A Concept for a Self-Sufficient Off-Grid and Backup Solutions for Power Supply and Grid Stabilization in Rural Areas with Wind-Solar-Hydropower for Central Asia

Eduard Siemens[1], Stephan Krause[2], Sebastian Dittmann[1,2], Claus Wittmann[3] and Jose Palacios[1]
[1]*Anhalt University of Applied Science, Bernburger Str. 55, Köthen, Germany,*
[2] *Fraunhofer-Center for Silicon Photovoltaics, Otto-Eißfeldt Str. 12, Halle, Germany*
[3]*KORA Industrie-Elektronik GmbH, Brigitta Str. 26, Hambühren, Germany*
eduard.siemens@hs-anhalt.de, sebastian.dittmann@hs-anhalt.de

Keywords: Decentralized Energy Systems, Central Asia, PV Systems, Micro-Wind-Power Stations, IIoT.

Abstract: The purpose of this work is to present a concept how to realize a decentral energy-efficient and self-sufficient energy supply system, consisting of a wind-photovoltaic (PV) or PV- micro-hydro power plants for a stable local energy supply. This comprises of subsystems for controlling the energy flows between power generators and consumers, sensor networks for keeping energy balance and to predict failures in particular subsystems (so called predictive maintenance), and optimization of energy demand tailored to remote areas in Central Asia. The energy production of this self-sufficient system shall be based on regenerative energy sources only such as wind, hydro and photovoltaic. The system will be supported by an appropriate energy storage system with, e.g., lithium ion or lead-gel or even lead-acid batteries. This study presents a higher-level management system based on IIoT networks and machine learning methods which control the individual energy generators (wind, hydro and photovoltaic) together with the connected consumers (load management) to avoid peak loads and to trigger suitable processes in case of energy surplus or deficiency. The dimensioning of each subsystem has to consider specific local energy demands and specific climate conditions with dedicated forecasting and machine learning methods.

1 INTRODUCTION

Due to the existing high occurrence of fossil energy resources in the Central Asia region, especially in Kazakhstan, Turkmenistan and Siberian part of Russia, the integration of renewable energy sources in the energy mix of Central Asia played in the recent past a minor role. Currently, the share of renewable energy in Kazakhstan is about 1 % [1]. However, the kazakh government has the ambitious goal to increase the share of removable energy to 50 % by 2050 [1] and to improve the supply infrastructure in rural regions. In this scenario renewable energies gain is of essential importance. In the neighbouring country Kyrgyzstan the share of renewable energies is much higher than in Kazakhstan. This is due to the dominance of large hydropower plants in Kyrgyzstan. However, the construction of such huge hydro-power plants causes also essential ecological damages. Besides this, in Central Asia, the distribution of the energy in rural arears is still an unsolved issue due to, e.g. very long distances and an overage grid structure. About 70 % of the total grid losses are within the voltage range of 0,4-10 kV – the dominant distribution technologies to the small settlements of the region. With this in mind, it is important to note that about 43 % of Kazakhstan's population (equals to approx. 7,7 million inhabitants) and 70 % of Kyrgyzstan's (equals to approx. 4 million inhabitants) live in remote villages [1]. In the Siberian region of Russia this portion is even higher than 80 % [2]. So, uninterrupted and stable energy supply in rural areas is one of the major goals of the governments of lots of central Asian countries, especially Kazakhstan and Kyrgyzstan. Therefore, there is consensus among politicians, local administrations and experts that decentralized energy production, e.g., based on small wind turbines (WT) or micro-hydro power plants (µHPP) combined with photovoltaic (PV) plants will play a central role in the near future. Small villages in rural areas are currently either cut off from a stable power supply or they operate diesel generators. The energy supply with renewable sources of those villages has a strategic priority of the Central Asian governments and has potentially an economic and ecological impact in this region. This challenge represents an opportunity to jointly transform the energy sector in Central Asia into a sustainable and environmentally friendly energy economy.

The energy supply of rural areas with decentralized energy solutions saves costs of complex infrastructure such as for installation and maintenance of complex power lines to remote villages. However, decentralized energy solutions require a very precisely coordinated energy management, which is real-time capable and fail-safe. Not only individual energy generators, including short-term storage must be considered but also the consumers side must be taken into account here.

