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Editorial

Design of Biomethane Supply System Using Ecodesign Approach and System Dynamics Modelling

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Biomethane can be produced from biogas by upgrading it to the quality of natural gas. This way it is possible to obtain a renewable substitute for natural gas, which may be injected into the natural gas grid and used in existing technologies without the need for replacement. Grid-supply of biomethane offers several important advantages. It allows substituting fossil for a renewable energy source in the technologies which require gaseous fuels, e.g. natural gas-fired industrial furnaces, gas engines and combined cycle gas turbine cogeneration plants. Biogas, after purification, can be diverted from distributed biogas-fired power plants, which often are relatively inefficient due to the lack of sufficient heat loads, to large district heating systems with efficient cogeneration possibilities. Biomethane supply via a natural gas grid would also facilitate maintenance and development of the natural gas supply infrastructure in future when consumption of natural gas may decline due to an increased share of renewable energy.

However, several important questions arise. First, is biomethane a sound choice from the environmental point of view in comparison with natural gas and potential renewable alternatives, e.g. biofuels, which also can be often used in natural gas-fired systems? Second, is biomethane an economically feasible alternative to natural gas? If not, what is the level of support required for production of biomethane to be put in price parity with natural gas? And finally, how should a support policy for a biomethane supply chain be designed to make it sustainable over time? These questions have been addressed in the research performed at the Institute of Energy Systems and Environment of Riga Technical University and the results have been published in several peer-reviewed papers.

In principle, the design of a biomethane supply system involves the system innovation from the ecodesign perspective since it allows improving environmental performance of the whole system currently using natural gas. Therefore, by following the ecodesign approach one should employ tools of environmental impact assessment, e.g. life cycle assessment (LCA), for the comparison of design alternatives from the environmental standing. This has been done by applying LCA to the case of brick production industry in Latvia and analysing “cradle-to-gate” environmental impacts per 1 ton of the product when the following fuels are used in the industrial furnace: natural gas, biomethane, and 1^{st} and 2^{nd} generation liquid biofuels. “*ReCiPe*” has been used as the environmental impact assessment method. The results show that the environmental impact could be reduced by circa 50% when biomethane is substituted for natural gas, and that biomethane and the 2^{nd} generation biofuel have roughly equal environmental impact as the 1^{st} generation biofuel, being far worse than even natural gas. Other studies based on life cycle inventory data have indicated that the use of biomethane instead of natural gas may reduce greenhouse gas emissions by nearly 80%. The environmental benefits of fuel substitution, i.e. system innovation versus gradual improvements of natural gas-fired equipment efficiencies, can thus be clearly seen.

Development of a biomethane supply chain can be started by installation of upgrading facilities to the existing biogas plants and their connection to the natural gas grid. The study of the location of the biogas plants relative to the natural gas transmission pipelines has been done for Latvia using GIS. The results show that the average distance from the biogas plants to the natural gas transmission pipeline was circa 18 km with the shortest distances being less than 1 km. In many places, the connection could be made to the natural gas distribution pipeline instead, thus, reducing the connection distance. Therefore, it can be claimed that in many places the connection of the biogas reactors to the grid may be feasible. The total costs of grid-injected biomethane produced would have to include capital, operation and maintenance costs of biogas production, upgrading and injection into the natural gas grid. The total costs have been calculated for 5 different biogas upgrading technologies and it has been found that the difference between the total biomethane production costs among these technologies was relatively small, i.e. approximately 3%. The total costs can be reduced significantly, i.e. by circa 30%, if biogas producers cooperate and build a single larger biogas production and upgrading facility instead of several of a smaller size. This indicates that the spatial distribution of biogas reactors and possibilities for cooperation among biogas producers to a large extent will determine competitiveness of grid-injected biomethane with natural gas. Currently, financial support is required for production of grid-injected biomethane since the minimum total costs of production achieved at the best scenario with 20 years of economic lifetime are nearly 50 EUR/MWh, exceeding the price of natural gas by approximately 16%. For economic lifetime of 10 years, the difference is about 34%. Therefore, we come to the need for the design of an appropriate support policy for the development of a biomethane supply system.

System dynamics modelling is a well-suited tool for the design of a renewable energy support policy since it allows analysing complex dynamic systems with feedbacks, delays and non-linearity. System dynamics has been successfully used at the Institute of Energy Systems and Environment for modelling of power and district heating supply systems, design of energy efficiency and waste management policies, analysis of the transport sector and sustainable energy supply systems. The challenge for energy policy makers lies in setting up the support system which leads to the perceived optimal growth of the renewable energy share and, for that reason, can be sustained over a long period of time. As experience shows, this is not a case in many countries, including Latvia, where support has led to the overshoot of the perceived limit of the financial support which can be carried by national economy, and it was corrected by a complete or nearly complete stall in the support. It is often noted that due to complexity of the energy supply system policy decisions for support of sustainability are difficult, i.e. it is difficult to foresee the dynamics of evolvement of the required support. Therefore, system dynamics has been chosen for creating the model which reveals the most crucial part in the support policy implementation, i.e. the structure of the policy system which leads to successful implementation of the support. Very few studies using system dynamics for the analysis of renewable energy policies have a focus on the structure of the support policy itself but rather look at the consequences in terms of the renewable energy share if the support is implemented or absent. The structure of the support policy for biomethane is built up by 2 parallel flows, i.e. the flow of granted permits to receive support, and the flow of actual investments into biomethane production facilities. Actual biomethane production is compared with the target value, which is based on the perceived limit of financial support at a certain period of time, and the feedback is taken back for adjusting dynamics of permit granting. This structure is similar to biological systems where a marginal increase of distribution of a certain plant in a limited territory decreases over time as space available for new plants shrinks. It is considered in the analysis of dynamics that not all permits will lead to actual investments and some will be cancelled after a certain period of time. This modelling approach allows comparison of several support alternatives, i.e. investment subsidies versus feed-in-tariff or feed-in-premium. Development of specific investments into technologies due to the learning effect and dynamics of a natural gas price are considered as well.

Combining life cycle assessment, GIS, technical and economic calculations with system dynamics modelling can be viewed as a method for system innovation leading from sound evaluation of alternatives to the actual policy for implementation of a particular system. This approach can be applied in the design of sustainable energy systems, waste management systems and other similar applications.

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Greywater Treatment with Simultaneous Generation of Energy Using Low-Cost Microbial Fuel Cells

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Microbial fuel cells (MFCs) are an emerging type of biological wastewater treatment units with simultaneous power generation. The present study demonstrates an effective treatment of greywater and generation of electricity in a double-chambered MFC. This MFC was fabricated using cost-effective and easily available materials replacing expensive materials like Nafion membranes, graphite electrodes, etc. Experimental results showed a maximum open circuit voltage of 0.64 ± 0.04 V and 114 ± 1.41 mA current during the study period. The results further indicate a maximum power generation of 24.50 mW along with 307.69 mW/m² of power density; 34.62 mA/m² of current density, 1.33 W/m³ of volumetric power density, 0.15 A/m³ of volumetric current density and a power yield of 0.40 mW/kg of COD removal. The chemical oxygen demand (COD) removal efficiency was 77.6%. The use of low-cost and easily available raw materials has brought down the total manufacturing cost of MFCs used in this study to less than USD 4.0. However, the performance of the MFCs used in the current study is comparable with other sophisticated MFCs built with expensive raw materials, as reported in the literature. This cost-effective MFC used in the present study might be an effective replacement of expensive MFCs for wastewater treatment at scaled-up levels.

Keywords: *greywater, microbial fuel cell (MFC), wastewater treatment, cost-effective, power output.*

1 Introduction

A huge volume of wastewater is being discharged annually from domestic, industrial and agriculture sectors. Greywater is the wastewater exiting from households; excluding the wastewater from toilets and including bathrooms, bathtubs, showers, hand wash basins, laundry machines and kitchen sinks. In order to manage the alarming threat of drinking water scarcity in and around the world, there is an increasing demand in the treatment and reuse of greywater. About 75% of residential sewage fraction is greywater (Eriksson *et al.*, 2002). As compared with black (toilet) water, greywater contains low concentrations of organic compounds, nutrients and pathogens (Otterpohl, 2002). Therefore, in order to manage the water scarceness, it makes sense to collect greywater separately and treat it for irrigation, washing or other non-potable applications. It should be treated properly to meet the discharge standards prior to their release into the environment (Suzuki *et al.*; 2002, Maekawa*et al.*, 1995).

Many treatment techniques have been proposed for the removal of inorganic and organic pollutants from wastewater. Most of these processes entail high operational costs or large areas of land for treatment (Min *et al.*, 2005). In this scenario, high energy requirements of conventional sewage treatment systems demand an alternative treatment technology, which will be cost-effective and require no or less energy. Anaerobic technologies have been finding increasing application in the past few decades in the treatment of domestic and industrial wastewater with dual benefit of wastewater treatment as well as energy production in terms of methane-rich biogas. Process instability and microbial flush-out are the main drawbacks of anaerobic reactors, particularly in a small-scale biogas plant (Gangrekar & Shinde, 2006). An alternative technique emerging more recently for wastewater treatment and energy production is microbial fuel cells (MFCs). In MFCs, electricity can be produced with simultaneous degradation of organic matter by microorganisms. MFCs are generally fabricated into 2 chambers: one is anode chamber, while the other is cathode chamber. The cathode chamber is maintained with anaerobic conditions and the organic material given as a substrate will be oxidised by the anaerobic microorganisms; the electrons lost in the process are transferred to the anode by either an electron carrier (mediator) added in the MFC or directly from the respiratory enzyme of the microbes (mediator less) (Logan *et al.*, 2007)

From the literature survey, it can be noted that extensive research on microbial fuel cells is going on on a laboratory scale and most of such studies have been using double or single chamber MFCs with expensive raw materials including Nafion-based proton exchange membranes (Logan *et al.*, 2007; Venkata Mohan *et al.*, 2008; Greenman *et al.*, 2009; Wen *et al.*, 2009; Sangeetha *et al.*, 2011). The generation of electricity using MFCs with different substrates has also been reported. In most of the MFCs, pure compounds such as acetate (Bond & Lovely, 2003), glucose (Rabaey *et al.*, 2003), sucrose (He *et al.*, 2006), amino acid (cysteine; Logan *et al.*, 2005), and proteins (bovine serum albumin) (Heilmann & Logan, 2006) are used as substrates. Wastewater from various industries, such as swine (Min *et al.*, 2005), meat packing (Heilmann & Logan, 2006), food processing (Kim *et al.*, 2004), beer brewery, paper (Mathuriya & Sharma, 2009a, 2009b), corn stover hydrolysates (liquefied corn stover) (Zuo *et al.*, 2006), food processing industries (Sangeetha *et al.*, 2011), and wastewater from domestic activities (Liu *et al.*, 2004) have also been treated using MFCs. Most of the previous studies have reported that MFCs operated with wastewater generate a lower amount of energy than those operated with pure compounds.

Greywater, even though it is a good source of organic matter, has not been reported so far as a substrate in MFCs. Hence, in the present study, greywater was used as a substrate in double-chambered MFCs. Double-chambered MFCs have been successfully operated by many researchers for the simultaneous generation of electricity and wastewater treatment (Min *et al.*, 2005; Raghavulu *et al.*, 2009; Jadhav & Ghangrekar, 2009; Sangeetha *et al.*, 2011) with expensive raw materials, such as graphite electrodes and Nafion-based proton exchange membranes. Hence, the development of MFCs with cost-effective raw materials is a thrust area of research in MFC studies. In this context, the major objective of the present study is to develop laboratory-scale MFCs with cost-effective materials and use them in greywater treatment. The performance of double-chambered MFCs treating greywater was assessed in terms of electricity production, removal of chemical oxygen demand (COD removal) and total solids (TS).

2 Materials and methods

2.1 Substrates used

Greywater was collected from the student's hostel of Mahatma Gandhi University and stored under the refrigeration at 4°C before use. After analysing the characteristics (Table 1), greywater was used as the substrate for MFC without any modifications, such as pH adjustment or the addition of nutrients/trace metals. The experiments were conducted using full-strength wastewater.

2.2 Microbial fuel cells

The whole experiment was designed with 2 double-chambered MFCs, which were fabricated with salt bridges as described by Mohan *et al.*, (2008) and Min *et al.*, (2005). Two polyethylene terephthalate (PET) bottles of 400 mL capacity were used as 2 chambers of each MFC. One bottle was used as the anode chamber and maintained under anaerobic conditions. The other bottle was used as the cathode chamber, maintained aerobic by providing an external air supply with a sparger network (Mohan *et al.*, 2007). Carbon brushes were used as electrodes in each chamber. The electrodes were kept 10 cm apart from each other and were externally connected through copper wires after sealing the contact area with epoxy resin. The chambers were provided with inlet and outlet ports. Both the anode and cathode chambers were connected through a salt bridge of 8.5 cm length and 1.1 cm inner diameter, prepared by using KCl solution and agar-agar.

2.3 Experimental methods. MFC operation

MFC operation was started by filling the anode chamber with 250 mL of greywater (substrate) and 50 mL of digested effluent from an ongoing anaerobic reactor as inocula. In all MFCs, the cathode chamber was kept in aerobic conditions with KCl solution (300 mL) as catholyte and was replenished once in a week as it got denatured. Initially, the MFCs were operated in the batch mode for 10 days, i.e. without further addition of the substrate during this period. This is to facilitate the acclimatisation of microbes with the substrate. After 10 days of the batch mode, both MFCs were operated semi-continuously for a total period of 30 days with 6 cycles of feeding at an interval of 5 days each. On each cycle, daily feeding of 50 mL of the substrate was carried out and, thus, at the end of each cycle, a total of 250 mL substrate was treated. The total experimental period including the batch mode of operation was 40 days. Daily monitoring of voltage and current was carried out during the study period, with different loads of resistance using a digital multimeter. Periodic assessment of greywater treatment in MFCs was done in terms of COD and total solids removal.

Total (dry) solids, volatile solids and chemical oxygen demand (COD) of the influent and the effluent of the MFCs were determined as per standard methods of APHA (1995). Power (W) was calculated using the relation $P = v^2/R_{external}$, where v represent voltage (V) and R is the external resistance load. Power density (mW/m^2) and current density (mA/m^2) were calculated by dividing the obtained power and current by the anode surface area (m^2). Power yield (W/kg COD removal) was obtained by dividing power with corresponding substrate (COD) removal values. Volumetric power (W/m^3) and current density (A/m^3) were calculated based on the anode liquid volume (Venkata Mohan *et al.*, 2007).

3 Results and discussion

The characteristics of greywater used in the study was analysed and the results are presented in Table 1. Daily monitoring of voltage and current was carried out during the study period, with different loads of resistance using a digital multimeter. Each measurement lasted for 3 minutes at each resistance and concordant values. The results were presented as average of MFCs calculated to evaluate the performance of respective duplicate cells of MFCs.

Table 1. Characteristics of greywater used as substrate in MFC.

Parameters	Characteristics					
	1st cycle	*2nd cycle*	*3rd cycle*	*4th cycle*	*5th cycle*	*6th cycle*
pH	6.30	6.52	6.45	6.25	6.20	6.14
Total Solids (mg/L)	1,915	1,910	2,440	2,555	2,030	1,900
Nitrate (mg/L)	6.50	6.81	7.13	7.77	7.43	7.89
Sulphate (mg/L)	15.85	15.67	16.47	15.69	15.15	16.33
Phosphate (mg/L)	22.69	23.71	24.25	24.16	22.80	23.69
Chemical Oxygen Demand (mg/L)	1,382	1,396	1,402	1,402	1,384	1,400

Results in terms of electricity generation from wastewater

After inoculation and feeding, a slow increase in the current was observed in all MFCs. After 10 days of acclimatisation of the microbes with the substrate, a steady current was observed as output in MFCs. The development of microbial population in the form of biofilm has been found to occur between 6 to 15 days until a stable current generation was obtained (Liu *et al.*, 2005). In the present study, the open circuit voltage (OCV) was also observed as a steady output after 10 days of operation. OCV is the cell voltage between 2 terminals of a device when disconnected from any circuit. The maximum OCV of 0.64 ± 0.04 V and 114 ± 1.4 mA of the current were recorded on day 36 (Figure 1). From the figure, it is clear that the potential of the MFC increases as the number of days increases. The results obtained in the present study are comparable with those of Dalvi *et al.* (2011), who conducted a study on electricity generation with paneer whey degradation with different microorganisms in a dual-chambered MFC and the results showed an OCV of 0.45 V.

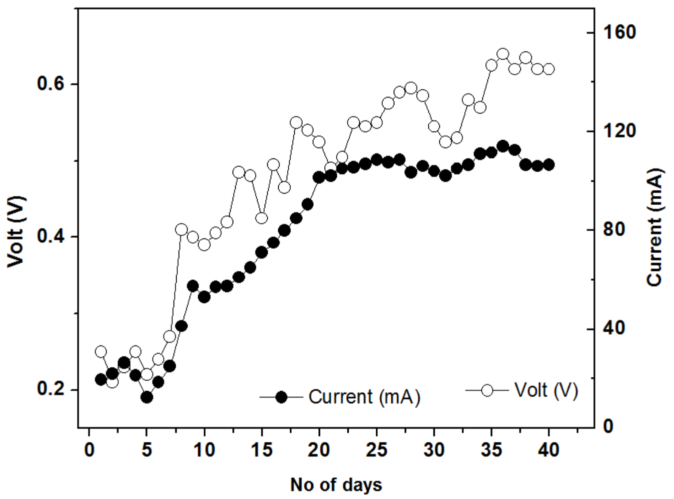

Figure 1. Open circuit voltage and current of MFC treating greywater.

Even though the performance of an MFC can be evaluated in many ways, it is principally done with power output. The power output is usually normalised to the projected anode surface area, where most of the biological activity occurs. In the present study, the power production in MFCs reached the maximum of 24.50 mW on day 36 (Figure 2). It may be noted that the power output showed increments after each feeding of MFCs, indicating multiplication of microbes and their acclimatisation to the new microenvironment. A gradual rise in power was observed after every fresh feed addition, which indicates that the attached microbes on the anode as biofilm contributed to the electricity generation rather than the suspended ones. Sangeetha & Muthukumar (2012) in their study on using sago wastewater have reported 8.1 mW power using graphite as electrode on day 17 of the experiment. Their results also supported the view that the power output showed increments after each feeding.

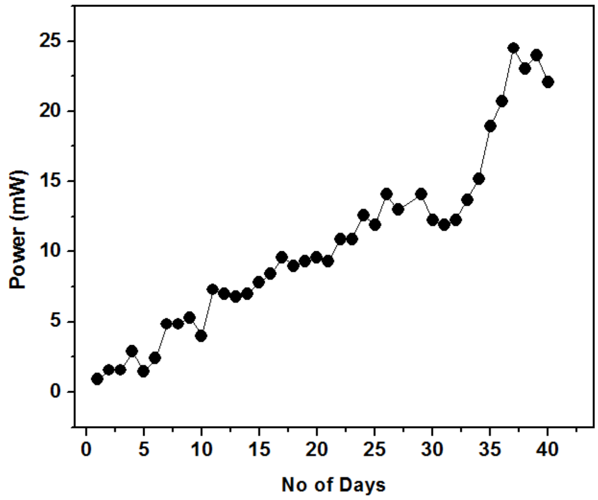

Figure 2. Power generation graph of MFC treating greywater.

Table 2 shows the power generation details of MFCs. At the continuous external load of 100 Ω resistances, the maximum power density of 307.69 mW/m^2, current density of 34.62 mA/m^2, volumetric power density of 1.33 W/m^3, and volumetric current density of 0.15 A/m^3 were recorded.

Table 2. Average power generation details of MFCs at 100 Ω resistances.

No of Days	Power density mW/m^2	Volumetric power density W/m^3	Current density mA/m^2	Volumetric current density A/m^3
1-10 days*	**0.275 ± 0.123**	**0.001 ± 0.001**	**1.231 ± 0.649**	**0.005 ± 0.003**
11	0.62	0.0027	3.0769	0.0133
12	0.77	0.0033	3.8462	0.0167
13	0.77	0.0033	3.8462	0.0167
14	3.08	0.0133	4.6154	0.0200
15	4.81	0.0208	6.1538	0.0267
16	6.92	0.0300	6.9231	0.0300
17	12.31	0.0533	6.1538	0.0267
18	19.23	0.0833	7.6923	0.0333
19	43.27	0.1875	7.6923	0.0333
20	23.27	0.1008	15.38462	0.0667
21	27.69	0.1200	15.38462	0.0667
22	43.27	0.1875	21.53846	0.0933
23	43.27	0.1875	22.30769	0.0967
24	37.69	0.1633	14.61538	0.0633
25	49.23	0.2133	34.61538	0.1500
26	49.23	0.2133	22.30769	0.0967
27	43.27	0.1875	27.69231	0.1200
28	49.23	0.2133	22.30769	0.0967
29	55.58	0.2408	29.23077	0.1267
30	55.58	0.2408	20.76923	0.0900
31	49.23	0.2133	15.38462	0.0667
32	49.23	0.2133	15.38462	0.0667
33	62.31	0.2700	21.53846	0.0933
34	76.92	0.3333	22.30769	0.0967
35	69.42	0.3008	14.61538	0.0633
36	173.08	0.7500	34.61538	0.1500
37	173.08	0.7500	22.30769	0.0967
38	307.69	1.3333	27.69231	0.1200
39	235.58	1.0208	29.23077	0.1267
40	76.92	0.3333	20.76923	0.0900

**1-10 days – the batch mode of operation was carried out, and the average values of the results are presented.*

Lu *et al.* (2009) operated an MFC with starch processing wastewater containing 4,900 mg/L of COD over 4 cycles and obtained the maximum power density of 239.4 mW/m^2 in the third cycle. Similar results were also reported by Sangeetha *et al.*, (2011) with food processing wastewater. The distance between cathode and anode plays an important role in power generation of fuel cells. As the distance between the 2 electrodes is less, the resulting power output will be high by dropping the ohmic resistance

(Jang *et al.*, 2004). In the present study, the electrodes of MFCs were kept at a distance of 10 cm resulting in good power output (Figure 2). The effect of electrode distance on MFC performance was carried out by Sangeetha & Muthukumar (2012) varying it as 10 cm, 12 cm and 15 cm. Their study revealed that electrode distance of 10 cm resulted in increased power production with a voltage of 900 mV (millivolts), current of 9.0 mA (milliamps) at 100 Ω resistances and COD removal of 94%. A similar trend of an increase in MFC performance with a decreasing distance between the electrodes was observed by Liu *et al.* (2005), Kim *et al.* (2007), Ghangrekar & Shinde (2007), and Cheng *et al.* (2006).

Effect of organic loading rate on power generation.

The amount of electricity produced from wastewater depends upon COD loading (Oh and Logan, 2005). The present study showed greater power output with high COD loading. Wastewater from various sources with a COD ranging 1,000 – 10,000 mg/L is a potential substrate for MFCs (Pant *et al.*, 2009). Greywater used in the present study had an average COD value of 1394.33 ± 9.04 mg/L. The overall COD removal efficiency observed in the present study was 71.36 ± 1.93%, demonstrating the feasibility of this configuration of MFCs as an effective wastewater treatment system, also ensuring better effluent quality. The organic matter present in greywater at the anode chamber was effectively consumed by microorganisms resulting in COD removal from greywater (Figure 3). Power yield of MFCs with respect to daily COD removal was calculated and shown in Figure 4. In accordance with the COD reduction results, MFCs showed a power yield of 0.40 mW/kg COD removal.

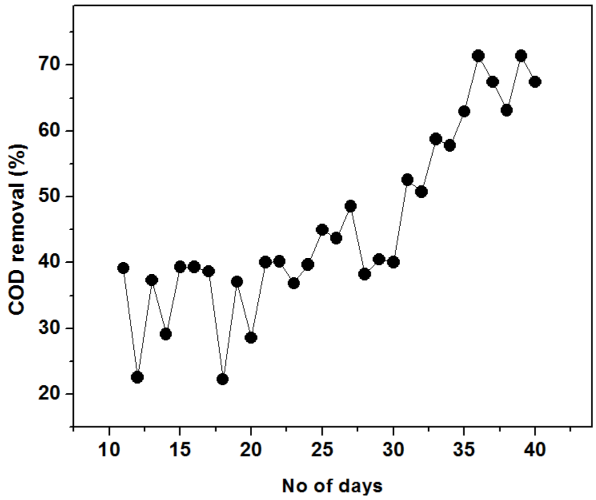

Figure 3. Results in terms of percentage COD removal.

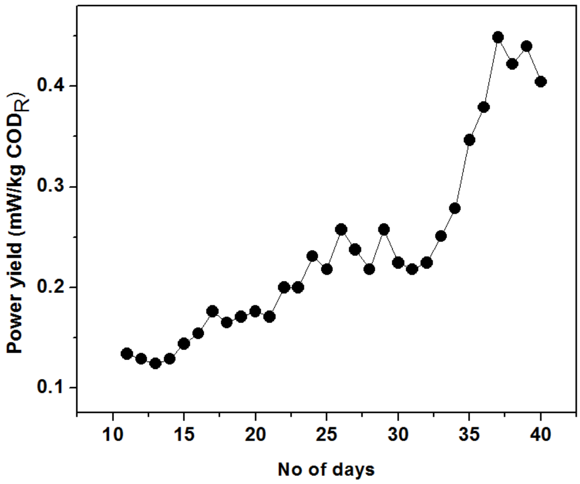

Figure 4. Power yield of MFC treating greywater.

The solid removal efficiency of MFCs was also analysed and the results are shown in Figure 5. During the study period, the effluent samples from both MFCs showed a gradual decrease in the concentration of total and volatile solids due to the microbial action.

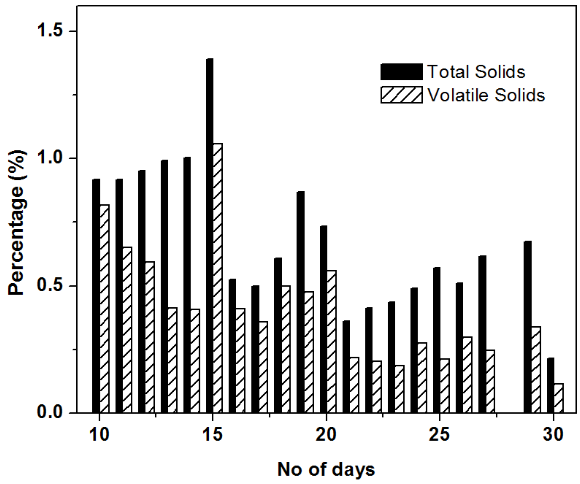

Figure 5. Total and volatile solid concentration in the effluent from MFCs.

4 Conclusions

The efficiency of MFCs used for the treatment of greywater was successfully evaluated in the present study with remarkable results of electricity production and COD removals. One of the major drawbacks of conventional MFCs, which utilize graphite electrodes and Nafion-based proton exchange membranes, is high cost. The significance of the present study is the cost effectiveness of the raw materials used for the fabrication of MFCs. In the present study, in order to transfer protons to the cathode, a salt bridge and carbon brushes were used as electrodes, which are less expensive and easily available. This low-cost MFC, with the manufacturing cost of less than USD 4.0, has performed with comparable performance on a par with many sophisticated MFCs employing expensive proton exchange membranes. The low-cost MFCs used in the present study may be an effective alternative for an expensive Nafion-based MFC in wastewater treatment at scaled-up levels. However, the lower electrode potential of the present MFC has to be improved by decreasing its internal resistance. Further studies are presently going on towards improving the performance of the cathode with less internal resistance using low-cost raw materials.

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Pilkojo vandens valymas ir elektros energijos generavimas, naudojant nebrangius mikrobinius kuro elementus

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Mikrobiniai kuro elementai (angl. microbial fuel cells – MFCs) – tai besivystantys biologinio nuotekų tvarkymo technologija, kuri tuo pačiu metu generuoja elektros energiją. Šis tyrimas pristato efektyvų pilkojo vandens valymą kartu su elektros energijos gamyba dvigubos kameros MFCs. MFCs buvo pagaminti naudojant rentabilias ir lengvai prieinamas medžiagas, pakeičiant tokius brangius metalus, kaip Nafion membranos, grafito elektrodai ir pan. Eksperimentiniai rezultatai parodė, kad tyrimo metu didžiausia atviros elektros srovės įtampa siekė 0,64 ± 0,04 V, o srovės stipris 114 ± 1,41 mA. Rezultatai taip pat parodė, kad išvystyta galia siekė 24,5 mW, kai galios tankis buvo 307,69 mW/m^2; srovės stiprio tankis 34,62 mA/m^2, galios tūrinis tankis 1,33 W/m^3, srovės stiprio tūrinis tankis 0.15 A/m^3 ir galios išeiga 0,40 mW/kg cheminio deguonies suvartojimo (ChDS) panaikinimui. ChDS pašalinimo efektyvumas siekė 77,6%. Nebrangių ir lengvai prieinamų žaliavų naudojimas leido sumažinti šiame tyrime naudotų MFCs bendrus gamybos kaštus iki mažiau nei 4,0 JAV dolerių. Nepaistant to, šiame tyrime naudotų MFCs rezultatai gali būti sulyginami su kitais sudėtingais MFCs, kurie yra sukurti naudojant brangias žaliavas, pateiktas literatūroje. Šie rentabilūs tyrime naudojami MFCs gali būti efektyvus pakaitalas brangiems MFCs, kurie naudojami nuotekoms valyti aukštesniuose lygiuose.

