DOI: 10.14621/ce.20170206

Fuzzy Logic Approach for Sustainability Assessment based on the Integrative Sustainability Triangle – An Application for a Wind Power Plant

Jan Bitter*, Stephan Printz, Kristina Lahl, René Vossen, Sabina Jeschke

Cybernetics Lab IMA/ZLW & IfU, RWTH Aachen University
Dennewartstraße 27, 52068 Aachen, Germany; jan.bitter@ifu.rwth-aachen.de

Abstract

The need for an energy revolution and thus, the transformation to a sustainable energy system, is widely recognized. It is mainly based on the use of renewable energy technologies (RET), such as wind power plants. RET have positive as well as negative impacts on ecological, economic and social environments throughout their life cycle. In order to investigate the influence of these impacts on the overall sustainability of RET and make them measurable, there are several approaches for sustainability assessments. One is the *Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle* (Fuzzy-IST).

The Fuzzy-IST utilizes the combination of a multi-stage fuzzy logic approach, which aggregates Basic Sustainability Indicators (BSI) into Sustainability Dimension Indices (SDI) and subsequently into a General Sustainability Index (GSI), with the Integrative Sustainability Triangle (IST) as a tool for the systematization of indicators and a visualization of the results. The definition of appropriate BSI is based on the sustainability dimensions ecology, economy and social issues, throughout the entire life cycle of the RET being assessed. By using stepwise aggregation to create SDI and a GSI, and representing the results of those calculations in a color-coded IST, all dimensions are made evaluable. By using a fuzzy logic approach, quantitative as well as qualitative indicators are included, and uncertainties and subjectivity are made processible. The representation of results in the color-coded IST provides a structured, clear and understandable visualization of the results and facilitates the deduction of options for action.

In this paper, the application of the Fuzzy-IST is presented, illustrated and verified by going through the different steps of the approach for sustainability assessment. This is done within a case study concerned with a wind energy project of a German utility company. Each step is explained, the results are presented and discussed, options for action are deduced and starting points for further research are identified. This contributes to answering the question of how the sustainability of RET can be assessed reliably in order to support the transformation to a sustainable energy system.

Keywords: Sustainability assessment; Fuzzy logic; Integrative sustainability triangle; Wind power plant; Fuzzy-IST

Article history: Received: 27 March 2017
Revised:
Accepted: 29 September 2017

1. Introduction

Facing major developments, such as climate change, scarce resources – especially fossil fuels – and increasing environmental awareness, the need for the energy revolution, i.e. the change to a sustainable energy system, is a widely recognized political, social and technological goal. The energy revolution is mainly based on the use of renewable energy technologies (RET) [1, 2]. Besides many positive impacts (e.g. low emissions, job growth etc.), all RET have certain negative ecological, economic and social impacts throughout their life cycle (e.g. noise pollution, fluctuating energy production, bird strike etc.) [3–5]. Ecology, economy and social issues are widely recognized as the three dimensions of sustainability [6, 7].

The *Integrative Sustainability Triangle* (IST) is an approach to systemize the three dimensions of sustainability [6]. It extends the classical sustainability triangle by adding discrete fields inside the triangle, thus providing a structured visualization of the three dimensions and their intersections and facilitating the allocation of elements to the different fields (see Figure 1). By using a color-code, levels of attainment within fields can be visualized [6].

For a comprehensive investigation of RET's sustainability, there is a need for adequate models, measures and tools to capture and assess sustainability [8]. The general objective of sustainability assessment is to provide decision makers from politics, public administration and economy, with the necessary information and context to support them in defining short- and long-term actions to foster sustainable development [8–10]. As of yet, diverse approaches to sustainability assessment exist, which are presented shortly in the next paragraphs.

These include, but are not limited to, multi-criteria-decision-analysis (MCDA) approaches [3, 5, 9–14]. Due to differences concerning focus, effort for data

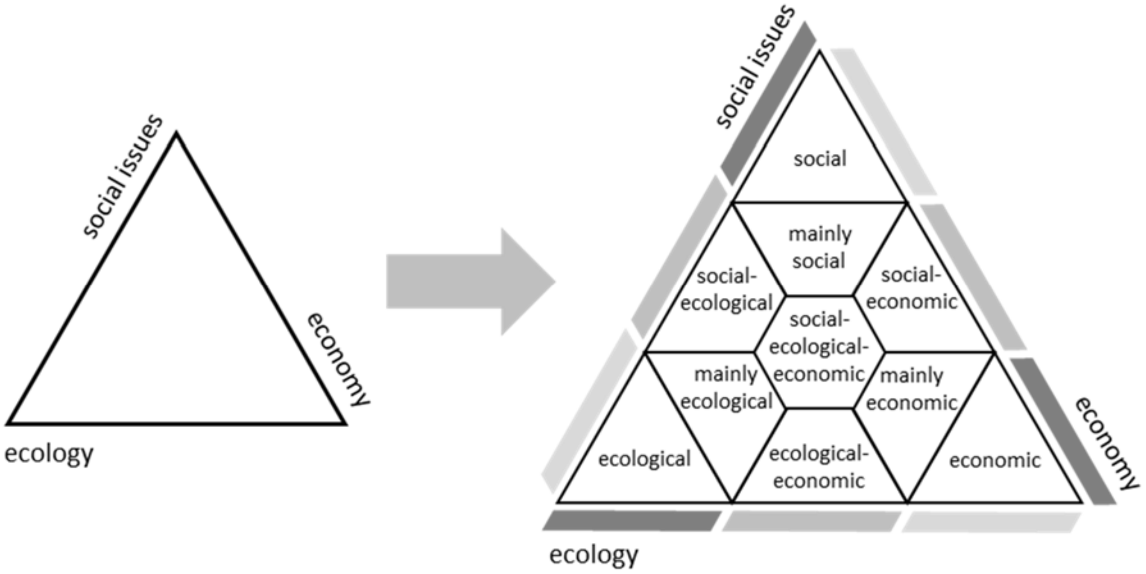

Figure 1. From Classical Sustainability Triangle to Integrative Sustainability Triangle [6]

acquisition and implementation, and result presentation, all these approaches have their own advantages and disadvantages [3, 9, 11, 15]. They are classically based on sustainability indicators, which are either assessed separately or combined with one another. Indices are combined indicators that are based on the transformation and (hierarchical) aggregation of sub-indicators with different units to a single, dimensionless number, i.e. a General Sustainability Index (GSI). Thus, indicators of different units are made comparable and the complexity of the sustainability assessment is reduced by combining indicators [5, 16].

