ENERGY

International Journal
Sustainable Future for Human Security
J-SustaiN Vol. 6 No. 1 (2018) 3–14
http://www.j-sustain.com

Feasibility Study of Hybrid Wind-Solar Stand-Alone Energy Systems for Remote Regions in Developing Countries: The Case of Post-Soviet Uzbekistan

Nigora Djalilova [a], Miguel Esteban [b]**

[a] ***Graduate Program in Sustainability Science-Global Leadership Initiative (GPSS-GLI), Graduate School of Frontier Sciences, University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa City T277-8563, Japan***

[,b] ***Research Institute of Sustainable Future Society, Faculty of Civil and Environmental Engineering, Waseda University, 60-106, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Tokyo, Japan***

Received: May3, 2018/ Accepted: July 20, 2018

Abstract

Uzbekistan is an emerging economy in the heart of Central Asia. Due to the country's diverse geographic and climatic conditions the population is unevenly distributed among its regions. This fact makes some small settlements in remote areas prone to electricity supply disruption, sometimes caused by outdated infrastructure and high transmission losses, which can cause system failures during peaks in power demand. As a result people in such regions become socialy and economically isolated. Given this situation, some remote villages opt to use diesel generators and other fuel alternatives which have a significant environmental footprint. This paper uses the case study of Uzbekistan, as an example of a developing post-Socialist country undergoing an economic transition from planned to market economy to analyse if hybrid wind or solar energy systems are economically viable, compared to diesel run systems. In order to do so authors fed real meteorological data for six selected regions in Uzbekistan into the HOMER software. Further, the authors investigate changes in monetary policy recently taking place in the country and question the consistency of such changes with the course taken towards increasing the share of renewables in power generation. The paper concludes that although renewables appear to be economically viable (even in a fossil-fuel rich country), the government needs to synchronise different policy tools in order to build an efficient, environmentally friendly and sustainable energy system. Uzbekistan is an emerging economy.

Keywords: *distributed hybrid energy systems; feasibility study; HOMER; developing country; energy economics; Central Asia.*

Abbreviations:

RES	:	Renewable Energy Sources
LCOE	:	Levelized Cost of Electricity
NPC	:	Net Present Cost
HOMER		Hybrid Optimization for Multiple Energy Resorces

1. Introduction

There is a growing concern amongst the international community regarding the problems that are being brought about by climate change, and the role of carbon dioxide emissions in exacerbating this process. As noted in the Intergovernmental Panel on Climate Change 5th Assessment report (or IPCC 5AR, IPCC 2014) since the 1950s the atmosphere and ocean have significantly warmed, and sea levels have risen. The idea of a "green economy" (as one of the ways to address environmental issues) is now frequently talked about by international institutions and in research agendas, and essentially attempts to establish a resource-efficient, socially inclusive, low carbon society (UNEP, 2008). Thus, it appears possible that human well being and social equity can be improved at the same time as reducing environmental risks and ecological scarcities (UNEP, 2011).

Remote regions in many developing countries around the planet often suffer from a lack of reliable energy supply. This might be caused by non-existent or outdated transmission infrastructure, or a lack of generating capacity, and can lead to many socio-economic problems. As a solution, many remote villages opt to use diesel generators and other alternatives, though these can be very costly solutions, and in an era of rapidly decreasing renewable costs it is not clear that they are the optimal solution. In order to analyse such issues, the authors chose to study the problem through the case study of Uzbekistan, a developing post-Socialist country undergoing an economic transition from a planned to a market economy. The country is rich in fossil fuels, and thus if such systems can be shown to work in its remote areas, they could potentially be more feasible in other countries that have to import coal, gas or oil (BP Statistical Review, 2017).

Uzbekistan is an emerging economy in the heart of Central Asia, with a territory of 447,400 km² and a population of about 32 million (Statistical Review of the

---

[*] *Corresponding Author*
Tel.: - ; E-mail: nigora.djalilova@s.k.u-tokyo.ac.jp

Republic of Uzbekistan, 2017). Due to the country's diverse geographic and climatic conditions (most of its north-western part is occupied by the Kizilkum desert, while the east is made up of the fertile Fergana valley) the population is unevenly distributed among its viloyats (regions). Geographic isolation makes some small settlements in remote areas prone to electricity supply disruption, sometimes caused by outdated infrastructure and high transmission losses (some of the transmission lines can be 40-50 years old, and have not been properly maintained), which can cause system failures during peaks in power demand (ADB, 2015). Due to these problems, a number of pilot low scale stand-alone renewable energy systems have been installed across hard-to-reach regions in Uzbekistan, through initiatives and support from international organizations, local NGOs, and other sources of external funding[†] (UNDP (2007), Azizov, (2015), Zakhidov et al (2015)). More recently, privately financed renewable energy system (RES) installations have slowly started to emerge, with the aim of supplying electricity to individual households.

Some experts claim that many of these projects have been successful[‡]. However, there is a lack of data on their actual outcomes, and so far no comprehensive technical and economic analysis has looked at the optimization of renewable energy systems (with the ultimate aim of minimizing the cost of the electricity provided by such systems). Previous studies have mainly just made preliminary technical and resource potential assessments, as described below. For instance, Zakhidov et al. (1995) attempted to model wind patterns to predict the output of wind turbines, in order to define the best turbine sizes for different regions of Uzbekistan. Zakhidov et al (2000) criticized the methodology used by Wijk et al (1994), Gartsman et al (1994) and in the "Recommendation on defining climatic characteristics of wind power resources" (1989) for the assessment of the potential wind power, as they used annual average wind speed or the specific power of wind flows (which is problematic for the case of Uzbekistan due to its diverse terrain and variability of wind patterns). Zakhidov et al (2000) also point out issues related to the density and distribution of weather stations, which are missing in many parts of the country, and estimates there is substantial wind power potential in the country, which could produce 330GWh per year. Essentially, wind patterns in the country vary significantly throughout a year, season, month, day and hour, both in magnitude and direction, due to climate differences and geographical terrain variations (Tadjiev et al, 2015). Thus, Tadjiev et al, (2015) attempted to identify the technical and economical parameters that would govern wind turbine deployment in different regions in Uzbekistan, using NASA data for wind speeds at a 50 m height. However, satellite data on wind speed might not necessarily be as accurate as real ground measurements.