Raktiniai žodžiai: *pilkasis vanduo, mikrobinis kuro elementas, nuotekų valymas, rentabili galios išeiga*.

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Assessment of Metal Pollution of Soil and Diagnostic Species Associated with Oil Spills in the Niger Delta, Nigeria

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An ecological impact assessment of crude-oil spills was carried out on the environment of an oil-rich community in the Niger Delta of Nigeria. Samples of the topsoil (0−15 cm), subsoil (15−25 cm) and the dominant species Gamba grass (*Andropogon gayanus*) were collected using the transect method from the point of spills. The samples were also collected from an unimpacted location (control). The samples were wet-digested and the concentrations of Pb, Cd, Cu, and Zn were determined by flame atomic absorption spectrophotometry, while the physico-chemical properties of the topsoil were determined by standard methods. The data were subjected to Student *t* test, ANOVA and Pearson correlation analysis, and the models for pollution assessment were employed to assess the pollution status of the soil and plant species. The results showed that concentrations of Pb, Cu and Zn in the topsoil exceeded international standards at close proximity to point of spills (0−200 m), while Cd concentrations exceeded the international standard at all the locations. Only Cd exceeded the international standard in the subsoil. Contamination (P_i) and integrated pollution (P_c) indices of the topsoil showed reducing trends from the point of pollution, and locations at 0 m and 100 m exhibited high P_c, while those at 200 m showed moderate P_c by all metals. The levels of Pb and Cd in the diagnostic species exceeded the World Health Organization limits and the pollution load index (PLI) portrayed severe contamination. In conclusion, the impact of crude-oil spills in the area was significant; soil remediation is important to avert ecological and human health disasters. Moreover, these findings will be useful for designing strategic measures for environmental control in the area.
Keywords: *oil spillage, integrated pollution index, soil remediation, pollution load index*.

1 Introduction

In the quest for industrialisation and greater economic empowerment, many developing countries, including Nigeria, have interfered with the environment to the extent that there is currently widespread environmental degradation and devastation with attendant climatic, economic and health effects. Since the beginning of petroleum production in Nigeria in 1958, many documents are available on the petroleum spills into agricultural lands through petroleum production operations (Odu *et al.*, 1985; Imoobe & Iroro, 2009). Although, the petroleum industry has contributed immensely to the economy and development of Nigeria, oil exploration, transportation and marketing operations have also presented some attendant negative impacts on the environment. Ozurumba (1999) showed that in 1999 alone about 47 major oil spillages due to vandalisation occurred in Nigeria resulting in damage to lives, plants and animals. Between 1976 and 1996, Gideon & Josephine (2008) reported that over 647 spillages occurred spilling 2,369,407.04 barrels of crude oil with only 549,060.38 barrels (23%) being recovered, while 1,820,410.50 barrels (77%) were lost to the environment. The cause of these serious spillages was attributed to blowouts, sabotage, corrosion of pipelines, equipment failure, operator or maintenance error, third party accelerant, natural spills and misery spills (Imoobe & Iroro, 2009). Ekundayo & Obuekwe

(2000) indicted oil spills for the introduction of heavy metals such as Cu, Ni and Hg into the soil, which impair the biota due to their toxicity. Oil spill affects the physical-chemical properties of the soil, such as temperature, structure, nutrient status and pH. The effects of heavy metal pollution may be immediate if crops planted in spill sites which have accumulated the metals are consumed by man and livestock.

Okordia and Oya in Ikarama community are hosts to Agip and Shell companies, but very little has been documented with respect to the impact of their activities on immediate environment. Based on this, the community needs to be environmentally audited from time to time so as to advise the stakeholders in the petrochemical industries, the government and the local communities on the potential health risks posed by the oil industry. Several studies have also indicated that metal pollution (e.g. Pb, Cd and Ni) is responsible for certain diseases of humans and animals (Gustav, 1974; Nolan, 2003; Young, 2005); and thus, there is a need for cleaning up oil-contaminated soil. So far, phytoremediation has proved to be cheaper and sustainably feasible in cleaning up pollutants from the soil (Joner *et al.*, 2004). Hence, identification of plants growing in oil-spill impacted land with potentials to accumulate metals is imperative in order to establish suitable plants for the clean-up of metals in oil-spill impacted locations. Therefore, this study was undertaken to investigate the impact of oil spill on the soil and vegetation of this oil-rich community with respect to their heavy metal loads.

2 Materials and methods

2.1 Study area

The study sites Okordia and Oya are in Ikarama (05°09'16" N, 06°27'11 E), a small community situated within Yenogoa Local Government Area, Bayelsa State, Nigeria (Figure 1). Bayelsa state is strategically located at the centre of the Niger Delta region of Nigeria, which is one of the richest wetlands in the world with a tropical climatic condition of a rainy season (April to November) and a dry season (December to March) and an annual rainfall ranging between 1,500 and 4,000 mm (Kuruk, 2004). Ikarama community is a host to Nigeria's Agip Oil Company and Shell Petroleum Development Company (SPDC). The SPDC pipelines linking Delta, Bayelsa and River states in Nigeria pass through Ikarama community and oil spills from equipment failure have been reported to be the major environmental contamination of this community (MOEN, 2008). The 2 study sites were chosen because of the frequent occurrence of oil spills in the sites. For example, 421 crude oil spills occurred between 18 December 1991 and 23 August 2008 in the state, while 9 major oil spills occurred within Ikarama community (MOEN, 2008). Moreover, more recent crude oil spills also occurred in December 2008 and June 2009 in Oya and Okordia, respectively.

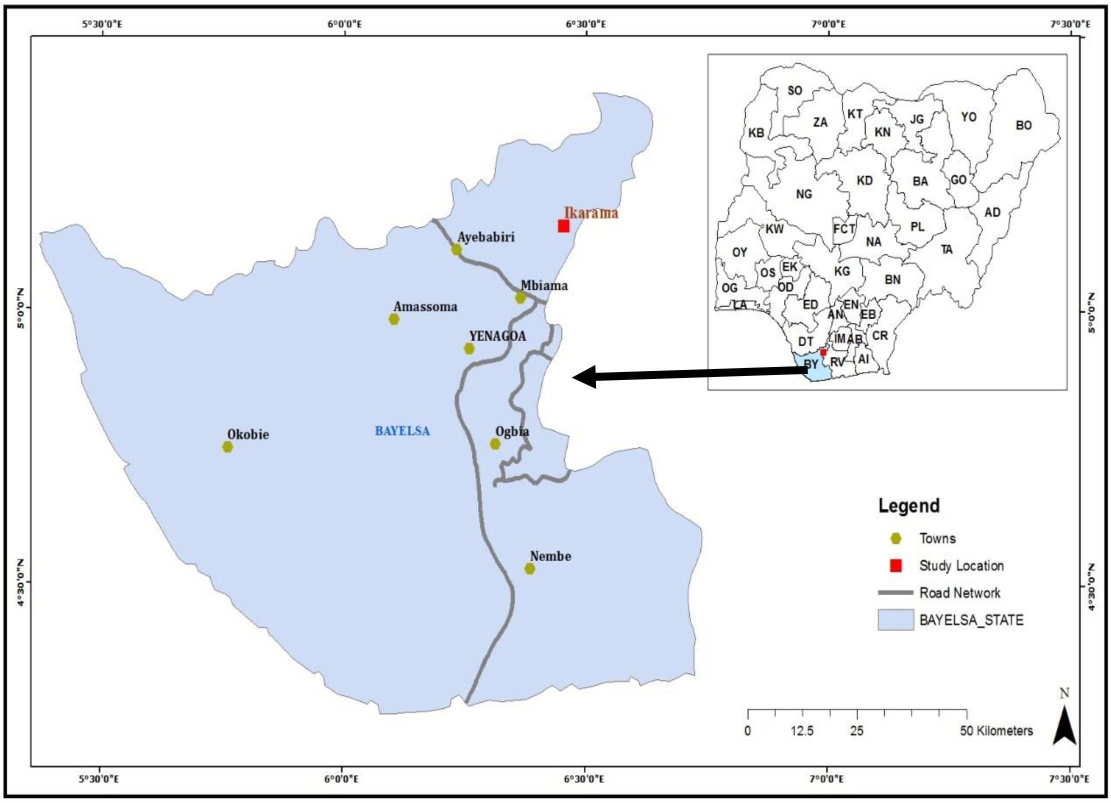

Figure 1. Map of Bayelsa state showing Ikarama community where the 2 study sites are located. Inset: Map of Nigeria showing different states.

2.2 Sampling and chemical analysis

Soil and plant samples were collected from 2 oil-spill impacted sites at Okordia and Oya and the sampling activities were carried out in September 2009. At each crude-oil impacted site, a line transect was set from the centre point of the spill in any accessible direction and soil samples were collected at every 100 m along the transect to a distance of 400 m. The short transect distance was premised on the fact that most of the area was inundated with seawater. At every sampling point, 5 soil samples were randomly collected from the depth of 0−15 cm and 15−25 cm, respectively (topsoil and subsoil, respectively), with a stainless soil auger, and a total of 50 soil samples (25 samples each of topsoil and subsoil) were collected in each site. The dominant plant species – Gamba grass (*Andropogon gayanus*) – was sampled at every point of soil collection in the 2 sites, while the samples that served as the control were collected at Zarama, a location that has not experienced crude oil spill. Roots of the samples were discarded at the site and the shoots were properly packed in a paper bag and labelled for laboratory analysis.

The soil samples were air-dried at room temperature, sieved through a 2-mm mesh and ground into fine powder. One (1) g of the soil sample was wet-digested using the *Aqua regia* method described by ISO (2002). The resulting digestate was filtered using Whatman No 42 filter paper into a beaker and diluted with deionised water to make up 25 mL. Four metal concentrations (Pb, Cd, Cu, and Zn) were determined by flame atomic absorption spectrophotometer (Bulk Scientific 210VGP, USA). One (1) g of the powdered plant sample was digested in 10 mL of conc. HNO_3 on a hot plate until fumes turned white. The solution was filtered using Whatman No 42 filter paper and analysed for Pb, Cd, Cu and Zn using the FAAS (Bulk Scientific 210VGP, USA).

Procedural blanks and replicates' digestion were carried out for QA/QC. A calibration graph for each element determined by the AAS was drawn by using a series of working standard solutions (CPI International, USA) and correlation coefficients greater than 0.850 were obtained for all the elements. The soil pH was determined in a soil-deionised water suspension (1:2.5 w/v) by a calibrated pH meter (PHS-3C model); electrical conductivity (EC) was determined using a conductivity bridge (Hanna EC–214 model) and soil particle size fractions were determined by the method of Bouyoucos (1962).

2.3 Statistical analyses and assessment of metal pollution

The data generated were subjected to the analysis of variance (ANOVA) and the means were separated with Duncan multiple range test (DMRT) using the Statistic Package for Social Sciences (SPSS) and Excel 2007 for Windows version 16. Student *t* test was employed to test a significant difference between the metal in the soil and the diagnostic plant, while Pearson coefficient of correlation was used to determine the relationship between the metal in the soil and the plant at $p < 0.05$, respectively.

Heavy metal pollution of the soil was assessed by the use of the contamination index (P_i) and integrated contamination index (P_c) models suggested by Huang (1987). The expression for the models is represented in Equations 1-4 and the applied threshold values (mg kg^{-1}) are presented in Table 1.

$$P_i = C_i / X_a \quad [C_i \le X_a] \tag{1}$$

$$P_i = 1 + \left[C_i - X_a / X_b - X_a \right] \quad [X_a < C_i \le X_b] \tag{2}$$

$$P_i = 2 + \left[C_i - X_b / X_c - X_b \right] \quad [X_b < C_i \le X_c] \tag{3}$$

$$P_i = 3 + \left[C_i - X_c / X_c - X_b \right] \quad [C_i > X_c] \tag{4}$$

where C_i is the metal concentration in the soil; X_a is the bo-pollution threshold value; X_b is the lowly polluted threshold value and X_c is the highly polluted value. The threshold values of X_a, X_b and X_c are defined in Table 1 based on the Chinese Environmental Quality Standard for soils (SETAC, 1995).

The integrated contamination index (P_c) for each study distance was calculated by the following formula:

$$P_c = \sum_{i=1}^{n} (P_i - 1) \tag{5}$$

The classes of P_i and P_c according to Huang (1987) are presented in Table 2.

Table. 1. Threshold values (mg/kg) for contamination index (P_i) (SETAC, 1995).

	Pb	Cd	Cu	Zn
X_a	35	0.2	35	100
X_b	250	0.3	50	200
X_c	500	1.0	400	500

Table 2. Classes of contamination index (P_i) and integrated pollution index (P_c) (Huang, 1987; D'Souza et al., 2013).

Class	Contamination index (P_i)	Integrated pollution index (P_c)
No	$P_i \le 1$	$P_c \le 0$
Low	$1 \le P_i \le 2$	$0 < P_c \le 7$
Moderate	$2 \le P_i \le 3$	$7 < P_c \le 21$
High	$P_i > 3$	$P_c > 21$

The heavy metal pollution status of the diagnostic species was assessed using the contamination factor (CF) and the pollution load index (PLI) suggested by Fernandez & Carballeira (2001) and Kalavrouzioti *et al.* (2012), respectively:

$$CF = C_m / C_b \tag{6}$$

where C_m is concentration of the metal determined in the plant species; C_b is concentration of the metal determined in the control.

CF < 1 – showed no contamination (NC); 1 < CF < 2 – suspected contamination (SC); 2 < CF < 3.5 – slight contamination (SLC); 3.5 < CF < 8 – moderate contamination (MC); 8 < CF < 27 – severe contamination (SEC); and CF > 27 – extreme contamination (EC) (Gonzalez-Miqueo *et al.*, 2010).

$$PLI = n\sqrt{\sum_{i=1}^{n} CF_1 \times CF_2 \times CF_n} \quad (7)$$

Values of PLI close to 1 indicate that elemental loads of plant species are near to the background level, PLI 1−3 shows moderate pollution, and values > 3 indicate severe pollution (Daud *et al.*, 2006).

3 Results and discussion

3.1 Level of heavy metals in topsoil and subsoil

The characteristics of the topsoil in the study sites are presented in Table 3. The topsoil was predominantly sandy with less than 2% silt and 8% clay and acidic. The sandy portions were found to constitute more than 90% of the topsoil in Okordia and Oya. The pH values of the soil ranged from 4.66 to 5.6 and from 4.09 to 4.76 for Okordia and Oya, respectively, showing that the soils were acidic. Increased acidity has been reported to enhance mobility, solubility and availability of elements in soils (Odu *et al.*, 1985; Sauve *et al.*, 1997). The acidic nature of the soil of the area is not surprising because most of the soils in the south-south geographical zone of Nigeria are acidic and which may be due to their exposure to excessive precipitation leading to leaching of the basic cations and being replaced by hydrogen ion (Ngobiri *et al.*, 2007). This finding was consistent with the reports of Osuji & Nwoye (2007) as they also reported a pH range of 4.9–5.1 in crude-oil polluted soil and 5.6 in unpolluted soil. The electrical conductivity (EC) of the 2 oil-impacted sites range from 0.08 to 0.15 dS/m and from 0.07 to 0.18 dS/m for Okordia and Oya, respectively. The high EC observed in these impacted soils may be linked to the crude-oil spill, suggesting the presence of highly soluble solutes.

Table 3. Physico-chemical characteristics of topsoil of Okordia and Oya.

		Soil characteristics				
Location	**Distance (m)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**pH (1:2.5)**	**EC (dS m-1) (1:2.5)**
Okordia	400	93.07±1.79	1.67±0.75	5.27±2.54	4.82±0.61	0.08±0.05
	300	93.63±2.51	0.60±0.20	5.73±2.39	5.06±0.90	0.09±0.06
	200	91.60±2.21	1.73±0.91	6.67±2.75	4.66±1.07	0.08±0.03
	100	91.27±2.01	1.77±0.93	6.93±2.47	5.09±0.77	0.13±0.02
	0	93.43±2.68	1.23 ±1.02	5.17±2.79	5.62±0.55	0.15±0.03
Oya	400	87.57±3.19	2.17±0.60	6.93±2.11	4.44±0.58	0.07±0.01
	300	91.17±2.47	1.63±0.95	7.20±2.25	4.76±1.09	0.08±0.02
	200	91.90±1.45	1.77±0.85	6.33±1.59	4.09±0.58	0.09±0.03
	100	92.37±0.81	1.73±0.91	5.90±1.47	4.69±1.34	0.12±0.08
	0	91.73±1.05	1.17±1.08	7.10±1.37	4.76±1.23	0.18±0.01

Heavy metal contents of the topsoil of Okordia and Oya at various distances are shown in Table 4. It was evident that metal concentrations of the soil decreased significantly (P<0.05) as the distance increased from the point of the spill; and metal concentrations were consistently and significantly higher (P<0.05) at 0 m.

Table 4. Heavy metal contents (mg kg^{-1}) of topsoil of Okordia and Oya.

Site	**Distance (m)**	**Concentration (mean±SD)**			
		Pb	**Cd**	**Cu**	**Zn**
Okordia	400	19.7±2.4^{e}	5.1±0.25^{d}	18.7±0.7^{d}	181.3±17.2^{d}
	300	23.7±1.1^{c}	5.9±0.35^{d}	21.6±0.8^{d}	185.3 ±15.0^{d}
	200	41.0±6.2^{c}	7.0±0.6^{c}	37.3±7.6^{c}	201.0±34.6^{c}
	100	88.2±4.2^{b}	9.3± 2.0^{b}	82.0±18.5^{b}	223.7 ±38.1a^{b}
	0	128.1±12.5^{a}	10.7±3.12^{a}	116.8±7.8^{a}	285.0±43.8^{a}
Oya	400	19.8±4.9^{e}	5.2±0.2^{d}	19.8±0.8^{d}	184.6 ±16.0^{d}
	300	23.3±6.5^{c}	2.2±0.2^{e}	22.6±1.4^{d}	190.7±16.8^{d}
	200	34.0±8.2^{c}	6.7±3.1^{c}	32.7±8.8^{c}	221.7±38.4^{c}
	100	82.5±23.3^{b}	9.2±2.7^{b}	78.5±15.0^{b}	272.5±77.6^{b}
	0	115.0±14.2^{a}	11.0±3.7^{a}	120.8±3.6^{a}	309.3±63.5^{a}
CCME*		70	1.4	63	200

Values with the same superscript along the same column are not statistically different at p ≤ 0.05.
** – CCME limits for metals in agricultural soils.*

The concentrations of Pb, Cu and Zn at 0 m doubled the concentrations at 300 m and 400 m, whereas the concentrations of Cd were in several folds of metal concentrations at 300 m. It is clear that the high concentrations of heavy metals in the topsoil up to 300 m distance in the 2 sites are resultant effects of the crude-oil spill. Essoka *et al.* (2006) reported high concentrations of Pb and Cd in the soil around a crude-oil polluted site in Warri, Delta state in Nigeria. Comparing the metal loads of the topsoil of the 2 crude-oil impacted areas with the limits stipulated for agricultural soil by the Canadian Council of Minister of Environment (CCME) (2007), it was observed that the concentrations of Pb and Cu in the topsoil exceeded CCME limits up to 100 m distance. Cd concentrations at the 2 sites were also several folds greater than the CCME limit, while Zn concentrations exceeded the CCME limit up to 200 m distance (Table 4).

These elevated values of heavy metals in the soil of Okordia and Oya of Ikarama suggest anthropogenic inputs into the soil due to several crude oil spillages in the area since more than 60 metals have been established to be in crude oil (Nduka *et al.*, 2012). The fact that there is significant metal pollution in the area becomes ecologically significant due to the agrarian nature of the community and the possibility of toxic metals being transferred up the food chain, thereby portending human health hazards.

The heavy metal loads in the subsoil of Okordia and Oya are shown in Table 5. Generally, the concentrations of Pb, Cd, Cu and Zn in the subsoil were lower than the concentrations in the topsoil. The subsoil of the 2 sites was contaminated with Cd at all locations, while Zn contamination was up to 200 m when compared with the CCME limits. The same pattern of reduction of metal concentrations in the topsoil as the distance increases was also observed for the subsoil.

Table 5. Heavy metal content (mg kg^{-1}) of subsoil of Okordia and Oya.

Site	Distance (m)	Concentration (mean ± SD)			
		Pb	**Cd**	**Cu**	**Zn**
Okordia	400	5.1±1.50^d	2.5±0.1^d	5.0±1.3^c	54.6.1±6.8^e
	300	4.8±0.37^d	2.8±0.1^d	5.6±0.7^c	185.3±4.12^d
	200	6.3±1.1^c	3.0±0.2^c	7.3±1.0^b	201.0±33.6^c
	100	8.8±1.7^b	3.6±0.1^b	8.8±0.8^b	223.7±38.1^b
	0	11.0±1.0^a	3.8±0.1^a	12.3±0.2^a	277.2±43.8^a
Oya	400	4.5±0.6^d	2.6±0.1^e	4.5±0.6^d	184.6±16.0^d
	300	6.8±1.0^c	3.0±0.2^c	4.7±0.8^d	190.6±16.7^d
	200	8.1±0.5^b	2.8±0.5^d	5.2±1.5^c	221.7±33.7^b
	100	10.0±0.8^a	3.1±0.7^b	11.5±1.7^b	272.5±77.5^a
	0	10.8±0.5^a	3.5±0.3^a	13.6±1.7^a	209.2±63.2^c
CCME		70	1.4	63	200

Values with the same superscript along the same column are not statistically different at $p \leq 0.05$.

3.2 Level of heavy metals in the diagnostic species *Andropogon gayanus*

The concentrations of metals in *Andropogon gayanus* (Gamba grass) used as biomonitor in this study are presented in Table 6. Generally, Gambia grass in the control had the lowest values of metals. The highest concentration of metals in the diagnostic plant was obtained at the point of the spill (0 m) and subsequently decreased significantly (P < 0.05) away from the source point of pollution up to 300 m away. This reported reduction in metal concentration in the diagnostic plant as the distance increased from the source point of pollution has been earlier reported by Bada & Olarinle (2012).

Table 6. Heavy metal content (mg kg^{-1}) of Andropogon gayanus growing at various locations in the study sites.

		Concentration (mean ± SD)			
Site	**Distance (m)**	**Pb**	**Cd**	**Cu**	**Zn**
Okordia	400	4.5±1.25^d	0.25±0.05^d	4.1 ±0.05^e	8.0±0.12^d
	300	3.5±0.25^e	0.5±0.25^c	5.6±0.64^d	7.8±0.37^d
	200	4.2±0.12^c	0.75±0.25^c	6.5±0.12^c	16.1±0.37^c
	100	4.7±0.12^b	1.2±0.07^b	7.7±0.02^b	27.2±.75^b
	0	6.3±0.25^a	3.5±1.5^a	9.0±0.12^a	31.7±4.25^a
Oya	400	4.6±0.12^d	0.25±0.25^e	2.5±2.87^e	6.5±0.25^d
	300	4.8±0.12^d	0.5±0.05^d	5.2±0.05^d	7.5±0.03^c
	200	6.3±0.25^b	1.0±0.05^c	6.3±0.12^c	12.7±0.12^b
	100	6.0±0.62^c	1.2±0.5^b	7.7±0.03^b	26.0±0.62^a
	0	8.1±0.62^a	2.2±1.50^a	9.1±0.11^a	26.7±0.25^a
Control		2.0±0.50	0.2±1.00	1.6±0.12	4.0±0.12
WHO limit*		2.0	0.2	10	n.a.
Phytotoxic level[a]		10-20	5-10	15-20	150-200

*Values with the same superscript along the same column are statistically the same at $p \leq 0.05$; * – WHO Permissible limit in plants; [a] – Varun et al. (2010).*

Compared with the WHO (1996) permissible limits of metals in plants, Pb and Cd exhibited elevated concentrations beyond the WHO limits at all locations. Ling *et al.* (2007) have asserted that heavy metal contamination of the soil may pose risks and hazards to humans through the food chain, which is soil-plant-human or soil-plant-animal-human, as well as reduction in food quality via phytotoxicity. Meanwhile, the concentrations of all the metals in *A. gayanus* were below the phytotoxic levels in plants as presented by Varun *et al.* (2010); and this could explain its continued survival in the presence of the elevated metal concentrations in the soil. There is also the possibility of *A. gayanus* being excluder of these heavy metals as the concentrations never reached phytotoxic levels despite their abundance in the soil of the area.

Student *t* test used to compare the metal contents of the topsoil with the grass and the Pearson correlation coefficient are presented in Table 7. The concentrations of heavy metals in the topsoil positively and significantly correlated ($p < 0.05$) with the concentrations of metals in *A. gayanus*, except Cd at Oya. This indicates the possibility of *A. gayanus* taking up the heavy metals solely from the polluted topsoil. Metals in *A. gayanus* were significantly lower than their corresponding concentrations in the topsoil at $p < 0.05$ (Table 7). This also evidently proves that high concentrations of metals in the soil do not always indicate similar high concentrations in plants; the extent of accumulation depends on plant and heavy metal species (Hart *et al.*, 2005).

Table 7. Pearson correlation coefficients (r) and Student t test between metals in topsoil and Andropogon gyanus in the study sites.

	Pearson correlation (r)		**Student *t* test**	
Metal	**Okordia**	**Oya**	**Okordia**	**Oya**
Pb	*0.725***	*0.844***	*4.790***	*0.808***
Cd	*0.746***	*0.360*	*10.232***	*5.600***
Cu	*0.908***	*0.828***	*4.703***	*4.566***
Zn	*0.798***	*0.756***	*16.350***	*13.078***

*** – Significant at $p \leq 0.05$.*

3.3 Pollution assessment of topsoil and diagnostic species

The pollution assessment of the topsoil using the contamination index (P_i) and the integrated pollution index (P_c) is presented in Figure 2.

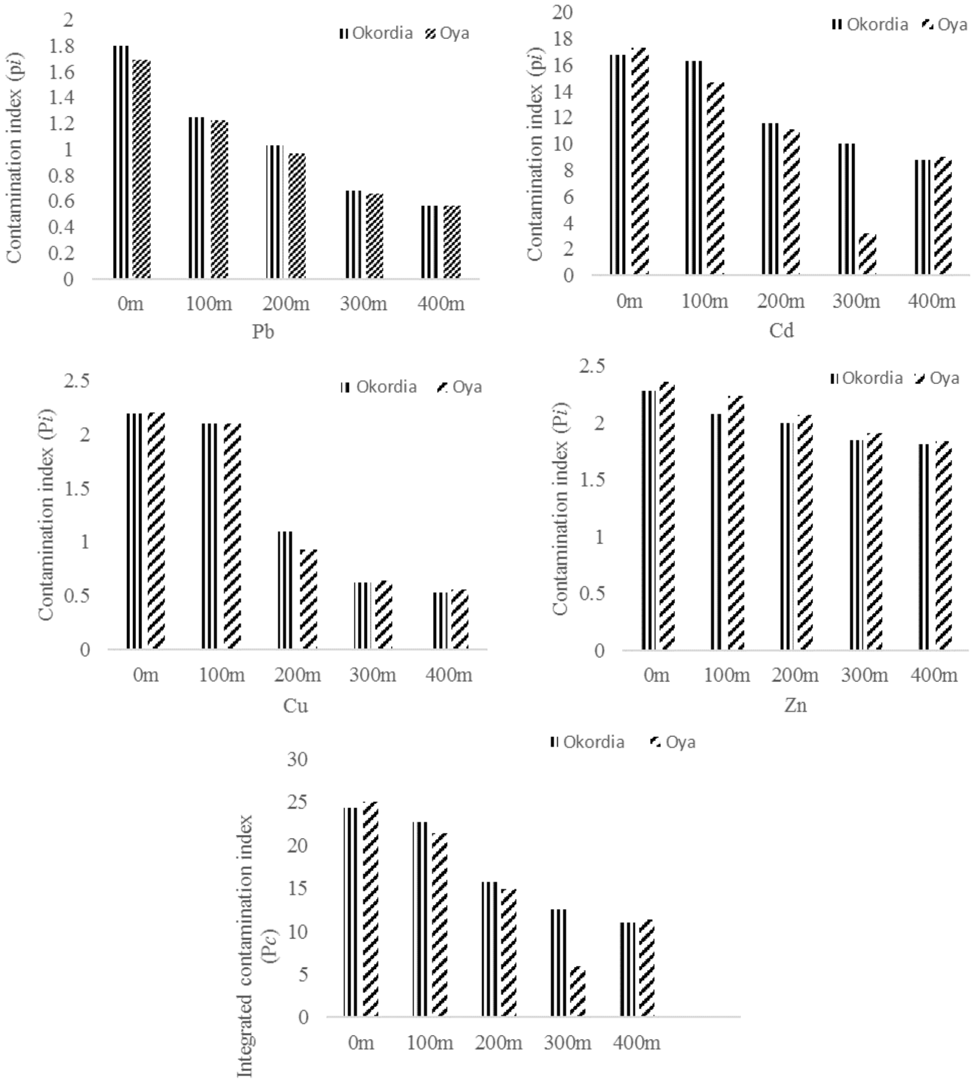

Figure 2. Contamination index (P_i) of (a) Pb, (b) Cd, (c) Cu, (d) Zn and (e) the integrated pollution index (P_c) of the topsoil of the 2 study sites.