One MCDA approach, that is commonly used for sustainability assessment, is Fuzzy Logic [3]. This approach is based on the assumption that objects can be attributed to more than one set, the attribution is therefore fuzzy. Fuzzy Logic provides mathematical tools with the ability to process crisp as well as fuzzy inputs to create clear, numerical outputs. Due to the complexity of sustainability, not all indicators can be measured quantitatively and thus have to be estimated or assigned qualitative values. This uncertainty and subjectivity, i.e. fuzziness of inputs, can be processed in a fuzzy system to provide a crisp, absolute output value [12].

The objective of this paper is to present and illustrate the holistic *Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle* (Fuzzy-IST) [17] and its application by means of a case study. This case study is about a wind energy project of a German utility company, planning the installment of a single wind power plant (WPP). The approach incorporates qualitative and quantitative indicators that depict all dimensions of sustainability and life cycle stages. In the following, the Fuzzy-IST is described briefly (Chapter 2), the case study is presented (Chapter 3), its results are discussed and conclusions are drawn (Chapter 4).

2. State of the art – Fuzzy Logic Approach for Sustainability Assessment based on the Integrative Sustainability Triangle

The *Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle* (Fuzzy-IST) uses the combination of a multi-stage fuzzy logic aggregation system and the IST as an instrument for the systematization of indicators and representation of the results. Basic Sustainability Indicators (BSI) are aggregated, on the one hand, first to Sustainability Dimension Indices (SDI) and then into a GSI and on the other hand, to the different life cycle phases (see Figure 4). The results are finally visualized in a color-coded IST and life cycle diagram [17]. The approach and its steps are visualized in Figure 2 and further illustrated in the following sections. A more detailed description and explanation of the FUZZY-IST is given in [17].

2.1. Indicator selection

In step one, BSI need to be selected (see Figure 2). The resulting BSI set should represent the current notion of sustainability, i.e. the three dimensions ecology, economy and social issues, and the entire life cycle of the RET under investigation. Additionally, the selected BSI have to be based on current and reliable information and clearly represent the fulfilment levels of sustainability goals [5, 18]. Generally, the BSI selection relies on theories, empirical analysis, pragmatism or a combination of the above, whereas the final number of indicators, as well as the type of indicators are variable [16]. Both aspects underlie a trade-off between level of detail and usability of the sustainability assessment [9, 12, 13]. In the Fuzzy-IST, there are four sub-steps for indicator selection: the pre-selection of BSI based on literature research, the systematization of pre-selection in a simplified IST and life cycle diagram, expert interviews to narrow down the number of indicators and the final selection of the BSI set and visualization in a simplified IST and life cycle diagram. The resulting set of indicators contains quantitative and qualitative indicators with different units. Normalization is needed to increase their comparability and processability.

2.2. Indicator selection

For the second step, normalization (see Figure 2), three different equations are used. Equation (1) is applied if a low input value is seen as advantageous. For an advantageous high value, (2) is used whilst (3) is applied if a proximity to the target value (x_i*) is desired. The normalized value (x_i) of the indicator (i) is calculated from the input value ($x_{i,s}$) of the indicator (i), the upper threshold (U_i) and the lower threshold (L_i). The variables (u_i) and (l_i) determine values close to (x_i*) [12]. The thresholds are based on international conventions, norms, laws, guidelines, expert opinions and studies. As the selected thresholds directly influence the resulting normalized values and thus the overall assessment results, it is crucial to ensure topicality and reliability of the threshold values [12].

$$x_i=\begin{cases} 1, & x_{i,s}\leq L_i \\ \dfrac{U_i\text{-}x_{i,s}}{U_i\text{-}L_i}, & L_i<x_{i,s}<U_i \\ 0, & x_{i,s}\geq U_i \end{cases} \tag{1}$$

$$x_i=\begin{cases} 0, & x_{i,s}\leq L_i \\ \dfrac{x_{i,s}\text{-}L_i}{U_i\text{-}L_i}, & L_i<x_{i,s}<U_i \\ 1, & x_{i,s}\geq U_i \end{cases} \tag{2}$$

$$x_i=\begin{cases} 0, & x_{i,s}\leq L_i \\ \dfrac{x_{i,s}\text{-}L_i}{l_i\text{-}L_i}, & L_i<x_{i,s}<l_i \\ 1, & l_i\leq x_{i,s}\leq u_i \\ \dfrac{U_i\text{-}x_{i,s}}{U_i\text{-}u_i}, & u_i<x_{i,s}<U_i \\ 0, & x_{i,s}\geq U_i \end{cases} \tag{3}$$

