cages mounted on wind turbine towers. Some birds get accustomed to wind turbines very quickly, while others take a somewhat longer time. A number of environmental assessment impact and monitoring measures studies (including offshore wind farms) came up with the conclusion that birds almost always modify their migratory routes. However, migratory routes of birds should be taken into account when siting wind turbines.

Wind turbines cast a shadow on the neighbouring area when the sun is visible. The rotor blades cause a flickering (blinking) effect while the rotor is in motion. In Germany, the judge tolerated 30 hours of shadow flicker per year (Hinweise zur Ermittlung und Beurteilung der optischen Immissionen, 2002). In addition, there are possibilities of computing a shadow map (Zlomusica, 2013).

Wind energy plays an important role in helping nations reach Kyoto Protocol targets. Environmental benefits of wind electricity can be assessed in terms of avoided emissions compared to other alternative electricity generation technologies (CO_2, SO_2 and NOx and other pollutants). Emissions that are avoided by using wind farms to produce electricity instead of coal or natural gas power plants are quantified in Table 3.2, comprising NGCC - Natural Gas Combined Cycle and NMVOC - Nonmethane volatile organic compounds. The CO_2 emissions related to the manufacture, installation, and servicing over the average 20-year life cycle of a wind turbine are offset after a mere three to six months of operation, resulting in net CO_2 savings thereafter (Lago, et al., 2009).

	BENEFITS		
	vs. coal	vs. Lignite	vs. NGCC
CO_2, fossil (g)	828	1051	391
SF_6, fossil (mg)	2546	236	984
NOx (mg)	1278	1010	322
NMVOC (mg)	65	3	123
Particulates (mg)	134	693	-6
SO_2 (mg)	1515	3777	118

TABLE 3.2 Emissions avoided by using wind farms to produce electricity *(Lago, et al., 2009)* / Source: CIEMAT

Wind energy is not only a favourable electricity generation technology that reduces emissions, it also avoids significant amounts of external costs of conventional fossil fuel-based electricity generation.

Wind turbines and access roads in wind parks occupy less than 1% of the area in a typical wind park. Table 3.3 shows land used by some power plants in terms of the power produced per square metre.

	SITE	**DATA**	**LAND USE**
Hydropower	Itaipu (Brasil) Spiez (Swiss)	12 600 MW 23 MW	6 W/m^2 70 W/m^2
Coal (lignite) fired plant	Schkopau (Germany) Buschhaus (Germany)	1000 MW 380 MW	8 W/m^2 31 W/m^2
Wind park	Germany	4.5 – 6 m/s	50-120 W/m^2 (rotor area). Foundation area is 10 times less

TABLE 3.3 Power per square metre land used *(Gasch & Twele, 2002)*

The average installed power of an onshore wind turbine reached 2.84 MW in Germany in the first part of 2016. The share of wind turbines with installed power 3.0 – 3.49 MW was 56.6% (Ender & Neddermann, 2016).

The average annual electricity consumption in households in Federation of Bosnia and Herzegovina is 4.483 kWh per year. The average number of occupants in a household is 3.2 (The Institute for Statistics of FB&H, 2016).

An example: The output of a wind turbine depends mainly on the turbine's size and the wind's speed at the location of the wind park. An average wind turbine (onshore) with a capacity of 3 MW can produce more than 6 million kWh per year for Bosnian wind conditions. It is enough to supply 1,338 average Bosnian households or 4,282 members of households with electricity.

3.2 PV - Solar Energy

PV-solar cells can be classified into three type of generation cells. The first generation is made of crystalline silicon (polycrystalline and monocrystalline silicon) and this is a dominant PV technology. The monocrystalline solar panels have the advantage of having the highest efficiency rates (15-20%). Most installed solar panels are monocrystalline panels. The main disadvantage of monocrystalline solar panels is their price. The process used to make polycrystalline silicon is simpler and not expensive. The efficiency of polycrystalline solar panels is about 13-16%.