Low contamination by Pb ($1 \leq P_i \leq 2$) was observed in the topsoil of Okordia and Oya from 0 m to 200 m distance whereas 300 m and 400 m locations showed no contamination ($P_i \leq 1$). High levels of contamination ($P_i > 3$) were recorded in the case of Cd across all locations. The sites showed moderate contamination ($2 \leq P_i \leq 3$) of Cu and Zn at 0 m and 200 m, while low contamination of Zn was observed from 200 m to 400 m in the 2 sites. Pb and Cu indicated no contamination from 200 m to 400 m in the 2 sites. It is noteworthy that the contamination levels in the 2 sites for all the metals showed a reducing trend from the source of pollution, and Cd was consistently at high levels across the locations.

The integrated contamination index (P_c) values of the locations for the 2 sites are presented in Figure 2f. The same reducing trend of the contamination index (P_i) observed at the 2 sites was also represented in the integrated contamination index (P_c). High integrated ($P_c > 21$) contamination was observed at 0 m and 100 m at the 2 sites due to their proximity to the source of pollution. Locations at 200 m, 300 m and 400 m in Okordia and locations at 200 m and 400 m in Oya indicated moderate integrated contamination ($7 < P_c \leq 21$). The location at 300 m in Oya indicated low integrated contamination ($0 < P_c \leq 7$). It is clear from the results that all the locations within the 2 sites does not fall within the threshold of no integrated contamination ($P_c \leq 0$); hence, there is urgent need for remediation of the soil to avert ecological and human health disaster.

The assessment of the contamination level of the diagnostic species (*A. gayanus*) used in this study is presented in Figure 3.

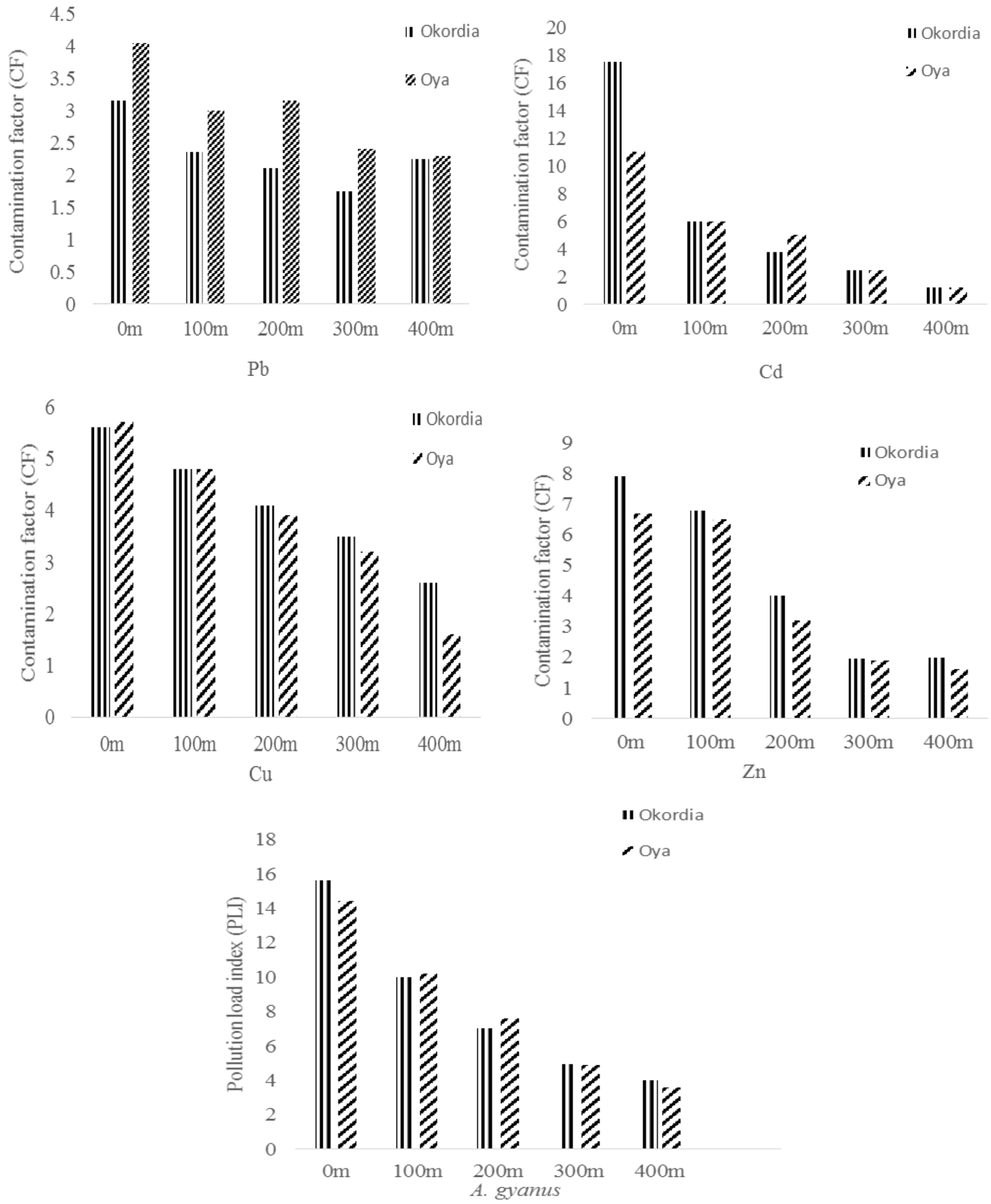

Figure 3. *The contamination factor (CF) of (a) Pb, (b) Cd, (c) Cu, (d) Zn and (e) the pollution load index (PLI) of A. gayanus in the 2 study sites.*

The concentrations of Pb in *A. gayanus* at 0 m, 100 m and 400 m in Okordia were within the slight contamination level. The same level of contamination was observed at 100 m and 200 m in Oya, while at 0 m the level of contamination of *A. gayanus* reached moderate contamination (Figure 3a). The concentrations of Cd in *A. gayanus* at 0 m and 100 m in Okordia and Oya reached the severe contamination level, while moderate contamination was observed at 200 m and 300 m in the 2 sites (Figure 3b). Cu concentrations in *A. gayanus* at 0 m, 100 m, 200 m and 300 m indicated moderate contamination, while slight contamination and suspected contamination were exhibited at 400 m in Okordia and Oya, respectively (Figure 3c). Moderate contamination of Zn was recorded in *A. gayanus* at 0 m, 100 m and 200 m in both Okordia and Oya, while at 300 m and 400 m suspected contamination of *A. gayanus* was exhibited (Figure 3d). The pollution load of the index of *A. gayanus* showed that all locations in the 2 sites were severely contaminated with heavy metals (Figure 3e). This portends a grave ecological problem as food crops planted in this agricultural land can possibly accumulate metals to the levels that portend health implications to animals and humans that depend on them for survival.

4 Conclusion

The study has revealed that the several incidences of crude oil spillage have really impacted on the environment of Ikarama with heavy metals. The pollution indices of the soil at 0 m and 100 m were high, while the other distances (200 m, 300 m and 400 m) were of low pollution. The high metal pollution of the soil at all the distances was reflected on the diagnostic plants, as *A. gayanus* showed the severe metal pollution status due to uptake and eventual accumulation of metals to toxic levels in the biomass. It is obviously imperative that the government improve environmental policies to protect the Niger Delta from a degradation effect of oil exploration. It is also important that the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) that stipulated that the spiller should be responsible for the clean-up of the site and restoration to the original state should be adequately empowered and enforced on oil prospecting companies in the Niger Delta to reduce the risk and hazard posed by heavy metals to humans and the ecosystem.

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Dirvožemio taršos metalais ir diagnostinių biologinių rūšių, susijusių su naftos išsiliejamais įvertinimas Nigerio deltoje, Nigerijoje

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Šiame tyrime buvo įvertintas žaliavinės naftos išsiliejimų ekologinis poveikis aplinkai Nigerijos Nigerio deltos bendruomenėje, kurioje gausu naftos išteklių. Buvo paimti viršutinio dirvožemio (0-15 cm), vidutinio dirvožemio (15-25 cm) ir vyraujančių rūšių – Gamba žolės (*Andropogon gayanus*) – bandiniai, naudojant skersinio pjūvio metodą tuose taškuose, kuriuose buvo išsiliejusi nafta. Bandiniai taip pat buvo paimti iš nepaveiktų vietų (kontrolei). Bandiniai buvo šlapiai kompostuojami ir buvo nustatytos Pb, Cd, Cu ir Zn koncentracijos, naudojant liepsnos atominę absorbcijos spektrometriją, o viršutinio dirvožemio fiziko-cheminės savybės buvo nustatytos standartiniais metodais. Informacija buvo panaudota Studento t-testui, ANOVA ir Pearsono koreliacijos analizei atlikti, o taršos įvertinimo modeliai buvo panaudoti nustatyti dirvožemio ir augalų rūšių taršos dydį. Rezultatai parodė, kad Pb, Cu ir Zn koncentracijos viršutiniame dirvožemyje viršijo tarptautinius standartus netoli išsiliejimų esančiose vietose (0–200 m), o Cd koncentracijos tarptautinius standartus viršijo visose vietose. Vidutiniame dirvožemyje tarptautinius standartus viršijo tik Cd. Užterštumo (P_i) ir Integruotos taršos (P_c) viršutinio dirvožemio rodikliai parodė mažėjančią tendenciją: taršos vietose (0–100 m) buvo didelė P_c, o 200 m atstumtu – visų metalų P_c buvo vidutinė. Pb ir Cd dydžiai diagnostinėse biologinėse rūšyse viršijo Pasaulinės Sveikatos organizacijos standartus ir Taršos apkrovos rodiklis (PLI) parodė didelę taršą. Apibendrinant, žaliavinės naftos išsiliejimų poveikis buvo žymus, todėl dirvožemio sutvarkymas yra svarbus, kad būtų išvengta ekologinės ir žmonių sveikatos katastrofos. Be to, šios išvados yra naudingos projektuojant vietos aplinkos kontrolei skirtoms strateginėms priemonėms.

Raktiniai žodžiai: *naftos išsiliejimas, integruotas taršos rodiklis, dirvožemio sutvarkymas, taršos apkrovos rodiklis.*

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Comparison and Suitability of SRTM and ASTER Digital Elevation Data for Terrain Analysis and Geomorphometric Parameters: Case Study of Sungai Patah Subwatershed (Baram River, Sarawak, Malaysia)

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Determination of suitability of satellite-derived elevation data sets in terrain characterisation in a tropical region was carried out on the Sungai Patah subwatershed in the interior of Sarawak, East Malaysia. The goal was to facilitate rapid assessment of topographic variables and spatial parameters related to the morphometric aspects of the region. The freely available SRTM (90 m) and ASTER (30 m) elevation data sets were compared and used to generate spatial and aspatial parameters. The cross-validation of SRTM and ASTER elevation surfaces with toposheet-derived elevation for 200 random points shows root mean squared errors (RMSE) of ± 35.08 m and ± 44 m, respectively. The spatial and aspatial parameters derived show certain major and minor variations in the outputs, which can be attributed to the differences in spatial and spectral resolutions of the data acquisition systems. The results and the findings of the present study suggest that both SRTM and ASTER elevation data sets can be used for terrain characterisation in regions similar to the study area, by replacing the traditional toposheet-derived elevation surfaces. However, minor errors are present when either set is used independently. This can be avoided by the concurrent use of SRTM and ASTER elevation data sets, which will reduce data errors and artefacts in both data sets and improve the accuracy of terrain variables and watershed parameters derived from them.

Keywords: *SRTM, ASTER, DEM, geomorphometry, hypsometry*.

1 Introduction

The elevation of an area, which controls the hydrological, geomorphological and evolutional characteristics of the region, has significant importance in the field of geomorphic analysis. Spatial variation in the relief of an area makes it more exposable and vulnerable to denudational processes, which operate in the region. In order to estimate relief-related parameters in shaping the surface and controlling the processes that operate, it is necessary to have good quality, high-resolution elevation data sets. In general, toposheet-contour-derived elevation data have been used conventionally for assessing the relief parameters. This may be more erroneous because accuracy depends on the capability of the analyst who generates the data sets. This can be overcome by replacing the conventional toposheet-derived data sets by satellite-derived digital elevation models (DEMs). Satellite-derived digital elevation models, along with the advancement in the geographical information systems (GIS), have enabled rapid progress in the field of geomorphometric analysis at varying scales and ranges (Zomer, Ustin, & Ives, 2002; Hilton, Featherstone, Berry, Johnson, & Kirby, 2003; Kamp, Tobias, & Jeffrey, 2005; Prasannakumar, Shiny, Geetha, & Vijith, 2011; Cook, Murray, Luckman, Vaughan, & Barrand, 2012; Czubski, Kozak, & Kolecka, 2013; Jozsa, Fabian, & Kovacs, 2014). A number of studies have been reported on the application of satellite-derived digital elevation models in various fields like morphometric analysis, hydrogeology, soil erosion mapping, slope management, flood plain delineations and regional neotectonic analysis (Kervyn, Ernst, Goosens, & Jacobs, 2008; Henkel *et al.* 2010; Hosseinzadeh, 2011; Sleszynski, 2012; Saleem, 2013). Most of the studies have used high ground resolution data sets (10 m or less) for detailed assessment of terrain characteristics for local large-scale studies. The freely available moderate resolution data sets (≥ 30 m) have been used for regional studies. Due to the increased availability of free, moderate resolution and highly accurate digital elevation models, many regional studies derive major elevation parameters from these sources only. The most commonly used free elevation data sets are derived from Shuttle Radar Topographic Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) with a ground resolution of 90 m and 30 m, respectively, and a vertical accuracy of ± 17 m (Rodriguez *et al.*, 2005; Tachikawa *et al.*, 2011).

The present study was framed with an objective of determining the usefulness of freely available digital elevation models, for generating and analysing the topographic parameters for terrain characterisation in the interior region of Sarawak, Malaysia. Determination of the best suitable satellite-derived DEM will accelerate scientific studies in the region in the fields of soil erosion, landslide modelling, morphotectonic analysis and drainage basin characterisation, because local and regional scale studies based on such data sets are currently absent. Hence, in the present study, a highly undulating area in the interior of the Baram river basin (Northern Borneo) was selected and the SRTM and ASTER elevation surface-derived terrain characteristics were cross compared and evaluated.

2 Materials and methods

2.1 Study area

The Sungai Patah subwatershed study area is one of the major subwatersheds of the Baram River, the second largest river in Sarawak (Northern Borneo, Malaysia). The subwatershed is elongated and has a total area of 1029 km^2. It extends between latitude 3° 20’ 23” to 3° 41’ 45” N and longitude 114° 35’ 17” to 115° 9’ 58” E (Figure 1). The elevation of the area varies from approximately 20 m to above 1,500 m above the sea level and exhibits varying landforms of highly undulating nature. The drainage pattern in the Sungai Patah subwatershed is dendritic to trellis. Geologically the area is composed of intensely folded sediments and meta-sediments of 3 different ages: Palaeocene deep water sediments, Oligocene sediments, and Miocene sediments, with Oligocene sediments being predominant. The tropical area receives high average annual rainfall in excess of 4500 mm and average minimum and maximum temperatures of 20°C to 30°C, respectively.

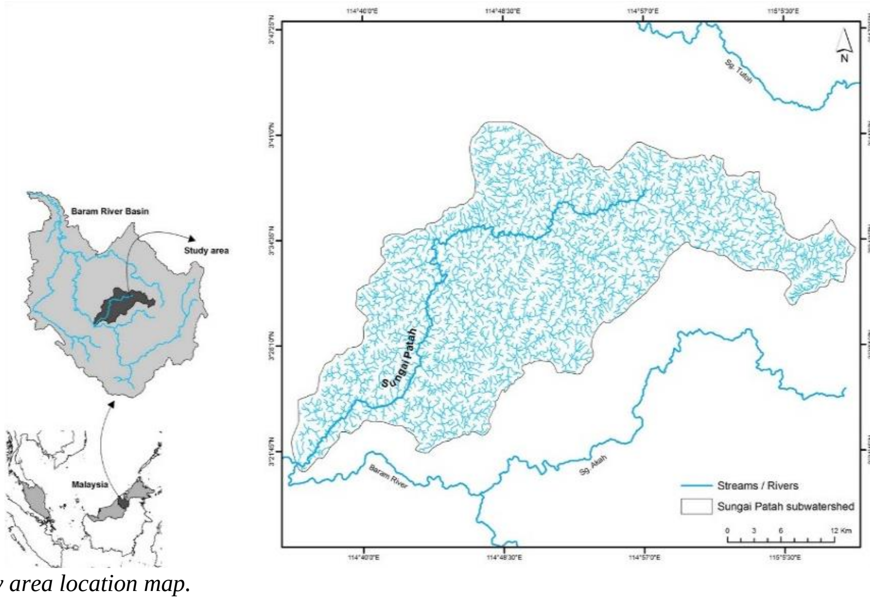

Figure 1. Study area location map.

2.2 Elevation data sources

2.2.1 Shuttle Radar Topography Mission (SRTM) data

A space shuttle based mission, jointly operated by the space agencies in the USA, Germany and Italy, aimed to map and generate elevation surface details of the globe between ± 60° and covered 80% of the total globe in 10 days in February 2000 (Farr, & Kobrick, 2000; Werner, 2001; Smith, & Sandwell, 2003; Rabus, Eineder, Roth, & Bamler, 2003; Farr *et al.*, 2007). In the present study, the latest version of SRTM data (version 4.1), available in the CGIAR consortium for spatial information (http://www.cgiar-csi.org) with a ground resolution of 90 m, was downloaded and analysed. In this version, maximum errors have been removed and data gaps have been filled using auxiliary data sets in order to provide better horizontal and absolute vertical accuracy of 8.8 m and 6.2 m fat a confidence level of 90% for the study region (http://www.cgiar-csi.org).

2.2.2 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data

Another mission, which was jointly conducted by NASA and Japan Ministry of Economy Trade and Industry (METI), using the Terra spacecraft, started collecting data of the earth surface and other atmospheric parameters in February 2000, using its 5 on-board remote sensors (GLCF, 2004). ASTER has the capability of off-nadir views (± 27°), which facilitate stereoscopic observation with a 30 m ground resolution. More details about the mission and data sets can be found in Abrams, Hook, & Ramachandran, 2002. The ASTER Global Digital Elevation Model (GDEM) generated from this data set is freely available from the website of Japan Space Agency since June 2009 (http://gdem.ersdac.jspacesystems.or.jp). In the present study, ASTER GDEM version 2 was used. It has horizontal and vertical accuracy of 8.68 m and 17.01 m at a confidence level of 95% (Tachikawa *et al.*, 2011).

2.3 Methodology

Before generating terrain variables and morphometric parameters from the SRTM and ASTER DEMs, both data sets were cross-compared with toposheet-derived (1:50,000) elevation data through 2 different kinds of analysis. In the first approach, random point elevation cross matching and, in the second approach, unique area based comparison of statistical parameters were carried out. Following the direct comparison of SRTM and ASTER data sets with the toposheet-derived elevation surface, a number of spatial and aspatial (geomorphometric) parameters were then derived from both DEMs for the Sungai Patah subwatershed. Derived spatial parameters are slope, slope aspect, and relative relief. The calculated aspatial parameters are standard geomorphometric parameters (linear, relief, and aerial parameters), and the detailed methodology adapted for the calculation is given in Table 1.

Table 1. Formulae used for computation of morphometric parameters with references.

Morphometric parameter		Formula	Reference
	Area (km^2) – (A)	Total area contributing	
	Perimeter (km) – (P)	The outer boundary of the watershed that enclosed its area	
Linear	Stream Order – (U)	Hierarchical rank	Strahler (1952,1964)
	Number of Segments – (N_u)	$N_u = N_1+N_2+……+N_n$	Horton (1945)
	Stream Length (m or km) – (L_u)	$L_u = L_1+L_2+……+L_n$	Horton (1945)
	Mean Stream Length – (L_{sm})	$L_{sm} = L_u/N_u$	Strahler (1964)
	Stream Length Ratio – (R_L)	$R_L = L_u/L_u\text{-}1$	Horton (1945)
	Bifurcation Ratio – (R_b)	$R_b= N_u / N_u+1$	Schumm (1956)
	Mean Bifurcation Ratio – (R_{bm})	Average of R_b	Strahler (1964)
	RHO coefficient – (ρ)	$\rho = R_L/R_b$	Horton (1945)
Relief	Basin Relief – (B_h)	$B_h = H-h$	Hardely and Schumm (1961)
	Relief Ratio R_h	$R_h = B_h / L_b$	Schumm (1963)
	Ruggedness number R_n	$R_n = R_h * D_d$	Patton and Baker (1976)
Aerial	Drainage Density D_d	$D_d = L_u/A$	Horton (1932, 1945)
	Stream Frequency F_s	$F_s = N_u/A$	Horton (1932)
	Texture Ratio T	$T = N_1/P$	Horton (1945)
	Form Factor R_f	$R_f = A/Lb^2$	Horton (1945)
	Circulatory Ratio R_c	$R_c = 4*\pi*A/P^2$	Miller (1953)
	Elongation Ratio R_e	$R_e = 1.128*\sqrt{A}/Lb$	Schumm (1956)
	Constant Channel Maintenance C	$C= 1/D_d$	Schumm (1956)
	Length of overland flow L_g	$L_g = 1/2D_d$ or $C/2$	Horton (1945)
	Shape Index S_w	$S_w = 1/R_f$	Horton (1945)
Elevation – Area	Hypsometric curve Hypsometric integral (I_{hyp})	Graph: h/H against a/A $I_{hyp} = (h_{mean} – h_{min})/(h_{max} - h_{min})$	Strahler (1952)

where N_1 = Number of segments in particular order, L_u-1 = stream length of next lower order, N_u+1 = number of streams in next higher order, H = maximum height of the basin, h = minimum height of the basin, Lb = basin length, Π = 3.14, h/H = proportion of the total height, a/A = proportion of the total area, H = total relative height, A = total area of the basin, a = area of the basin above a given line of elevation h, h_{mean}= average height of the area, h_{max} = maximum height of the area, h_{min} = minimum height of the area

Two other important geomorphometric parameters, i. e., hypsometric curve and integral and longitudinal profile, which ultimately help to characterise and classify the watershed, were also derived from both DEMs. The successful extraction of these parameters from the DEMs will facilitate the rapid analysis and interpretation of terrain variables by substituting the traditional topographic-sheet-derived contour-based analysis of terrain parameters.

3 Results and discussion

3.1 Cross validation of SRTM and ASTER DEMs with toposheet-derived elevation surface

Two approaches were taken to compare and validate data quality and error factors associated with the data sets before deriving and analysing morphometric parameters for the Sungai Patah subwatershed. In the first approach for the whole area, a random point generation method was used in which a total of 200 points were generated and elevation values corresponding to each point were extracted from the toposheets, SRTM and ASTER digital elevation surfaces (Figure 2).

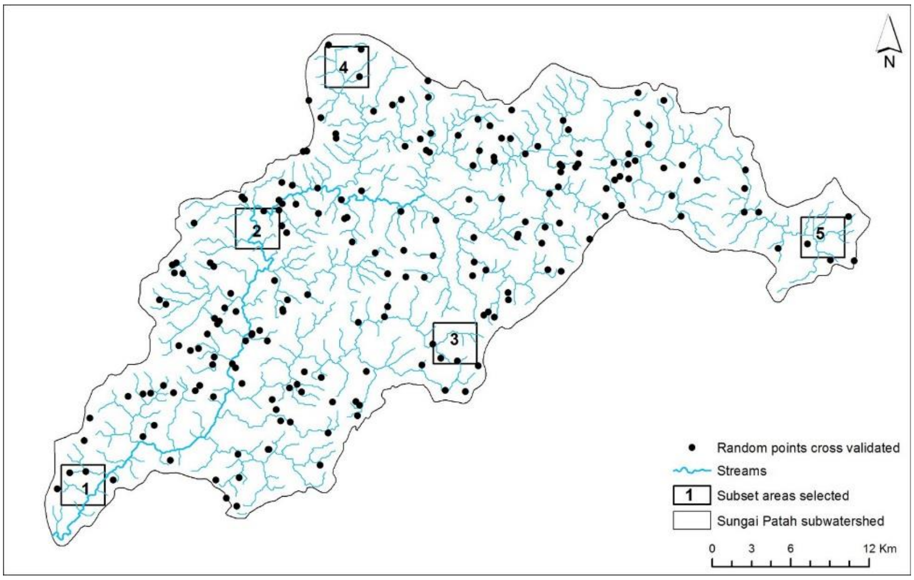

Figure 2. Cross-validation points and sample areas selected.

The mean elevation for the 200 points was found to be 427.8 m, 430.74 m, and 424.2 m, respectively. Although the mean elevations differed by only a few meters for a very small number of sampling points, differences of up to approximately 150 m were found. Elevation values derived from the toposheets were plotted against the SRTM and ASTER elevation values, which indicated a good correlation with correlation coefficient of $r = 0.98$ and $r = 0.97$, respectively (Figure 3).

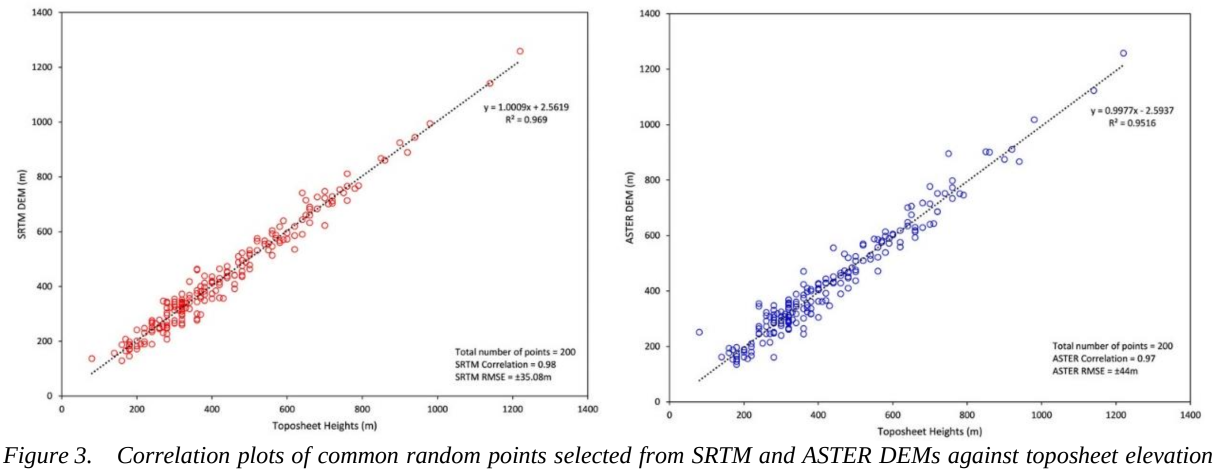

Figure 3. Correlation plots of common random points selected from SRTM and ASTER DEMs against toposheet elevation showing RMSE of ± 35.08 m and ± 44 m, respectively.