There is very limited research that has been conducted on hybrid stand-alone energy systems in remote regions of Uzbekistan, and their performance under real meteorological data. For instance, Abdullaev and Isaev (2002) discussed the electricity output of wind turbine and PV panels under real conditions in Charvaq region. Consequently, Zakhidov et al (2015) emphasized the fact that a significant part of Uzbekistan is characterized by having a great number of unevenly distributed villages and small settlements, which use little electricity. In such a situation, the power supply to such remote areas could be improved through the use of distributed power generation. They conclude that the modernization and extension of grid would be expensive and economically unviable, due to shortages of generation capacity in some regions. These authors also conclude that the use of distributed power generation sources (namely renewables such as wind and solar power) is a promising way to improve energy supply in remote regions. However, no studies have been carried out on the cost viability and performance of these systems with regards to alternative conventional options in rural regions of Uzbekistan. Conducting such studies with real meteorological data is of crucial importance if they are to be successful, as for renewable systems to succeed they must be both technically and economically viable. Thus, in order to fill-in this gap in literature, the present work raises the following set of questions: To what extent are wind and solar energy systems feasible in countries well-endowed with fossil fuels? Can they represent an alternative to existing diesel-run systems? And, finally, what are the factors which may have an impact on this process?

By answering these questions, the present work will thus contribute to literature in a number of ways. First, it uses the case of Uzbekistan as an example to demonstrate the challenges and issues faced by countries which are undergoing a transition from government-led economic models to the post-Socialist model of economic governance. Second, by nuancing the current development of renewable energy markets in such countries, through an analysis of the economic viability of wind/solar energy systems in Uzbekistan, this research provides an outline of major problems which go beyond the issues faced by Central Asian (CA) countries, and which are often felt by many other post-Socialist countries (tightly related to political, economic and social systems). Finally, this research also offers certain clues about the particularities of transitioning from traditional energy resources to renewable energy consumption in developing countries, touching on certain important elements related to government policy.

The choice of methodological tools employed by the authors to answer the questions raised above is not arbitrary. There are a number of widely accepted

---

[†] Pilot RES installations were installed in Rural Health Centers (RHU), small business such as farming, stockbreeding, weaving or pottery shops.

[‡] This information was obtained by the main author through personal communication with local RES installing companies between August – September, 2016 in Tashkent, Andijan and Namangan in Uzbekistan.

methodologies to model optimal RES systems (Erdinc and Uzunoglu, 2012). Zhou et al. (2010) attempted to analyze the algorithms hidden inside some software tools for solving multi-objective tasks, revealing their limitations. When focusing simultaneously on several objectives, it is typical that some of them may be in conflict with others (Collette Siarry, 2004, Angelis-Dimakis et al, 2011). Multi-objective optimization attempts the simultaneous resolutions of various objectives, Pelet et al (2005), Bernal-Agustin et al (2006), Lopez and Bernal-Agustin (2008, 2009). The HOMER software package has been used for many remote and hard-to-reach regions, using control strategies based on Barley Winn (1996). The design, control and optimization of a hybrid system is usually a very complex task, and HOMER can be used to find optimum solutions in the design of a hybrid energy system with the least Levelized Cost of Electricity (LCOE) and Net Present Cost (NPC), while considering aspects such as climate conditions, technological advancements, and other economic indicators.

Due to their intermittency, neither wind nor solar energy systems can provide continuous power supply for stand-alone systems. Integrating several energy sources thus helps to improve the efficiency and reliability of energy supply, reducing energy storage requirements when compared to systems that are comprised of only a single type of RES (Yang et al 2008). Khan and Iqbal (2005), in a pre-feasibility study of hybrid stand-alone energy systems, conclude that fuel cells could prove to be an important alternative for conventional batteries, potentially decreasing the capital costs of hybrid RES in the future. Moreover, they point out that instead of using single stand-alone units, larger hybrid RES systems would be more cost-competitive for remote communities, due to economies of scale. Asrari et al (2012) conducted an economic evaluation of a hybrid RES system for a remote village, critically examining whether it is cost-effective to extend the national grid to that location due to high capital costs, providing evidence that supports the development of hybrid RES systems. Other studies (Kaldellis, 2010; Ngan and Tan, 2012; Hafez and Bhattacharya, 2012; Dalton et al, 2009) have also expressed support for the necessity to diversify electricity generation in favor of renewables, to lessen the reliance on the highly volatile nature of the prices of fossil fuels and reduce concerns about greenhouse gas emissions and climate change.

As stated earlier, despite the proliferation of such studies worldwide, to date very limited work has been done for the case of Uzbekistan, and none of these studies have attempted to analyze the actual cost viability and performance using real atmospheric data. To address this important gap in literature the authors gathered data from Uzbekistan's meteorological agency and utilized the HOMER software to analyze what would be the most desirable strategy (from a socio-economical point of view) to ensure the sustainable energy supply of remote villages in the country.

2. Outline of case study sites

In the current research the authors attempt to fill in the missing gaps in previous research on renewable energy sources in Uzbekistan by conducting a pre-feasibility study on 6 electricity consumer units in 5 different regions (viloyats). The authors categorized the current work as a "pre-feasibility study"[§], since it represents a detailed analysis that involves the use of metrics and data specific to the hypothetical projects that could be considered in each region. In the first part of this study, the authors evaluate a variety of RES and diesel hybrid energy systems using the HOMER simulation software, based on the cost effectiveness and environmental consequences of each system (in terms of greenhouse gas emissions during the operation of the systems, mainly as a result of burning fuel by diesel generator. The assessment of other costs, such as lifecycle emissions from the construction of PV panels, was not included in the assessment).

The regions considered all have different weather conditions and are distributed throughout the territory of Uzbekistan, allowing for an identification of the areas that would be most suitable for the introduction of stand-alone RE systems. The location of the weather stations utilized in this study is summarized in Table 1 below, and a brief description of the areas surrounding them is also provided. Note that while there are other weather stations in Uzbekistan, the ones that were used in this study essentially represent all stations that record both solar irradiation and wind speed data, as others do not measure solar irradiation.

Table 1 Location of weather stations and outline of case study site.

Station	Latitude	Longitude	Region	Population (millions)
Tashkent	41°20'N	69°18'E	Tashkent	5.3
Fergana	40°23'N	71°45'E	Fergana	3.56
Termez	37°11'N	67°19'E	Surkhandaryo	2.46
Tamdi	41°44'N	64°37'E	Navoi	0.94
Takhiatash	42°21'N	59°35'E	The Republic of Karakalpakstan.	1.82
Tashkent	41°20'N	69°18'E	Tashkent	5.3

3. Methodology and system design

As stated earlier, the present work used HOMER to investigate the potential of hybrid RES deployment as an alternative to grid extension or diesel run power in the most remote areas of Uzbekistan, or at least as a complementary source of power. Also, the study attempted to identify how changes in discount rate policy affect the economics of particular RES projects, through a sensitivity case study assessment. It should be noted that the scenarios presented are deemed to be "conservative", as the PV and wind power

---

[§] As opposed to Preliminary Economic Assessments (PEA), or scoping studies, which are generally based on industry standards rather than being derived from detailed site-specific data.

technologies used in the simulation employed technical and economical parameters which are less favourable than the state-of-the-art technologies available in other countries (such parameters were obtained from local RES installing and producing companies, and if better technologies are included the results of the present work would make renewables even more cost-effective).