In order to make this economically viable, however, further innovative methods must be developed and implemented. This paper presents a basic concept and first technical ideas of the development of such decentralised systems. These ideas have been already presented to the scientific audience at a travelling conference titled “Industry 4.0 for Renewable Energy and Energy-saving Technologies for Central Asia”, held in March 2019 in the cities Astana (now Nur Sultan), Karaghandy, Oskemen, Almaty in Kazakhstan, Bishkek and Osh in Kyrgyzstan. After an intensive discussion with players from academy, energy research centers, with representatives of ministries and local municipal administrations, energy providers, and grid operators, a concept of decentral energy systems based on renewable energy have been elaborated. The following sections present the main ideas of a decentral energy system or known as DeEN_CA *system (**DE**central **EN**ergy system for **C**entral **A**sia*).

2 OBJECTIVES

The overall aim of the DeEn_CA system is to realize local energy-efficient and self-sufficient energy supply systems, which consists of wind and PV or PV and micro-hydro power plants with a nominal power between 10 and 100 kW. This includes systems for controlling the energy flow between power generators and consumers, sensor networks to predict failures in all subsystems, known as predictive maintenance, and optimization of energy demand of the location. The energy production in the developed system will be realized completely from regenerative energies sources such as wind, hydro and photovoltaic and will be supported by an appropriate energy storage system with, e.g., lithium-ion batteries or lead-gel or even lead acid batteries. A high-level management system shall be used to control the individual energy generators together with the connected consumers, e.g., loads like milking aggregates cooling systems or small production machines. This allows to avoid peak loads and to trigger suitable processes in case of energy surplus or deficiency. A successful implementation is linked to further objectives and sub-goals considering the initial situation. The objectives are:

- Adaptation of small water turbines (WT) for operation under harsh climatic conditions and the optimization of the local energy gain under the conditions in Central Asia;
- Adaptation of PV modules for large temperature fluctuations and optimization of the energy yield of PV systems with new concepts such as bifacial PV modules under the climatic conditions in Central Asia (local irradiation conditions, high albedo absorption potential due to diffusion and reflections of snow-covered surfaces, low module operating temperature);
- Optimization of the charge and discharge process of lithium-ion or lead-acid batteries to extend their operational life time at the specific climatic conditions at the target area.
- Increasing of reliability and durability of the components such as power electronics and batteries by means of prioritized energy supply to air conditioning of the central container, de-frosting of the PV modules and de-icing of the wind turbine mechanics;
- Operation of communication systems, software implementation to control small scale decentralized energy supply systems, and adaptation of power generation to the needs of consumers, e.g., considering short- and mid-term weather forecast;
- Sensor support system with interconnection by other subsystems via Industrial IoT means to implement a predictive maintenance paradigm;
- Construction of weatherproof computer systems based on one-chip systems, operation of communication systems considering local regulatory frequency restrictions and under harsh conditions such as temperature range from -55 °C to + 45 °C. A conceptual view of such a DeEn_CA system is shown in Figure 1 below.

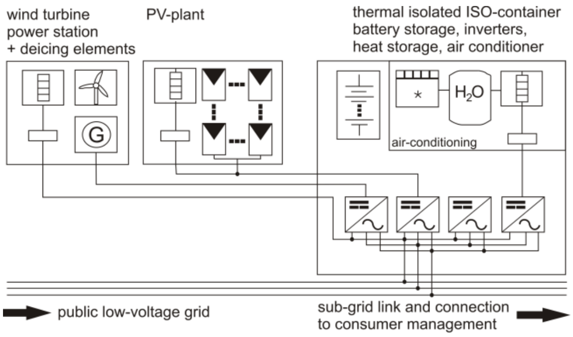

Figure 1: Overview of a DeEn_CA system with wind and photovoltaic, batteries and inverters.

3 CONCEPT AND PROPOSED APPROACH

To reach the project's objectives we propose to construct a few pilot systems in several places across Kazakhstan and Kyrgyzstan, which differ significantly from each other according to the local energy sources, climatic conditions and the customer needs. A previous study will collect specific data of each location such as energy demand, weather data and the local infrastructure to select the best solution. With the collected data and experiences, we will create an energy supply and consumption chain for agriculture in rural areas. This will clearly add value to small farmers and thus trigger a positive socio-economic reaction in the area towards the ecological and sustainable cultivation of rural areas in Kazakhstan and Kyrgyzstan.