The average elevation residual values for both data sets were found to be in the range of ± 3 m (SRTM) to ± 4 m (ASTER) when compared with the toposheet-derived elevation points; however, the root mean square error of the compared data sets was ± 35.08 m and ± 44 m. In the second approach, 5 distinct areas of uniform size (10 km^2) were selected from the study area (at varying elevations and terrain conditions), the DEMs were clipped and the data for the 5 subsets were analysed statistically. Though the spatial resolutions of the DEMs are varying, the results of the statistical analysis show certain similarities and are given in the Table 2. The general statistical parameters, such as minimum, maximum, mean, and standard deviation of these selected subsets, are comparable, generally differing by less than 40 m, while the RMSE is quite variable, ranging from ± 10.81 m to ± 68.81 m, with an average RSME of ± 29.73 m. These findings support the choice of using SRTM and ASTER elevation data sets instead of toposheet-derived elevation surface in the present analysis.

Table 2. Comparison of selected statistics of topo, SRTM and ASTER DEMs.

	DEM	Min	Max	Mean	STD	RMSE
Subset 1	Topo	80	460	228.5	96.3	
	SRTM	61	494	237.1	97.8	±27.54
	ASTER	33	493	234.3	99.0	±40.61
Subset 2	Topo	120	320	205.4	49.8	
	SRTM	123	335	205.4	43.9	±10.81
	ASTER	24	336	197.2	51.9	±68.81
Subset 3	Topo	400	1000	631.6	127.1	
	SRTM	424	1004	645.1	117.0	±17.20
	ASTER	400	1020	663.5	120.4	±14.14
Subset 4	Topo	280	900	570.7	136.4	
	SRTM	292	938	590.3	137.5	±28.17
	ASTER	247	937	568.3	142.9	±35.05
Subset 5	Topo	680	1140	818.9	93.81	
	SRTM	648	1160	815.5	100.3	±26.68
	ASTER	598	1140	802.7	100.9	±57.98

3.2 Spatial parameters

The spatial parameters, such as slope, slope aspect, and relative relief, which play a major role in the analysis of hydrological and denudational processes, were generated and evaluated for the study area using ArcGIS software. The comparison of SRTM- and ASTER-derived elevation surface reveals differences in the minimum and the maximum values and spatial distributions. For the Sungai Patah subwatershed, the elevations derived from SRTM range from 43 m to 1,530 m, while those derived from ASTER have a greater range from 11 m to 1,566 m (Figure 4a, 4b). The variation in the basic statistical parameters such as mean and standard deviation for both data sets is within the tolerable limit and varies in between ± 1 to ± 5. Both DEMs show a highly developed fluvial network with some isolated residual hills.

In mountainous terrains, most of the denudational processes are related to the action of flowing water and controlled by the terrain slope (Anbalagan, 1992; Vijith, Krishnakumar, Pradeep, Ninu Krishnan, & Madhu, 2013). Slope of the area plays a major role in hydrogeology, soil erosion, landslide and other related geo-environmental parameters and processes. Figures 4c and 4d show terrain slopes in the Sungai Patah watershed as derived from the SRTM and ASTER DEMs, respectively. The maximum slope derived from SRTM is 50°, whereas the slope derived from ASTER exceeds 80°. The discrete class analysis of slope surfaces indicates that, for the SRTM-derived slopes, the majority of the pixels (>83%) fall in the slope range of 5–25°, where only 64% of the pixels of the ASTER-derived slopes are in that class range. Over 20% of the pixels of the ASTER-derived slopes fall in the higher sloping 25–35° class. Steep sloping areas have higher influence on landslide occurrence and soil erosion and the ASTER data set appears to be the better tool for this sort of analysis as it gives a better representation of steep slopes.

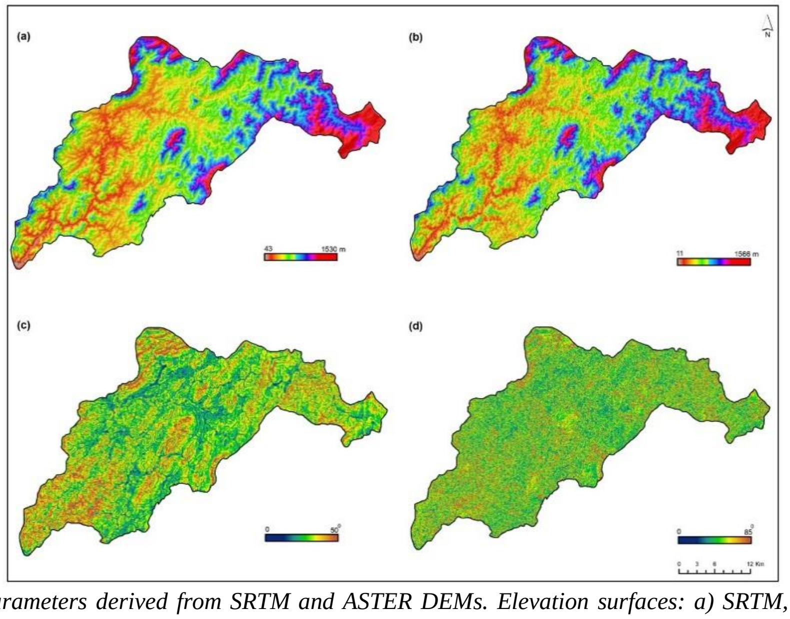

Figure 4. Spatial parameters derived from SRTM and ASTER DEMs. Elevation surfaces: a) SRTM, b) ASTER. Slope: c) SRTM, d) ASTER.

Another parameter considered is slope aspect, the direction towards which the terrain slope faces with respect to the north. This parameter is important as there may be directional influence on terrain processes. Generally, the aspect is expressed in compass degrees with the values varying from 0 to 359° or is designated as -1 for flat areas. The numerical value of the slope aspect may be classified into 8 compass directions (N, NE, E, SE, S, SW, W and NW) or it may be considered flat (no slope aspect). The slope aspect has the potential to influence physical properties of the terrain, such as temperature, moisture, vegetation content, etc., which ultimately influence the susceptibility of the terrain to weathering and erosional process (Rajakumar *et al.*, 2007). The aspect surfaces generated from the SRTM and ASTER DEMs are shown in Figures 5a and 5b, respectively. Both DEMs show similar mean and standard deviation of the slope aspects: the mean of 187.53° and 182.64°, demonstrating the predominance of south facing slopes, and the standard deviation of 102.16° and 102.71°, but with significant spatial variation.

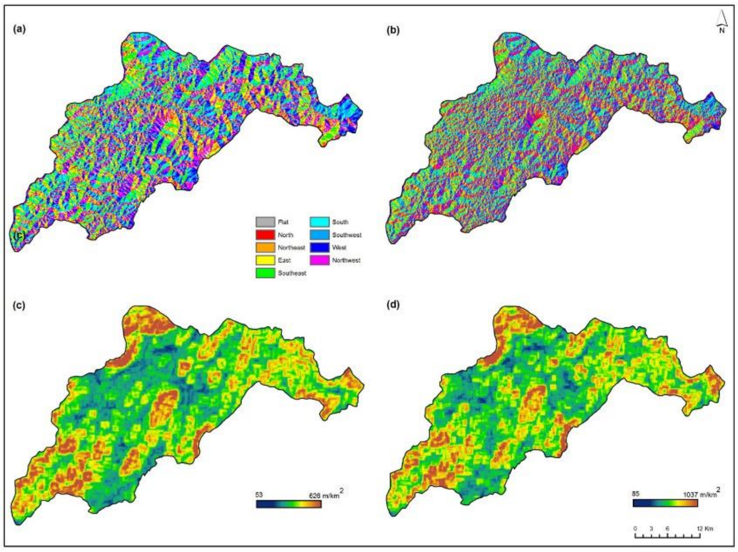

Figure 5. Spatial parameters derived from SRTM and ASTER DEMs. Aspect: a) SRTM, b) ASTER. Relative relief: c) SRTM, d) ASTER.

Relative relief is another parameter of importance in geomorphometric studies and represents the elevation variation per unit area as it influences the down slope movement of sediments and other earth materials and it plays a crucial role in terrain evolution (Vijith, & Madhu, 2007; Prasannakumar, Shiny, Geetha, & Vijith, 2011). In order to identify the elevation changes in the Sungai Patah subwatershed per unit area, relative relief maps were calculated from the available SRTM and ASTER elevation surfaces (Figure 5c and 5d). The relative relief maps, thus, generated from both elevation surfaces show the minimums of 53 m/km^2 and 85 m/km^2, the maximums of 626 m/km^2 and 1037 m/km^2 with means of 225.23 m/km^2 and 273.08 m/km^2 and standard deviations of 81.59 and 85.25, respectively, for SRTM- and ASTER-derived maps. Although the ranges of the relative relief are different between the 2 DEMs, the spatial distribution of the relative relief is remarkably similar. The results show similarity in the spatial pattern with differences in the minimum and the maximum values, which is due to the changes in resolution.

3.3 Geomorphometric parameters

Before assessing the geomorphometric parameters from the SRTM and ASTER DEMs, the basic characteristics of the selected subwatershed and streams obtained from these elevation models were cross-compared with those derived from the topographical map. In the present analysis, the subwatershed boundary derived from the topographical map was used to extract the elevation surfaces from the SRTM and ASTER DEMs (because of that the area, perimeter, and basin length were the same). After extracting the study area from the elevation surfaces, the basic parameters needed for the geomorphometric analysis, the stream network with order and length were generated using the ArcHydro extension of ArcGIS 9.3. Table 3 shows the total number of streams, number of first-order streams and order of the subwatershed, assessed from the 3 data sources. While comparing the data, it was noted that the topographic-sheet-derived information was comparable only with the subwatershed order assessed from the ASTER-derived stream networks. A major difference was observed in the total number of streams and the number of first-order streams. However, a common spatial pattern of stream network is observed. The spatial pattern of the stream networks (Figure 6) shows the lateral shift and order variations in the streams derived from both DEMs. The difference in the stream networks derived from the different resolution DEMs demonstrates the sensitivity of the elevation surfaces to the hydrological analysis. The lower ground resolution SRTM data classified the subwatershed as the 5th order, while the ASTER-derived stream networks and the topographic sheet both classified it as the 6th order subwatershed. The number of the stream orders and the number of the first-order streams are underestimated by the lower ground resolution of the SRTM data.

Table 3. Basic characteristics of drainage networks derived from SRTM and ASTER.

Data	Scale or ground resolution	Total no. of streams	No. of 1st order streams	Order of the subwatershed
Toposheet	1:50,000	3,204	1,640	6
SRTM	90 m	617	316	5
ASTER	30 m	4,081	2,101	6

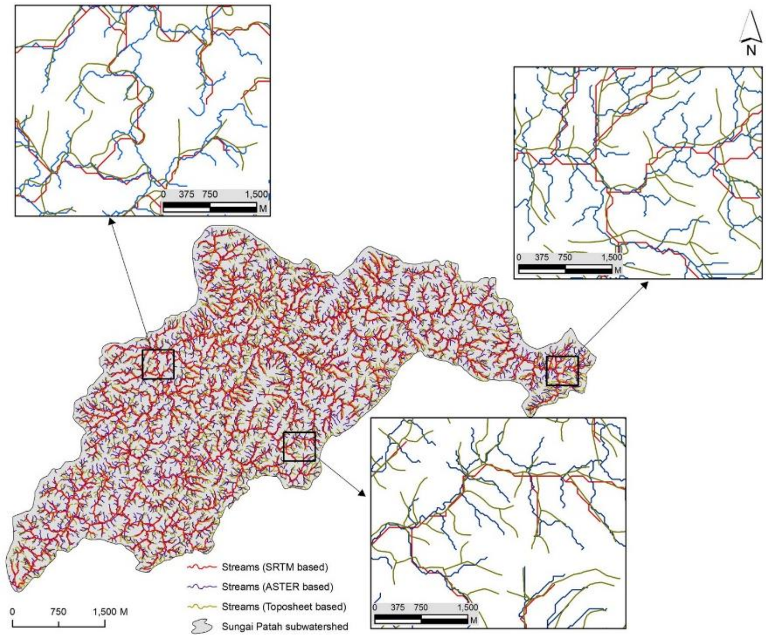

Figure 6. Cross-comparison of drainage networks derived from toposheets, SRTM and ASTER DEMs.

Geomorphometric analyses give insight into the geological, hydrological and topographical characteristics of the area (Strahler, 1952, 1964; Pike, & Wilson, 1971; Pike, 2000). The analysed geomorphometric parameters based on the standard methods of the calculation given in Table 1, using the stream networks and the elevation values derived from the SRTM and ASTER DEMs, were grouped into the following 4 categories: linear, relief, aerial, and elevation-area parameters; the results are provided in Table 4.

The analysis was started by comparing the subwatershed order, number and length of stream segments of each order. The lower ground resolution SRTM-derived stream network consists of fewer streams (particularly of lower order), with significantly shorter stream length than the higher ground resolution ASTER-derived stream networks. The SRTM-derived stream network shows a total of 617 streams with 5th as the higher order of the stream. The ASTER-derived data show a total of 4,081 stream segments with 6th as the highest order. This difference resulted in the length of each segment and the total length of streams, which vary from 978 km to 2,416 km, respectively, for SRTM and ASTER derived stream networks. As a result of the discrepancy in the number of segments and stream length, significant differences are also apparent in the mean stream lengths, which are 1.35 km and 0.52 km, respectively. Other geomorphometric parameters, which are derived from stream length and/or number of segments are also affected, such as stream length ratio (0.84 and 0.59), drainage density (0.95 and 2.35 km/km^2), stream frequency (0.60 and 3.97 km^2), ruggedness number (0.02 and 0.05 km/km^2), texture ratio (1.55 and 10.28 km^{-1}) and constant of channel maintenance (1.05 and 0.43 km), respectively, for SRTM- and ASTER-derived stream networks. The basin relief was found to be 1,555 m with the higher resolution ASTER DEM, compared with 1,487 m for SRTM. Geomorphometric parameters which are not directly derived from stream length and/or number of segments were generally found to be in good agreement between the 2 DEMs. This is the case for mean bifurcation ratio (1.81 for both data sets), Rho coefficient (0.29 and 0.31), and relief ratio (0.0204 and 0.0214). Other parameters, such as form factor (0.19), circularity ratio (0.31), elongation ratio (0.50), and shape index (5.15) are equivalent for both data sets since they are based on common factors, such as area, perimeter, and basin length. The results obtained for the Sungai Patah case study indicate that both DEMs can be used to derive basic geomorphometric parameters, but those derived from ASTER DEM are closely matched to the toposheet-derived parameters and should be used preferentially where number of segments, stream order, and stream length are critical. Based on the calculated geomorphic parameters, the terrain can be considered as structurally complex, highly dissected and prone to the fluvial erosion process due to high runoff potential.

Table 4. Geomorphometric parameters calculated for Sungai Patah subwatershed from SRTM and ASTER data sets.

Type of parameter	Parameters calculated for Sungai Patah		SRTM	ASTER	Unit
	Common parameters from topographical sheets (identical to both data sets)*	Area (A)*	1,029.24		km^2
		Perimeter (P)*	204.44		km
		Basin Length (Lb)*	72.81		km
Linear parameters	No. of segments (Nu)	1st Order	316	2,101	No.
		2nd Order	129	878	No.
		3rd Order	87	535	No.
		4th Order	32	296	No.
		5th Order	53	134	No.
		6th Order	-	137	No.
		Total	617	4,081	No.
	Stream length (Lu)	1st Order	589.37	1,415.08	km
		2nd Order	176.32	450.51	km
		3rd Order	118.25	281.42	km
		4th Order	29.99	139.28	km
		5th Order	63.86	63.50	km
		6th Order	-	66.32	km
		Total	977.79	2,416.12	km
	Mean stream length (Lsm)	1st Order	1.87	0.67	km
		2nd Order	1.37	0.51	km
		3rd Order	1.36	0.53	km
		4th Order	0.94	0.47	km
		5th Order	1.20	0.47	km
		6th Order	-	0.48	km
		Average	1.348	0.521	km
	Stream length ratio (RL)	1st Order	-	-	-
		2nd Order	0.30	0.32	-
		3rd Order	0.67	0.62	-
		4th Order	0.25	0.49	-
		5th Order	2.13	0.46	-
		6th Order	-	1.04	-
		Average	0.837	0.586	-
	Bifurcation ratio (Rb)	1st Order	2.45	2.39	-
		2nd Order	1.48	1.64	-
		3rd Order	2.72	1.81	-
		4th Order	0.60	2.21	-
		5th Order	-	0.98	-
		6th Order	-	-	-
	Mean bifurcation ratio (Rbm)		1.813	1.806	-
	RHO coefficient (ρ)		0.29	0.31	-
Relief parameters	Basin relief (Bh)		1,487.00	1,555.00	m
	Relief ratio (Rh)		0.0204	0.0214	-
	Ruggedness number (Rn)		0.02	0.05	km/km^2
Aerial parameters	Drainage density (Dd)		0.95	2.35	km/km^2
	Stream frequency (Fs)		0.60	3.97	km^{-2}
	Texture ratio (T)		1.55	10.28	km^{-1}
	Form factor (Rf)*		0.19		-
	Circularity ratio (Rc)*		0.31		-
	Elongation ratio (Re)*		0.50		-
	Constant of channel maintenance (C)		1.05	0.43	km
	Length of overland flow (Lg)		0.53	0.21	km
	Shape index (Sw)*		5.15		-
Elevation-area parameter	Hypsometric integral (I*hyp)*		27.62	28.17	%

The comparison of area and elevation data of drainage basins provides detailed information about the geomorphic evolutional history and the stages of landscape development. This can be achieved through generation and analysis of hypsometric curve and hypsometric integral, which work on the basis of area-altitude relationship (Pike, & Wilson, 1971; Hurtrez, Sol, & Lucazeau, 1999; Singh, 2008; Kurse, 2013). Before analysing the hypsometric characteristics of the Sungai Patah subwatershed, a general assessment of area-elevation relationship was carried out by classifying the SRTM and ASTER elevation surfaces into 100 m elevation classes from 0 to 1400 m (Figure 7).

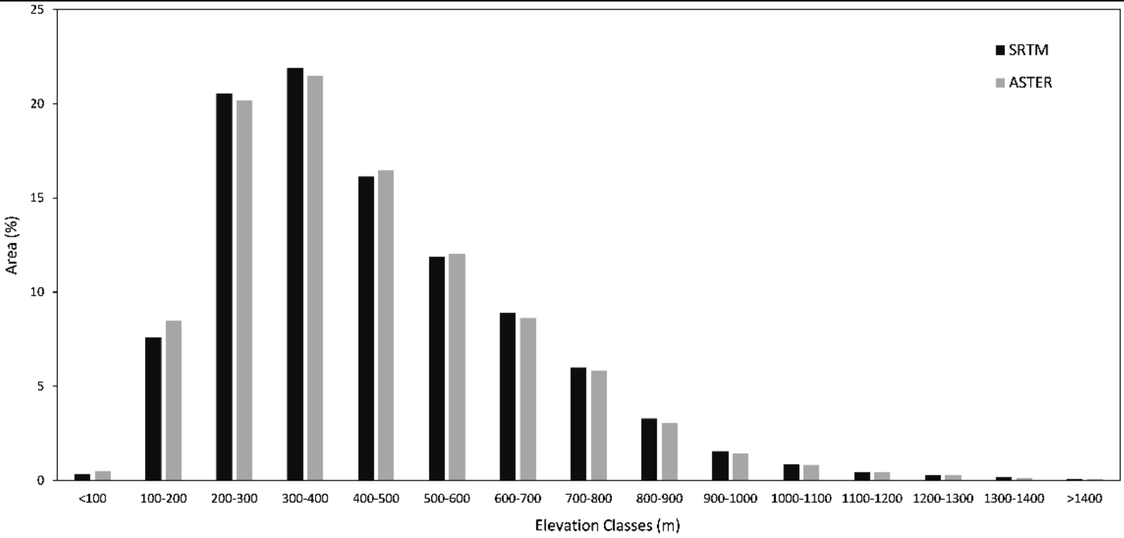

Figure 7. Area-elevation relationship and distribution assessed from SRTM and ASTER DEMs.

It is noted that 70% of the subwatershed area (>70%) falls between 200–600 m for both the SRTM and ASTER elevation surfaces, indicating the usability of both DEMs in terrain analysis. These results facilitated the generation of a hypsometric curve, a non-dimensional area-elevation curve, which allows a ready comparison of catchments with diverse areas by plotting the proportion of the total height (h/H) against the proportion of the total area (a/A) of the subwatershed and the hypsometric integral (*Ihyp*). The hypsometric integral is an indicator of geomorphic maturity (Strahler, 1952). Both SRTM and ASTER DEMs indicate similarly S-shaped hypsometric curves with a concave upward upper region and with very closely matching hypsometric integrals of 0.2762 (27.62%) and 0.2817 (28.17%), respectively (Figure 8).

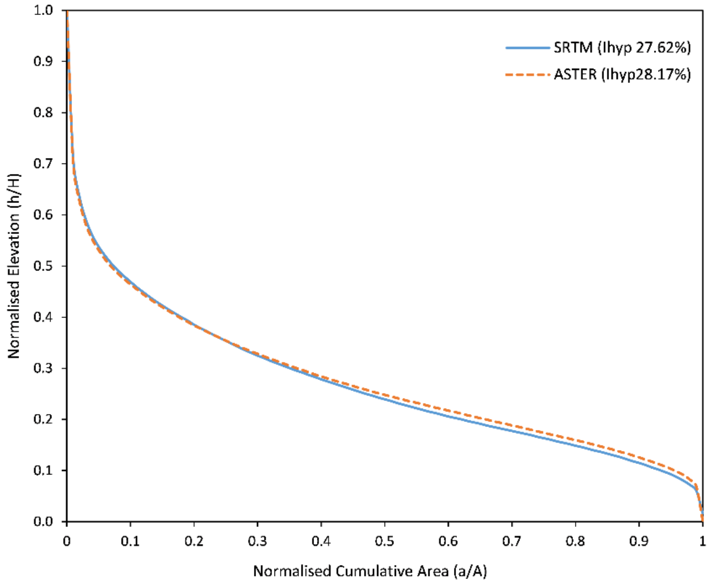

Figure 8. Hypsometric curves and integrals derived for the study area.

The hypsometric integral values are low and this suggests that the Sungai Patah subwatershed drainage basin has reached the old age (monadnocks) stage of evolution (Strahler, 1952). Low hypsometric integrals indicate that fluvial erosion processes operating in a mature fluvial network are dominant over erosive hillslope processes. Both data sets lead to a similar hypsometric integral value and conclusions indicating that they are both suitable in such a kind of analysis.

Another important parameter which can be derived from digital elevation models is a longitudinal profile of streams, which shows altitude against distance and can give insight and real evidence of geological processes operating in watersheds and their influence over river networks (Ferraris, Firpo, & Pazzaglia, 2012; Giaconia *et al.*, 2012). The longitudinal profile of streams reflects available relief, base level changes (due to tectonic disturbances), and the processes of erosion and deposition (Aiken, & Brierley, 2013; Ambili, & Narayana, 2014). In order to generate the longitudinal profile of Sungai Patah, elevation values were extracted from both SRTM and ASTER elevations surfaces for a series of sampling points at a 1-km distance along the stream (Figure 9).

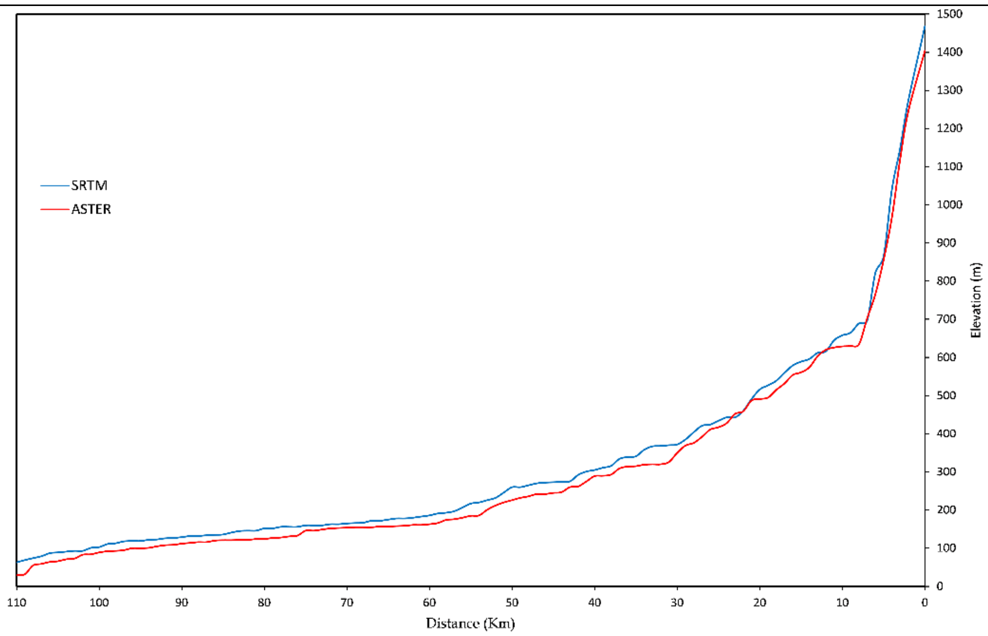

Figure 9. Longitudinal profile of Sungai Patah extracted from SRTM and ASTER DEMs.

The profiles generated from both DEMs showed a very similar pattern with only slight variation in the elevation values. The SRTM DEM gives a higher curve, by approximately 30 m. Both profiles indicated evidence of disturbances in the base level of the river. These are evident from the longitudinal profile, where they are marked with knick points and breaks of slope, indicating modification of the terrain in response to tectonic disturbances and/or lithological changes. Both DEMs are equally suited for this type of analysis.

4 Conclusion

The present study demonstrated the usability and potentiality of available moderate resolution digital elevation data sets (SRTM and ASTER) for basic terrain analysis in the interior regions of Sarawak, Northern Borneo. The data sets can be used in the geo-environmental applications like soil erosion modelling, tectonic indices derivation and landslide prediction. The assessment of basic error factors and statistics indicates good agreement with the toposheet-derived elevation values, but with differences in spatial distribution. While generating stream networks for the geomorphometric analysis, stream networks derived from SRTM gave a coarser stream network than the ASTER-derived streams. The lower ground resolution of SRTM leads to underestimation of the number of stream segments, stream lengths and the subwatershed order, while the ASTER data give slightly overestimated results. Both data sets are found to be very useful in generating secondary derivatives like slope, slope aspect, relative relief and the quantitative information needed for geomorphometric analysis. They can also provide valuable information for studying the evolutional history of the basin, through the hypsometric analysis and longitudinal profile extraction, for which both data sets provided consistent results. In general, it is suggested that, besides using the SRTM and ASTER DEMs independently for terrain analysis, they can be used concurrently to overcome the limitations in both data sets and can substitute for the use of toposheet-contour-derived elevation surfaces in areas which exhibit similar terrain conditions.

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SRTM ir ASTER skaitmeninės aukščio informacijos palyginimas ir tinkamumas vietovės analizei bei geomorfometriniai parametrai: Sungai Patah subbaseino (Baram upė, Sarawak, Malaizija) atvejo studija

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Šiame tyrime buvo nustatytas iš palydovo gautų aukščio informacijos rinkinių vietovei charakterizuoti tinkamumas tropiniame Sungai Patah subbaseino regione, Sarawak viduje, Rytų Malaizijoje. Šio tyrimo tikslas buvo palengvinti greitą topografinių kintamųjų ir erdvinių parametrų, susijusių su morfometriniais regiono aspektais, įvertinimą. Buvo palyginti viešai prieinami SRTM (90 m) ir ASTER (30 m) aukščio informacijos rinkiniai ir jie panaudoti kuriant erdvinius ir neerdvinius parametrus. Kompleksinis SRTM ir ASTER aukščio paviršių, gautų iš topografiniuose lapuose atsitiktinai parinktų 200 taškų, patikrinimas parodė, kad vidutinės kvadratinės šaknies (RMSE) paklaidos buvo atitinkamai ± 35.08 m ir ± 44 m. Gauti erdviniai ir neerdviniai parametrai rodo tam tikras dideles ir mažas variacijas, kurios gali būti susijusios su informacijos priėmimo sistemų erdvinių ir spektrinių rezoliucijų skirtumais. Šio tyrimo rezultatai parodė, kad SRTM ir ASTER aukščio informacijos rinkiniai gali būti naudojami į tyrimo regioną panašiai aplinkai charakterizuoti, pakeičiant iš tradicinių topografinių lapų gautus aukščio paviršius. Vis dėlto kai rinkiniai naudojami atskirai, atsiranda nedidelės klaidos. To gali būti išvengta naudojant SRTM ir ASTER aukščio informacijos rinkinius kartu, kas sumažintų informacijos klaidas ir trikdžius abiejuose informacijos rinkiniuose bei pagerintų aplinkos kintamųjų tikslumą ir iš jų gautus baseino parametrus.