3.1. Data inputs

Daily average solar irradiation, wind speed, and air temperature data were obtained from the National weather agency "UzHydroMet", for all the weather stations described in the previous section.

Solar Irradiation

Average solar radiation data for each case study location is shown in Figure 1, indicating how the solar radiation in some regions reaches a minimum of 1.7kWh/m^2/day in January and a maximum of 14kWh/m^2/day during summer months.

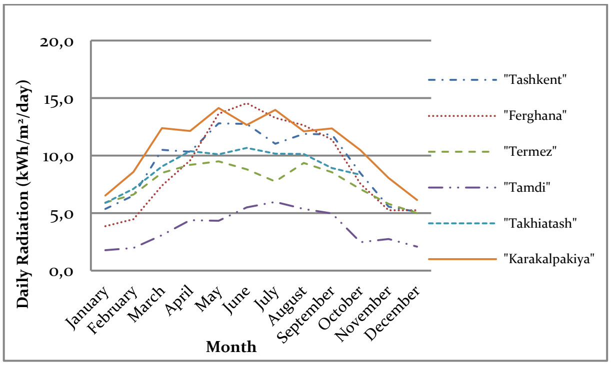


Figure 1 Average daily solar irradiation in 2015 (created by authors based on data obtained from "UzHydroMet")

Wind speeds

Wind speeds and patterns vary significantly throughout the territory of Uzbekistan. The windiest regions are centered on the Aral Sea in Karakalpakstan (north-west), around the Plato Ustyurt, and Navoi and Bukhara viloyats, which includes the Kizilkum desert. The average wind speed data for each site at a 10m elevation is shown in Figure 2. The lowest wind speed during the year varies for each particular region, though there is an increase in wind speed during spring and winter months in most areas, with the highest wind speed typically taking place in December.

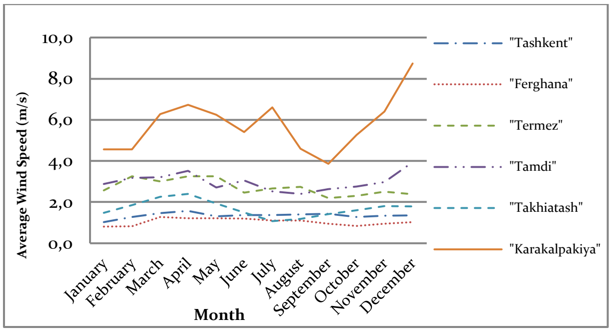


Figure 2 Average wind speed in 2015 (created by authors based on weather data obtained from "UzHydroMet")

Load profile

Since hourly load profiles for the selected sites were not available, HOMER was used to synthesize the load profiles by entering the average values of electricity consumption for a typical day for an average household, with a peak load in January[**]. Then, a synthetic load was created for 10 average households, which was the size of the proposed "case study village projects" at each of the study sites. Both day-to-day and time-step-to-time-step randomness were set at 3%, and the monthly average load profile for the case study village for each month of the year is shown in Figure 3.

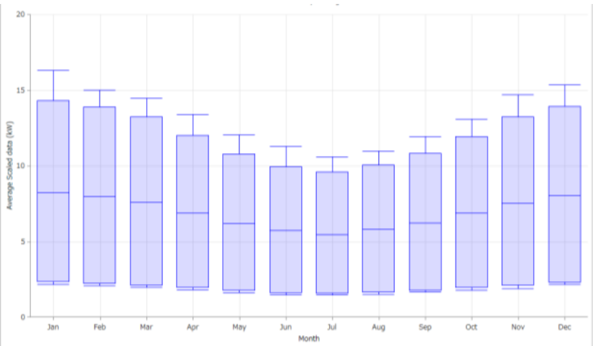


Figure 3 Monthly average load profile for the case study village

3.2. System design

In order to arrive at the optimum power mix it is necessary to take into account a number of possible power mixes. To do so, the authors considered different combinations of the five potential elements (diesel generators, PV panels, wind turbines, power converters and batteries) that could be used by the system. When detailing the different scenarios the authors ensured that the maximum capacities of each type of energy source had the chance of entirely supplying the "case study project village" with electricity (i.e. it was possible for example that energy demand was fully satisfied

---

[**] Obtained through personal communication with a former national grid engineer

with either solar or diesel power), though all combinations of lower capacities were computed, as long as they could satisfy the overall electricity demands specified in Figure 3 The best size combinations for each region will be described in the following section. For an assumed project lifetime of 25 years, the annual discount rate was taken at 9 %, as was officially set by the Central bank of Uzbekistan up to the year 2017 (note that changes to this discount rate will be investigated later in this paper).

Diesel generator

In this scenario an autosize diesel generator with a capacity of 18kW was selected to cover the peak load of 16.3 kW. The operating reserve was set as 10% of the hourly load. The initial capital cost of the generator was assumed to be USD 2700/20kW. Replacement and operational costs were USD2000/20kW and USD 0.030/h, respectively[††]. The operating lifetime was considered to be 15,000 hours. The current diesel price in Uzbekistan is about 1 USD per litre, though it consistently increases as one progresses towards remote regions, due to higher transportation costs and random speculation. However, in order to be conservative the authors neglected such issues, and assumed a value of 1 USD per litre.

PV panels

Installation and replacement costs for 1 kW solar power systems, considering the market of PV panels in Uzbekistan, were taken as USD 2600 and USD 2000, respectively. Maintenance costs were considered to be USD10/year. The lifetime of PV panels was taken as 25 years, with no tracking system. In this study, nine different sizes of PV arrays (0, 5, 10, 15, 20, 25, 30, 35, 40 kW) were considered.

Wind energy conversion system (WECS)

Locally produced wind turbines with a rated capacity 1-3kW were considered. Unit cost was set to be USD 3900, with replacement and maintenance costs of USD 3000 and USD 30/year, respectively. The lifetime of a turbine was set to be 15 years. To allow the simulation program to find the optimum system size solution, seven options were fed into the system design for analysis (0, 1, 2, 3, 5, 6, 7 turbine units).