As a typical consumer in Kazakhstan we consider a medium-sized dairy farm with about 100-200 cows and with a few attached residential houses. Depending on the season, usually such a dairy uses two to three times a day an electrical milking machine. In addition, a local refrigerating storage house to preserve the milk is used. These consumers have a certain energy demand, which can be adapted to the needs and the current weather conditions and thus it would be possible to reduce the size of the energy storage. Furthermore, the electrical lighting of the farm and the residential building will be realized with the same system.

3.1 Wind power plants

Two different types of wind turbines will be built. One adapted wind turbine with a classical horizontal axis design as provided e.g. from enbreeze GmbH or other German manufacturers and at the same site a wind turbine with a vertical rotor system. This type of wind turbine is developed by Prof. Bolotov, AUPET (Almaty) for very cold regions with dominance of multi-modal winds [3]. Thus, valuable results can be gained during the project to investigate the best wind turbine structure for providing an optimized yield and high reliability under the specific wind conditions of Kazakhstan.

3.2 Photovoltaic power plants

The aimed project will also consider to emerge PV technologies to increase the potential energy yield and the reliability in respect to the climate and geographical conditions at the installation sites. The very high temperature differences and irradiation properties over the north-south expansion of Kazakhstan shift the requirements on the installed PV modules for a more accurate dimensioning. High amount of snow can on one hand force damages on the module due to high weight but on the other hand snow can increase the energy yield due to its high reflectivity. So, we will use framed glass-glass PV modules to increase the reliability and bifacial PV modules to increase the energy yield. Bifacial PV modules use not only the in-plane irradiance on the front but also the reflected irradiance from the ground. Section 4.2 shows simulation of a bifacial PV system for different locations in Kazakhstan and Kyrgyzstan and a comparison to standard monofacial PV modules.

4 METHODS AND RESULTS

4.1 Requirements of the wind turbine system

Wind turbines with power ranges of 5 to 30 kW will be basically used. Especially, a 15 kW wind turbine will be redesigned mechanically and electronically, whereby the mechanical design and construction will be adapted to geographical requirements at the target area. Due to harsh climatic conditions it is not possible to use existing wind turbine solutions without region-specific adoptions. In addition, we want to investigate alternative solution to protect moving parts and electronics against icing and compare them to conventional solutions such as heating of the rotor blades, which are economical not feasible. Therefore, appropriate test trials in a climate chamber will be carried out to simulate long-term reliability. In addition, R&D work will be carried out when integrating the WT to the energy-management system.

The electronics and the rotor head control will be realized by IIoT sensor networks. The detected environmental/weather and technical/yield data from the system will be used for machine learning methods to predict electricity generation and demand on consumer site in short (minutes till hour) and medium-term (days). Those methods shall increase system efficiency and predictive maintenance options for essential components.

4.2 Simulation of PV energy yield at five specific location in Kazakhstan and Kyrgyzstan

4.2.1 Meteorological data

To estimate and compare the PV energy yield we have choosen five different location across five different climate zones in Kazakhstan and Kirgizstan. In Kazakhstan Nur-Sultan (former Astana) has a temperate continental climate (Dfb), Almaty has a warm continental climate (Dsa) and Ceyfullino represent a cold desert climate (BWk). Ceyfullino takes on special relevance as it is located in an agricultural isolated region in the desertic part of the country, therefore, it is qualifying for the established consumers' profile of the project. In Kyrgyzstan we have choosen Bishkek with a temperate mesothermal climate (Csa) and Osh in the high-mountain region of the country which represent a cold semi-arid climate (BSk). For comparison, we have choosen our own PV test filed at Anhalt University (Köthen, Germany) [4] which represent a moderate continental climate (Cfb) at the same latitude as Nur-Sultan. Table *1* shows an overview of all selected location with their geographical coordinates, climate zone and the optimal tilt angle for PV modules.

Table 1: latitude, longitude, optimal tilt angle and climate zone [5] of different locations in Kazakhstan, Kirgizstan and Germany.