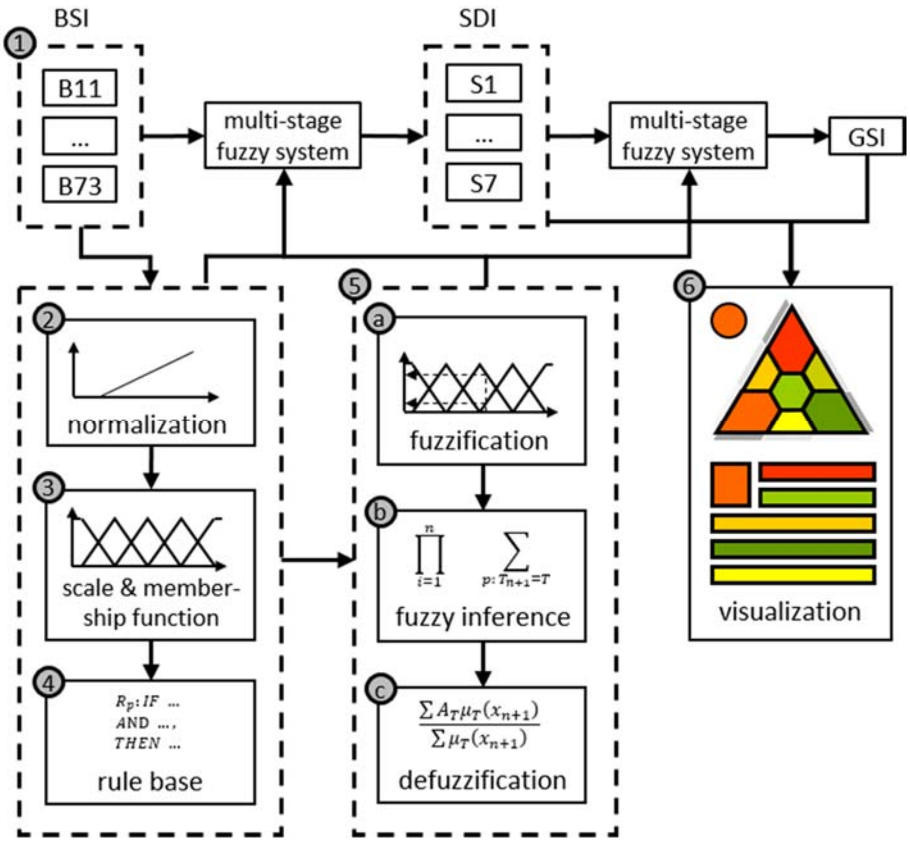

Figure 2. Process of the Fuzzy Logic Approach for Sustainability Assessment based on the Integrative Sustainability Triangle (Fuzzy-IST) [17]

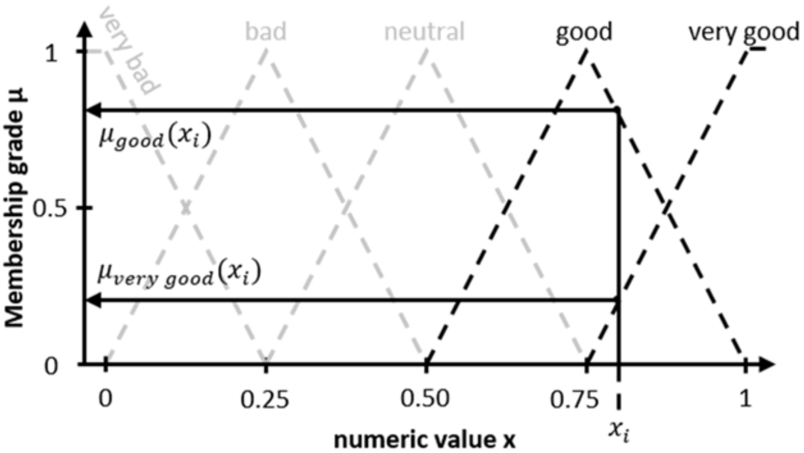

Figure 3. Fuzzification of indicator (i)

After normalization, each indicator is represented by a dimensionless value between 0 and 1. A value below 0.5 has a negative impact on the sustainability of the considered BSI, a value above 0.5 on the other hand has a positive impact. The closer the value is to 0.5, the lower the positive or negative impact. In order to further prepare the processing of the normalized input values, individual scales and membership functions are needed.

2.3. Scales and Membership Functions

In the third step, scales and membership functions are assigned to each indicator (see Figure 2). By using normalized indicators, the interval of the scale for each indicator is naturally [0,1]. Each scale is divided into five discrete sets, that are represented by linguistic terms and overlapping triangular membership functions. The terms and membership functions indicate the extent to which the input value is attributed to the discrete sets. The overlap between membership functions represents the attribution of input values to two adjacent sets (see Figure 3). Here, the discrete sets are represented by the linguistic terms *very bad*, *bad*, *neutral*, *good* and *very good* on a scale [0,1]. The relationships between linguistic sets, that are attributed to different indicators, are defined by the rule base.

2.4. Rule base

Step four is concerned with defining the rule base. It specifies the aggregation of indicators and consists of simple IF-THEN rules, which connect the linguistic variables of the indicators to one another. The rules consist of two parts: the premise (IF) and the conclusion (THEN). In the Fuzzy-IST, a premise consists of several conditions, i.e. the assignment of input values to linguistic variables. The conditions are combined using operators of classic set theory, such as conjunction (AND) and adjunction (OR).

The general form of a rule (R_p) using conjunction is illustrated in (5). The linguistic Term ($T_{i,p}$) of the indicator (i) is assigned to the normalized input value (x_i). The conclusion comprises the linguistic term ($T_{n+1,p}$) and the corresponding output value (x_{n+1}) of the aggregated (sub-) index (n+1). For adjunction, the AND-operator in has to be exchanged with OR.

$$R_p\text{: } IF\left(x_1 \text{ is } T_{1,p}\right) AND \ldots AND \left(x_n \text{ is } T_{n,p}\right), \\ THEN \left(x_{n+1} \text{ is } T_{n+1,p}\right) \tag{5}$$

2.5. Fuzzification, Inference, Defuzzification

Step five of the Fuzzy-IST consists of three sub-steps. Firstly, the input values are fuzzified, i.e. translated from crisp inputs into linguistic terms using defined membership functions (see Figure 2). A normalized input value (x_i) is assigned to the linguistic term ($T_{i,p}$) with a membership grade of ($\mu_p(x_i)$). The membership grade is a real number in the interval [0,1] (see Figure 3).