Power converter

To maintain energy flow between AC and DC busses the authors included a power converter (Leonics 15kW). For a 1kW system the installation and replacement costs were considered as USD 600. Four different sizes of converter were used in the simulation (0, 10, 20 and 30kW). The lifetime was assumed to be 15 years, with an efficiency of 90%.

Battery

For the current analysis the authors considered an autosize battery (Trojan Ind9-6V) with initial and replacement per unit (string) costs of USD 850, and a maintenance cost USD of 10/year[‡‡]. To find the optimum configuration, the system was assumed to contain any number of 0, 10, 20 or, 30 unit (strings) batteries. The operation lifetime of the battery depends on the system's configuration, and in the present case studies it can vary between 6.55 years for hybrid RES system and 18.8 for diesel-battery energy system.

4. Optimization results

Based on the optimization results all feasible systems for each selected location were ranked based on indicators such as lowest net present cost (NPC), lowest cost of energy (LCOE), lowest greenhouse gas (GHG) emissions and highest fraction of renewables. Then, the systems with the lowest LCOE from each region were compared to find the most promising areas in the country to install renewable energy systems.

Case study 1: "Tashkent"

As can be seen from Tables 2 and 3, a PV-diesel-battery system (Scenario #1) consisting of a 25kW PV array, 18kW diesel generator, 30 batteries and 15 kW converters would be the most economically feasible solution, with a minimum NPC of USD 286,539 and LCOE of USD0.277/kWh. The Renewables fraction in the system is 73%.

Moreover, in terms of environmental impact this RES system is also considered to be the best, with CO_2 emissions as low as 16,618 kg/year, and a fuel consumption of 6,318 litres/year. If compared with a system that is 100% dependent on electricity produced by diesel generators, the system prevents CO_2 emissions equal to 47,000 kg per year, saves 17,000 litres of diesel, and producing electricity at almost half the price. Adding wind turbines to the system does not significantly affect either the LCOE, renewables fraction or CO_2 emissions, while it increases the NPC. This can be explained due to the insufficient wind power resources in this particular area of the country.

The most expensive system was based solely on a diesel generator, with a cost of electricity equal to USD 0.415 (which was actually true for all case studies in the current research). In this sense it is important to note that while RES systems require high upfront costs, the costs of diesel-run systems are almost equally distributed through its lifetime (mainly related to the price of diesel) and will eventually exceed that of RES. Also, it is important to note

---

[††] This information was obtained by the main author through personal communication with local RES installing companies and a grid expert between August – September, 2016 in Tashkent

[‡‡] This information was obtained through personal communication with national grid expert

that if the volatility of diesel prices increases the cash flow patterns of those depending on them can suffer.

Table 2 Scenario optimization results for "Tashkent".

Scenario	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
1	25		18	30	15
2	25	1	18	30	15
5			18	10	15
6		1	18	10	15
7			18		

Table 3 Cost and environmental performance of each scenario.

Scenario	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/ yr)	Fuel Cons (l/yr)
1	101,930	10,746	286,539	0.277	73	16,618	6,318
2	105,830	10,808	291,489	0.281	73	16,611	6,308
5	19,930	23,534	424,207	0.409	0	57,099	21,683
6	23,830	23,595	429,153	0.414	0	57,091	21,680
7	2,430	24,872	429,699	0.415	0	62,263	23,644

Case study 2: "Fergana"

In this area a PV-diesel-battery system (Scenario #1, Table 4) consisting of a 25kW PV array, 18kW diesel generator, 30 batteries and 15 kW converters would be the most economically feasible solution, with a minimum NPC of USD 293,842 and LCOE of USD 0.274/kWh (Table 5). The renewables fraction in the system is considerable, and equals to 69%. In terms of environmental impact this RES system is also considered the best, with CO_2 emissions equal to 19,387 kg/year and fuel consumption of 7,362 L/year.

Table 4 Scenario optimization results for "Fergana".

Scenario	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
1	25		18	30	15
2	25	1	18	30	15
5			18	10	15
6		1	18	10	15
7			18		

Table 5 Cost and environmental performance of each scenario.

Scenario	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/ yr)	Fuel Cons (l/yr)
1	101,930	11,171	293,842	0.284	69	19,387	7,362
2	105,830	11,234	298,831	0.288	69	19,386	7,362
5	19,930	23,406	422,022	0.407	0	57,550	21,855
6	23,830	23,469	427,010	0.412	0	57,550	21,854
7	2,430	24,872	429,669	0.415	0	62,263	23,644

Case study 3 and 4: "Karakalpakiya"and "Takhiatash"

Two of the following case study sites are located in one region. However, due to differences in weather conditions, the system design and costs and other indicators vary significantly.

Thus, for the case study 3: "Karakalpakiya" a PV-wind-diesel-battery system (scenario#1, Table 6) consisting of 15kW PV array, 7 locally produced 3kW wind turbines, 18kW diesel generator, 30 batteries and 10 kW converters, would be the most economically feasible solution with a minimum NPC of USD 217,113 and LCOE of USD 0.210/kWh (see Table 7). The renewables fraction in the system is as high as 84% of the electricity consumed, with the system only producing 11,786 kg/year of CO_2 emissions.

Table 6 Scenario optimization results for "Karakalpakiya"

Scenario	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
1	15	7	18	30	10
2		7	18	20	10
4	25		18	30	20
7			18	10	10
8			18		

Table 7 Cost and environmental performance of each scenario

Scenario	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/ yr)	Fuel Cons (l/yr)
1	100,230	6,804	217,113	0.21	84	10,212	3,878
2	52,730	12,273	263,567	0.254	55	26,373	10,015
4	104,930	11,242	298,048	0.288	69	18,757	7,123
7	16,930	23,323	417,594	0.403	0	57,550	21,855
8	2,430	24,872	429,699	0.415	0	62,263	23,644

The second most economically feasible system consists of 7 units of 3kW wind turbines, 18kW diesel generator, 20 batteries and 10 kW converters (Table 6), with a NPC of USD 263,567 and LCOE of USD0.254/kWh (Table 7). It worth to note that this is an exceptional situation, and the only case in which a wind-diesel-battery system is the second best option.

Meanwhile, for the case study 4:"Takhiatash", a PV-diesel-battery system (Scenario #1, Table 8), consisting of a 25kW PV array, 18kW diesel generator, 30 batteries and 15 kW converters would be the most economically feasible solution, with a minimum NPC of USD 286,773 and LCOE of USD0.277/kWh as shown in Table 5. The renewables fraction in the system is equal to 74% of the electricity produced (Table 9). Essentially, this scenario is very similar to Scenario # 1: "Tashkent", due to the similarity in weather conditions in this region.