Raktiniai žodžiai: *SRTM, ASTER, DEM, geomorfometrija, hipsometrija.*

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Hybrid Solar-Wind Installation Prospects for Hot Water and Heating Supply of Private Homes on the Apsheron Peninsula of the Republic of Azerbaijan

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This paper analyses the environmental problems arising from the use of traditional energy resources for the production of electricity and heat. The advantages of replacing conventional energy resources and shifting to wind and solar energy technologies are explained. The possibilities of the combined use of solar and wind energy to provide an average family of 5 people with hot water and heating are explored. Experimental results were obtained from full-scale tests under prevailing conditions at Baku. Solar-wind hybrid systems for heating and hot water were designed and developed at the Institute of Radiation Problems of the Azerbaijan National Academy of Sciences. The paper also examines the possibility of supplying a family of 5 people with hot water produced by solar energy year-round and presents the results of the calculation of the energy balance of such facility.
Keywords: *flat-plate solar collectors, wind turbine, hybrid solar-wind installation, cold water tank.*

1 Introduction

In recent years, environmental conditions have become much worse as a result of technogenic and anthropogenic processes taking place in the world. Literature sources indicate that since the 1980s flat-plate solar collectors (FSC) have been used to supply heating (HS) and hot water (HWS) (Kharchenko, 1991; Bekman *et al.*, 1982; Salamov *et al.*, 2006; Carbonell *et al.*, 2014; NREL, 2012; Sun & Wind Energy, 2014). However, the dependence of solar radiation intensity on arbitrary changes over time, in particular the stochastic nature of this change, causes interruptions in heat and hot water supplies in differing weather conditions. One way to resolve this situation is to use very large surface area flat-plate solar collectors. Another option is to install additional equipment for the accumulation of solar radiation. Neither strategy is economically ideal. Thus, a continuous and reliable way of providing energy to consumers through the use of large surface flat-plated solar collectors in winter is not productive in spring and summers seasons, because only 10−15% of the thermal energy produced is used in place while the rest, which could be converted into other energy forms, is lost in an inefficient manner. In this case, FSCs are operating at a very critical temperature, which is harmful for inner pipes of collectors and can result in premature failure. On the other hand, the surface of a needed FSC being 5 to 6 times more than the normal size can increase costs in the same way (Salamov *et al.*, 2006). Heat accumulative systems can be productive only in the daily and monthly provision of heat and hot water supplies, which cannot be applied for seasonal demand, and this again leads to an increase in the unit cost (Polyanin, 1998; Abdelmoneym, 1998). Thus, to provide consumers with a continuous hot water supply all year round and to ensure a sustainable heating season, solar thermal power plants are used in combination with alternative energy sources (Ushakova, 1986; Shershnev, Dudarev, 2006; Sun & Wind Energy, 2014). To this end, private residential homes with natural gas use electrically-powered heating devices, and social order houses use diesel-fuelled power generators. However, in these cases, either directly (in private homes) or indirectly (thermal power plants), the use of existing resources from traditional fuel cannot be considered effective from an economic and environmental point of view. The use of wind power as a heating supply has been discussed since the 1990s; however, it is considered ineffective from an economical and ecological point of view. That is why from the beginning of this century the combined use of solar and wind energy started to become more and more important. The issue of special significance solar-wind combined installations for the production of heating and hot water supplies has become an important topic for the 'Transformation of Renewable Energy Types' Laboratory of the Institute of Radiation Problems of the Azerbaijan National Academy of Sciences since the beginning of the 21st century as well, and successful results have been obtained. The results have been published in the periodical press from time to time (Salamov *et al.*, 2006, 2009, 2010).

Given these premises, a combined solar and wind power installation (CSWPI) experimental model was designed and created by the 'Transformation of Renewable Energy Types' Laboratory of the Institute of Radiation Problems of the Azerbaijan National Sciences Academy. This experimental model was tested under the natural climatic conditions occurring on the Apsheron Peninsula. Below is a description of the device, its working principles, the results of the calculation and the testing of the device for supplying heating and hot water to consumers. One of the main objectives of the study is to prepare long-term strategies for high demand consumers such as schools, kindergartens, hospitals, sanatoriums, public catering facilities, factories outside the city, difficult to access strategically important locations, military installations, all based on the experience gained from the usage of the CSWPI on the Apsheron Peninsula.

Azerbaijan is one of the leading countries in the world with regard to solar and wind energy reserves. It has been determined that the Apsheron Peninsula, which is located at 40°24′ latitude, and Baku City have 300 sunny days during a year, receiving nearly 3000 annual hours of sunshine. The average solar radiation energy reaching every 1 m^2 of the horizontal surface is 1900 W/m^2 per year, the maximum rating of solar radiation intensity during each day is 950 W/m^2, and the average annual rating of the same index is near 200 W/m^2. The ratings for working hours in winter and summer seasons are 4.8−7.8 and 7.2−12.5 hours, respectively (Salamov *et al.*, 2013).

When it comes to the wind regime, the amount of windy days during a year on the Apsheron Peninsula and Caspian coastlines is 270−280 days, the average annual wind speed is 7−8 m/s at a height of 12 m, but in some places it is more than 10 m/s. All these show that the Apsheron Peninsula has significant wind potential (Salamov *et al.*, 2010; Hashimov *et al.*, 2012)

As can be seen, the use of ecologically clean and inexhaustible solar and wind energy to provide for the hot water and heating demands of homes has an exceptional significance on the Azerbaijani area, especially in the climatic conditions present on the Apsheron Peninsula and Baku City. For this reason, combined solar and wind energy facilities could provide consumers with more sustainable and continuous thermal energy.

2 Materials and methods

2.1 Schematic structure of experimental CSWPI

It is commonly known that the energy needs of consumers for hot water and heating can currently be satisfied by flat-plate solar collectors (FSC) and pipe-like collectors that utilise solar radiation and do not require monitoring systems when operated. Along with their simple structure, another advantage of FSCs is their low cost. They allow for maximal utilisation of solar energy due to their capacity to run within a wide range of solar radiation intensity (SRI) values (Kharchenko, 1991; Panjiyev, 2007). However, studies show that a family composed of 5 members may not have a guaranteed hot water supply in winter, not to mention a supply of heating energy (Salamov *et al.*, 2006). Under the Baku City's climatic conditions, such families will need an FSC with an overall surface area of 9−12 m^2 for a reliable hot water supply, while reliable heating energy will require a much larger surface area, exceeding 50 m^2. First of all, this is not an economically feasible option. Besides, such a large surface area makes the natural circulation of a heat transfer agent impossible due to the fact that connecting several FSCs in a series increases the pressure within the circulation circuit. This results in force-feed circulation, which requires operation of a circulating pump. In addition, it becomes necessary to provide automatic regulation for heat transfer agent consumption in accordance with daily fluctuations in SRI values. Such additional interventions greatly complicate the installation's structural design and reduce the consumer's interest in its utilisation. Therefore, individual households should be provided with additional energy resources for a heating power supply during heating seasons in addition to a year-round hot water supply. It has been established that wind turbines may serve as such an additional source, while their use in combination with FSCs is of even greater interest (Salamov & Salmanova 2010; Salamov *et al.*, 2013).

Given the above-mentioned premises, a combined solar and wind power installation experimental model was designed and created by the 'Transformation of Renewable Energy Types' Laboratory of the Institute of Radiation Problems of the Azerbaijan National Sciences Academy. This experimental model was tested under natural climatic conditions on Apsheron Peninsula. The following text provides a description of the device, the principles behind its operation, and the results of calculations for testing the device, which would be providing heating and hot water supplies to consumers.

Figure 1 and Figure 2 show the general appearance of the CSWPI and its simplified electric circuit diagram, respectively.

Figure 1. General appearance of the CSWPI.

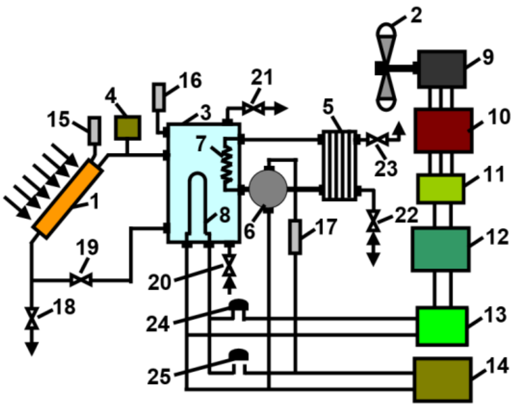

Figure 2. Simplified electric circuit diagram of the CSWPI.

The CSWPI consists of an FSC (1), a Wind Electric Machine (WEM) (2), a hot water tank (3), an expansion tank (4), a heating radiator (5), and a circulation pump (6) ensuring circulation of a heat transfer agent along the circuit. A snake heat-exchanging unit (7) is installed inside the hot water tank (close to its lateral wall) and an electrical resistance heater (8) (at the centre of the tank's bottom wall). At the centre of the tank's bottom wall is located geared wind turbine (9). A voltage-reducing transformer (10) is connected to the power generator's outlet. The transformer's outlet is connected to the accumulator terminal (12) by the block for automatic control of charge and discharge processes (11). The accumulator terminal is also connected to the inlet of a phase inverter device (13). The option of using a centralised power network (14) in cases of calm weather conditions and during the hours of darkness is also foreseen. In cases where fully autonomous operation of the installation is required, a solar-photovoltaic power source may be utilised in place of a centralised power network. It should be remembered that such calm weather conditions seldom occur on the Apsheron Peninsula, especially in Baku City. For better control, the CSWPI is equipped with thermometers (15, 16), which receive signals from the thermocouples installed in the FSC's outlet and hot water tank (thermocouples are not shown in Figure 2). Start and shutdown of the circulating pump are directly controlled by the thermometer (17) with electrical contacts installed in the relevant place in a heated room. The installation is also equipped with regulating drain valves 18−23. Valve 18 is considered for the discharge of a heat transfer agent in cases of long absence of inhabitants when freezing weather is anticipated, in order to prevent the bursting of FSC's pipes. As it is shown in Figure 2, Valve 19 is connected to the hot water tank according to a natural circulation scheme (in a thermo-syphon mode) and ensures the regulation of circulating heat transfer agent consumption, and by doing this, regulates the temperature regime of hot water. Valves 20 and 21 serve for filling the hot water tank and use of hot water by inhabitants, respectively. Valves 22 and 23 serve to fill the heating radiator (5) with a heat transfer agent (water also may be used as a heat transfer agent) and to eliminate any vapour locks (steam pockets). The electrical resistance heater (8) is connected to the inverter's outlet (13) and the centralised power network (14) by electrical switches 24 and 25 respectively.

2.2 Operating principle of the experimental CSWPI

The operating principle of the experimental CSWPI model is as follows: at the start, the surface of the FSC is turned towards the southwest and fixed at a required angle of inclination. Meanwhile, the hot water tank is placed at least 2−3 m above the FSC in order to enable natural circulation of a heat transfer agent. To start the operation, first, Valve 18 is closed and Valves 19−23 are opened. In this stage, the pipes of the FSC are flooded, the hot water tank is primed with cold water, and water begins to flow through Valves 21 and 23. At that moment, except for Valves 19 and 20, all other Valves (21, 22 and 23) are closed. Sunrays passing through transparent glass surfaces of the FSC are absorbed by the heat absorbing plate, and this heats the plate. Some portion of the absorbed heat is transferred to the pipes that are directly connected to the plate. These pipes transfer this heat to the water circulating through them and the remaining heat is repelled toward the glass surface. The glass surface is not transparent to heat radiation and the repelled heat returns to the plate's surface and is absorbed by it. As a result, water flows in the FSC's pipes and the hot water tank. Later, the water that flows through Valve 19 is also heated up and provides additional heat to the hot water tank. If in winter it becomes necessary to protect the pipes of the FSC against freezing, Valves 18 and 21 should be opened simultaneously, while all other valves should be kept closed. Water is then drained from the FSC through Valve 18. Since no control signal from the contact thermometer is received by the circulating pump in summer, this pump remains idle and the heating radiator's circuit stays in the closed position. In winter, this circuit, receiving control signals from the contact thermometer, automatically connects to the system and the rooms in the house begin to receive heat.

2.3 Analysis of the results obtained from the experiment

However, studies of the CSWPI show that the FSC has played scarcely any role in heating individual households taken as study objects. This is not surprising if one remembers that on cloudy days, or during the night time hours of winter or other seasons, the FSC would not be capable of producing sufficient quantities of hot water for users without relying on additional accumulating systems. Thus, the task of providing consumers with an uninterrupted supply of hot water and heating is mainly fulfilled by a wind turbine. The use of wind turbines also offers the following advantages: the circulating pump does not need to be fed from the power network during winter, and since no home heating is required in summer, the majority of hot water needs are reserved by the FSC, and the energy accumulated in WEM may be utilised for other purposes. For example, though this study is mainly focused on the heating of individual households, it should be remembered that in summer they are badly in need of air conditioning. Upon filling the need for hot water, the remaining energy of a wind turbine may be directly supplied to fans and other electrical equipment installed in the house. The accumulator block (12) is connected to the wind turbine's outlet. Inhabitants may be fully supplied with hot water in the summer time day and night by the CSWPI on partly cloudy or cloudy days when the SRI intensity drops abruptly, or under windless conditions. Upon achieving a sufficient reserve of hot water (200−300 litres), the wind turbine may supply power to a fan in the experimental house during the hotter second half of the day and ensure an indoor temperature range of 20−22° C under outside temperatures of 35−40° C.

There are a number of other advantages of wind turbine usage. During winter, there is no need to rely on the electric network to power the circulation pump. Since there is no need for heat provision during the summer season, all hot water supplies can be provided by the flat-plate solar collector. Energy produced by the wind turbine can be used for other purposes, such as refrigerators, electric lights, TVs, washing machines, vacuum cleaners, etc. In this regard, the present case discusses the heating of individual apartments, but in summer there is huge demand for the cooling of apartments, which is why the additional electricity produced by a wind turbine can be directed to electrical cooling equipment, providing sustainable cooling for residential buildings. In summer, people usually decide for themselves how to make use of electrical power produced by wind turbines.

At this time, except for electric lamps, which are not directly connected to the power grid, the remainder of household appliances are feeding phase-inverters. It is difficult for small wind turbines to directly connect to the grid-connected system; however, there is no such problem for large-scale wind turbines. If there is a sufficient hot water supply (200−300 L), WES can produce sufficient energy to cool a room to under 22° C when it is 35−40° C outside. In this case, the decline in the rooms' heating and cooling temperature is probably the same. That is why the installed equipment needs some amount of power to provide cooling in summer and heating in winter.

The FSC in the experimental CSWPI surface extends to 4 m^2. The plates absorbing sunrays are equipped with a selective cover. The top surface of plates is covered with a single-layer of glass, while the bottom surface has a thermal coating, which reduces heat waste to a minimum.

Information on equipment used in the experiment

The wind turbine is a product of Yangzhou Shenzhou Wind-driven Generator Co., Ltd (SWG), a Chinese company. It is a 3-bladed, high-speed motor model SWG -E-2000, with a 3.2 m diameter rotor and rotor sweep area of 8.0 m^2. Its specifications are as follows: nominal output power – 2000 W; power generator type – assembled on the basis of a permanent magnet; generator – Nd-Fe-B model with 5 magnetic pole couples and a nominal output power of 48 V; the wind's maximal operating speed – 18 m/s; the maximum permissible wind speed – 35 m/s; and the maximum rotation speed of a wind turbine's rotor spinning axis – 400 rpm. The wind turbine is connected to 4 RA12-260DG model gel accumulators. Their parameters are given in Table 1. In addition, an Xtender XTH 8000-48 model inverter with pure sinusoidal output voltage was used with following specifications: input voltage – 48 V; optimal power – 7.0 kWh; AC voltage – 220/180 V ± 2 %; frequency – 50−45 Hz ± 0.05 %; and maximum efficiency – 96 %. The inverter stops automatically in cases of overloads and short circuits. It generates sound signals until the moment of automatic stoppage in cases of overheating. The inverter is equipped with an automation block, which regulates the accumulator charge and discharge processes.

Table 1. Constructive and energetic characteristics of gel battery type RA12-260DG combined exit of electric battery

Type	Capacity A/hour	Size, mm	General height, mm	Weight, kg	Max inflow movement, A	Max vacuum movement, A	Internal resistance, Ω
RA12-260DG	260	520x269x203	224	74.0	2600	52.0	8.0

WEM has been installed on the property of the Radiobiology Center of the Institute of Radiation Problems of the Azerbaijan National Academy of Sciences. The small wind turbine is situated on a rooftop at a height of 12 m from the ground. In order to measure the wind speed, a Meteos (JDC) type anemometer was used. This anemometer also allows the measurement of air temperature. The device records 3 indicators in its light table: current wind speed on the upper line; maximum wind speed on the medium line; and average wind speed on the bottom line. In order to get precise results in the measurements, the data from the Azerbaijan Republic Department of Metrology were collected for 15−20 years at the height of 10−12 m with the same shading information. At the study site, the wind speed varies between 3−25 m/s at that height. Figures 3 and 4 show the WEM's output power – wind speed and noise signals (when operating) – wind speed diagrams.

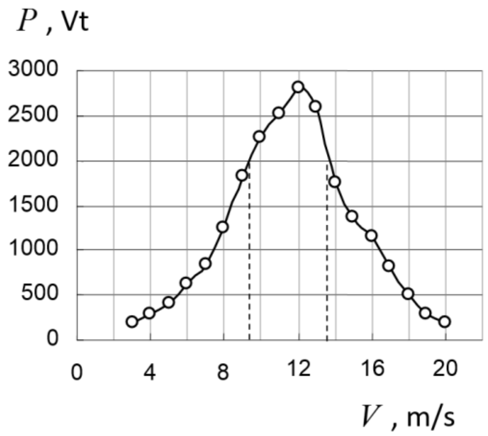

Figure 3. Graphics of wind plant power's exit power depending on wind speed.

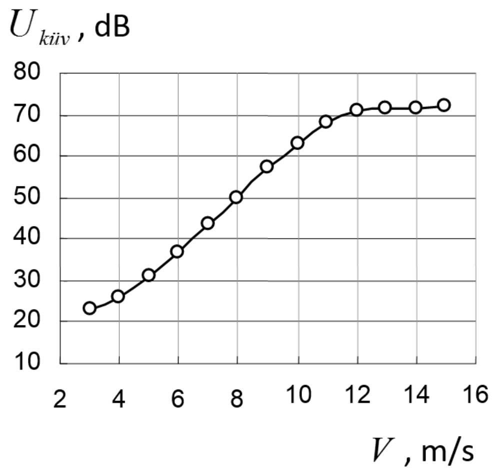

Figure 4. Graphics of noise sound level during wind power plant's operation depending on wind speed.

In order to assess the environmental impact of the wind turbine, the noise level was measured. For the purpose of measuring the sound level, an Italian-produced type HT 154, small-sized, digital apparatus was used. This apparatus was placed in special housing to absorb sound caused by wind and dimension interval changes ranging between 30−130 dBA. The precision is ± 1.5 dBA, and the frequency ambit is 5−8 kHz. Dimensions were implemented every 2 m from a 1 to 20 m distance from the wind power plant (5 measurements were made), and then an average rating was made. As seen from the dimensions, the level of the sound signal created by the wind power plant when operating at maximum capacity is not significant for the human ear.

The selection of the accumulator battery type RA12-260DG in the apparatus is related to this battery's capacity. Secondly, it can work sustainably in the regime of both the buffer and deep inflow-vacuum. Thirdly, its sustainability is longer than other accumulator battery types (about 10−15 years), and finally, they can work in a very wide temperature interval. Figure 5 shows graphics of accumulator battery capacity, which is dependent on temperature.

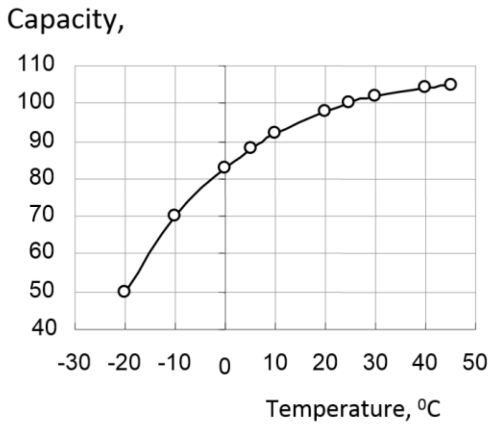

Figure 5. Graphics of gel accumulator's changing capacity type RA12 260DG depending on temperature.

2.4 *Wind regimes in meteorological stations on the Apsheron Peninsula*

There are 7 meteorological stations on the Apsheron Peninsula. In these areas, anemometers have a height of 10−12 meters and the flugers are in open areas. These stations include Apsheron Lighthouse, Pirallahi Island, stations in Baku, Zabrat, Mardakan, Mashtagha and the Sari Islands. In Figure 6, the changing graphics of the average monthly speed of wind for Apsheron Lighthouse, Zabrat, Mashtagha and Baku stations are illustrated. When measurements were taken at these stations, real conditions were taken into consideration in much closer distances (to 2 km) for the possibility of impediment that results in a shadow. The results of these measurements were corrected. Since most of the meteorological stations are surrounded by the Caspian Sea, these stations can be attributed to the higher classes for the degree of shading. But these stations are surrounded by settlements, villages, vegetation and hills, which can cause errors with changes in wind direction. These are not measurement errors but are related to statistical factors. We used references from the paper 'Prospects of Wind Energy Application in Azerbaijan' (Salamov *et al.*, 2010). The experiments were conducted by the Hydrometeorology Investigation Bureau. We used the results from those data books.

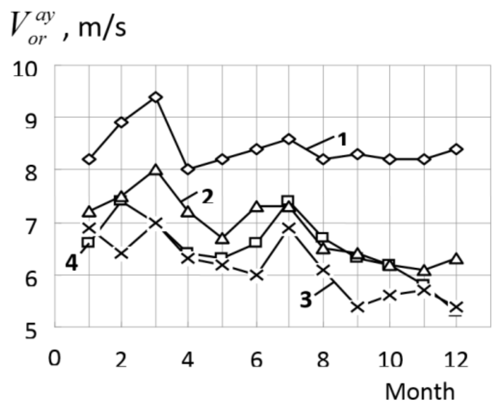

Figure 6. Graphics of changes in average monthly wind speed during a year at different locations on the Apsheron Peninsula: 1 – Apsheron Lighthouse; 2 – Zabrat; 3 – Mashtagha; 4 – Baku.

The observations showed that the greatest annual average speed of wind at the meteorological stations on the Apsheron Peninsula was at Apsheron Lighthouse, and the least annual average speed of wind at the meteorological stations was at Sari Island (Salamov *et al.*, 2010). But the annual average speed of wind at Sari Island is 6.2 m/s at a height of 30 m. This is a suitable regime for using a wind power plant that can be used in an individual form for energy production. However, considering the annual average wind speed, it would be incorrect to speak about the efficient use of a wind power plant in any district. For this, distribution characteristics should be learned during a year for the momentary wind speed for its different ranking of the annual average wind speed, as well as the amount of windless days and hours during a year. These issues were previously researched in detail for all of Azerbaijan (Salamov *et al.*, 2010). Then, the parameters for Baku's climatic conditions were researched and the overall result was studied (Salamov *et al.*, 2013). The results of measurements gathered at installed meteorological stations in the Mashataga settlement revealed that generally on the Apsheron Peninsula, as well as in Baku, the windless period (silence regime) of less than 12 hours captures 80% of the entire windless regime. The windless period, which continues up to 24 hours, captures 4−18% of the entire windless regime, while a 3-day windless regime reduces the capacity by only 1%. However, research studies have shown that energetic silence of a more than 3-day duration period has not been observed at Mashtagha meteorological station in the last 5 years. The location where the wind's annual average speed is 8 m/s for the number of days for different gradations of the momentary wind speed is given in Figure 7 (where V_{ani} – instantaneous wind speed).

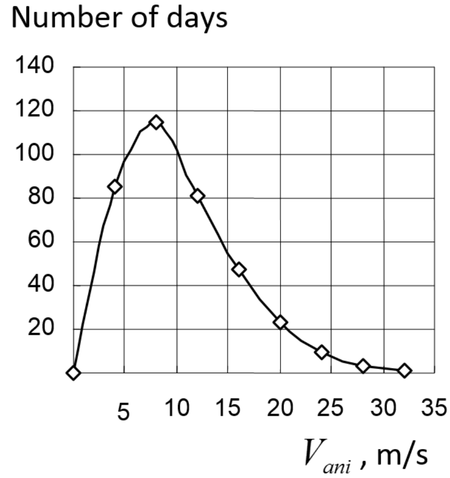

Figure 7. Frequency curve of instantaneous wind speed in the Apsheron Peninsula for the wind speed value of 8 m/s.

V_{ins} < 4 - 85; 4 < V_{ins} < 8 - 114.6; 8 < V_{ins} <12 - 81; 12 < V_{ins} <16 - 47.8; 16 < V_{ins} < 20 - 23.4; 20 < V_{ins} < 24 - 9.1; 24 < V_{ins} < 28 - 3; 28 < V_{ins} < 1.1. Consequently, as it appears from the data above, on the Apsheron Peninsula, particularly with Baku City's climatic conditions, the number of days with the wind speed at which a wind turbine will be able to operate at nominal output power (V_{ani} >8 m/s) is 365 – 80 = 280 days. Thus, a single installation including both a wind turbine and an FSC may supply a family of 5 with uninterrupted hot water throughout the year, and with household heating for 8−9 months in a year, where hot water temperature will be 55–60° C, while the CSWPI productivity will be 400 litres/day. In winter, maintaining the required indoor temperature by the CSWPI may present certain difficulties; therefore, in such cases, the centralised power network may need to be relied on an alternative energy source. On such days, an electrical heating element with the maximum required power of 1.5 kW and coated with an insulation layer may be employed as the heating element. This heating element, installed inside the hot water tank (hot water tank also playing the role of an accumulator), is connected to the wind turbine and the centralised power network by electric switches (24) and (25). Considering the minimum heat load and intended use, a single-circuit system based on natural circulation (thermo-syphon) of a heat transfer agent was used in the experimental model. At present, this choice has also been utilised with the aim of eliminating additional energy losses occurring due to the connection of the circulating pump to the circulation circuit of the hot water tank.

2.5 Heat and hot water supply using flat solar collectors in B and C zones

In addition to all of the above, we studied the possibility of providing a family of 5 living in areas with no expedient wind regime (zones B and C) (Salamov *et al.*, 2010), using only solar energy (FSCs) even for WEMs with 10−15 m heights were insufficient in such zones for serving consumers' needs for hot water and heating. We accepted a person's daily hot water needs as being 80 litres. First, the quantity of daily average thermal load (TL) was calculated based on formulas from the reference literature. Thus, the daily heat load needs per person of a 5-member family was calculated using 80 litres water as a norm, and then this need was multiplied by the days of monthly water needed to achieve the result for heat load every month.

$$Q_{iY}^{sut} = aG_p \rho m N (t_{q.su} - t_{s.su}^{ay}) \quad (1)$$

where, a is hot water norm per person litres/s; G_p – heat load of water, W/(kg °C); ρ – water density, kg/L; m – number of family members; N – days per month; $t_{q.su}$ $və$ $t_{s.su}^{ay}$ – monthly temperature average of cold and hot water.

If we put the numbers in Equation (1) (a = 80 L/s; G_p = 1.16 W/(kg °C); ρ = 1; m = 5; N =1; $t_{q.su}$ = 50° C; $və$ $t_{s.su}^{ay}$ = 15° C), then we obtain the following results for heat load: 16.3 kWh per day; 489 kWh per 30-day month; 505.3 kWh per 31-day month; and 460 kWh for February. Then, the heat load of cold water for Baku City was calculated (Kharchenko, 1991; Salamov and Abbasova, 2006). TL was calculated for the following parameters: temperature of water – 15° C, temperature of hot water – 50° C, temperature of the heat transfer agent at the FSC output – $t_{h.tr.agent}^{outp}$ = 55° C; and temperature of air – monthly average value for the zone. Temperature of water was taken as 15 °C, taking into account the annual water average in Baku City. The calculated values of daily, monthly and annual average TL are as follows: $Q^d_{TL.}$ = 16.3 kWh, Q^m_{TL} = 496.1 kWh and Q^{an}_{TL} = 5963.6 kWh.