Second generation or thin-film PV panels have about 12% efficiency rates. The different types of thin-film solar cells can be categorised by which photovoltaic material is deposited onto the substrate:

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIS/CIGS)
- Organic photovoltaic cells (OPC)

Solar panels based on amorphous silicon, cadmium telluride, and copper indium gallium selenide are currently the thin-film technologies that are commercially available on the market. Their mass-production is simple, and they are cheaper, but they require a lot of space in comparison with e.g. monocrystalline.

The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics. Most of them are still in the research or development phase.

For those with limited space, crystalline-based solar panels are the best choice, but if you want the lowest investment costs per rated power then it is advisable to investigate the thin-film solar panels. Different computer programs (calculators) have been developed to calculate the size and costs of PV systems for certain locations and conditions (e.g. PVGIS, see more at: http://photovoltaic-software.com/pvgis.php or HOMER, see more at: http://www.homerenergy.com/pro-faq.html).

A PV-plant doesn't emit gaseous and pollutants, but in the case of fire CIS and CdTe modules, there is a risk of emitting of highly toxic substances into environment.

Building-integrated PV modules can be in facades, roofs, windows, walls (e.g. noise barriers alongside highways) which do not require additional land. It will be visible to neighbours, and it can be attractive or not.

Multi-megawatt PV-plants are installed on land specially designated for that purpose and this will have visual impact. The total land required, at a rough estimate, for a 1 MW power plant setup is around 1.5-2 hectares for crystalline technology and around 2.5-3 hectares for thin-film technology, and this may vary based on type of technology, efficiency of panels, and the location of the solar plant.

4 The Resilience Concept

The sudden change of the indicator and its return to the primary state is the measurement of the capacity of the respective system to withstand the changes of the system. There are several potential changes of every system that may result in the eventual catastrophic event. It is important to visualise the characteristic behaviour of the sudden change of the indicator. The integral value of the indicator in the time scale, until it reaches the steady state, is the measuring parameter of the resiliency index (Afgan, 2010; Afgan & Cvetinović, 2011; Holling, 1973; Kainan, 2006). It is possible to use the Sustainability Index as the resilience metric parameter.

It is assumed that the Sustainability Index (Afgan, 2010; Afgan & Carvalho, 2008; Zlomušica & Afgan, 2010) is a linear agglomeration function of products between specific indicators and corresponding weighting coefficients. It will be adapted so that each of the specific indicators is weighted by the respective weighting coefficient. The sum of a specific indicator multiplied by the corresponding weighting coefficient will lead to the Sustainability Index, $Q(t)$, with the following mathematical formulation:

$$Q(t) = \sum_{i=1}^{i=k} w_i q_i(t)$$

Where are:
w_i - weighting coefficient for the i-th specific indicator;
q_i - i-th criterion for sustainability assessment.

The evaluation of the energy system as the complex system is the prestigious goal of the modern approach to the validation of the energy system. In this context, the notion of the Resilience Index is introduced as the agglomerated indicator for the measurement of the energy system quality (Afgan, 2013). The Resilience Index presented in Fig. 4.1 is a graphical presentation of the sudden Sustainability Index change in time and its recovery to the initial state of the system.