Table 8 Scenario optimization results for "Takhiatash"

Scenario	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
1	25		18	30	15
2	25	1	18	30	15
5			18	10	15
6		1	18	10	15
7			18		

Table 9 Cost and environmental performance of each scenario.

Scenario	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/ yr)	Fuel Cons (l/yr)
1	101,930	10,760	286,773	0.277	74	16,526	6,276
2	105,830	10,812	291,573	0.281	74	16,495	6,264
5	19,930	23,534	424,207	0.409	0	57,099	21,683
6	23,830	23,583	428,962	0.414	0	57,062	21,669
7	2,430	24,872	429,699	0.415	0	62,263	23,644

Case study 5: "Tamdy"

Table 6 shows that a PV-diesel-battery system (Scenario #1, Table 10), consisting of 30kW PV array, 18kW diesel generator, 30 batteries and 15 kW converters, would be the most economically feasible solution, with a minimum NPC of USD 358,354 and LCOE of USD0.346/kWh (Table 11). The renewables fraction in the system is a little bit lower than in previous cases, at around 67%.

However, compared to other case studies the LCOE is rather high, and adding extra battery storage only slightly decreases the cost of the system.

Table 10 Scenario optimization results for "Tamdy"

Scenario	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
1	30		18	30	15
2	30	1	18	30	15
5			18	10	15
6		1	18	10	15
7			18		

Table 11 Cost and environmental performance of each scenario.

Scenario	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/ yr)	Fuel Cons (l/yr)
1	11,4930	14,170	358,354	0.34	51	28,942	10,991
2	16,1830	11,331	356,477	0.34	68	28,370	10,773
5	19,930	23,534	424,207	0.40	0	57,099	21,683
6	23,830	23,384	425,532	0.41	0.12	56,539	21,474
7	2,430	2,4872	429,699	0.41	0	62,263	23,644

Case study 6: "Termez"

Table 12 shows how a PV-diesel-battery system consisting of a 25kW PV array, 18kW diesel generator, 30 batteries and 15 kW converters would be the most economically feasible solution with a minimum NPC of USD 284,232 and LCOE of USD 0.274/kWh (Table 13). The renewables fraction in the system represents 74% of the electricity produced.

Table 12 Scenario optimization results for "Termez"

Scenario	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
1	25		18	30	15
2	25	1	18	30	15
5			18	10	15
6		1	18	10	15
7			18		

Table 13 Cost and environmental performance of each scenario.

Scenario	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/ yr)	Fuel Cons (l/yr)
1	101,930	10,612	284,232	0.274	74	15,915	6,044
2	105,830	10,570	287,400	0.277	75	15,632	5,936
5	19,930	23,534	424,207	0.409	0	57,099	21,683
6	23,830	23,461	426,857	0.412	0	56,740	21,547
7	2,430	24,872	429,699	0.415	0	62,263	23,644

Summary of optimization results for 6 regions

In Table 14 the authors summarized the optimization results for the best RES systems in terms of the lowest LCOE, to compare the economic feasibility and environmental footprint of the potential types of projects that could be envisaged for different regions. The cost of employing RES systems is lower than using diesel generators, even in regions which are comparatively less rich in solar and wind power resources ("Tamdy"). The optimization results for "Karakalpakiya" revealed two different configurations that had an LCOE that was lower than any for the other 5 case study sites (Table 15). Such an endowment in both wind and solar power clearly offers substantial flexibility for any potential project developers and investors in this region.

5. Wind and solar power economic sensitivity to the discount rate

In this part of the study the authors investigate how recent policy changes in the discount rate[§§] of the Central bank of Uzbekistan, which in the year 2017 raised its discount rate from 9% up to 14% (Sputniknews-uz, 2017b), would affect the development of RES projects in Uzbekistan. Since most of the costs in RES projects are upfront capital costs, the LCOE of such projects is very sensitive to the discount rate applied, in the same way as with other renewable sources with long payback times, such as hydropower (IRENA, 2013;

[§§] Discount rate (nominal) is used to calculate the real discount rate which considers inflation rate and used for simulating scenarios in HOMER

IPCC, 2011). Essentially, the theory of the time value of money states that a dollar invested today costs more than a dollar tomorrow, and it is important to consider the effects of this on a project's lifetime cash flow. In order to demonstrate and test how the change in discount rate will affect the economics of an RES project, the authors decided to run a simulation for the "Fergana" region with two discount rates (9 and 14%), to test the sensitivity of the system to this parameter (Figure 4)[***].

Table 14 Scenario optimization results for six regions: Summary

Case study	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)	Scenario
Karakalpakiya	15	7	18	30	10	1
Karakalpakiya		7	18	20	10	2
Termez	25		18	30	15	3
Takhiatash	25		18	30	15	4
Tashkent	25		18	30	15	5
Fergana	25		18	30	15	6
Tamdi	30		18	30	15	7
Base case (diesel only)			18			8

Table 15 Cost and environmental performance of each scenario.

Case study	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	CO_2 emis. (kg/yr)	Fuel Cons (l/yr)	Scenario
Karakalpakiya	100,230	6,804	217,113	0.21	84	10,212	3,878	1
Karakalpakiya	52,730	12,273	263,567	0.254	55	26,373	10,015	2
Termez	101,930	10,612	284,232	0.274	74	15,915	6,044	3
Takhiatash	101,930	10,760	286,773	0.277	74	16,526	6,276	4
Tashkent	101,930	10,746	286,539	0.277	73	16,618	6,318	5
Fergana	101,930	11,171	293,842	0.284	69	19,387	7,362	6
Tamdy	114,930	14,170	358,354	0.346	51	28,942	10,991	7
Base case (diesel only)	2,430	24,872	429,699	0.415	0	62,263	23,644	8

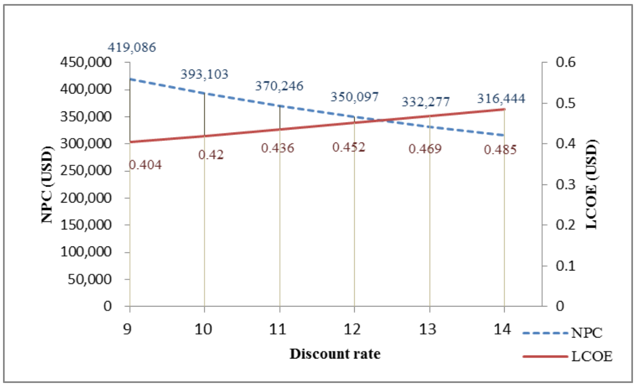


Figure 4 Sensitivity of NPC and LCOE when changing the discount rate from 9 to 14% for the "Fergana" case study (see also Table 16 and Table 17).