The following sub-step is the actual calculation for the aggregation of BSI that is defined by the rule base, namely the fuzzy inference (see Figure 2). In the Fuzzy-IST, the Takagi-Sugeno-Kang (TSK) inference is used. For rules using conjunction, the algebraic product rule from (6) is used. For adjunction, an algebraic sum rule, as illustrated in (7), is used. If more than one rule assigns the same linguistic variable (T) to the input value (x_{n+1}), the membership grade ($\mu_T(x_{n+1})$) is calculated using (8).

$$\mu_{n+1,p}(x_{n+1}) = \prod_{i=1}^{n} \mu_{i,p}(x_i) \tag{6}$$

$$\mu_{n+1,p}(x_{n+1}) = 1 - \prod_{i=1}^{n} 1 - \mu_{i,p}(x_i) \tag{7}$$

$$\mu_T(x_{n+1}) = \sum_{p:\, T_{n+1}=T} \mu_{n+1,p}(x_{n+1}) \tag{8}$$

Next, crisp outputs are calculated from the membership values of the aggregated inputs (defuzzification, see Figure 2). In the Fuzzy-IST, Singleton defuzzification is used. It provides clear and crisp output values with minimal calculation effort [12]. The output value (x_{n+1}) is calculated as in (9), while (A_T) is the numerical value of the linguistic variable (T) at ($\mu_T = 1$).

$$x_{n+1} = \frac{\sum_T A_T \mu_T(x_{n+1})}{\sum_T \mu_T(x_{n+1})} \tag{9}$$

The three sub-steps, fuzzification, inference and defuzzification, are repeated throughout the multistage hierarchical aggregation, from BSI, to SDI, to GSI, with the outputs of each stage being used as inputs for the next stage (see Figure 2). Additionally, in an analogous multistage hierarchical aggregation procedure the BSI are combined to the different life cycle phases. All aggregation results are then visualized to facilitate their interpretation.

2.6. Visualisation

The sixth step is concerned with the graphical representation of the results (see Figure 2 and Figure 4). The visualization is based on a simplified IST and a life cycle diagram. The fields of the IST, representing the sustainability dimensions and their intersections, are color coded (*red – yellow – green*) based on their calculated sustainability values. Low values (below 0.5) are coded *red – orange – dark yellow* and represent a negative influence on the sustainability value of the dimension being considered. The lower the calculated value, the more negative the influence on overall sustainability. High values (above 0.5) are coded *light yellow – light green – dark green* and represent a positive influence on the sustainability value of the dimension. The higher the calculated value, the more positive the influence on overall sustainability. Thus, advantageous and disadvantageous dimensions can be identified at a glance and recommendations for actions can be easily deduced. The color-coded circle in the top-left corner (see Figure 4) represents the overall sustainability – i.e. the value of the GSI.

The graphical representation of the sustainability values in the life cycle diagram uses the same color code as mentioned above. Again, advantageous and disadvantageous life cycle phases can be identified quickly and recommendations for action can be deduced.

3. Application of the Fuzzy-IST for a wind power plant

3.1. Case study

In order to test and validate the Fuzzy-IST, its applicability is investigated by conducting a case study. The case study is concerned with a real-life wind energy project of a German company of the utility sector (because of a non-disclosure agreement, the respective company and the specific case cannot be named explicitly). The company plans to install a single WPP close to a midsized city. The planned WPP uses a geared double-fed asynchronous generator with a nominated capacity of 2.4 MW. At the time of the preparation of this work, all necessary reports (e.g. for shadowing, sound emissions etc.) are completed and are used as one type of source for the indicator values of the BSI. Due to proximity of the planned WPP to inhabited areas, there are concerns among the public related to optical influences on landscapes, periodical shadowing and sound emissions. Because of proximity to a breeding and hunting area of red kites, there are also concerns about endangerments for wildlife.

In the Fuzzy-IST, these specific concerns and general challenges of sustainability are represented by the selected BSI. Following the steps of the indicator selection (see Section 2.1), 24 BSI are selected. They are summarized in Table 1. The BSI are allocated to the seven sustainability dimensions and intersection represented in the simplified IST as well as to the six life cycle phases. The indicators have different measures and units.

For the normalization of the BSI, upper and lower thresholds need to be determined. Table 2 shows the normalization thresholds for the indicator set for WPP, the equations used, explanations and the respective sources.

In this case study, the input values for the BSI are collected from different sources in order to reach a complete depiction of all relevant effects on sustainability. Table 3 shows the input values ($x_{i,s}$), the normalized values (x_i), the lower and upper linguistic terms ($T_{l,i}$ and $T_{u,i}$), the corresponding membership grades ($\mu_{l,i}$ and $\mu_{u,i}$) and the sources used.

The normalized BSI are aggregated stepwise according to the process as illustrated in Figure 2 and Section 2.5. The rule base for the aggregation contains 545 rules. Table 4 shows the sustainability values of the SDI and the

Table 1: Indicator set for sustainability assessment of wind power plants
(P = Planning, R = Resource extraction, M = Manufacturing, L = Logistics & Installation, O = Operation, E = End-of-Life)

Dimension	No.	Indicator	Life Cycle Phase	Measure	Unit
social	B11	Shadowing	O	Deviation from threshold	h/a
	B12	Safety	L, O	Deaths through accidents	#/GWa
	B13	Social acceptance	P, L, O, E	Expert estimation	qualitative
	B14	Situation in supply chain	All	Expert estimation	qualitative
social-ecological	B21	Land use	L, O	Space requirement	m^2/GWh
	B22	Optical landscape influences	P, O	Expert estimation	qualitative
	B23	Sound emissions	O	Deviation from threshold	dB(A)
ecological	B31	Climate-relevant emissions	All	CO2-equivalent	g/kWh
	B32	Effects on biodiversity	O	No. of threatened species	#
	B33	Effects on water	R, M, L, O, E	Water usage	m^3/TJ
	B34	Effects on soil	R, L, O, E	Expert estimation	qualitative
ecological-economic	B41	Resource consumption	R, M, L, O	Material use	kg/MWh
	B42	Recycling quota	E	Mass percentage	%
	B43	Recycling approaches for critical materials	E	Qualitative comparison	qualitative
economic	B51	Energy efficiency	All	Energy return on invest	No unit
	B52	Economic profitability	All	Cost of energy production	€-cent/kWh
	B53	Technical reliability	O	Technical availability	%
social-economic	B61	Jobs	All	Job growth	%
	B62	Participation, transparency and fairness	P, L, O	Expert estimation	qualitative
	B63	Political support	All	Expert estimation	qualitative
	B64	Supply security	O	Quality of prognosis	%
social-ecological-economic	B71	External costs	All	External costs	€-cent/kWh
	B72	Use of critical resources	R, M	Material usage	kg/MW
	B73	Future potential	All	Expert estimation	qualitative

GSI, the corresponding lower and upper linguistic terms and membership grades. The results are visualized according to the methodology illustrated in Section 2.6 (see Figure 4).