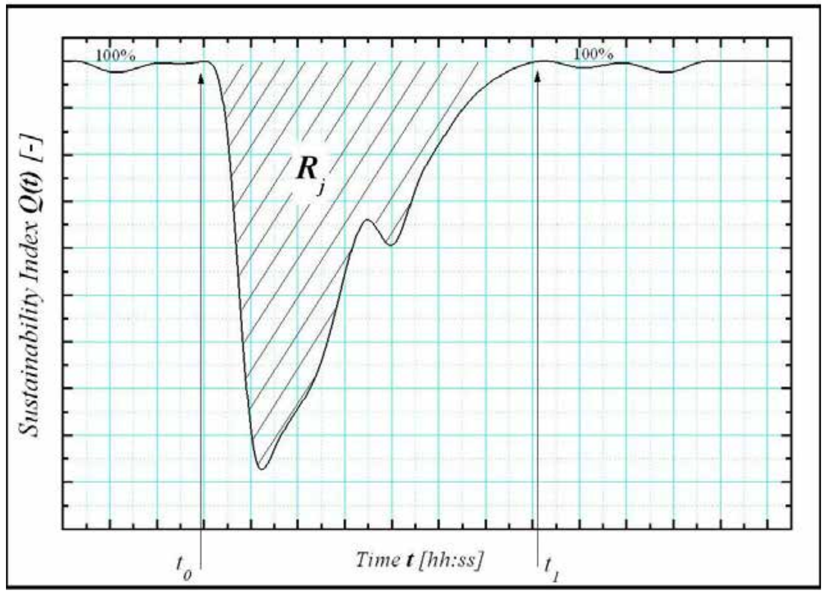

FIG. 4.1 Graphical presentation of Resilience Index *(Afgan, 2013)*

The Resilience Index is integral to the Sustainability Index between time of sudden change in the respective indicator and the time when it resumes a steady state value (Afgan, 2013; Afgan, 2010; Afgan & Cvetinović, 2010). The Resilience Index for an energy system is composed of the following elements: economic, environmental, technological, and social indicators. The Resilience Index is expressed with following mathematical formulation:

$$R_j = \sum_{i=1}^{i=k} w_i \int_{t=t_o}^{t=t_1} [100 - q_i]\, dt$$

Where *j* stands for resilience indicator.

In this definition it is anticipated that the time is an independent constant for every indicator. The sudden change of the specific indicator from the initial value will be recovered within the time period Δt. Under the assumption that the sudden indicator change represents a linear function of time, then it can be written as:

$$R_j = \frac{1}{2}\, w_i(\Delta q_i \Delta t_i)$$

Where are:
Δq_i - indicator change;
Δt_i - time change.

If it is assumed that the time interval for resuming starting state is equal for all indicators and then the Resilience Index for the individual case is:

$$R_j = \frac{\Delta t_0}{2}\, w_i \Delta q_i$$

The total Resilience Index is an additive function of all Resilience Indexes is:

$$R_{tot} = \sum_{n} R_j$$

Where are:
Rtot – total Resilience Index;
Ri – specific change.

5 Selection of the Resilience Index Indicators

In analysis of the Resilience Index of an energy system, the following indicators can be taken into consideration: economic, environment, and social indicators.

Change of energy (power) consumption of the system indicator and the Investment Cost indicator are used as the economic indicators, as shown in Fig. 5.1. The recent problem of global warming has introduced the need for the assessment of man-made pollution with the substitution of new energy sources in order to prevent further pollution problems. It is very common that the change of environment in the vicinity of an energy system is change of concentration pollution gases. The Social Indicators, the elements of resilience at the community level, can be observed through: employment, crime rates, tourism, education, health care, city infrastructure, demographic factors, or other culturally defined variables. But at the individual level, choices in livelihoods and social investments are more likely to be observed through income and other variables such as migration, which indicate stability at the household level. Fig. 5.1 presents an example of an agglomeration scheme of the Resilience Index of energy system.

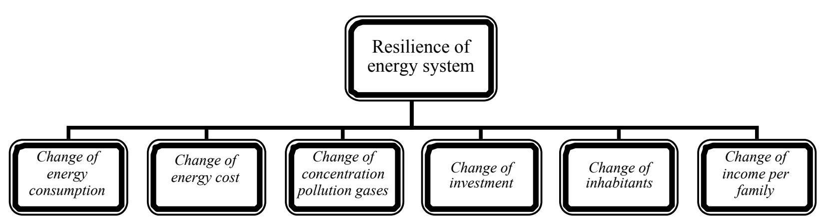

FIG. 5.1 Agglomeration scheme of the Resilience Index

Change of energy (power) consumption of the system (kWh/cap)
The change of energy consumption is an imminent problem for any energy system. There is possibility to have sudden increase of the power demand in some urban regions leading to the potential critical state of the energy system. It is important to emphasize that the change in power consumption and its maximum value may result in the catastrophic event.

Change of energy costs

The energy costs indicator is one of the economic indicators that is subject to sudden changes due to market fluctuation. It is usually expressed in the c€/kWh reflecting the market change of the economic environment. Analysis shows that the maximum change of energy cost indicator value is e.g. 30% of the standard energy costs while its minimal value is zero, meaning that there is no change of this indicator under this condition.