Table 16 Scenario optimization results for "Fergana".

Discount rate	PV (kW)	WECS (number)	Generator (kW)	Battery (number)	Converter (kW)
9	33.3		50	30	30
10	32.5		50	30	30
11	31.3		50	30	30
12	30.8		50	30	30
13	29..6		50	30	30
14	29.2		50	30	30
9	Diesel run system		50	20	15
14			50	20	15

Table 17 Cost and environmental performance for each scenario.

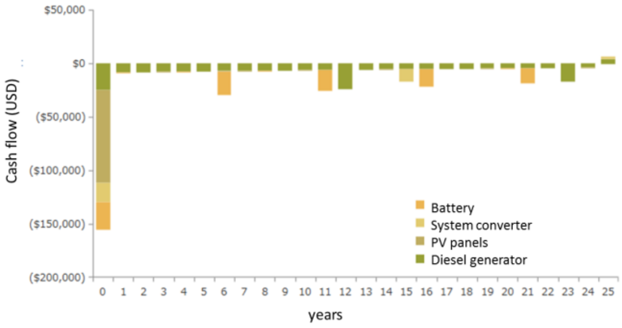
Discount rate	Initial capital (USD)	Operating Cost (USD /yr)	Total NPC (USD)	LCOE (USD/kWh)	Renew fraction (%)	Fuel Cons (l/yr)
9	155,167	15,363	419,086	0.404	72	6,845
10	153,000	15,480	393,103	0.42	71.6	6,939
11	149,750	15,667	370,246	0.436	71	7,093
12	148,667	15,698	350,097	0.452	70.7	7,149
13	145,417	15,900	332,277	0.469	70	7,331
14	144,333	15,920	316,444	0.485	69.7	7,397
9	51,000	47,721	870,792	0.840	Diesel run system	28,014
14	51,000	47,607	565,677	0.868		28,014

In Figure 5 (a), (b) and Figure 6 (a), (b) it is possible to observe the differences in the discounted cash flows for RES and diesel run system scenarios at a discount rate of 9 and 14%. The impact of the discount rate change is less severe in diesel run systems than in RES, as they have a more evenly distributed pattern of costs through the project's lifetime (mainly the cost of fuel) and lower upfront costs, compared

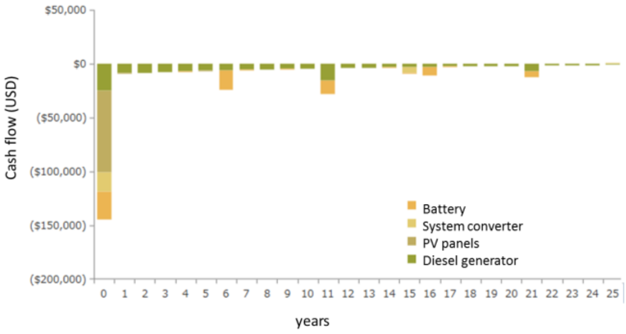
---

[***] In order to compare RES systems at different discount rates the authors extended the potentially battery capacity to 50kW.

to RES, where the greatest costs happen at the start of the project. Figure 6 shows how the change in discount rate has a more obvious effect on the more evenly distributed costs of diesel-run systems, which involve the acquisition of fuel and spare parts every few years.

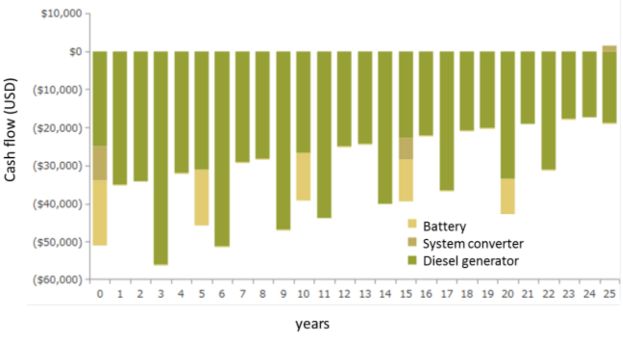


(a)

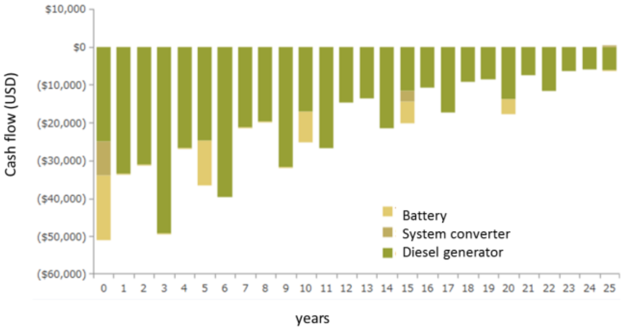


(b)

Figure 5 (a), (b). Discounted cash flow under a 9% and 14% discount rate for the "Fergana" case study hybrid RES system (Table 16 and Table 17). The jumps in cash flow every 7 years in Figure5 (a) are due to battery replacement, and on the 15th year there is also a need to replace the converter.



(a)



(b)

Figure 6 (a), (b). Discounted cash flow under 9% and 14% discount rate for a 100% diesel run and battery system ("Fergana" case study (Table 16 and Table 17)

This increase in the discount rate affects the optimization results and RES system choice, and in these cases point towards a reduction in PV installed capacity (Table 16, see also Figure 5 (a), (b)). Nevertheless, it is noteworthy that even after this change in discount rates the optimum system still has a sizeable component of renewables in it, indicating the economic viability of such projects in remote areas of Uzbekistan. However, the behaviour of the LCOE under an increasing discount rate is the opposite as that of the NPC (Table 17), as the LCOE is not just the sum of depreciated costs during the project's life, but also considers the cost of paying back the loan at an increased discount rate.

6. Hybrid RES projects sensitivity to the exchange rate

Another important variable that needs to be considered (which is important for developing economies with unstable foreign exchange markets but is not included in HOMER) is the fluctuation in currency exchange rates, in this case the Uzbek som with regards to the US dollar. For example, the cost of replacement parts is distributed unevenly through the lifetime of the project and can be affected by fluctuations in the exchange rate, which can have adverse consequences on the economics of projects.