Location	Latitude	Longitude	Optimal Angle	Climate Zone
Nur-Sultan (Kz)	51,1°N	71,4°E	38°	Dbf
Almaty (Kz)	43,2°N	77,0°E	35°	Dsa
Ceyfullino (Kz)	45,0°N	64,9°E	38°	BWk
Osh (Kg)	40,5°N	72,7°E	31°	BSk
Bishkek (Kg)	42,8°N	74,6°E	35°	Csa
Anhalt (D)	51,2°N	12,0°E	36°	Cfb

Figure 2 shows the yearly global irradiation at optimum tilt angle and azimuth (blue bars), rear-side in plane irradiation (yellow bars) together with the average ambient temperature (grey line) of the chosen locations in Kazakhstan, Kyrgyzstan and Germany.

Locations with high latitudes, such as Nur-Sultan, have a low irradiation tendency, whereas south located ones are prone to high irradiation such as Ceyfullino. The yearly global irradiation in Nur-Sultan is about 1350 kWh/m²/a and at Ceyfullion 1800 kWh/m²/a [6]. The average ambient temperature of the five locations is between 4 °C in Astana and 22 °C in Osh. However, the temperature range of the PV module can be between -50 °C to 60 °C at night and day, respectively.

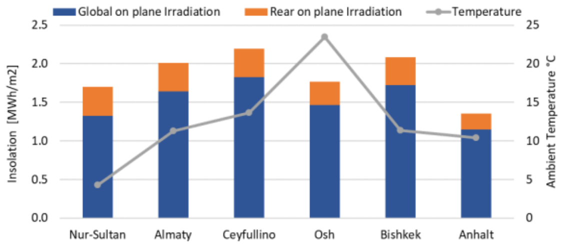

Figure 2: Yearly global irradiation at optimum tilt angle and azimuth (blue bars), surface rear irradiation (yellow bars) and average ambient temperature (grey line) of the locations in Kazakhstan, Kyrgyzstan and Germany.

In order to simulate the energy yield of bifacial module it is important to have information of the so-called Albedo at the given location. As per definition Albedo is the diffuse reflectivity of a horizontal surface which is defined as the ratio of the reflected irradiance by the surface and the received irradiance. Since the simulation of the bifacial PV module energy yield requires the in-plane rear-side irradiance. We need to consider the rear/front side irradiance ratio α at a given incidence angle [7], [8].

The influence of rear-side ratio is relevant for the consideration of energy generation of bifacial modules. The rear-side generates a significant addition to the front-side irradiation, particularly in winter due to intensive snowfalls in central, north and west of Kazakhstan. Thus, locations in the north that usually expose a higher number of snow days, like Nur-Sultan, are strongly beneficiated than locations in the south as Osh. However, seasonal variation such as due to vegetation can influence α. At Ceyfullino, located in a desert has seldom snow events during the year but the rear-side ratio can be higher due to local soil.

Due to the leak of rear-side irradiance data in metrological data in this study we consider α measurements of similar climates.

Figure 3-bottom shows the histogram of α for Anhalt and Vermont (continental climate) together with the mean (μ), the median and the standard deviation (σ). In the moderate climates such as Anhalt α is wider distributed around the mean value while in the temperate continental climate at Vermont we see two maxima in the distribution. One around 0.2 which represent the summer month and around 0.7 which represent the winter months with snow cover. Figure *3* shows instead the monthly mean value of α in a boxplot diagram. Seasonal variation could be observed at Anhalt due to the change of vegetation. In summer the grass turns from green to yellow/grey. Sandia_VT shows higher α values in winter due to snow. The ground is covered with snow from November to March. The high fluctuation is due to the fact that sometimes the snow melts and the substrate is visible. However, snow refreshes quick and therefore no long-term soiling issues are observed. Other location in desert climates show α of 0.2 to 0.4 without any seasonal variations [7].