Change of the investment costs

The Investment Cost indicator comprises the investment (material, manpower, and capital costs) needed to recover damage caused to the hardware elements induced in the potential change of system structure. These changes are followed by the expenses expressed in EUR (€). The maximum value of this indicator is e.g. 10%, while the minimum value is 0.

Change of concentration pollution gases

It is very common that the change of environment in the vicinity of an energy system is manifested by the change of concentration pollution gases. In some evaluations, changes in CO_2 can be taken into a consideration, meaning the increase of concentration of CO_2 in exhaust gases. CO_2 emissions are the sum of the CO_2 emissions per unit of electricity produced expressed in kg/MWh. In the assessment of the potential changes of this indicator, it is anticipated, for example, that the maximum value of this indicator is 400 g/kWh while its minimum value is zero.

Change of the income per family

If a sudden change of income per family is introduced with other indicator changes this option will correspond to potential social impacts to the Resilience Index. As was defined for other options, if the sudden change of income per family leads to an unexpected change of the Resilience Index, then even the catastrophic can be expected. Otherwise, this situation can lead to social events that may be difficult to control. Analysis shows that the sudden changes can lead to no salary, discount salary, or full salary.

Change of the inhabitants

Mobility and migration are important indicators of resilience. However, resilience or changes in resilience cannot simply be inferred from the presence or absence of migration in any given community, the degree of labour mobility, or an increase/decrease in total population over time (as in the Western Balkans). Significant population movement may be evidence of instability, or could be a component of enhanced stability and resilience, depending on the type of migration. Migration may be caused by an adverse state of affairs in the local community or state level and often has negative impacts on social infrastructure on both sides of the migration. The maximum value of this indicator may be, for example, 5% in next 10 years.

Indicators, as shown in this section, can have multiple sub-indicators. In the following simplified examples, only some indicators were used.

6 Demonstration of Photo-Voltaic Power Plant Resilience

The quality of the photo-voltaic (PV) plant can be defined by the sustainability index, including economic, environment, and social indicators. The economic indicator includes electricity costs and electricity production. The electricity production indicator reflects total energy production by the PV plant. The environment indicator comprises reduced CO_2 emission; it is anticipated that 1 GW coal fired power plant produces 6 Mt CO_2 /year. The social indicator includes maintenance costs which arise from the need for cleaning PV modules. Indicators analysed in this example are: electricity costs, electricity production, and CO_2 emission, with maximum, minimum, and mean values of the specific indicator. See Table 6.1.

ELECTRICITY COSTS (EC) EUR/kWh	ELECTRICITY PRODUCTION (EP) kWh/DAY	CO_2 EMISSION (ENI) g/kWh
0.23	40	0
0.115	80	100
0	0	220

TABLE 6.1 Sustainability indicators *(Afgan, 2010)*

The Sustainability Index based on the indicators as shown can be defined by following expression:

$$Q = w_1 q_1 + w_2 q_2 + w_3 q_3$$

Where are:
w_1 - weighting coefficient for electricity costs indicator;
w_2 - weighting coefficient for electricity production indicator;
w_3 - weighting coefficient for CO_2 emission reduction indicator;
q_1 - electricity costs indicator- EUR/kWh;
q_2 - electricity production indicator – kWh/day;
q_3 - CO_2 emission reduction indicator – g/kWh.

The first step in the Sustainability Index determination is the normalisation of the indicators. This means that the special procedure is adapted for the formulation of the Sustainability Index as the aggregation function of the indicators. The next step is to define the constraints for the weighting coefficient. In this analysis it has used following cases of constraints:

- Case 1 - Electricity Costs > Electricity Production = Environment Indicator
- Case 2 - Electricity Production > Electricity Costs = Environment Indicator
- Case 3 - Environment Indicator > Electricity Costs = Energy Production

The resilience of the PV power plant is the capacity of the plant to withstand sudden changes of the indicators. The Resilience Index will be determined as the sum of all indicators of sudden change multiplied by time period needed for their recovery. The Resilience Index rating for each case will be obtained in numerical form, corresponding to the constraints as specified for each case. For each case, the maximum value Resilience Index will be determined and presented as the rating among the analysed cases. This approach will give us the possibility to validate the change of indicators in terms of safety of the energy system under a specific constraint. The Resilience Index for PV plant is defined by formula:

$$R = (w_1 \Delta q_1 + w_2 \Delta q_2 + w_3 \Delta q_3)\Delta t$$

Where are:
Δq_1 - change of electricity costs;
Δq_2 - change of electricity production;
Δq_3 - change CO_2 emission.