3.2. Results

As shown in Table 3, fifteen of the BSI have a normalized value of above 0.750. Three normalized BSI-values are between 0.500 and 0.750 and one BSI has a normalized value between 0.500 and 0.250. Finally, four normalized BSI-values are below 0.250. The input values of the BSI are taken from project related sources and other literature. This leads to implications for the assessed WPP specifically and for wind energy in general. Weaknesses arise regarding *Shadowing*, *Sound Emissions*, *Energy Efficiency*, *Recycling Approaches for Critical Materials* and *Influences on Biodiversity*. All other BSI have a positive impact on sustainability. Especially minimal *Influences on Water*, positive effects

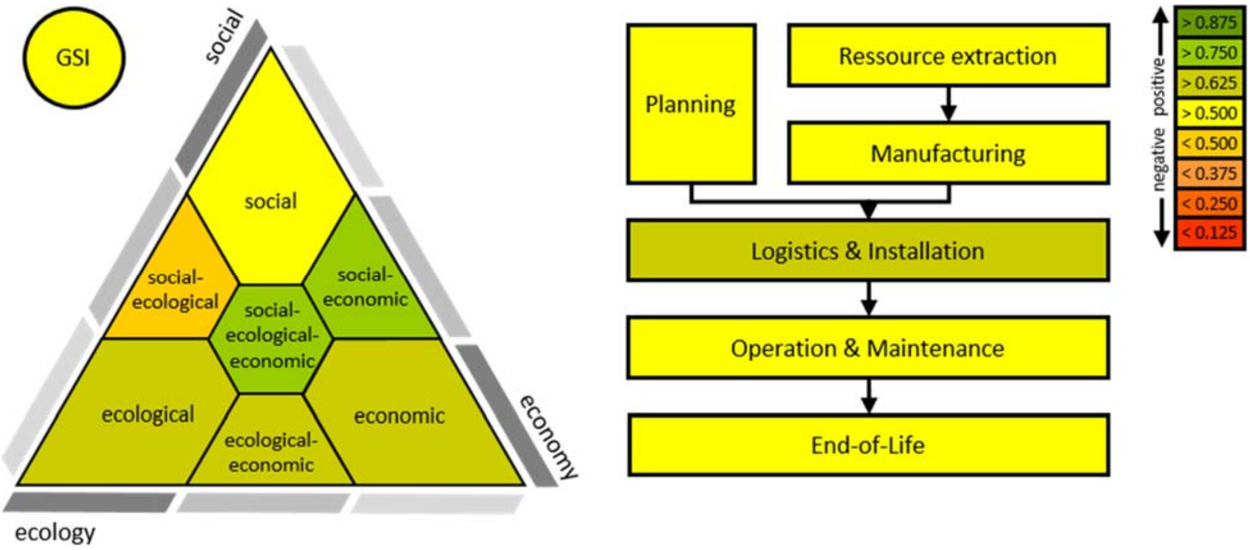

Figure 4: Graphical representation of results of the case study

Table 2: Thresholds for normalization of BSI for sustainability assessment of wind power plants

L_i = Lower threshold, U_i = Upper threshold, Eq. = Equation,
* = referring to maximum value of all power generation technologies, s.d. = self-defined

No.	L_i	U_i	Eq.	Explanation	Source
B11	0	30	(1)	Threshold of max. permitted duration of shadowing p.a./measuring point	[19]
B12	0	0.135	(1)	Average number of deaths through accidents in coal industry*	[20]
B13	0	8	(2)	Self-defined, qualitative scale with 8 = complete social acceptance	s.d.
B14	0	8	(2)	Self-defined, qualitative scale with 8 = Very good situation in supply chain	s.d.
B21	0	12,600	(1)	Average land use for energy production from biomass*	[21]
B22	0	8	(1)	Self-defined, qualitative scale with 8 = very high neg. landscape influence	s.d.
B23	-35	0	(1)	Dist. from threshold of max. permitted sound emissions/measuring point	[19]
B31	0	980	(1)	Average climate-relevant emissions of energy production from coal*	[22]
B32	0	96	(1)	Max. number of endangered species and presence of increased hazard	[23]
B33	0	15,100	(1)	Average water usage and alteration in hydro energy*	[24]
B34	0	8	(1)	Self-defined, qualitative scale with 8 = very high negative impact on soil	s.d.
B41	0	11,271	(1)	Average material usage of energy production from lignite*	[25]
B42	0	100	(2)	Max. possible recycling quota	[26]
B43	0	1	(2)	Self-defined, discrete scale for recycling approaches	[27]
B51	1	94	(2)	Average energy return on invest of hydro energy*	[28]
B52	0	21	(1)	Average cost of energy production in photovoltaics*	[29]
B53	0	100	(2)	Max. possible technical reliability	[30]
B61	0	13	(2)	Job growth in wind energy industry 2013 to 2014*	[31]
B62	0	8	(2)	Self-defined, qualitative scale with 8 = complete partic., transp. & fairness	s.d.
B63	0	8	(2)	Self-defined, qualitative scale with 8 = complete political support	s.d.
B64	0	7.53	(1)	Variation coefficient of deviation from prognosis for PV in 2014*	[32]
B71	0	10.75	(1)	Average external costs of energy production from lignite*	[33]
B72	0	217.5	(1)	Average material usage of rare earths in gearless wind power plants	[34]
B73	0	8	(2)	Self-defined, qualitative scale with 8 = very high future potential	s.d.