As it is known, using FSCs for a hot water supply requires optimal angular positioning of solar collectors' surfaces in relation to the horizon in order to ensure optimal daily, monthly and annual thermal loads. This angle is calculated as follows:

$$\beta = \varphi + \delta \quad (2)$$

where β is the inclination angle of the FSC surface in relation to the horizon; φ is the circle of the latitude angle (for the Apsheron Peninsula and Baku City, the value is taken as 40°24′); δ is the inclination angle of the vector (directed toward the sun at noon) in relation to the horizontal plane (also called 'solar declination' in reference literature), which has a positive value for the Northern hemisphere and negative value for the Southern hemisphere.

Figure 8 shows the annual variation of the solar declination angle's monthly average values. The average monthly optimal inclination angle of FSC surfaces was determined on the basis of Equation (2), which is based on the monthly average δ values provided in Table 2.

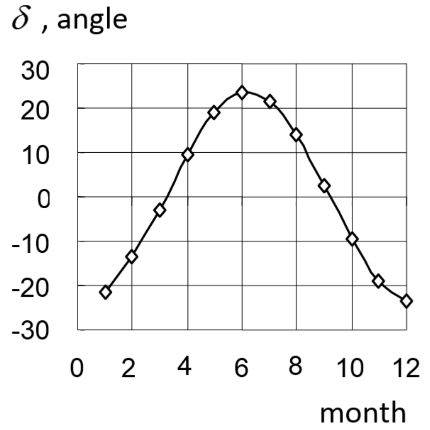

Figure 8. Annual variation of solar declination angle's monthly average values.

Testing and research work performed over a number of years have shown that even though FSCs have their own optimal inclination angle values for each day, direct connection of their structures to relevant utility lines (water, etc.) does not allow for daily angular adjustments and even the employment of automatic control systems does not prove their worth. In fact, changing the FSC surfaces' angles even during a month or only once in a season presents certain difficulties, and, therefore, they are usually fixed at some particular angular position, which may be considered the most optimal one throughout the year, while all heat- and energy-related calculations are performed for this single angle. In such cases, the solar declination angle in Equation (2) is taken to be equal to zero, which, according to Figure 8, roughly corresponds to the spring (March) and autumn (September) seasons.

Table 2. The average monthly optimal inclination angle of FSC under Baku City's climatic conditions.

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
β, ang. degrees.	61.22	53.78	42.80	30.79	21.55	17.35	19.32	26.75	38.52	50.23	59.51	63.45

According to the reference literature, taking optimal inclination angles of FSC surfaces for the winter, spring/autumn and summer seasons ($\beta = \varphi + 15°$, $\beta = \varphi$ and $\beta = \varphi - 15°$, respectively) is considered more feasible in connection with operation of FSC-based solar water heating units (SWHU). The average monthly value of SRI absorbed daily by 1 m^2 of the surface is determined for these values of angles: 7′, 8′, and 11′, respectively. In this case, the optimal inclination angles of FSC surfaces for the winter, spring/ autumn and summer seasons will be: β_W = 40° 24′ + 15° = 55° 24′, $\beta_{sp\text{-}au}$ = 40° 24′ and β_{summ} = 40°24′ -15° = 25°24′, respectively. It is also important to note that when choosing between the above 3 cases for the annual average inclination angle of FSC surfaces, the latitude and longitude of the SWHUs′ operation site, as well as the optimal orientation of the FSC toward the sun's trajectory (poles), should be taken into account. In order to determine the most feasible inclination angle for

FSCs, we determined the energy and heat parameters, as well as monthly average values of its coefficient of efficiency. For this purpose, and in conformity with the study methodology, we determined average monthly values of SRI for 1 m^2 of the inclined surface $\dot{I}^{IS}_{tot}$ based on analogous values for the horizontal surface $\dot{I}^{HS}_{dir}$, specifically, 3 and 8. First, we determined monthly average values of relevant slope coefficients ($R^{mon}_{Inc.} = \dot{I}^{IS}_{tot}/\dot{I}^{HS}_{tot}$), and then monthly average values of $\dot{I}^{IS}_{tot}$ were found. Based on the obtained results, the annual variation graphs were prepared. Figure 9 shows the annual variation of the monthly average values of daily direct ($\dot{I}^{HS}_{dir}$), dispersed ($\dot{I}^{HS}_{disp}$) and total ($\dot{I}^{HS}_{tot}$) SRI for 1 m^2 of the horizontal surface, while Figure 10 shows annual variation of the monthly average values of daily total ($\dot{I}^{HS}_{tot}$) SRI for 1 m^2 of the inclined surface and β_{summ} = 25°24′ (Curve 1), β_{sp-au}= 40°24′ (Curve 2) and β_w = 55°24′ (Curve 1) values.

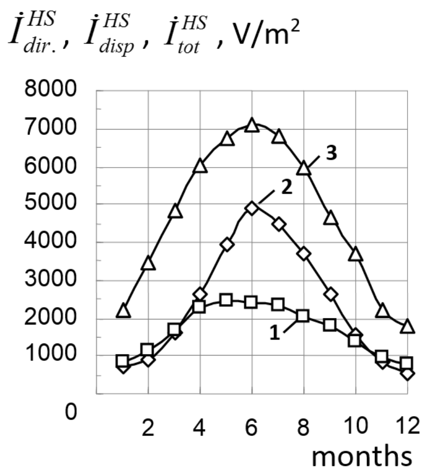

Figure 9. Annual variation of the monthly average values of daily direct ($\dot{I}^{HS}_{dir}$), dispersed ($\dot{I}^{HS}_{disp}$) and total ($\dot{I}^{HS}_{disp}$) SRI for 1 m^2 of the horizontal surface 1 – $\dot{I}^{HS}_{dir}$; 2 – $\dot{I}^{HS}_{dir}$; 3 – $\dot{I}^{HS}_{disp}$.

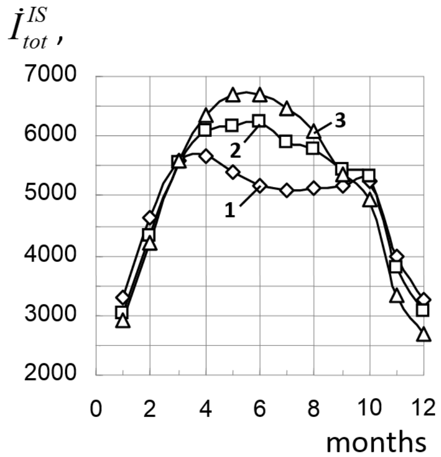

Figure 10. Annual variation of the monthly average values of daily total ($\dot{I}^{HS}_{disp}$) SRI for 1 m^2 of the inclined surface.

When comparing these 2 graphs, it becomes clear that even though the annual variation of monthly average values for 1 m^2 in 3 cases showed similar behaviour (this is statistical data from Baku City), Figure 10 shows that when FSC's optimal inclination angle is set for that of the summer optimal angle (Curve 3), the maximum value of SRI will be in summer and the minimum value in winter. Similarly, if one were to turn FSCs to the optimal inclination angle for winter, the maximum value of SRI would be in winter and the minimum value in summer. This comparison is not about SRI between winter and summer.

The comparison is the SRI monthly average between sloping surfaces and horizontal surfaces in 1 m$^{2.}$ On the one hand, this is a desirable option for the thermal load required in winter. It is greatly increased due to higher heat losses caused by multiple factors. In addition, the factor of utilisation of an additional energy resource diminishes.

The 3 optimal values for the FSC inclination angle, including the way the SRI for 1 m^2 changes and assumes different values for winter and summer optimal angles, depend on the changing behaviour of a monthly average value of the slope coefficient $R^{mon}_{Inc.}$. Figure 11 shows annual variation of the slope coefficient $R^{mon}_{Inc.}$ for installation of an FSC at optimal angles for winter, spring/autumn and summer.

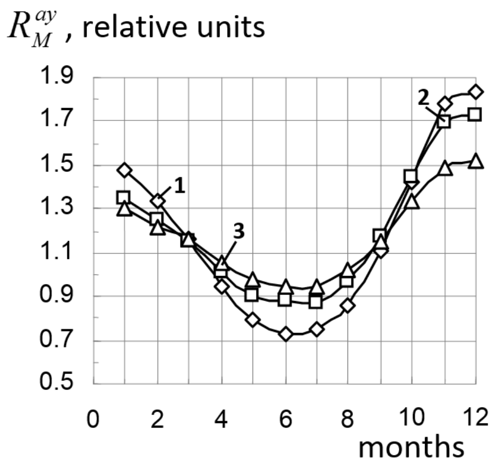

Figure 11. Annual variation of the average monthly value of the inclination angle. Curves 1, 2, and 3 represent FSC surface's inclination angles 55°24′, 40°24′, and 25°24′, respectively.

The amount of solar energy falling on 1 m^2 of the sloped FSC surface was calculated, such calculated values for β_w = = 55°24′, β_{sp-au}= 40°24′ and β_{summ} = 25°24′ being 1764.5 kW/hour, 1846.5 kW/hour and 1864.9 kW/hour, respectively, while for the horizontal surface (β = 0°) it amounted to 1691.6 kWh. The comparative analysis of the obtained data shows that the installation of an FSC at the angle that is optimal for the spring/ autumn period would be more feasible. Taking this into account, heat and energy calculations of SWHU in connection with compensation of daily thermal load required for supplying experimental house inhabitants with hot water during different months were made on the basis of the FSC inclination angle equal to the Baku City's circle of the latitude angle (β_{sp-au} = 40°24′).

Average monthly values of air temperature (t^{month}_{air}), heat transfer agent's temperature at FSC entrance ($t^{ent}_{h.t.a.}$) and cold water temperature ($t^{month}_{co.w.}$)

as well as SWHU's daily uninterrupted operation time (t_{op}^{month}) and overall surface area for ensuring the daily thermal load S_{FSC}^{month} were also taken into account during calculations (annual variation of these parameters is shown in Figure 12 below).

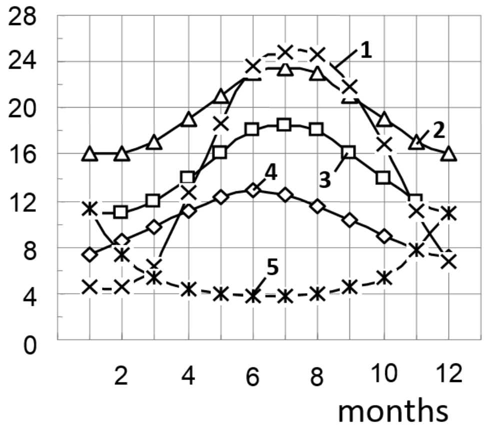

Figure 12. The average monthly values of air temperature (t_{air}^{month}), heat transfer agent's temperature at FSC entrance ($t_{h.t.a.}^{ent}$), cold water temperature ($t_{co.w.}^{month}$), SWHU's daily uninterrupted operation time (t_{op}^{month}) and overall surface area for ensuring the daily thermal load S_{FSC}^{month} (curves 1, 2, 3, 4 and 5, respectively)

For the determination of optimal values of overall FSC surfaces, the average monthly values of daily absorbed SRI by 1 m^2 of such surfaces I_{abs}^{day} were calculated in the first instance, where the following assumptions were made: the reduced absorption capacity of FSC surface – θ = 0.73; reduced heat loss coefficient – $U_{h.l}$ = 6 W/m^2 °C; and heat transfer agent's temperature at FSC outlet – $t_{h.t.a.}^{ent}$ = 55°C. Then, the monthly thermal load values S_{FSC}^{month} required for supplying experimental house inhabitants with hot water during different months were determined along with the values of SRI absorbed by 1 m^2 of the FSC surface during different months of the year I_{abs}^{day} and the amount of the daily energy $Q_{eff.}^{daily}$ absorbed by an FSC and efficiently used. Figure 12 (Curve 5) shows the annual variation in optimal values of the FSC overall surface, while Figure 13 shows the annual variation of I_{abs}^{day} and $Q_{eff.}^{daily}$ parameters.

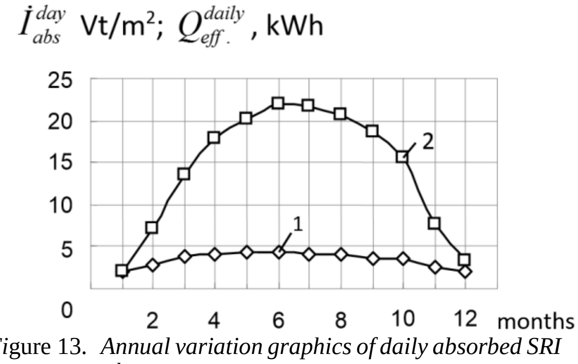

Figure 13. *Annual variation graphics of daily absorbed SRI I_{abs}^{day} in 1 m^2 of an FSC and effective use of solar energy $Q_{eff.}^{daily}$ by all the surface of an FSC: curves 1 and 2, respectively.*

Further calculations revealed that if one were to choose FSC overall surfaces in accordance with the spring/autumn season requirements ($S_{FSC}^{ov.} \approx$ 5 m^2), then, except for during winter months, users of an FSC would receive sufficient quantities of hot water, while in December, January, and February, the quantity of hot water produced daily would be 73, 54, and 52 litres, respectively. Therefore, an additional energy source should be utilised for an uninterrupted and sufficient supply of hot water. Such alternative sources may be those which run on natural gas or wind power. In cases of operation of the installation in places distant from centralised power and gas supply networks, such alternative sources may be photovoltaic power sources or WEMs. If one were to take FSC overall surfaces as equal to summer's optimal values (~4 m^2), SWHU would be capable of supplying consumers with 80 litres of hot water per person both in winter and spring/autumn months. However, this will require the use of additional energy sources, which have a negative impact on SWHU's economic feasibility. The average monthly values of the SWHU's coefficient of efficiency η_{SWHU}^{month} as well as factors of utilisations f_{AES}^{month} of alternative energy sources and FSC f_{FSC}^{month} were determined and relevant graphs were constructed on the basis of the obtained results (see Figure 14).

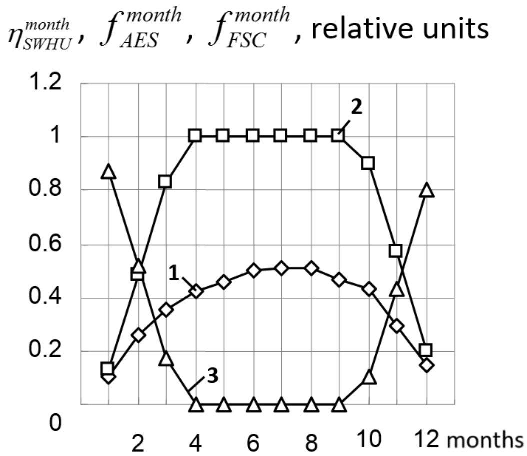

Figure 14. Annual variation of SWHU's coefficient of efficiency η_{SWHU}^{month} as well as factors of utilisations f_{AES}^{month} of alternative energy sources and FSC f_{FSC}^{month} : curves 1, 2, and 3, respectively.

Finally, monthly and yearly fuel savings for cases of alternative energy source utilisation (gas E_{gas}^{month} and electricity $E_{el.}^{month}$) were determined. Figure 15 shows annual variation of these parameters.

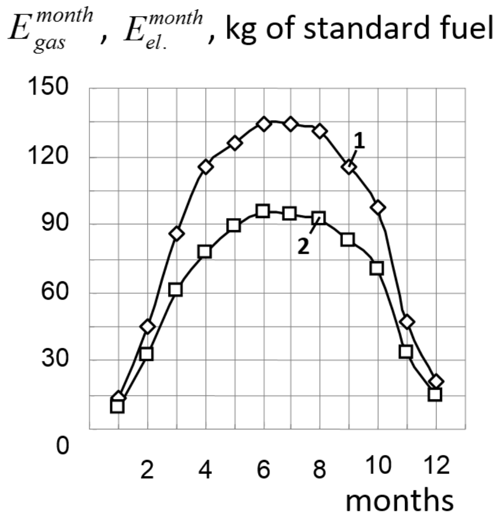

Figure 15. Annual variations of monthly and yearly amount of fuel savings for cases of alternative energy source utilisation (gas E_{gas}^{month} and electricity $E_{el.}^{month}$): curves 1 and 2, accordingly.

3 Results and conclusion

1. In this paper, damage to the atmosphere caused by conventional energy resources was reviewed. The usage perspective of low potential solar collectors was analysed. Since solar collectors cannot by themselves provide sufficient energy for heating and hot water during winter, the hybrid use of solar collectors and small wind turbines is considered to be practical.

2. It was determined that in Baku the number of sunny days equals 300 days and the number of sunshine hours are 3000 hours per year. During a year, sun radiation for a 1 m^2 horizontal surface is 1900 W/m^2, and the maximum intensity of solar radiation is 950 W/m^2.The average annual value of that indicator is 200 W/m^2. Active solar radiation collection periods for winter and summer seasons are 4.8−7.8 and 7.2−12.5 hours, respectively. On the Apsheron Peninsula and along coastal areas of the Caspian Sea, there are 270−280 windy days, and the average wind speed is 7−8 m/s, which in some places exceeds 10 m/s. In order to show the efficiency of wind energy, various graphs were illustrated and analysed.

3. The results of the measurements gathered at installed meteorological stations in the Mashataga settlement revealed that generally on the Apsheron Peninsula, as well as in Baku, the windless period (silence regime) of less than 12 hours captures 80% of the entire windless regime. The windless period, which continues up to 24 hours, captures 4−18% of the entire windless regime, while a 3-day windless regime reduces the capacity by only 1%. However, research studies have shown that energetic silence of a more than 3-day duration period has not been observed at Mashtagha meteorological station in the last 5 years. The location where the wind's annual average speed is 8m/s for the number of days for different gradations of the momentary wind speed is given: $V_{ins} < 4$ - 85; $4 < V_{ins} < 8$ - 114.6; $8 < V_{ins} < 12$ - 81; $12 < V_{ins} < 16$ - 47.8; $16 < V_{ins} < 20$ - 23.4; $20 < V_{ins} < 24$ - 9.1; $24 < V_{ins} < 28$ - 3; $28 < V_{ins}$ < 1.1, where V_{ins} is instantaneous wind speed.

4. The subject area of research was a 5-person single family house in Baku. The possibility of providing that house with heat and hot water by using hybrid solar and wind energy was investigated. For this purpose, in the laboratory of Radiation Problems Institute, a CSWPI was established and that application was being tested for 2 years under Baku's climatic conditions. The testing revealed that the device was able to provide the family with hot water for the whole year and with heating for 8−9 months of the year (except for winter months). In order to obtain heat for the remaining months (winter months), additional energy sources were needed. For this purpose, a 1.5 kW maximum power consumption electric heater was sufficient. This device was powered by the electricity network. A photoelectric solar panel or a small wind turbine can also be added to make the system 100% renewable.

5. In the paper, the general view and the blocking scheme of a CSWPI were characterised and its working principles were explained in detail. Technical characteristics and the main components of an FSC and a small wind turbine were described. In particular, wind turbine exit power and noise levels are illustrated in the graphs in relation to the wind speed. The capacity changes for accumulating batteries in relation to temperature were depicted with graphs. It was determined that between the wind speeds of 9.5 m/s and 13.5 m/s a small wind turbine performs at its nominal power. In the conditions when the wind speed is lower than 9.5 m/s or higher than 13.5 m/s, the power output of a wind turbine decreases. At the maximum noise level with the maximum wind conditions, the noise level does not exceed the nominal level for human health. The capacity of accumulators changes in relation to temperature. At temperatures between 0° C and 50° C, the capacity increases to between 84% and 115%, respectively. At temperatures lower than -10° C and -20° C, the capacity decreases abruptly. However, these low temperatures are not observed in Baku. Thus, accumulating batteries lead to reserve energy for silent regimes without wind and still ensure that the demand for heating and hot water is met for some hours (10−12). This is considered normal for the wind regime on the Apsheron Peninsula.

6. It was determined that in the summer season consumers are fully provided with hot water and there is no need for heating during that season. The energy generated from a small wind turbine remains unused for the intended purpose. Therefore, during summer, energy from a small wind turbine can be utilised for air conditioning and other domestic uses in electric appliances.

7. In the paper, the possibility of providing a 5-person household with hot water and heating by using a flat solar collector was also investigated. The quantity of hot water needed per person was considered to be 80 litres daily and the monthly amount of heating for all family members was

determined. The monthly quantity of solar radiation intensity for 1 m^2 of a flat solar collector and daily quantity of SRI for the whole sloping surface were determined. This was done by measuring SRI for 1 m^2 in different months and the data were obtained from data books. To this end, for transition from the horizontal surface to the slope surface, the first monthly numbers of inclined coefficients were determined. The coefficient changes during the year were depicted in the graphs of FSC's inclination angle changes during the winter, spring/autumn and summer seasons. Then, monthly numbers of effectively utilised heat energy absorbed by the surface of flat solar collectors were established. Taking into account the monthly amount of heat needed to supply hot water, the annual value of conventional fuel savings was identified. When identifying the amount of monthly savings for conventional fuel, natural gas and electricity costs as a source of additional energy, both electric heater and natural gas were taken into account. It was determined that the conventional fuel savings for gas and electric heater were 1061 kg and 749 kg, respectively. It is a good indicator for application used individually. Monthly prices for conventional fuel savings are given in the form of a graph dependency. It is also used as an individual figure which illustrates a single power plant in a very good way

8. In order to assess the perspective of providing an experimental single family house with hot water and heating throughout the year, the calculation was conducted by taking into account the following: the energetic parameters of wind turbines and flat solar collectors; monthly and daily heating loads needed for heating and hot water; wind speed; environmental temperature and cold water temperature; and quantity changes for some other indicators. This is due to the fact that wind turbines and flat solar collectors are of an inherently complex nature. Experimentally, it is impossible to make a judgement about the heat-energy balance and other characteristics resulting from wind turbines and flat solar collectors. Even the data of the same month can vary significantly from year to year. That is why we took into consideration 20-year worth of data results in making our calculations.

9. The average monthly price of SWHU efficiency, FSC and an alternative source use ratio were determined. It was revealed that SWHU's maximum efficiency occurs in July and August (0.51) and the minimum cost is in January (0.1). The average annual cost of efficiency is 0.37, the average annual value of the FSC use ratio is 0.758, while the alternative source annual use ratio value is 0.242. The average monthly price changes are depicted in the graphics. The results in terms of solar energy use for hot water and heating supplies show that in Azerbaijan it is significantly effective. In this sense, the energy from small wind turbines can be used effectively for the entire year. The prospects for solar and wind energy usage in Azerbaijan, as well as their use for heating and hot water supplies, were researched. In the paper, detailed information was provided about the potential of solar and wind energy on the Apsheron Peninsula.

10. According to the research, it can be concluded that in order to provide different consumers with hot water and heating supplies the usage of hybrid solar wind installations is justified both economically and environmentally. These installations are considered for individual usage and can be applied broadly to isolated areas, complex terrains, as well as for supplying hot water and heating to military installations. During summer months, heat consumption is minimal. The usage of small wind turbines enables the use of electricity for the needs of power processors (such as domestic air conditioning).

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Karšto vandens ruošimo ir šildymo nuosavuose namuose, naudojant hibridinį saulės ir vėjo energijos įrenginį, galimybės Apsherono įlankoje, Azerbaidžano Respublikoje

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Šiame tyrime analizuojamos aplinkos apsaugos problemos, atsirandančios naudojant tradicinius energijos išteklius elektros ir šiluminės energijai gaminti. Pateikiami įprastinių energijos šaltinių pakeitimo į vėjo ir saulės energiją naudojančias technologijas privalumai. Darbe buvo tyrinėtos kombinuotos saulės ir vėjo energijos panaudojimo galimybės tiekti energiją vidutinei 5 asmenų šeimai. Eksperimentiniai rezultatai buvo gauti atlikus išsamius tyrimus vyraujančiomis aplinkos sąlygomis Baku. Azerbaidžano Nacionalinės mokslų akademijos Radiacijos problemų institute buvo suprojektuotos ir išvystytos saulės ir vėjo hibridinės šildymo ir karšto vandens ruošimo sistemos. Darbe taip pat buvo analizuojamos karšto vandens ruošimo galimybės 5 asmenų šeimai ištisus metus, naudojant tik saulės energiją, ir pateikti tokio įrenginio energijos balanso skaičiavimo rezultatai.

Raktiniai žodžiai: *plokštieji saulės kolektoriai, vėjo jėgainė, hibridinis saulės ir vėjo įrenginys, šalto vandens cisterna.*

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Local Sustainable Energy Strategies as Opportunity for European Union Regional Development

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The aim of this article is to create the methodology of energy strategies at the local, municipality level and to provide insight into the effectiveness of innovative policies and unique policy design components that can be adopted by other governments, at the local or state levels. The Regional Policy of the EU, also referred to as Cohesion Policy, is a policy with the stated aim of improving the economic well-being of regions in the EU and avoiding regional disparities. The strategy Europe 2020 stresses the so-called 20/20/20 targets.

The paper was prepared using the material, collected and analysed by implementing the Baltic Sea Region 2007–2013 programme project 'Public Energy Alternatives – Sustainable energy strategies as a chance for regional development' (PEA). The novelty of this methodology is in its holistic approach – municipality, community, business and researchers' cooperation is used. In this article, the main stages of a municipal strategy development are analysed and recommendations for regional energy strategy preparation are given.

Keywords: *sustainable development, renewable energy sources, regional strategies.*

1 Introduction

Current approaches to energy are not sustainable enough. Emphatically, energy is directly related to the most critical social aspects affecting sustainable development, such as poverty, jobs, income levels, gender disparity, population growth, agricultural production, climate change, environmental quality and economic/security targets (Peng *et al.*, 2011). It is necessary to pay more attention to the critical importance of energy on all these aspects as the global social, economic and environmental goals of sustainability cannot be achieved without them (Štreimikienė & Mikalauskienė, 2007). One of the key challenges is to realise these goals. Failure to take action will lead to continuing degradation of natural resources, increasing conflicts over scarce resources and widening gaps between the rich and the poor. Implementation of sustainable energy strategies is one of the most important levers in creating a sustainable world (El Bassam *et al.*, 2013). Implementing the appropriate and complementary policy at each level of government, based on each government's competencies, allows for the creation of a synergistic policy environment that addresses multiple barriers to clean energy development. Policy implementation at the local, municipality level can provide insight into the effectiveness of innovative policies and unique policy design components that can be adopted by other governments, at the local or state levels.

Improvement and dissemination of knowledge on the methods (Calvert *et al.*, 2013), policies and technologies for increasing the sustainability of development, taking into account its economic, environmental and social pillars, as well as the methods for assessing and measuring sustainability of development, regarding energy, transport, water and environment systems and their many combinations are the key tools for cohesive development of communities (Duić *et al.*, 2013; Kaygusuz, 2012).

There are still many barriers limiting current and future renewable energy production growth (Doukas, 2013). The main barriers indicated are slow diffusion of recent and current innovations, market incentives and barriers, developer incentives, cost-effectiveness and urban implementation (Walker, 2008). It is important to emphasise that the evolution of policy instruments applied to the environment, social and economic sectors has made a significant influence on sustainable development framing (Zaccai, 2012).

Although the European Union is one of the richest parts in the world, there are large internal disparities of income and opportunity between its regions. Regional policy transfers resources from richer to poorer regions. The argument for regional policy is that it is both an instrument of financial solidarity and a powerful force for economic integration. The Regional Policy of the EU, also referred to as Cohesion Policy, is a policy with the stated aim of improving the economic well-being of regions in the EU and avoiding regional disparities (Peng *et al.*, 2011). More than one-third of the EU's budget is devoted to this policy, which aims to eliminate economic, social and territorial disparities across the EU, restructure declining industrial areas and diversify rural areas which have declining agriculture. In doing so, the EU regional policy is geared towards making regions more competitive, fostering economic growth and creating new jobs. The policy also has a role to play in wider challenges for the future, including climate change, energy supply and globalisation (Atici & Ulucan, 2011).