In order to determine the specific value of the Resilience Index for the individual cases, the following options are taken into a consideration. The option design is based on the priority given to the change of individual indicators. Each option is defined using a maximum change of specific indicator and the changes to which other indicators are introduced, as specified in Table 6.2. The following options of PV plant resilience were taken into consideration:

- Option A is based on the assumption of an Environmental indicator change (EnI) of 0 g/kWh, with an Electricity production indicator (EP) of 4 kWh/day and Electricity costs (EC) of 0.023 EUR/kWh.
- Option B represents a maximum of Electricity production indicator change (EP) of 8 kWh/day, while other indicators have some mean values.
- Option C represents an Electricity cost indicator change of 0 and the other indicators change as shown in row Option C in Table 6.2.

OPTIONS	ELECTRICITY COSTS (EC) CHANGE ΔEUR/kWh	ELECTRICITY PRODUCTION CHANGE (EP) ΔkWh/DAY	CO_2 EMISSION (ENI) CHANGE Δg/kWh
Option A	0.023	4	0
Option B	0.0115	8	10
Option C	0	0	20

TABLE 6.2 Resilience indicators for PV power plant *(Afgan, 2010)*

The total Resilience Index is determined for the following cases, where priority is given to the criteria in a specific case, while other indicators have the same value:

- Case 1 - Electricity Costs Change > Energy Production = Environment Indicator
- Case 2 - Electricity Production >Electricity Costs Change = Environment Indicator
- Case 3 - Environment Indicator > Electricity Costs Change = Energy Production

7 Demonstration of Wind Power Plant Resilience

In this case, it will be assumed that every indicator is measured in the time interval *Δt*. In addition, it is assumed that the air temperature and air pressure are constant. The following indicators are taken into consideration:

- Change of wind power density
- Change of efficiency of wind power plant
- Change of frequency
- Change of electricity costs

Nominal values and sudden changes of indicators are given in Table 7.1

OPTIONS	WIND POWER DENSITY (WPD) Δm/s	EFFICIENCY OF WIND PARK (EWP) Δ%	POWER FREQUENCY (PF) Δ AMPERE	ELECTRICITY COSTS (EC) EUR/kWh
Options 1	4/20	2.5	1.25	0
Options 2	2	5/100	2.5	1.25
Options 3	1	1.25	5/50	2.5
Options 4	0	0	0	5/20

TABLE 7.1 Resilience indicators for wind power plant *(Afgan, 2010; Afgan & Cvetinović, 2010)*

In the design of the analysed objects, it is assumed that the sudden change of indicators is triggered at the same moment for all indicators. Additionally, the changes of indicators are normalised and the maximum change for each of the indicators is expressed in a normalised value. Each object is defined as the composition that simulates sudden changes in all indicators, as shown on Table 7.1. The total Resilience Index is determined for the following cases:

- Case 1 - WPD > EWP = PF = EC
- Case 2 - EWP > WPD = PF =EC
- Case 3 - PF > WPE = EWP = EC
- Case 4 - EC > WPPD = EWP = PF

The results obtained for these cases are shown in Table 7.2.

In terms of the wind power plant analysis, it is proven that, in the most stable case, the sudden change of the indicators is in Case 2, when the priority of the indicators is given to the Efficiency Wind Power plant.

CASE	RESILIENCE INDEX
Case 1	0.755
Case 2	0.866
Case 3	0.612
Case 4	0.647

TABLE 7.2 Rating list *(Afgan, 2010; Afgan & Cvetinović, 2010)*

8 Conclusions

The Resilience Index is a stability parameter of any system and it can be used as the measuring parameter for the assessment of potential hazard events.

The sustainability change in time is defined as the resilience of the system. It describes the safety capacity of the system. With the monitoring of the sustainability change of the system in time, it can be used as the diagnostic parameter of the system's safety.