Table 3: Input data for BSI

No.	$x_{i,s}$	x_i	$T_{l,i}$	$\mu_{l,i}$	$T_{u,i}$	$\mu_{u,i}$	**Sources**
B11	44	0.000	very bad	1.000	bad	0.000	Shadowing report
B12	0.00178	0.987	good	0.050	very good	0.950	[20]
B13	middle-high (5)	0.625	neutral	0.500	good	0.500	Expert interview
B14	good (6)	0.750	good	1.000	very good	0.000	Expert interview
B21	2,100	0.833	good	0.667	very good	0.333	[21]
B22	low-middle (3)	0.625	neutral	0.500	good	0.500	Expert Interview
B23	- 1.5	0.043	very bad	0.829	bad	0.171	Sound emission report
B31	12	0.988	good	0.049	very good	0.951	[35]
B32	49	0.490	very bad	0.021	neutral	0.979	Species protection report
B33	1.3	1.000	good	0.000	very good	1.000	[24]
B34	low (2)	0.750	good	1.000	very good	0.000	Expert Interview
B41	133	0.988	good	0.047	very good	0.953	Diverse
B42	80	0.800	good	0.800	very good	0.200	[26]
B43	Energ. and mat. recovery	0.300	bad	0.500	rather bad	0.500	[36]
B51	22	0.226	bad	0.097	bad	0.903	[28]
B52	8	0.619	neutral	0.524	god	0.476	[29]
B53	98	0.980	good	0.080	very good	0.920	Expert Interview
B61	13	1.000	good	0.000	very good	1.000	[31]
B62	high-complete (7)	0.875	good	0.500	very good	0.500	Expert Interview
B63	high (6)	0.750	good	1.000	very good	0.000	Expert Interview
B64	0.96	0.873	good	0.510	very good	0.490	[37]
B71	0.1	0.991	good	0.037	very good	0.963	[38]
B72	30	0.862	good	0.552	very good	0.448	[34]
B73	high (6)	0.750	good	1.000	very good	0.000	Expert Interview

Table 4: Sustainability values of SDI and GSI

No.	x_i	$T_{l,i}$	$\mu_{l,i}$	$T_{u,i}$	$\mu_{u,i}$
S1	0.500	neutral	1.000	good	0.000
S2	0.431	bad	0.276	neutral	0.724
S3	0.733	neutral	0.070	good	0.930
S4	0.649	neutral	0.405	good	0.595
S5	0.718	neutral	0.127	good	0.873
S6	0.750	good	1.000	very good	0.000
S7	0.858	good	0.568	very good	0.432
GSI	0.500	neutral	1.000	good	0.000

on *Jobs*, low *External Costs*, low *Climate-Relevant Emissions*, efficient *Resource Consumption* and high levels of *Security* can be highlighted.

By aggregating the BSI to SDI and life cycle phases, positive and negative effects are included equally. This is reflected in the SDI-values. From the SDI-values in Table 4 and the graphical representation in Figure 4, the social-economic SDI (S2) has a slightly negative impact on sustainability. This is due to the strong negative influence of *Sound Emissions*. The impact of the social SDI is neutral. The positive effects of *Safety* and *Social Acceptance* are compensated for by the strong negative effect of *Shadowing*. All other SDI have a positive effect on sustainability (see Figure 4). The positive effects of some BSI are mitigated by the negative impact of other BSI on a sustainability dimension.

By aggregating the SDI to a GSI, the positive and negative effects of the sustainability dimension are balanced. The crisp output value of the GSI is 0.500. In the sense of balanced sustainability, the individual sustainability aspects are not mutually substitutable. This aspect is underlined by the fact that the negative effects of BSI and SDI ultimately lead to a *neutral* sustainability assessment of the assessed WPP. The positive effects of BSI and SDI are offset by negative effects. The goal of sustainable development is to achieve a high level of sustainability for each individual BSI and thus for the different sustainability dimensions and, ultimately, for overall sustainability.

Regarding the visualization of the sustainability values in the life cycle diagram (see Figure 4), the sustainability effects of all phases are slightly positive. The life cycle phase *Logistics & Installation* has the highest value, which is due to the fact that only the negatively influencing *Energy Efficiency* has an effect on this phase. From these results, no specific weakness in the life cycle can be identified, whereby an improvement in the sustainability values is advantageous in all phases. The results of the sustainability assessment, represented by the numerical values of the BSI, SDI and the GDI and their graphical representation, have several implications for the considered project, wind power plants and wind energy in general, which are discussed in the final Chapter 4.

4. Implications and conclusion

4.1. Implications for the project, wind power plants and wind energy

For the project being assessed in this case study, the results of the Fuzzy-IST indicate, that the installation of the planned WPP, from a sustainability point of view, cannot be recommended without restrictions. First, actions need to be taken in order to increase the overall sustainability of the planned WPP by improving the values of the negatively evaluated BSI and thus the SDI. Starting points for such actions are presented in the following paragraphs.

The impact of *Shadowing*, for example, can be reduced by decreasing the annual shading of the surrounding residential buildings. This can be implemented by a stricter automatic switch-off or an increase in the distance between the installation and the residential building. The impact of *Sound Emissions* can also be minimized by increasing the distance to residential buildings or improving the insulation of the WPP. The impact on *Biodiversity* can be decisively influenced by the site selection for the WPP. In the vicinity of the planned location are red kites, which are regarded as an endangered species. Countervailing measures must be taken to minimize the risk of collision. For this purpose, new hunting grounds for red kites can be created elsewhere and the area around the WPP can be made unattractive as a hunting area for the red kites by cultivating high grass. The need for compensatory measures creates a risk for biodiversity. Such risks can be minimized by selecting a site without endangered species.