Nevertheless, strategy Europe 2020 stresses the importance of energy efficiency in the EU more specifically (Baležentis *et al.*, 2011), the so-called 20/20/20 targets, namely a reduction of greenhouse gas emissions (by 20%), an increase in the share of renewable energy (20%), and an increase in energy efficiency, thus, saving up to 20% of energy consumption; the strategy also implies the need for elaborating appropriate policy measures aimed at achieving the aforementioned aims by 2020 (Tolón-Becerra, Lastra-Bravo, & Botta, 2010). Article 4 of the Renewable Energy Directive (2009/28/EC) requires EU Member States to submit national renewable energy action plans and provide detailed road maps of how each Member State expects to reach its legally binding 2020 targets for the share of renewable energy in their final energy consumption.

A very important target in this area is diversification of energy sources and climate change mitigation policies (Lindseth, 2004; Sperling *et al.*, 2011; Tolón-Becerra *et al.*, 2010). The main issues and the background of sustainability in the energy sector are reduction of energy intensity and increasing energy efficiency.

The benefit of these strategies covers not only mitigation of the climate changes, but also improvement in the quality of living conditions in a city and the health of inhabitants. Also, it is very important to implement statements and obligations of the Covenant of Mayors, which cover the aims of sustainable energy development strategies (Sperling *et al.*, 2011). To promote sustainable energy strategies requirements, policy measures, environmental and energy agencies' data were analysed (Lantz *et al.*, 2007). Local policy development allows experimentation as each government creates the policy adopted to the local conditions (Lutsey & Sperling, 2008). In contrast, the policy developed at the state or national level to be implemented by local governments may not provide effective flexibility in the local context (Rammel & Van Den Bergh, 2003). Implementing the appropriate policy at each level, based on each stakeholder's competencies, allows for the creation of a synergistic impact of the policy that addresses multiple barriers to sustainable development. Policy implementation at the local level can provide innovative sight and unique design components that can be adopted at the local or state levels creating the policy (Lindseth, 2004). Moreover, policy development at the local level may be more effective in addressing some barriers because achievement of social acceptance on a smaller scale is easier. It is necessary to create local issue and to increase involvement of local community in the local processes because inhabitants have the ability to be involved in the decision-making process (Busche, 2010). Moreover, business stakeholders cannot make significant influence over local governments and citizens can make influence on policy development at the local level (Byrne *et al.* 2007). The clean energy idea grows in many communities and it makes implementation of sustainable energy policies at the local and national levels easier. It is important to mention that action at the state level is significant, but local governments should make essential impact on the framing of the sustainable energy policy (Štreimikienė & Mikalauskienė, 2007).

The essential principle for local sustainable development (SD) is that municipalities decide themselves on the main targets on which they will focus. Local stakeholders know better where the best chances of successful implementation lie. They can develop environmental and other measures or understand how to adapt the policy to local needs. The fact that municipalities can adapt a local SD policy to their own local environment makes local SD policy specific and valuable. This removes the risk of vagueness and disparity between communities and other stakeholders. Improved social, economic and environmental situations are the points that enter the idea of the sustainable energy strategy and give shape to realistic aims within a clearly defined structure (Peterson & Rose, 2006).

Policy implementation at the local level creates flexibility to understand local needs. Local governments' knowledge can help frame the local discussion covering clean energy, and also demonstrates benefits addressing to local issues (Busche, 2010).

Assimilation of EU structural funds for local projects creates the possibility to address regional disparities and local needs and achieve the main objectives of the European policy more effectively. Therefore, the main strengths are greater experimentation by a variety of policy makers, large flexibility, better correspondence to specific local needs, citizens' involvement, lower impact of lobbies and better transparency of financial instruments. Several functions of municipalities related to sustainable energy development issues are:

- preparation of programmes related to the development of housing;
- organisation of heating and water supply and wastewater collection and treatment;
- development of municipal waste management, maintenance of municipal buildings, roads and streets of local significance;
- implementation of regional development programmes.

As a result, municipalities play an important role in the energy sector and have the ability to introduce renewable energy systems and increase energy efficiency. Municipalities have opportunities in local energy plans to involve energy-efficient housing, waste collection and management systems, renovation and modernisation of the heating system and renewable energy sources projects (Del Río, 2011). The implementation of efficient street lighting is also an important source of energy savings at the local level. Municipalities have powers in preparation of long-term strategic development plans, detailed master plans and short-term strategic activity plans (Štreimikienė & Mikalauskienė, 2007).

2 Materials and methods

This paper was prepared using the material, collected and analysed by implementing the Baltic Sea Region (BSR) 2007–2013 programme project 'Public Energy Alternatives – Sustainable energy strategies as a chance for regional development' PEA. In total, 21 partners from 6 countries (Estonia, Finland, Germany, Latvia, Lithuania and Poland) around the Baltic Sea together with experts from various scientific areas of expertise analysed what potential energy saving capacities existed that could be added, strengthened and expanded. The project was designed to work out energy strategies for 9 municipalities that would help countries all over the Baltic Sea region and beyond to rethink their energy production, raise awareness of alternative energies and encourage municipalities and regions to meet European energy standards as soon as possible. The strategies are prepared on the basis of existing approaches for energy strategies, regional SWOT analysis, networking with regional, national and transnational business and scientific partners and benchmarking at the European level. The targets are allocated for short-term, medium-term and long-term perspectives. Finally, the activities are added to the targets established. Baltic Energy Strategies for the regions were elaborated and compiled to a set of measures and possible results for other regions in the BSR.

The Law on Energy from Renewable Sources was adopted in Lithuania in 2011. According to this law, all municipalities were obligated to prepare strategies for usage of renewable energy sources in Lithuania. The lack of uniform methodology on preparation strategies existed in that period and still exists. A compilation of paper findings will help to make the possibilities of public energy management visible, help other communities and regions to elaborate their ideas and find their ways into the future with renewable energy and lower energy costs.

3 Results and discussion

3.1 Preparation of sustainable development strategy

In a common approach, each region worked out a strategy that was discussed and enhanced by the partnership in a transnational environment. The strategies are developed through the evaluation of existing approaches towards energy strategies, regional SWOT analysis, networking with regional, national and transnational business and scientific partners as well as benchmarking at the European level. The first step for preparation of an SD strategy is evaluation of the situation in the local environment and region. Self-assessment analysis is based on statistic indicators. The next step is to frame targets for municipalities. The targets are presented for short (5 years), medium (15 years) and long terms (25 years). The flow chart of the framework of local SD strategy development is presented in Figure 1.

The municipality should establish policy guidelines for short-term, medium term, long-term periods, and the framework should cover industry, agriculture and forestry, municipal services, households, transport, local electricity and heat production, as well as waste management. Moreover, local SD plans should cover the areas under jurisdiction of municipalities, establish actions for climate change mitigation and increase energy savings and use of renewable energy sources in these areas (e.g. local road infrastructure, implementation of efficient street lighting, increase in forest area, improvement of a waste management system and use of collected biogas from landfills for energy generation). The national targets for green gas emission (GHG) reduction, energy savings and use of renewable energy sources are presented for the year 2020 and they should be used as the guidelines for establishing targets at the local level.

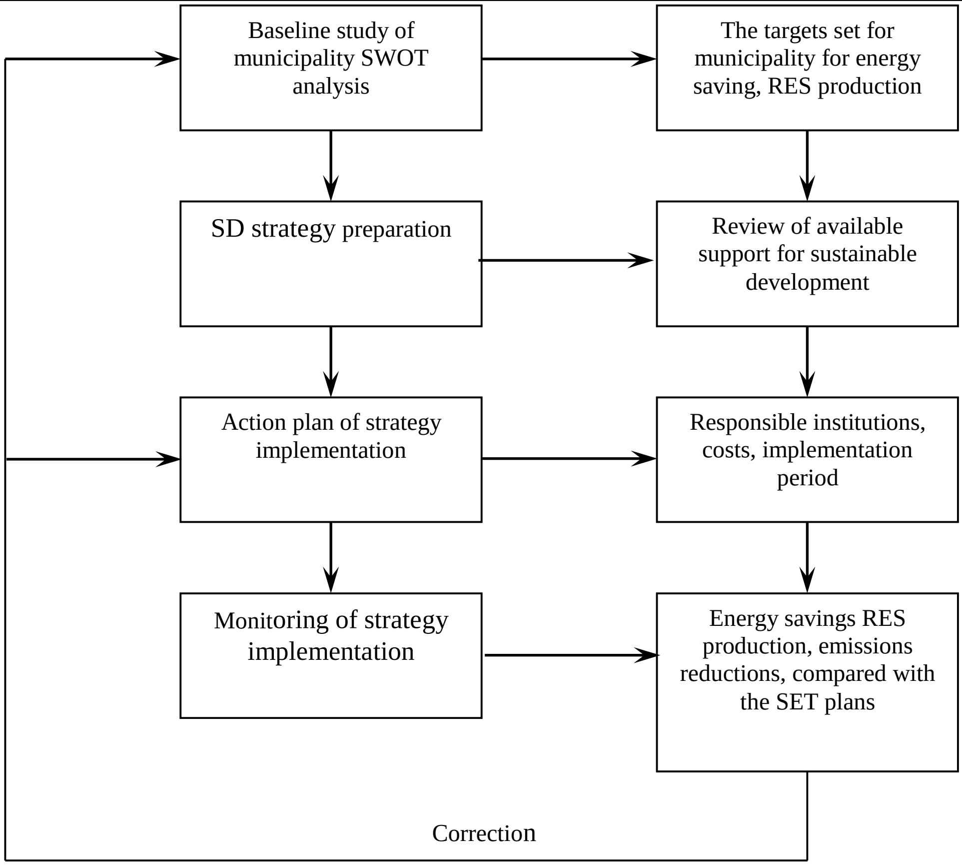

Figure 1. The framework of local sustainable development strategy.

3.2 Management

Within the PEA project, regional energy strategies were elaborated for the following partner regions: RCG Prignitz in Germany, Mustvee, Rauge and Varu in Estonia, Lahti and Ylivieska in Finland, Kraslava in Latvia, Ignalina in Lithuania and Niepolomice in Poland. The main aim of this work was to outline measures and possible results for other regions. The general strategy aims at reduced energy usage and higher added value based on regional resources. Energy efficiency and the use of alternative energy sources are not only technical problems but also strategic ones. It is not enough to say that energy should be saved and new forms of energy production must be considered – the question remains: what can they do to establish themselves as ‘Energy Regions’, to create new profiles and to get fit for competition in social, political and economic contexts? To simply regard sustainability and self-sufficiency aspects alone is not enough. An energy measure should not only be financeable but also profitable for the region and actors. In this way, the strategy will gain acceptance and support from citizens and, thus, will have increased chances for successful implementation throughout. The main problems result from the high-cost level of most of the measures. Also, not all of the factors and variables can be considered, because there is a limited scope of responsible stakeholders and actors. There are fields like the demographic change or energy price fluctuations, which are very difficult to control. All these problems were tackled in a common but individualised approach, i.e. each region worked out a strategy that, in the course of work, was discussed and enhanced by the partnership in a transnational environment. The strategies were developed through the evaluation of existing approaches towards energy strategies, regional SWOT analysis, networking with regional, national and transnational business and scientific partners, benchmarking at the European level, etc. Developing strategies for sustainable energy consumption and energy production from (preferably renewable) locally available energy sources helps the regions to improve their overall development options as regional development mainly depends on the capacity of innovation and on the readiness to improve and change a given situation. The regional energy strategies of the partner regions demonstrate that there are 3 main requirements to achieve this: raising the awareness of energy problems, working on new financial and management models, and concrete implementation measures.

A regional energy strategy as a document should work on an agreed basis for further development and decision making in the energy sector. Now that the partner regions have compiled their baseline papers and regional energy strategies, a set of recommendations has been compiled as a supporting ‘manual’ for all those regions which would like to carry out a similar exercise in future.

3.3 Recommendations for regional energy strategy development

The whole process of strategy development can be divided into 5 stages, starting with collection of information and the mapping of a *status quo*. This leads to a gaps analysis, then an estimate for the potential realisation and, finally, results in a detailed action plan for implementing identified preferred measures.

The following diagram illustrates these main components of the development of a regional energy strategy:

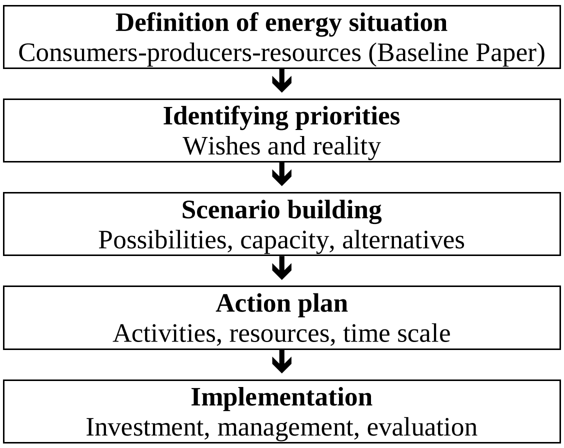

Figure 2. The main stages of strategy development.

3.3.1 Analysis and definition of the energy situation. Preconditions

The reliability of an energy strategy depends on the quality of preliminary work and initial data.

Before an energy balance (energy production and consumption) is drawn up, it is important to think over the preconditions. Before starting the work, the following questions must be answered:

1. Why is it necessary to do the strategy?
2. What was the situation before?
3. Is there enough competence to make the strategy?
4. Is there a team for the task ahead?
5. Is there enough knowledge to ensure that the strategy is prepared properly?
6. Where and how can the necessary demography, housing, energy, fuel, etc. related data be acquired?
7. Will it be possible to collect the necessary data, what kind of data is available?
8. Who are the stakeholders of the region, whose opinion should be considered?
9. Who can help in case of the need for assistance?
10. Are there sufficient finances secured for the development of a strategy?

3.3.2 First activities - baseline paper

The first important steps are a mapping exercise and data collection. Each region that is going to develop a regional energy strategy should prepare a paper on the *status quo* of the region first. This includes general information on the region (location, economic development, demographic development, size and geographic background) and general information on energy issues, such as power capacity, consumption and sources of energy production. It is important to analyse background data, such as reasons for varying energy consumption, the mix and size of energy consumption, etc.

Each region should collect the relevant data (preferably in the form of a SWOT analysis to identify strong and weak points of the region and its potential for future development and identification of planning potentials and threats). The resulting baseline paper is a prerequisite for developing a regional energy strategy.

For the preparation of a comprehensive energy strategy, local regional administration should be checked for the availability of:

1. development plans, decisions concerning the energy sector and earlier local regional development strategies, especially those including the energy sector analysis;
2. legal documents and statistic information;
3. economic analysis information about the land use;
4. other relevant data and documents (available renewable energy sources (RES) and rational use of energy (RUE) potentials).

General advice can be given for the elaboration of a successful energy strategy baseline:

- Professional management actions should be used for active involvement members of the team.
- Reliable data are key in making a reliable strategy. Time invested here is time saved on correction of mistakes later.
- Some examples of high-quality strategies should be studied.
- It is always good to learn from the mistakes of others to avoid yours.

Having collected all the data necessary for further planning, the outcome should be analysed, the resource potential should be estimated, graphics drawn, tendencies analysed and then the following questions should be answered:

1. Does the outcome of the analysis match the expectations?
2. Are the goals for the future realistic? A specialist should be consulted.
3. Is the committed work beneficial?
4. Are there enough people/resources/land/forest to achieve the goals?
5. Are the goals in consistency with national priorities regarding regional development and energy sector?
6. Are there enough funds for achieving the goals? If not, what are the alternative funding sources?
7. Does the idea for the future of the region cope with the needs of the region?

Planning and forecast for a regional energy strategy

Before starting to develop a regional energy strategy, one more critical look should be taken at the outcome of analyses of the collected data. It is very important to understand that some essential information is still missing or some sources of information or members of the community have been neglected. The gaps should be bridged and the work continued.

An appropriate time span for planning and forecasting should be set. Time range allowing the team to cope with the task should be chosen.

Below are the pieces of advice for successful planning and forecasting:

- Planning should be realistic, originating from real data and figures.
- Overestimation and too optimistic figures should be avoided in the forecast.
- All development options should be communicated to local community, involving and listening to them.
- Conflicts with local community should be avoided. Solutions which will not be accepted or which might damage local historic cultural heritage should not be forced.
- Priorities and goals should be revised if necessary.
- A holistic approach should be used for a regional energy strategy.
- Specific situation in the target region should be considered.

3.3.3 Setting objectives and identifying priorities

It is very important to identify clear objectives and priorities. It will give a direction for all stakeholders. A target could be described as greenhouse gas emission reduction to become energy self-sufficient in the long-term period. The main idea of that could be described as work for a better climate to participate in reaching national objectives.

In order to reach all target groups, it is important to raise awareness and readiness to exploit new possibilities. It is also important to consider all stakeholders that take part in the energy strategy:

- government/municipality;
- private actors/consumers;
- local and regional enterprises;
- organisations and associations.

An increase in sustainability in a certain region can only be reached when the strategy includes some essential steps and issues. First, reduction of greenhouse gas emission is of concern. It is important to involve individual emissions of the local community. Also, energy usage has to be reduced and the share of renewable energy increased through the use of local resources. At the end of this process, the goals should be evaluated. In order to set certain goals, it has to be considered whether municipalities cannot achieve objectives on their own. All stakeholders should be involved from the community, business, research area and municipality. Furthermore, objectives should be considered in combination due to the correlation of related aspects.

Criteria to identify a realistic feasibility have to be defined in order to determine the practicability of strategies, and setting criteria will enhance the transparency of the sustainable energy strategy.

The first criterion covers economy. An energy strategy should lead to budget revenue but also keep those benefits within the region and the country.

The second one is the contribution to local socio-economic environment, which is especially important in areas with declining populations and revenue. The idea is that the economic revenue provides mutual benefit for both the economy and the society.

The third criterion is oriented to sustainable development and each stakeholder should be able to evaluate an idea or measure and its effectiveness in terms of contributing to energy objectives. Energy planning might not be the equivalent of a formula, e.g. placing wind turbines within vulnerable landscape may not be sustainable in the long term.

3.3.4 Scenarios and pilot projects

The development of scenarios reveals the impact of a strategy. Scenarios can be worked out on the basis of technical potential, different criteria, and the impact of a strategy that focuses only on one source or a strategy using a combination of sources. A combination of those scenarios is a common practice in the development of energy strategies. Possibilities can also build up on:

- an energy saving scenario;
- a renewable energy scenario;
- a scenario based on the lowest investment costs;
- a scenario based on the lowest energy price for end users;
- the lowest spatial impact;
- the highest level of participation from stakeholders.

Scenarios will clarify the challenges and the processes that project planners will use to facilitate the process of engaging different partners to become involved in sustainable energy planning.

Pilot projects can serve as a basic line, to explore in the case of uncertainty or gain support by setting a small but convincing example for comparison. It could also be used to indicate or benchmark certain indicators. In some environments, pilot projects work as a teaser to attract awareness and create further demand. A pilot project can also be the first part of a series of steps and may create the required basis for starting another activity under improved conditions.

There is a difficulty and hazard regarding pilot projects and their comparability, as conditions may vary over time. If a topic becomes unattractive during the implementation of a pilot project, the implementation could suffer as a consequence. If the findings of a pilot project are not as convincing as hoped for, often mechanisms and dynamics may develop on besides the rationale of it. These 2 situations are difficult for a project to control and need to be included in the scenarios to prepare for appropriate and satisfactory reactions.

3.3.5 Development of an action plan

In order to ensure sustainability and durability of regional energy strategies, it is important to work out action plans for implementation. This will include elaboration of concrete work, definition and identification of actors and partners for regional implementation processes, setting the time frame and correspondences for different actions and defining the financial conditions (investments, rewards, expectations and thresholds). As for establishing an energy region certain preconditions are necessary, it is clear from the start that not all partner regions and municipalities are able to reach this status. However, efforts will be made to create regional/local profiles on energy-related topics that will help the respective partner(s) to find ways for a sustainable and future-oriented development, but also to scale individual involvement and contribution for efficiency.

A further important part of action plans should be the activation of relevant public and political actors beyond the group of upfront participants. All these actors should be involved in decision-making processes and should be enabled to contribute with their own ideas and express their resentments.

Implementation also includes multiple and significant financial aspects. In general, investments should be conducted in order to provide the basis for implementation, and they need to follow standards of procurement and transparency, wherever public money or public bodies are involved. Search for and commitment of investors should be professionalised and made available for overall economic development of the regions. In the end, agreements for co-investments of municipalities and private investors should be explored, e.g. in the form of public private partnerships. Options and possibilities should be identified and documented and experiences shared and discussed with project partners. Know-how transfer should play an important role. Eventually, all these activities should lay the grounds for investments and pilot projects and smoothen the way for other fields of actions, too, e.g. by attracting to think in parallels and similarities of the best practice.

Raising awareness of energy topics for municipalities and regions is one of the main aims of the action plan. This is also true for implementation strategies – it will not be enough to elaborate strategies on what could be done; it is also important to show how it can be done. The key aspect is communication on various levels. It needs to be stressed that the key to successful communication and final adoption of the efforts (a kind of a success story) has to do with a sophisticated communication plan and structure. While the action plan, and especially the action, is closely followed and positive events along implementation are to be wished for, communication also has a role to reveal and alarm in the event of shortcomings and to report and document how any mischief was overcome. Therefore, while this aspect dominates, it plays a vital role to enable and secure progress and success throughout all 5 steps.

3.3.6 Implementation

For the implementation process to work out well, with control and continuation secured, it is important to have full-time staff allocated (preferably not e.g. a politician, who might lose his/her constituency during the lifetime of a project). The strategy itself should be reviewed and reconfirmed periodically, best once a year. The change in relevant indicators should be observed. If needed, the action plan has to be adapted. For any change to the layout, specialists and local stakeholders should be involved. Before large-scale investments are made, different opportunities and several offers have to be considered. Since the strategy concerns the development of the environment and the social community of the region, up-to-date information and professionals on the required field must be utilised.

If full investment cannot be made right away, a step-by-step approach should be used. Everything done should have considerable outcomes and impact. Advice can be the following:

- to secure communication between stakeholders;
- investments are easier to be proven if one can refer to ‘best practices’.

4 Conclusions and recommendations

A specific energy strategy is transferrable in principle, but not likely 1 to 1. Therefore, a universal energy strategy for all regions does not exist. It is important to understand that the strategy has to adjust the specific energy situation and the peculiarities in the target region and has to integrate all participating stakeholders (government, private actors/consumers, local enterprises, organisations and associations).

Furthermore, the following aspects of advice should be considered for developing an individual energy strategy: have a multidimensional and holistic approach; base it on a long-term strategy, stakeholder commitment and political consensus; raise awareness in the population; the strategy must be financeable and realistic.

Reasonable and feasible goals on reducing energy usage should be defined in order to meet the target of wider schemes like national and European energy strategies. The energy strategies should be elaborated at the regional and local level, which makes a broad involvement of public and private experts and stakeholders necessary. All actors involved in producing the strategies and all potential levels and organisations for implementing them must be involved at an early stage of a project. Stable regional networks should be developed. This will only be possible through constant and transparent communication; all activities and plans need to be discussed not only in expert rounds but should be made known to a broader interested public. Participation processes need to be moderated in order to not only integrate everyone concerned at appropriate prioritisation, but also to make use of the information and input that comes from outside core groups working on the strategy. A regional energy strategy should consider the specific situation in a region.

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Darnios energetikos strategijos – kaip galimybė Europos Sąjungos regioniniam vystymuisi

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(gauta 2015 m. liepos mėn.; priimta spaudai 2015 m. lapkričio mėn.)

Straipsnio tikslas yra sukurti metodiką, leidžiančią įgyvendinti darnios energetikos strategijas vietiniu, savivaldybės ir nacionaliniu lygiu, siekiant efektyviau diegti inovatyvias politikos priemones bei komponentus. Šis tikslas atitinka Europos Sąjungos regioninę politiką bei Europos Sąjungos strategiją „Europa 2020“, kurią įgyvendinant užtikrinama geresnė ekonominė ir socialinė aplinka bei mažinama atskirtis tarp regionų.

Tyrimas buvo atliktas remiantis Baltijos jūros regiono programos (Baltic Sea Region 2007–2013 programme) „Energetikos alternatyvos visuomenei“ (PEA) projekto įgyvendinimo metu surinkta medžiaga. Atliktame darbe buvo taikoma darnios energetikos strategijų rengimo metodika, kurios pagrindinis bruožas yra holistinis požiūris, atsirandantis bendradarbiaujant savivaldybėms, bendruomenėms, verslui bei tyrėjams. Straipsnyje yra analizuojami pagrindiniai darnios energetikos strategijos įgyvendinimo žingsniai bei pateikiamos tokios strategijos rengimo rekomendacijos.

Raktiniai žodžiai: *darnus vystymasis, atsinaujinantys energijos šaltiniai, regioninės strategijos.*

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Assessment of Overall SCP State of the Company: New Integrated Sustainability Index I_{SCP}

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The encouragement of sustainable consumption and production (SCP) in order to continuously improve the well-being of present and future generations is the most important goal stated in the European Union (EU) Sustainable Development Strategy, which was renewed in 2006.

The challenge for every company on the way to SCP is not only to use appropriate methods and measures to solve their specific sustainability problems, but, first of all, to select appropriate performance indicators and implement an effective sustainability performance evaluation system. It may be useful to apply an integrated indicator as a single comparable index, reducing the number of sustainability decision-making criteria that need to be considered.

However, despite various approaches to create frameworks and methodologies for the development of integrated sustainability indicators that measure, monitor and assess the progress of an enterprise towards sustainability, there is still no comprehensive framework for integrated sustainability assessment of the overall company state on the basis of manufacturing processes, products/services as well as relationship with various stakeholders.

An algorithm is here presented in respect of this demand. This algorithm offers methodical suggestions to assess the customers' opinion about the presence of company's environmental and social sustainability activities and initiatives, to identify and select most appropriate sustainability indicators, to determine their significance according to analytic hierarchy process (AHP), and to solve the most important sustainability problems in 3 aforementioned levels by adapting most suitable tools. The final suggestions are based on the values of 3 sub-indices of a new integrated index for the overall assessment of the SCP state in the company, I_{SCP}.

Keywords: *sustainable consumption and production (SCP), companies, sustainability performance indicators, integrated index, analytic hierarchy process (AHP).*

1 Introduction

Sustainable Consumption and Production (SCP) was firstly put on the global policy agenda at the United Nations (UN) Conference on Environment and Development in Rio de Janeiro in 1992 (Szlezak *et al.*, 2008) where unsustainable consumption and production patterns were recognised as the main factors influencing unsustainable world's development (Jackson, 2006; Liu *et al.*, 2010; Szlezak *et al.*, 2008). According to the classical definition of sustainable development (SD), the UN Commission on Sustainable Development described SCP as the consumption of products and services that are necessary to satisfy essential needs and ensure better quality of life, while reducing consumption of natural resources, emissions of toxic substances and wastes through all their life cycles with the aim to cause no threat for the demands of future generations (Norris *et al.*, 2003; Welfens *et al.*, 2010; Welford *et al.*, 1998). Ten years after the Rio conference, during the World Summit on Sustainable Development (which took place in Johannesburg in 2002) transformations in SCP models were recognised as a fundamental goal on the way to SD (Jackson, 2006), since without essential changes in the production and consumption system the global sustainable development goal cannot be achieved (Szlezak, *et al.*, 2008; Watson, *et al.*, 2010).

Although consumption is the most important factor for economic growth (Abeliotis *et al.*, 2010), it can affect the environment in many different ways (Abeliotis *et al.*, 2010; Hansen & Schrader, 1997; Orecchia & Zoppoli, 2007). The current unsustainable pattern of consumption and production determines climate change, pollution, accumulation of hazardous wastes, depletion of natural resources and decline in biological diversity; it also influences an increase in global migration and differences in economic and social welfare between and within countries (Čiegis & Zeleniūtė, 2008; Nash, 2009). Higher levels of consumption influence higher levels of production, which require larger inputs of energy and material as well as generate larger quantities of waste by-products (Kletzan *et al.*, 2002; Orecchia & Zoppoli, 2007).

During the last decades, initiatives in sustainable production have successfully focused on improving the resource efficiency in manufacturing systems (Jackson, 2005; Sikdar, 2011). However, despite the improvement in results of environmental practices of many individual producers, an increase in the amount of general consumption often exceeds the achieved progress (the so-called *rebound* effect) (Staniškis & Stoškus, 2008; Staniškis *et al.*, 2012; Stø *et al.*, 2006). It is becoming obvious that technological approaches are not enough to realise the goal of SD without critical assessment of human choices (Hertwich, 2005; Jackson, 2005; Dahl, 2012). Thus, in order to determine the most suitable direction for the actions towards SCP, it is essential to analyse the relation between consumption and production systematically, considering not only producers and consumers, but also all the other interested groups in the SCP system, such as government, non-governmental organisations (NGOs), shareholders, suppliers, academic community and media, etc. (Gold *et al.*, 2010).