Since October, 2016 the official rate of Uzbek som (UZS) has depreciated significantly with regards to the USD (Trading Economics, 2017). Recently, the government announced that it would proceed to liberalize the foreign exchange, with the aim to achieve "economic growth, ensuring attractive climate for foreign direct investments, and increase in competitiveness of national products on international markets" (Sputniksnews-uz, 2017(a). On September 2nd, 2017, President Sh. Mirziyoyev signed the Decree "On the measures on foreign exchange policy liberalization" guaranteeing free and unhindered access to buy and sell foreign currency in commercial banks of Uzbekistan at the rate set by the Central Bank of Uzbekistan (CBU). In one night the national currency lost half of its value against the US dollar (and other reserve currencies). Prior to September 05, 2017 the official exchange rate set by the Central Bank of Uzbekistan (CBU) was 4,154 UZS per 1 USD[†††]. On September 5, 2017 the CBU set the exchange rate at 8,100 UZS per 1 USD (close to the exchange rates that were previously obtained in the "black market" in Uzbekistan).

One way to avoid exchange rate fluctuations would be to conduct all transactions in the local currency. However, most of the components for RES systems are paid for through international contracts remunerated in one of the reserve currencies (typically US dollar or Euro). The other way would be to increase the localization of the production of the components of RES systems, which could lead to a lowering of costs, especially if local production could use modern technologies and research. If so, this could also lead to an increase in competitiveness of locally produced components versus those acquired in international markets, especially given the new open economic policy. However, this would obviously require a proactive commitment by the government, which could try for example to convince some international PV manufacturing companies to set up factories in Uzbekistan.

7. Conclusions and Policy recommendations

In Uzbekistan there is a substantial potential for renewables to contribute to the energy mix. RES deployment in remote areas of the country could lead to benefits at the local community. Firtsly, RES installation could assist in improving the reliability of electricity supply in remote regions, compared to diesel run sytems, which provide electricity at a price 8 times higher than that provided by national electricity provider "Uzbekenergo" through the grid, and 2 times higher than that provided by hybrid RES systems. Secondly, RES deployment could cause less harm to the environment at a global scale.

Moreover, by deploying low-scale hybrid wind-solar power systems in remote regions in Uzbekistan, it is possible to meet the country's growing energy demand, lessen the burden on the national grid (especially during peak hours) and facilitate the sustainable and inclusive economic development of the country.

Additionally, RES deployment could contribute to improve the energy security of small communities in remote areas and ensure their sustainable development by improving local livelihoods at the possibly lowest economic costs and environmental footprint. However, for this to happen, a number of technical and political challenges must be overcome.

With the recent RES development targets set by the government, Uzbekistan has sent positive signals to the RES industry, academia and potential investors in this sector. However, it is still unclear what are the next steps that the government will take to support and incentivize RES deployment at different levels and scales to reach these targets. Meanwhile, the attempts to let the national currency of the country float freely have been followed by a fast depreciation of the Uzbek som with respect to US dollar and other reserve currencies, which also affects the economics of RES projects. One way to protect and incentivize RES deployment in such economic conditions would to localize production of RES components by . Also, the experience from small-scale hybrid RES projects could be used to improve the understanding of RES market specifics, which are highly influenced by the specifics of the economic system in the country.

It is thus imperative that a clearer and more thought out approach to the entire renewable sector is outlined by the government. This should answer questions as to whether the government will implement RES sector specified financial mechanisms and tools, such as preferential loans, feed in tariffs or taxation regimes to support renewables at the early stage of their development. Depending on this, and many other factors, RES deployment can either help to promote a sustainable energy future, or further aggrevate energy supply and environmental problems in the country.

Acknowledgements

The authors would like to acknowledge the financial support from the Graduate Program in Sustainability Science Global Leadership Initiative (GPSS-GLI) and the Japanese Ministry of Education (Mombukagakusho).

References

[1] Abdullaev D.A. and Isaev R.I., 2002. Resources of Solar Radiation and Wind Energies in Uzbekistan and System of Their Combined Utilization. ISESCO Science and Technology Vision - Volume 1 (May 2005) (76-82)

[2] ADB (Asian Development Bank). (2015). Proposed Loans. Republic of Uzbekistan: Northwest Region Power Transmission Line Project. Report and Recommendation of the President to the Board of Directors. Available at http://adb.org/sites/default/files/projdocs/2014/45120-003-rrp.pdf (last accessed on June 1, 2018).

[3] Angelis-Dimakis A., Biberacher M., Dominguez J., Fiorese G., Gadocha S., Gnansounou E., Guariso G., Kartalidis A., Panichelli L., Pinedo I., Robba M., 2011. Methods and tools to evaluate the availability of renewable energy sources. Renewable and Sustainable Energy Reviews 15 (2011) 1182–1200

[4] Asrari A., Ghasemi A., Javidi M.H., 2012. Economic evaluation of hybrid renewable energy systems for rural electrification in Iran-A case study. Renewable and Sustainable Energy Reviews 16 (2012) 3123– 3130

[†††] This rate is used for all simulations in this research

[5] Azizov, Sh. A. (2015). On Measures for Supporting and Forming the Legislative and Regulatory Framework for the Development of the Use of Renewable Energy Sources in the Republic of Uzbekistan. Applied Solar Energy, 51(4), pp. 332–335.

[6] Barley C.D., Winn C.B., 1996. Optimal dispatch strategy in remote hybrid power systems. Solar Energy 1996;58(4–6):165–79.

[7] Bernal-Agustin J.L., Dufo-Lopez R., Rivas-Ascaso D.M., 2006. Design of isolated hybrid systems minimizing costs and pollutant emissions. Renewable Energy 2006;31 (14):2227–44

[8] Bernal-Agustin J. L., Dufo-Lopez R., 2009. Simulation and optimization of stand-alone hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 13 (2009) 2111–2118

[9] BP (British Petrrolium). (2017). Statistical Review of World Energy, June 2017.

[10] City Population, 2017. https://www.citypopulation.de/Uzbekistan.html. Accessed on July 24, 2017.

[11] Collette Y., Siarry P., 2004. Multiobjective optimization: Principles and case studies, 1st edn., Springer; 2004.

[12] Erdinc O., M. Uzunoglu, 2012. Optimum design of hybrid renewable energy systems: Overview of different approaches. Renewable and Sustainable Energy Reviews 16 (2012) 1412– 1425

[13] Dalton G.J., Lockington D.A., Baldock T.E., 2009. Case study feasibility analysis of renewable energy supply options for small to medium-sized tourist accommodations. Renewable Energy 34 (2009) 1134–1144

[14] Gartsman L., Zakhidov R., Rudak M., 1994. Wind power resources in Central Asia. GUGM publisher under Cabinet of Ministers of the Republic of Uzbekistan, SANIGMI, Tashkent, 1994, 75 p.