Energy efficiency is determined by the recovery factor, i.e. the ratio of energy produced to energy used over the life cycle [39]. It can either be improved by increasing energy production or by reducing energy expenditure. This is achieved, for example, by raising the energy yield by means of larger rotor diameters and/or generators with a higher nominated capacity. On the other hand, it is possible to reduce the energy expenditure in the other life cycle phases, e.g. in *resource extraction*, *manufacturing* and the *end-of-life*. To this end, the processes and technologies used, need to be optimized and new approaches to be explored. Another negative factor is the selection of the recycling or disposal method for critical materials such as the fiber composite rotor blades. Various approaches to comprehensive recycling exist, none of which has yet been applied in industrial scale. The value of this BSI can be increased by further research and implementation of these approaches, e.g. a complete material recycling of the rotor blades [40].

The overall neutral assessment of the case study shows that wind turbines are not unrestrictedly sustainable. It is realistically impossible to reach maximum levels for all BSI and SDI. The sustainability values are limited by technical and economic feasibility limits as well as natural laws. In the sense of the balanced sustainability, improvements of all aspects of sustainability are equally to be strived for. This can be achieved, for example, through technological innovations, strict political guidelines and a categorical rethinking of producers and consumers. Economic considerations will always be a determining factor, since costs are incurred in all phases of the life cycle, which must be weighed up by the profits generated by electricity generation.

In order to transfer the wind energy from a CO_2-neutral to a genuinely sustainable technology, the players of the wind industry, such as project developers, manufacturers, operators and recycling companies, but also citizens and environmental protection associations must work together. On the one hand, the above-mentioned areas offer starting points for innovations. On the other hand, subjective factors and situation-dependent factors such as *Social Acceptance* or *Optical Landscape Influence* must be influenced by a transparent and open planning process involving all stakeholders.

4.2. Conclusions and outlook

In [17], the authors show that the Fuzzy-IST fulfills all requirements for a holistic method for sustainability assessment based on aspects described in the literature [3, 4, 7, 9, 11, 12, 14, 41]. The application of the Fuzzy-IST, by means of this case study, underlines that the approach is suitable for the investigation of positive and negative effects of RET on sustainability during their life cycles. The exemplary sustainability assessment conducted in this work leads to an overall neutral assessment result for the WPP being considered as it shows strengths and weaknesses in the various dimensions and life cycle phases. The visualization of the results and corresponding numerical values provide comprehensive decision making support.

However, further research is required to improve and validate the Fuzzy-IST. One starting point is to investigate the influence of the number of aggregation steps on the results, which is directly related to a trade-off between level of detail and usability of the approach. Equally, the number of linguistic terms for BSI, SDI and GDI influence this trade-off. Furthermore, the current model as applied in this case study does not consider interdependencies or weights of BSI and SDI. A deeper exploration of these aspects is required to reach a more detailed representation of sustainability and completely integrate all dimensions and life cycle phases. Other starting points for future research are the application of the approach to other RET and other domains. Currently, the authors' research is concerned with transferring the Fuzzy-IST to the sustainability assessment of photovoltaics, hydro energy and companies in the automotive and utility sector. First results indicate that especially new BSI sets must be selected to adapt the approach to other fields. The general process of the Fuzzy-IST is directly transferrable, indicating a wide applicability of the approach.

Another starting point for further research is to "reverse" the Fuzzy-IST, meaning that instead of assessing single projects and/or potential sites for RET and deducing their strengths and weaknesses, to apply a wider scope and scan whole regions (districts, states, countries etc.) to find suitable sites for more sustainable RET projects. This would require extensions of the Fuzzy-IST, e.g. combining it with a Geographic Information System (GIS). The "reversed" Fuzzy-IST could aid the prospective design of a sustainable expansion of RET in contrast to the retrospective assessment and subsequent measures to improve sustainability, which can be costly and time-consuming.

References

[1] S. Teske, S. Sawyer, and O. Schäfer, "energy [r]evolution - A sustainable world - Energy outlook 2015," Greenpeace International, Global Wind Energy Council, SolarPowerEurope, World Energy Scenario 5, 2015.

[2] United Nations, "Sustainable development goals - United Nations," *United Nations Sustainable Development*, 2016.

[3] R. Abu-Taha, "Multi-criteria applications in renewable energy analysis: A literature review," *Technology Management in the Energy Smart World (PICMET), 2011 Proceedings of PICMET'11*, pp. 1–8, 2011.

[4] A. Bond, A. Morrison-Saunders, and J. Pope, "Sustainability assessment: the state of the art," *Impact Assessment and Project Appraisal*, vol. 30, no. 1, pp. 53–62, 2012.

[5] G. Liu, "Development of a general sustainability indicator for renewable energy systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 31, pp. 611–621, 2014.

[6] A. Kleine and M. von Hauff, "Sustainability-Driven Implementation of Corporate Social Responsibility: Application of the Integrative Sustainability Triangle," *Journal of Business Ethics*, vol. 85, no. S3, pp. 517–533, 2009.

[7] R. B. Gibson, "Beyond the pillars: sustainability assessment as a framework for effective integration of social, economic and ecological considerations in significant decision-making," *Journal of Environmental Assessment Policy and Management*, vol. 8, no. 3, pp. 259–280, 2006.

[8] J. Bebbington, J. Brown, and B. Frame, "Accounting technologies and sustainability assessment models," *Ecological Economics*, vol. 61, no. 2–3, pp. 224–236, Mar. 2007.

[9] P. Ghadimi, N. M. Yusof, M. Z. M. Saman, and M. Asadi, “Methodologies for measuring sustainability of product/process: a review,” *Pertanika Journal of Science and Technology*, vol. 21, pp. 303–326, 2013.

[10] B. Ness, E. Urbel-Piirsalu, S. Anderberg, and L. Olsson, “Categorising tools for sustainability assessment,” *Ecological Economics*, vol. 60, no. 3, pp. 498–508, 2007.