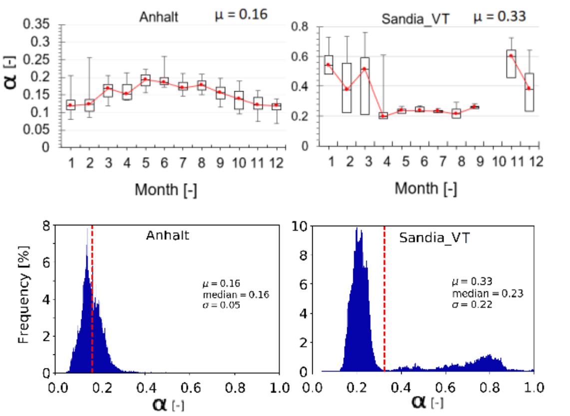

Figure 3: Seasonal variation, monthly average of rear/front side ratio (top), (bottom) Histogram of α together with mean (μ), median and the standard deviation (σ), (Sandia_VT: no data for October) [7].

Base on this study we assumed the number of days with snow and calculate the rear-side irradiance at the given location. The yellow bars in Figure 2 represent the calculated rear-side irradiation.

4.2.2 Bifacial energy yield simulation

Based on the above described metrological data we have simulated a 24 kWp PV system for all five locations using PVsyst version 6.86 [9]. In order to show the benefit of bifacial modules the simulation is carried out with monofacial and bifacial PV modules. Both module types consist of the same cell technology but the monofacial module consists of a white backsheet instead of a transparent one.

Figure 4 shows the monthly energy yield at Nur-Sultan (top) and Bishkek (bottom) together with the monthly irradiation. The grey bars show the energy yield of the monofacial PV modules and the orange bar the bifacial energy gain, i.e. the sum of both represent the specific energy yield of the bifacial modules. The red line represents the font-side irradiation while the blue line the total irradiation, i.e. sum of front and rear-side.

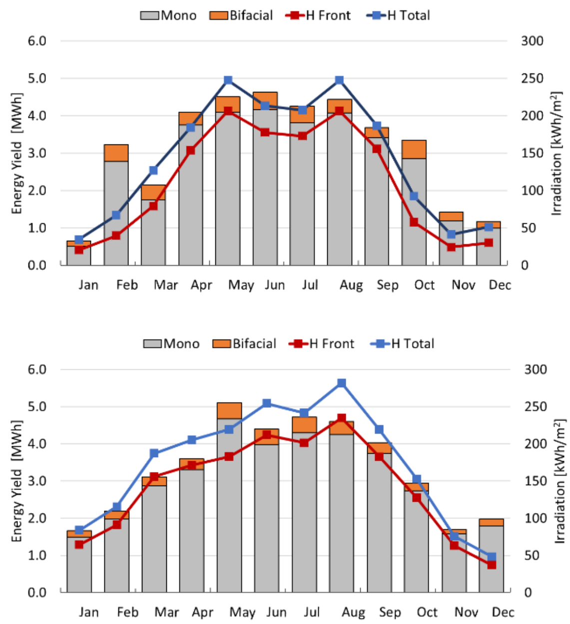

Figure 4: Monthly simulated energy yield for monofacial and bifacial PV modules together with front and total (front+rear-side) irradiation for Nur-Sultan (top) and Bishkek (bottom).

With a 24 kWp PV system consist of monofacial PV modules at Nur-Sultan the simulated energy over the year is about 34 MWh/a. This correspond to a specific energy yield of 1390 kWh/kWp. If instead of monofacial modules bifacial modules are used the energy yield is about 37,5 MWh/a or 1564 kWh/kWp. This is a gain of 12.4 % by using the same installation area and mounting structure. In the spring and summer months from April to September the energy gain is in average 9 %. Due to the snow cover in the winter months from October to March the energy gain is in average 20% in respect to the monofacial modules.

At Bishkek we calculate a yearly energy yield of about 37 MWh/a (1530 kWh/kWp) for the monofacial and 40 MWh/a (1670 kWh/kWp) for the bifacial, respectively. This is a gain of about 9%.

Due to the temperate mesothermal climate the gain is rather constant over the year with about 9%.

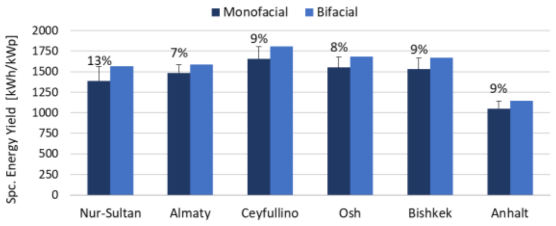

Figure 5: Yearly specific energy yield of a PV systems with monofacial (blue) and bifacial PV modules (dark blue) at six different locations in Kazakhstan, Kyrgyzstan and Germany.