[15] Hafez O., Bhattacharya K., 2012. Optimal planning and design of a renewable energy based supply system for microgrids. Renewable Energy 45 (2012) 7-15

[16] HOMER (Hybrid Optimization Model for Electric Renewables). http://www.homerenergy.com

[17] IPCC (Intergovernmental Panel on Climate Change). (2014). Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report, In Edenhofer, O., et al. (eds.), IPCC, Cambridge University Press, Cambridge, United Kingdom and New York.IPCC (Intergovernmental Panel on Climate Change). (2011). Special Report Renewable Energy Sources and Climate Change Mitigation, Working Group III-Mitigation of Climate Change, IPCC, Cambridge University Press, Cambridge, United Kingdom and New York.

[18] IRENA, 2013. Renewable energy technologies: cost analysis series. Hydropower, Volume 1: Power Sector Issue 3/5.

[19] Kaldellis J.K., 2010. Optimum hybrid photovoltaic-based solution for remote telecommunication stations. Renewable Energy 35 (2010) 2307-2315

[20] Khan M.J., Iqbal M.T., 2005. Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. Renewable Energy 30 (2005) 835–854

[21] National Renewable Energy Laboratory (NREL). http://www.nrel.gov/

[22] Ngan M. S., Tan C.W., 2012. Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia. Renewable and Sustainable Energy Reviews 16 (2012) 634– 647

[23] Pelet X, Favrat D, Leyland G., 2005 Multi-objective optimisation of integrated energy systems for remote communities considering economics and CO2 emissions. International Journal of Thermal Sciences 44(12): 1180–1189.

[24] Podrobno.uz,2017. http://podrobno.uz/cat/politic/prezident-uzbekistana-podpisal-ukaz-o-vvedenii-svobodnoy-konvertatsii/ Accessed 25 Sept 2017

[25] Recommendation on defining climatic characteristics of wind power resources. Gidrometeoizdat, Leningrad, 1989, 65p.

[26] Sputniksnews-uz,2017(a). http://m.ru.sputniknews-uz.com/economy/20170726/5900546/uzbekistan-minfin-kredit-valutnaya-reforma.html Accessed on August, 28 2017.

[27] Sputniksnews-uz, 2017 (b). http://m.ru.sputniknews-uz.com/economy/20170624/5685571/cb-ruz-stavka-refinansirovaniya.html Accessed 25 Sept 2017

[28] Statistical Review of the Republic of Uzbekistan. State Statistics Committee of the Republic of Uzbekistan. (2017). Available at https://stat.uz/ru/press-tsentr/novosti-komiteta/433-analiticheskie-materialy-ru/2055-demograficheskaya-situatsiya-v-respublike-uzbekistan(last accessed on December 11, 2017).

[29] Tadjiev U. A., Kiseleva E. I., Tadjiev M. U., and Zakhidov R. A., 2015. Features of the Formation of the Wind Flow over the Territory of Uzbekistan and Opportunities for its Use for Electric Power: Part 1. Applied Solar Energy, 2014.

[30] Tadjiev U. A., E. I. Kiseleva, M. U. Tadjiev, and R. A. Zakhidov, 2013. Estimated Technical and Economic Indicators of Wind Power Installations That Convert Wind Energy of Surface Layers of the Atmosphere in the Plains of Uzbekistan. Applied Solar Energy, 2013, Vol. 49, No. 2, pp. 105–109.

[31] Tadjiev U. A., Kiseleva E. I., Tadjiev M. U., and Zakhidov R. A., 2015. Features of the Formation of the Wind Flow over the Territory of Uzbekistan and Opportunities for its Use for Electric Power: Part 2. Applied Solar Energy, 2015, Vol. 51, No. 1, pp. 62–68.

[32] Tradingeconomics, 2017. https://tradingeconomics.com/uzbekistan/currency accessed on August, 28 2017.

[33] UNDP (United Nations Development Programme). (2007). The Outlook for the Development of Renewable Energy in Uzbekistan. Available at http://www.uz.undp.org/content/uzbekistan/en/home/library/environment_energy/the-outlook-for-the-development-of-renewable-energy-in-uzbekista.html (last accessed on June 1, 2018).

[34] *Uzreport, 2017. 314,1 trillion Uzbek soms will be allocated for the development of renewable energy sources. http://news.uzreport.uz/news_4_r_152650.html.* Accessed on July 13, 2017.

[35] UNDP, 2015. Towards Sustainable Energy. Stategy for Low Carbon Emission Strategy of the Republic of Uzbekistan (K ustoychivoy energii: strategiya nizko-uglerodnogo razvitiya Respubliki Uzbekistan). (in Russian).

[36] UNEP, ILO, IOE, ITUC. (2008). Green Jobs: Towards decent work in a sustainable, low-carbon world. WorldWatch Institute, available at http://adapt.it/adapt-indice-a-z/wp-content/uploads/2013/08/unep_2008.pdf (last accessed on June 1, 2018).UNEP (United Nations Environmental Programme). (2011). Towards a Green Economy, Pathways to Sustainable Development and Poverty Eradication – A Synthesis for Policy Makers, United Nations Environment Programme. Available at www.unep.org/greeneconomy (last accessed on June 1, 2018).

[37] Wijk, A. van, Brummenel M., Coeling J., Alsema E., 1994. Solar and wind electricity potential in OECD-Europe. Energy

technologies to reduce CO_2 emissions in Europe: prospects, competition, synergy. Conference proceedings, April 11-12, Netherlands.

[38] Yang H., Zhou W., Lu L., Fang Z., 2008. Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm. Solar Energy 82 (2008) 354–367

[39] Zakhidov R.A., Tadjiev U.A., Kiseleva E.I., Tadjiev M. U., Saliev G.S., Gorobtsov S.I., 2015. Experience and prospects of using solar-wind low power energy complex in power supply systems of remote objects

[40] Zakhidov R.A., Kiseleva E.I., Orlova N.I., Tadjiev U.A., 1995. Modelling of wind flows patterns and output of wind generators (Chislennoe modelirovanie rejimov vetrovih potokov I raboti vetroelektroustanovok). Geliotekhnika, 1995, No. 4, pp. 90–97. In Russian.

[41] Zakhidov R.A., Kiseleva E.I., Orlova N.I., Tadjiev U.A.,2000. Assessment of wind power potential in Uzbekistan based on ground measurements data from weather stations (Prognoznaya otsenka energeticheskogo potenciala vetra po dannim nablyudeniy seti meteorologicheskih stanciy na territorii Uzbekistana). Geliotekhnika, 2000, No. 4, pp. 67–75. In Russian.

[42] Zhou W., Lou C., Li Z., Lu L., Yang H., 2010. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Applied Energy 87 (2010) 380–389.