Integration of sustainability thinking and practice into an organisational structure requires a system approach with an appropriate management framework. However, there is no generic 'off-the-shelf' management framework for every organisation that could enable a systematic and structured approach to manage their corporate sustainability (Azapagic, 2003). Thus, the challenge for every company on the way to SCP is to use appropriate methods and measures to solve their specific sustainability problems (Carson, 2007). To manage integration of the tools and to ensure effective information flows for decision-making, selection of appropriate performance indicators and implementation of an effective sustainability performance evaluation system are needed (Staniškis and Arbačiauskas, 2009). It may be useful to use an integrated indicator as a single comparable index, linking many sustainability issues and, thus, reducing the number of decision-making criteria that need to be considered (Azapagic, 2003; Krajnc & Glavič, 2005a; Singh *et al.*, 2007, 2009, 2012).

Currently, there are various approaches to create frameworks and methodologies for the development of integrated sustainability indicators that measure, monitor and assess the progress of an enterprise towards sustainability. However, despite these attempts, there is still no comprehensive framework for integrated sustainability assessment of the overall company state on the basis of manufacturing processes, products/services as well as relationship with various stakeholders.

In respect of this demand, the algorithm for integrated sustainability assessment of the overall company state, which can help to solve the most significant problems in 3 levels – manufacturing processes/company's activities, products/services as well as relationship with various stakeholders – is presented. This framework proposes the assessment of current sustainability conditions of the company based on sub-indices of the composite index I_{SCP} for sustainability evaluation and, according to them, can help to select and introduce the most suitable SD tools for a particular enterprise to achieve its environmental and social performance goals.

2 The algorithm for evaluation of the impact of company's sustainability performance

There are a number of frameworks of sustainability assessment that evaluate the performance of companies (Singh *et al.*, 2009, 2012) as well as dozens of indicators that have been suggested for use in determining improvements made to processes, manufacturing sites or enterprises (Krajnc & Glavič, 2005, 2005a). However, only some of these measures have an integral approach taking into account environmental, economic and social aspects (sometimes the fourth dimension, namely institutional, introduced by the UN approach (Labuschagne *et al.*, 2005) is included as well), not focusing on only one of them (Singh *et al.*, 2009, 2012). A detailed discussion on sustainability indicators can be found in the publications of Azapagic & Perdan (2000), Veleva & Ellenbecker (2001), Azapagic (2003), Krajnc & Glavič (2005), Singh *et al.* (2009, 2012), Moldan *et al.* (2012) and others.

Sustainability reports usually introduce a set of SD indicators that can be used to measure sustainability performance of the company (Azapagic, 2003). Whilst it is important to identify and quantify all the relevant indicators, it may sometimes be difficult to make business decisions based on a large number of performance criteria (Azapagic, 2003; Krajnc & Glavič, 2005, 2005a; Singh *et al.*, 2007). To help decision makers in this respect, it could be beneficial to use integrated indicators that link many sustainability issues and hereby reduce the number of decision-making criteria (Azapagic, 2003; Krajnc & Glavič, 2005a; Singh *et al.*, 2007, 2009, 2012). Thus, composite indicators, being an innovative approach to evaluate sustainable performance, are increasingly recognised as a useful tool for policy making as well as public participation in sustainability discussion

(Krajnc & Glavič, 2005; Singh *et al.*, 2007, 2009, 2012).

Currently, there are various approaches to create frameworks and methodologies for the development of integrated sustainability indices that measure, monitor and assess the progress of an enterprise towards sustainability. Significant examples are presented in the publications of Azapagic (2003), Krajnc & Glavič (2005, 2005a); Singh *et al.* (2007, 2009, 2012), Kang *et al.* (2010); Kinderytė *et al.* (2010) and Kinderytė (2010, 2011, 2013) as well as Laurinkevičiūtė & Stasiškienė (2010). Despite these attempts and urgent demand to find better performance indicators (Dahl, 2012), there is still no comprehensive framework for integrated sustainability assessment of the overall company state on the basis of manufacturing processes, products/services as well as relationship with various stakeholders.

In respect of this demand, the algorithm (see Figure 1) was developed offering methodical suggestions to assess the customers' opinion about the presence of company's environmental and social sustainability activities and initiatives; to identify and select the most appropriate sustainability indicators; to determine their significance according to analytic hierarchy process (AHP); and to solve the most important sustainability problems in 3 levels – manufacturing processes/company's activities, products/services and stakeholders by adapting the most suitable sustainable development tools. The final suggestions of the algorithm are based on the values of the 3 sub-indices of a new integrated index for the overall assessment of the SCP state in the company, I_{SCP}.

The steps of the algorithm for integrated sustainability assessment of the overall company state based on the calculation of I_{SCP} are explained below.

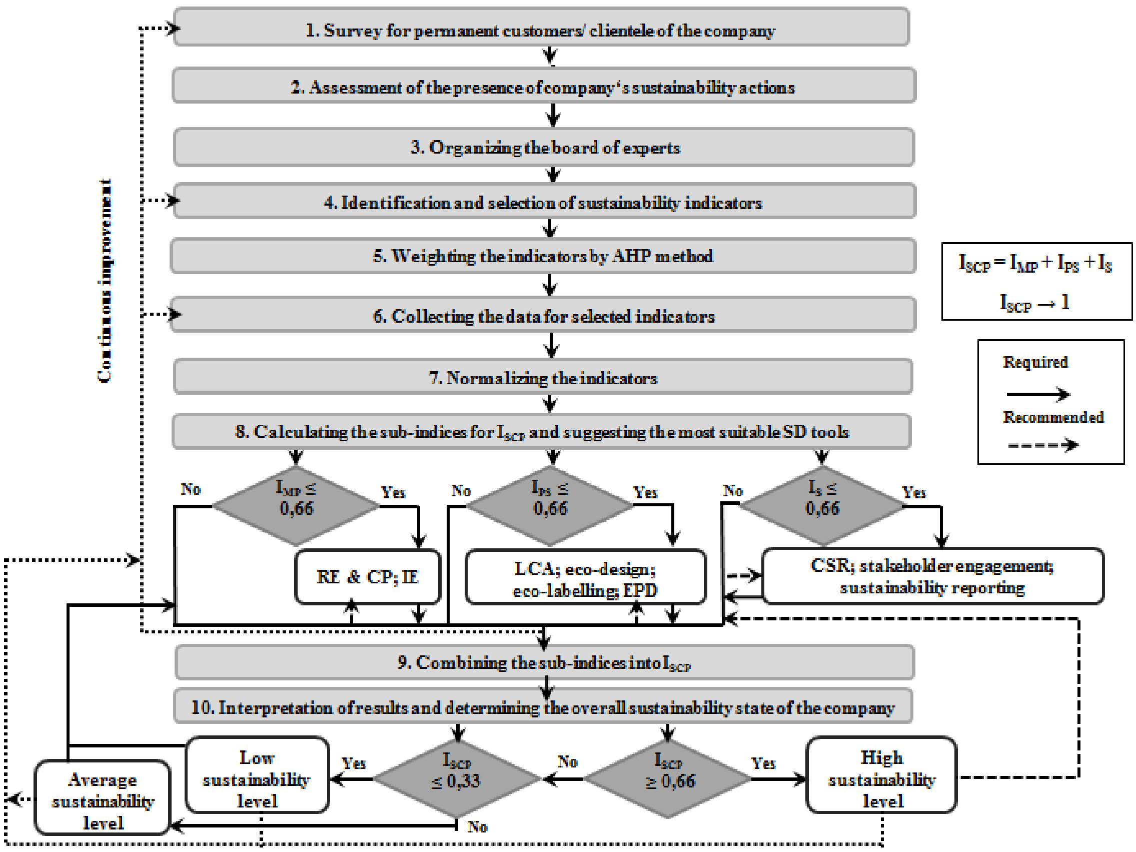

Figure 1. The algorithm for integrated sustainability assessment of the overall company state on the basis of manufacturing processes/company's activities, products/services as well as relationship with various stakeholders

2.1 Survey for permanent customers/clientele of the company

The aim of the survey is to assess the opinion of company's customers about the presence of environmental and social sustainability activities and initiatives of the enterprise in every of the 3 levels as well as to express their overall satisfaction regarding company's performance. The respondents are asked to evaluate each of 25 presented statements, related to manufacturing processes/company's activities (4 statements), products/services (4 statements) and collaboration with stakeholders (10 statements) as well as their general satisfaction regarding company's sustainability activities (7 statements) (Table 1). The formulation of some of these clauses is partially based on the statements for the green customers' satisfaction analysis proposed by Chen (2010). They are asked to rate these statements on a 5-point Likert scale, assessing the level of their (non)acceptance of each item (where 1 = strongly disagree, 5 = strongly agree). The results of the survey are compiled and the mean values of each statement as well as each set of statements are determined.

2.2 *Assessment of the presence of company's sustainability actions*

The presence of company's sustainability actions related to manufacturing processes/company's activities, products/services and stakeholders is based on the values of the coefficients K_j (K_{MP}, K_{PS} and K_S). These coefficients are evaluated recalculating the mean values of customers' answers in every of the 3 prime aforementioned sets of the statements to the parts of percentage (where $1 \rightarrow 0$; $2 \rightarrow 0.25$; $3 \rightarrow 0.5$; $4 \rightarrow 0.75$ and $5 \rightarrow 1$). The index of general green customers' satisfaction I_{GCS} is calculated similarly to the coefficients K_j, assessing the average results of the respondents' answers from the fourth set of statements.

Table 1. Sets of statements in the customers' survey related to manufacturing processes/company's activities, products/services, collaboration with stakeholders as well as general customers' satisfaction for company's sustainability activities.

Statements related to manufacturing processes/company's activities	
1.	Company implements and uses efficient and modern technologies, applies preventive management and organisational measures
2.	Manufacturing processes/company's activities correspond to or even exceed the environmental requirements and principles of social responsibility
3.	Company efficiently and economically uses all the materials, energy, water and other resources
4.	Company suitably manages, reuses and recycles all its wastes
Statements related to company's products/services	
1.	Company creates and designs products/services considering various environmental and social criteria and standards
2.	Company's products/services correspond to or even exceed the environmental requirements and principles of social responsibility
3.	Company increases the offer of environmentally friendly products and services in the market
4.	Company proposes clear, easy understandable and comparable information about the characteristics and impacts of its products/services
Statements related to company's cooperation with its stakeholders	
1.	Company promotes sustainability initiatives between its employees, raises their consciousness and motivation, organises special trainings
2.	Company incorporates sustainability criteria for products and services in its purchasing procedures (green purchasing)
3.	Company proposes requirements for its suppliers to correspond to the particular environmental and social criteria
4.	Company cooperates with other enterprises, learns from their sustainability initiatives, intercepts examples of best practices and motivates them to accept both environmentally and socially sustainable decisions
5.	Company enhances environmental consciousness of its customers/consumers, promotes sustainable consumption, educates them about environment protection, eco-labelling and other sustainability topics
6.	Company engages in public environmental initiatives and campaigns, participates in various events for society sustainability promotion
7.	Company closely cooperates with NGOs that promote sustainability initiatives, e.g. green movement organisations, associations for environment protection, etc.
8.	Company cooperates with educational and science institutions that support the increase in sustainability knowledge and perception as well as help to apply and implement technological and other innovations, etc.
9.	Company cooperates with media, publicising its environmentally and socially sustainable products/services as well as motivating and educating society to consume sustainably, etc.
10.	Company periodically represents the information about its environmental and social practices through publicly available reports
Statements related to general consumer satisfaction regarding environmental and social sustainability of company's activities and products/services	
1.	Company contributes to the realisation of SCP goals through its products/services
2.	The name/brand of the company associates with environmental sustainability and social responsibility
3.	I assess the company regarding its environmental and social practices better than other enterprises that produce analogous products and/or render analogous services
4.	Company sufficiently corresponds to the requirements and expectations of environmentally responsible consumers
5.	I believe that I contribute to the realisation of SCP goals when I choose products/services of this company
6.	I will buy products/services of this company in the future
7.	I recommend products/services of this company to my family members, friends and acquaintances, etc.

2.3 Organising the board of experts

As different stakeholders of the company have different priorities, needs and expectations, they could share the decision-making power with corporate management (Madsen & Ulhøi, 2001) in the following steps of identification, selection and weighting of sustainability indicators. Ideally, the board of experts should include representatives from all the internal and external stakeholder groups of the company.

2.4 Identification and selection of sustainability indicators

For the assessment of sustainability, a number of indicators exist, which are used to evaluate organisation's progress towards sustainability (Krajnc & Glavič, 2005a). However, every indicator is not relevant for each branch of the industry and it may not be useful to put all these indicators into the proposed framework (Singh *et al.*, 2007). To make sustainability performance evaluation meaningful in terms of better enterprise management, the company has to develop its own individual set of indicators that reflect its profile and needs (Labuschagne *et al.*, 2005; Staniškis & Arbačiauskas, 2009). The set of indicators can be identified in a number of ways, including theory findings, empirical analysis, consultations with stakeholders, etc. (Azapagic, 2003; Singh *et al.*, 2007).

As indicators guide management control and strategic planning, they should be defined with care and should take the specific interests of the company into account (Krajnc & Glavič, 2005). Azapagic (2003) suggests that indicators should be quantitative whenever possible; however, for societal aspects of sustainability, qualitative descriptions may be more appropriate (Krajnc & Glavič, 2005a).

Decision-makers of companies have different views and are interested in different indicators; thus, they should be selected by taking into account appropriate communities of interest (Singh *et al.*, 2009, 2012). This task is realised through the board of experts, including representatives from all stakeholder groups of the company. In this step, quantitative and qualitative sustainability indicators related to manufacturing processes, products/services and collaboration with stakeholders are identified. It is recommended to use the list of performance indicators from the Global Reporting Initiative (GRI) guidelines as a primary set of indicators to perform this identification. In order to ascertain the most relevant indicators for a particular company, every individual from the aforementioned board of experts is asked to rate each of them on a 5-point Likert scale. The results are compiled and the mean value of each indicator is determined. The best-rated indicators for each level are selected for further weighting procedure in step 5.

2.5 Weighting the indicators by AHP method

To determine the weights of indicators, evaluators are often confronted with a lack of data. Therefore, a pairwise comparison technique is used in order to derive relative weights of each indicator practically. The pairwise comparison technique is based on the method developed by operation research pioneer Saaty (1980) and is called the Analytic Hierarchy Process (AHP) (Krajnc & Glavič, 2005a). The AHP has been accepted as a leading multi-attribute decision model both by practitioners and academics (Krajnc & Glavič, 2005; Singh *et al.*, 2007) and has been widely applied in many areas including SD (Singh *et al.*, 2007). The AHP method was already applied to the development of composite sustainability performance indices in the earlier publications of Krajnc & Glavič (2005, 2005a), Singh *et al.* (2007) as well as Laurinkevičiūtė and Stasiškienė (2010).

Pairwise comparisons between each pair of indicators are made by posing the question which of them is more important with respect to the ultimate SCP goals of the company, namely resources and energy savings as well as an increase in consumers' acceptance and satisfaction. The intensity of preference is expressed on a factor scale from 1 to 9 (where 1 = equal indicators, 9 = 1 indicator is 9 times the importance of the other). The same process of comparison is repeated for each column of the matrix, making independent judgments over each pair of indicators (Krajnc & Glavič, 2005, 2005a; Singh *et al.*, 2007). Saaty (1996) has shown that solving the right eigenvector of the matrix will provide an excellent estimate of the relative weights W_{ji} of the indicators evaluating their priority level (Singh *et al.*, 2007).

2.6 Collecting the data for selected indicators

This step of the algorithm involves collection of reliable, high quality quantitative and qualitative data for previously selected indicators, reflecting the performance of the company for the period of 1 year or 3 years. As Kinderytė (2010, 2011, 2013) has suggested, the evaluation of the company's sustainability according to qualitative indicators is built on a 3-level scale: worst evaluation – 0; medium evaluation – 0.5 and best evaluation – 1.

2.7 Normalising the indicators

The main problem of aggregating a set of indicators into an integrated one is the fact that they may be expressed in different units. One way to solve this problem could be to normalise each indicator (Kinderytė, 2010, 2011; Krajnc & Glavič, 2005, 2005a). Many methods for normalisation of the indicators are reported in the literature and the selection of an appropriate method depends on the data and the analyst (Singh *et al.*, 2009, 2012).

The normalisation of all the indicators in the presented algorithm is recommended to be made by applying Min-Max (Kinderytė, 2010, 2011, 2013; Krajnc & Glavič, 2005, 2005a) or Z-score (Singh *et* *al.*, 2007) methods using formulas (Equations 1, 2, or 3):

$$I_{N,ijt}{}^{+} = \frac{I_{A,ijt}{}^{+} - I_{min,jt}{}^{+}}{I_{max,jt}{}^{+} - I_{min,jt}{}^{+}} \tag{1}$$

$$I_{N,ijt}{}^{-} = 1 - \frac{I_{A,ijt}{}^{-} - I_{min,jt}{}^{-}}{I_{max,jt}{}^{-} - I_{min,jt}{}^{-}} \tag{2}$$

where $I_{A,ijt}{}^{+}$/ $I_{A,ijt}{}^{-}$– indicator whose increasing value has a positive/negative impact on sustainability; $I_{min,jt}{}^{+}$/ $I_{min,jt}{}^{-}$ – indicator with minimum value and positive/negative impact on sustainability; $I_{max,jt}{}^{+}$/ $I_{max,jt}{}^{-}$– indicator with maximum value and positive/negative impact on sustainability; $I_{N,ijt}{}^{+}$/ $I_{N,ijt}{}^{-}$– normalised indicator whose increasing value has a positive/negative impact on sustainability; i – sustainable development indicator; j – group of sustainable development indicators: manufacturing processes/company's activities, products/services and collaboration with stakeholders; t – time in years.

$$I_{N,ijt} = \frac{(I_{A,ijt} - I_{avg,jt})}{SD} \tag{3}$$

where $I_{avg,jt}$ – average value of indicator; SD – standard deviation of indicator.

Moreover, in order to minimise the sensitivity of the Min-Max normalisation method, the following normalisation conditions, suggested by Kinderytė (2013), were defined (Equations 4 – 8):

1. If an indicator whose increasing value has a negative impact has constant minimum values, then it is assumed as the best possible value and by normalisation 1 is assigned:

if $I_{A,ijt}{}^{-} = I_{min} = const$, then $I_{N,ijt}{}^{-} = 1$. (4)

2. If an indicator whose increasing value has a positive impact has constant maximum values, then it is assumed as the best possible value and by normalisation 1 is assigned:

if $I_{A,ijt}{}^{\mp} = I_{max} = const$, then $I_{N,ijt}{}^{+} = 1$. (5)

3. If an indicator whose increasing value has a positive impact is expressed in percent, then by normalisation: $I_{N,ijt}{}^{+} = I_{A,ijt}{}^{+}/100$. (6)

4. If an indicator has a constant but not possible maximum or minimum value, then by normalisation 0.5 is assigned:

if $I_{A,ijt} = const$, then $I_{N,ijt} = 0.5$. (7)///

5. If values of indicators are not constant, but the difference is very small, then by normalisation 0.5 is assigned:

if $\frac{I_{A,ijt}}{I_{A,ijt+1}} \geq 0.99$, then $I_{N,ijt} = 0.5$. (8)

2.8 Calculating the sub-indices for I_{SCP} and suggesting the most suitable SD tools

The sub-indices $I_{S,jt}$ for all the 3 levels – manufacturing processes/company's activities (I_{MP}), products/services (I_{PS}) and stakeholders (I_S) – are evaluated according to the formula (Equation 9) (Kinderytė, 2011, 2013; Krajnc & Glavič, 2005, 2005a; Singh *et al.*, 2007), considering the weights of every indicator W_{ji} (Equation 10), which were generated during an expert weighting procedure as well as coefficients K_j from the consumers' survey:

$$I_{S,jt} = (\sum_{jit}^{n} W_{ji} I_{N,ijt}{}^{+} + \sum_{jit}^{n} W_{ji} I_{N,ijt}{}^{-}) \times K_j \tag{9}$$

$$\sum_{ji}^{n} W_{ji} = 1, W_{ji} \geq 0 \tag{10}$$

Each of these sub-indices shows the tendency of company's sustainability development regarding the SCP in one of the corresponding levels. The minimal value of a particular sub-index indicates that the related level is the weakest in the whole system; thus, the condition of it should be improved by applying suitable tools and measures. If the lowest value is recorded at the level of manufacturing processes/company's activities ($I_{MP} \leq 0.66$), the model suggests realising resource efficiency and cleaner production (RE & CP) as well as industrial ecology (IE) opportunities. Poorest conditions regarding the characteristics of products and services ($I_{PS} \leq 0.66$) can be fixed by applying life cycle assessment (LCA) based measures, such as eco-design, eco-labelling and environmental product declarations (EPD). If the weakest area of the enterprise seems to be relations with stakeholders ($I_S \leq 0.66$), corporate social responsibility (CSR) according to an international standard ISO 26000, various stakeholder engagement initiatives as well as improvements in sustainability reporting should be reconsidered.

2.9 Combining the sub-indices into I_{SCP}

Finally, the calculated sustainability sub-indices $I_{S,jt}$ are combined into an integrated index for the assessment of the overall SCP state of the company, I_{SCP}, using the formula (Equation 11):

$$I_{SCP,t} = \sum_{jt}^{n} W_j I_{S,jt} \tag{11}$$

where W_j denotes the factor for representing *a priori* the weight given to group j of SD indicators (manufacturing processes/company's activities, products/services and relations with stakeholders), reflecting the hierarchies and/or priorities in the opinion of decision-makers (Krajnc & Glavič, 2005, 2005a). In the final calculation of the I_{SCP}, an approach that uses estimated weights can be considered;

however, it is recommended to use equal weights for all the sub-indices (Kinderytė, 2011, 2013; Krajnc & Glavič, 2005, 2005a).

2.10 Interpretation of results and determination of the overall sustainability state of the company

In general, the integrated index helps to make decisions about the overall level of enterprise's sustainability (Azapagic, 2003; Kinderytė *et al.*, 2010) and highlight the achieved progress (Azapagic, 2003; Krajnc & Glavič, 2005a; Singh *et al.*, 2007). As the composite indicator integrates a large amount of information into an easily understood format for a general audience (Singh *et al.*, 2007), it can be used to inform decision-makers and various interested parties of SD trends in the company. The higher is the value of the index, the greater is the improvement of the company towards sustainability. The same is true for sustainability sub-indices as well. For any given year, the composite index and sub-indices reveal the performance of the company in that year compared with other years (Krajnc & Glavič, 2005a). Also, if analogous methodology and similar indicators for index calculation were applied to different companies, it would be possible to compare and rank them according to the current sustainability state (Krajnc & Glavič, 2005, 2005a).

The integrated index I_{SCP} that is proposed in the algorithm can help to disclose the overall SCP state of the company. If this index is lower than the value 0.33, the particular company can be named as unsustainable and must urgently rethink the whole business strategy, implementing all the possible actions and measures in all the system levels with the purpose of improving its overall sustainability condition. If the calculated value lies between 0.33 and 0.66, the enterprise shows the average level of the sustainability state regarding the implementation of SCP practices. In this case, it is strongly recommended to implement suitable measures and tools, especially in those particular levels, which show the worst results according to the values of sub-indices. And finally, if I_{SCP} exceeds the critical value of 0.66, it can be stated that the enterprise is on the right way to become comprehensively sustainable and its overall sustainability is as high as the value of I_{SCP} is closer to 1. However, even on a high level of sustainability, the company can still improve its current sustainability state by implementing additional measures and tools and, thus, exploiting all its sustainability potential.

Furthermore, the value of the green customers' satisfaction index I_{GCS}, determined from the average results of customers' answers in step 2, can also be helpful as an additional parameter to appreciate purchasers' general satisfaction regarding environmental and social sustainability of company's activities and products/services. Analogous to the integrated index I_{SCP}, the general satisfaction of sustainably engaged customers is as high as the value of I_{GCS} is closer to 1.

2.11 Periodical review of customers' opinion and periodical assessment of company's sustainability state

Periodical review of the customers' opinion and periodical assessment of the company's sustainability state compose a very important part of the algorithm that guarantees continuous improvement of the enterprise's sustainability state. These assessments could help to estimate the results of sustainability enhancement concerning newly implemented measures and to observe changes in the customers' opinion. Periodical review and assessment can be realised in 3 levels – by applying the algorithm from the very beginning or by performing the inner evaluation selecting new sustainability indicators or barely collecting data for the indicators that have been already chosen to estimate the changes in 3 levels of company's activities.

3 Conclusions and recommendations

The presented algorithm can help to assess current sustainability conditions of the company and, according to them, select and introduce the most suitable tools to achieve SCP goals. This algorithm offers methodical suggestions to assess the customers' opinion about the presence of company's environmental and social sustainability activities and initiatives; to identify and select most appropriate sustainability indicators; to determine their significance according to analytic hierarchy process (AHP); and to solve the most important sustainability problems in 3 levels – manufacturing processes/company's activities, products/services and stakeholders – by adapting the most suitable tools. These final suggestions were based on the values of the 3 sub-indices of a new integrated index for the overall assessment of the SCP state in the company, I_{SCP}. Moreover, a simple additional parameter to appreciate customers' general satisfaction regarding environmental and social sustainability of company's activities and products/services – the green customers' satisfaction index I_{GCS} – was also introduced.

This framework is created as a guidance to apply a theretofore designed SURESCOM (SUstainable and RESponsible COMpany) model (Jonkutė and Staniškis, in press) based on a classical closed-loop cycle scheme for an integrated management system and suggests a plan for consistent integration of SCP principles in organisation's practices; it can, therefore, be easily incorporated into a common management system of any enterprise.

As the subjected algorithm is still theoretical, there is an urgent necessity to verify its real potential in particular enterprises. The verification procedure performed in different sectors, including both manufacturing and service companies, could disclose all the opportunities of this framework.

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Įmonės bendros darnumo būklės įvertinimas tausojančio vartojimo ir darnios gamybos atžvilgiu: naujas sudėtinis darnumo rodiklis I_{SCP}

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Tausojančio vartojimo ir darnios gamybos skatinimas, siekiant nuolatos didinti esamų ir būsimų žmonijos kartų gerbūvį, yra svarbiausias tikslas, išreikštas 2006 m. atnaujintoje Europos Sąjungos Darnaus vystymosi strategijoje.

Kiekviena įmonė, norėdama įgyvendinti tausojančio vartojimo ir darnios gamybos tikslus, susiduria su iššūkiu ne tik naudoti tinkamus metodus ir priemones, siekiant išspręsti konkrečias darnumo problemas, bet, visų pirma, pasirinkti tinkamiausius darnumo vertinimo rodiklius ir diegti efektyvią veiklos darnumo vertinimo sistemą. Įmonėms gali būti naudinga turėti vieną palyginamąjį sudėtinį rodiklį, sumažinantį darnumo vertinimo kriterijų, į kuriuos reikia atsižvelgti, kiekį.

Nepaisant įvairių bandymų sukurti gaires sudėtinių darnumo rodiklių, skirtų įmonės progreso darnumo link matavimui, kontrolei ir įvertinimui, išsamių metodinių rekomendacijų įmonės bendros darnumo būklės įvertinimui, atsižvelgiant į jos gamybos procesus, gaminius (paslaugas) ir santykius su suinteresuotomis šalimis, vis dar nėra.

Atsižvelgiant į šį trūkumą, straipsnyje pristatomas algoritmas, teikiantis metodinius pasiūlymus, vertinant pirkėjų (klientų) nuomonę ir pasitenkinimą įmonės vykdomos veiklos aplinkosauginiu ir socialiniu darnumu; nustatant ir atrenkant įmonei tinkamiausius darnumo rodiklius; įvertinant jų reikšmingumą, taikant analitinį hierarchijos procesą (AHP); ir sprendžiant svarbiausias problemas trijose anksčiau minėtose srityse, diegiant tinkamiausias darniojo vystymosi priemones. Šie galutiniai algoritmo taikymo rezultatai pagrįsti trijų naujo sudėtinio rodiklio įmonės bendros darnumo būklės įvertinimui tausojančio vartojimo ir darnios gamybos atžvilgiu I_{SCP} skaitinėmis vertėmis.

Raktiniai žodžiai: *tausojantis vartojimas ir darni gamyba, įmonės, darnumo vertinimo rodikliai, sudėtinis rodiklis, analitinis hierarchijos procesas*.