[11] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, and J.-H. Zhao, “Review on multi-criteria decision analysis aid in sustainable energy decision-making,” *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9, pp. 2263–2278, 2009.

[12] Y. A. Phillis and V. S. Kouikoglou, *Fuzzy measurement of sustainability*. New York: Nova Science Publishers, 2009.

[13] R. K. Singh, H. R. Murty, S. K. Gupta, and A. K. Dikshit, “An overview of sustainability assessment methodologies,” *Ecological Indicators*, vol. 9, no. 2, pp. 189–212, Mar. 2009.

[14] B. G. Hermann, C. Kroeze, and W. Jawjit, “Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators,” *Journal of Cleaner Production*, vol. 15, no. 18, pp. 1787–1796, Dec. 2007.

[15] S. Valdivia, G. Sonnemann, C. M. L. Ugaya, and J. Hildenbrand, *Towards a life cycle sustainability assessment - Making informed choices on products*. Paris: UNEP/SETAC Life Cycle Initiative, 2011.

[16] T. Hák, B. Moldan, and A. L. Dahl, *Sustainability Indicators: A Scientific Assessment*. Island Press, 2012.

[17] J. Bitter, S. Printz, K. Lahl, R. Vossen, and S. Jeschke, “Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle (accepted),” *Proceedings of the IEEE WCST 2016 World Congress on Sustainable Technologies*, 2017.

[18] N. H. Afgan, M. G. Carvalho, and N. V. Hovanov, “Energy system assessment with sustainability indicators,” *Energy Policy*, vol. 28, no. 9, pp. 603–612, Jul. 2000.

[19] “BImSchG - nichtamtliches Inhaltsverzeichnis.” [Online]. Available: http://www.gesetze-im-internet.de/bimschg/. [Accessed: 06-Mar-2017].

[20] P. Burgherr and S. Hirschberg, “Comparative risk assessment of severe accidents in the energy sector,” *Energy Policy*, vol. 74, pp. S45–S56, Dec. 2014.

[21] E. Masanet *et al.*, “Life-Cycle Assessment of Electric Power Systems,” *Annual Review of Environment and Resources*, vol. 38, no. 1, pp. 107–136, Oct. 2013.

[22] M. Whitaker, G. A. Heath, P. O’Donoughue, and M. Vorum, “Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation: Systematic Review and Harmonization,” *Journal of Industrial Ecology*, vol. 16, pp. S53–S72, Apr. 2012.

[23] *Gesetz über Naturschutz und Landschaftspflege (Bundesnaturschutzgesetz - BNatSchG)*. 2015.

[24] M. M. Mekonnen, P. W. Gerbens-Leenes, and A. Y. Hoekstra, “The consumptive water footprint of electricity and heat: a global assessment,” *Environ. Sci.: Water Res. Technol.*, vol. 1, no. 3, pp. 285–297, 2015.

[25] C. Liedtke *et al.*, “Resource Use in the Production and Consumption System—The MIPS Approach,” *Resources*, vol. 3, no. 3, pp. 544–574, Aug. 2014.

[26] E. Seiler, B. Bilitewski, and J. Woidasky, “Recycling von Windkraftanlagen.” 2013.

[27] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheut (BMUB), “Eckpunkte des neuen Kreislaufwirtschaftsgesetzes,” 2012.

[28] M. Dale, “Global Energy Modelling: a Biophysical Approach (GEMBA),” Doktorarbeit, University of Canterbury, 2010.

[29] P. A. Narbel and J. P. Hansen, “Estimating the cost of future global energy supply,” *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 91–97, 2014.

[30] E. Hau, *Windkraftanlagen*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

[31] U. Lehr, D. Edler, M. O’Sullivan, F. Peter, and P. Bickel, “Beschäftigung durch erneuerbare Energien in Deutschland: Ausbau und Betrieb, heute und morgen,” GWS, DIW, DLR, Prognos, ZSW, Osnabrück, Endbericht (Studie), 2015.

[32] Amprion, “Photovoltaikeinspeisung,” 2015. [Online]. Available: http://www.amprion.net/photovoltaikeinspeisung. [Accessed: 10-Aug-2015].

[33] Bundesverband WindEnergie e.V. (BWE), “Fakten zur Windenergie - A bis Z,” Bundesverband WindEnergie e.V., Berlin, Apr. 2015.

[34] A. Pehlken and R. G. Sanchez, “Strategische Ressourcen in der Windenergie,” in *IT-gestütztes Ressourcen- und Energiemanagement*, J. Marx Gómez, C. Lang, and V. Wohlgemuth, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 545–554.

[35] S. L. Dolan and G. A. Heath, “Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization,” *Journal of Industrial Ecology*, vol. 16, pp. S136–S154, Apr. 2012.

[36] R. Cherrington, Goodship V., J. Meredith, and B. M. Wood, “Producer responsibility - Defining the incentive for recycling composite wind turbine blades in Europe,” *Energy Policy*, vol. 47, pp. 13–21, 2012.

[37] Amprion, “Windenergieeinspeisung,” 2015. [Online]. Available: http://www.amprion.net/windenergieeinspeisung. [Accessed: 10-Aug-2015].

[38] H. Niederhausen and A. Burkert, “Nachhaltigkeit der elektrischen Energieversorgung,” in *Elektrischer Strom*, Springer, 2014, pp. 181–190.

[39] C. A. S. Hall, J. G. Lambert, and S. B. Balogh, “EROI of different fuels and the implications for society,” *Energy Policy*, vol. 64, pp. 141–152, Jan. 2014.

[40] K. Larsen, “Recycling wind,” *Reinforced plastics*, vol. 53, no. 1, pp. 20–25, 2009.

[41] H.-L. Pesonen and S. Horn, “Evaluating the Sustainability SWOT as a streamlined tool for life cycle sustainability assessment,” *The International Journal of Life Cycle Assessment*, vol. 18, no. 9, pp. 1780–1792, Nov. 2013.