There are a number of the indicators that can be used for the assessment of the stability of the system. The selection of appropriate indicators is a primary goal in the design of the system stability. It reflects the quality of the system measured by the appropriate changes of the indicators.

The Resilience Index will be determined as the sum of all sudden change indicators multiplied by the time period for their recovery. The Resilience Index rating for each case will be obtained in the numerical form, corresponding to constraints as specified for each case. For each case, the maximum value for the Resilience Index will be determined and presented as the rating among the analysed cases.

As a conclusion it is important to mention that the Resilience Index is the parameter of the system that can be used as the diagnostic tool in the assessment of the potential hazard event of the system, as is clearly shown in this paper.

References

Afgan, N. (2010). Sustainability Paradigm: Intelligent Energy System. *Sustainability 2*, 3812-3830. doi:10.3390/su2123812

Afgan, N. (2010). *Sustainable Resilience of Energy Systems (Energy Science, Engineering and Technology).* New York: Nova Science Publishers, Incorporated.

Afgan, N. (2013). *Resilience of Sustainable Power Plant Systems in Catastrophic Events.* San Diego, United States: Elsevier Science Publishing Co Inc.

Afgan, N., & Carvalho, M. (2008). *Quality, Sustainability and Indicators for Energy System.* New York: Begell House Publisher.

Afgan, N., & Cvetinović, D. (2010). Wind Power Plant Resilience. *Thermal Science 14(2)*, 533-540. DOI: 10.2298/TSCI1002533A

Afgan, N., & Cvetinović, D. (2011). Resilience of High Voltage Transmission System. *Energy and Power Engineering 3*, 600-606. doi:10.4236/epe.2011.35075

Avdić, S., Imamović-Kaljanac, N., Vesković, A., & Šečerbajtarević, A. (2016). *Survey on energy consumption in households 2015.* Sarajevo: The Institute for Statistics of FBiH.

Ender, C., & Neddermann, B. (2016). Wind Energy Use in Germany - Status 30.06.2016. *DEWI magazin 49*, 62-72.

Folkea, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, 253–267.

Gasch, R., & Twele, J. (2002). *Wind Power Plants.* Berlin: Solarpraxis.

Holling, C. (1973). Resilience and Stability of Ecological System. *Annual Review of Ecology and Systematics*, 1-23.

Johnsen, B., Baars, A., & Ellinghaus, T. (2007). *Wind Turbine Market 2007, Types, Technical Characteristics, Prices.* Hannover: SunMedia Verlags-GmgH.

Kainan, A. (2006). *Concepts and Practices of "Resilience": a compilation from various secondary sources.* Bangkok: United States Indian Ocean Tsunami Warning System Program.

Lago, C., Prades, A., Lechón, Y., Oltra, C., Pullen, A., & Auer, H. (2009). *Wind Energy – The Facts, Part V.* Retrieved from http://www.wind-energy-the-facts.org/

Länderausschuss für Immissionsschutz (2002). *Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen* (WEA-Schattenwurf-Hinweise), [Instructions for the determination and assessment of the optical emissions of wind power plants].

Nghiem, A., & Mbistrova, A. (2017). *Wind in power - 2016 European statistics*. Brussels: WindEurope.

REN21. (2016). *Renewables 2016 Global Status Report*. Paris: REN21 Secretariat.

REN21. (2017). *Renewables 2017 Global Status Report*. Paris: REN21 Secretariat.

Sustainable Energy for All (2015). *Tracking Progress*. Retrieved from http://www.se4all.org/tracking-progress

Sustainable Energy for All (2015). *Our Objectives*. Retrieved from http://www.se4all.org/our-vision/our-objectives

Sustainable Energy for All (2015). *United Nations Decade of Sustainable Energy for All 2014-2024*. Retrieved from http:// www.se4all.org/decade

Zlomusica, E. (2013). Wind - Energy sources of the future. K. M. Lee, & J. Kauffman, *Handbook of Sustainable Engineering*. New York: Springer-Verlag.

Zlomušica, E., & Afgan, N. (2010). Sustainability Evaluation of Resident Building in Bosnia and Herzegovina. *The 10th International Conference for Enhanced Building Operations - ICEBO*. Kuwait City.