Figure 5 shows yearly specific energy yield of a PV system with monofacial (blue bars) and bifacial PV modules (dark blue bars) at the six presented locations. It is clear visible that the energy yield increases with higher irradiation potential. Compared to Anhalt (Germany) all locations in Kazakhstan and Kyrgyzstan show a higher PV energy generation, e.g., Astana has about 23 % higher PV potential as Anhalt. This due to higher irradiation in winter month, more clear days and lower temperatures. In general, at all location the yearly bifacial gain is about 9%. For the northern region it is a bit higher due to the snow in the winter.

During the project we will carry out detailed measurement of the pilot system in order to improve energy yield simulation and optimize the energy management of the DeEn_CA systems.

5 CONCLUSIONS

We showed concept of a solution for energy-efficient and self-sufficient energy supply system in rural areas in Kazakhstan and Kyrgyzstan based on a combination of either wind-PV or µHP-PV combination. We believe that such small power decentral systems for very local demands in the radius of some hundred meters are economically feasible and can play as game-changers for the live in rural regions of Central Asia and Siberia. The presentations at the said travelling conference in March 2019 in Kazakhstan and Kyrgyzstan as well as in June in Almaty to experts in agriculture and energy sector of Kazakhstan, Kyrgyzstan and Tajikistan have proven the high relevance of implementation of such a system

The photovoltaic potential is at least 20 % higher than in Germany. Bifacial PV modules can enhance the energy yield be at least 9% by using the same amount of installation area and mounting structure.

In a next step we are aiming at establishing of a strong consortia of research institutions along with corporate players to perform necessary applied research, tests and adoption of the industrial systems for implementing a field setup in a context of a suitable funding program in Central Asia.

ACKNOWLEGMENT

This work was funded in part by the German Federal Ministry of Research and Higher Education, FKZ: 01DK18019. “Industrie 4.0 für Energieeffizienz und erneuerbare Energien in Zentralasien.

We would like to acknowledge all our partners in Kazakhstan and Kyrgyzstan.

REFERENCES

[1] AHK, Delegation der Deutschen Wirtschaft für Zentralasien, “Kasachstan – Netzintegration von Erneuerbaren Energien – Zielmarktanalyse”, 2017.

[2] U. Lohse, T. Andreeva, R. Brückmann, J. Tallat-Kelpšaitė, C. Blajin and C. Urbschat, “Enabling PV in Russia”, eclareon GmbH, 2019.

[3] S. Bolotov, vol. 10, 2019, [Online] Available: https://www.windrotor-bolotov.com/.

[4] S. Dittmann, “Energy Yield Measurements of bifacial PV Modules in Different Mounting Scenarios”, invited talk at PV Asia Scientific Conference, Singapore, 2018.

[5] M.C. Peel, B.L. Finlayson and T.A. McMahon, “Updated world map of the Köppen-Geiger climate classification”, Hydrol, Earth Syst, Sci. vol. 11, 2007, pp. 1633-1644.

[6] “Photovoltaic geographical information system of the European Commission (PVGIS)”, vol. 12, 2019, [Online] Available: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html.

[7] S. Dittmann, H. Sanchez, L. Burnham, R. Gottschalg, S. Oh, A. Benlarabi, B. Figgis, A. Abdallah, C. Rodriguez, R. Rüther and C. Fell, “Comparative Analysis of Albedo Measurements (Plane-of-Array, Horizontal) at Multiple Sites Worldwide”, in: 36th European Photovoltaic Solar Energy Conference and Exhibition. Marseille, France, 2019, pp. 1388-1393.

[8] L. Burnham, S. Dittmann, R. Gottschalg, A. Benlarabi, B. Figgis, T. Reindl, S. Oh, K. Kim, J. Choi, R. Ruther and C. Fell, “Photovoltaic Collaborative to Advance Multi-Climate Performance and Energy Research (PV CAMPER)”, in: 36th European Photovoltaic Solar Energy Conference and Exhibition, 2019, pp.10-11.

[9] PVsyst 6.86, vol. 12, 2019, [Online] Available: https://www.pvsyst.com/.