RETSCREEN MODELING FOR COMBINED ENERGY SYSTEMS: FERTILIZERS PLANT CASE

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ABSTRACT

Switching from traditional industrial systems to a modern way of organizing all processes (including energy supply) on the principles of 'green' economy is an up-to-date task, especially for countries under development. The article discusses the using of alternative energy sources to supply part of the energy demands of a chemical plant to produce fertilizers from natural gas in Ukraine. Fertilizers plants consume dozens of MW of power supplied from the grid. A plant pre-analysis showed that there was a high potential for using alternative energy sources. By using RETScreen 4 software it was possible to model systems with one or several alternative energy sources, calculate energy balances, and compare their performance. The results showed that hybrid electricity supply systems can perform beneficially for industry in terms of economy, diversification and environment.
*Keywords:*Combined Energy Supply, Hybrid Energy Systems, RETScreen Modeling, Ukraine Energy, Renewable Energy

NOMENCLATURE

b_{eq}	specific cost for auxiliary equipment as a share from main
b_m	specific maintenance cost from the main funds
C	expenses for new technology implementation [$]
CF	capacity factor [%]
c_f	cost of fuel unit [$/m^3]
c_m	maintenance cost [$/kWh]
C_u	cost of generating unit [$]
g	acceleration of gravity [9.81 m/s^2]
h	falling height, head [m]
P	installed capacity [kW]
P_n	nominal capacity [kW]
P_{th}	power theoretically available [W]
q	fuel use per kWh of energy production [m^3/kWh]
T_{eq}	exploitation term of auxiliary equipment [years]
T_u	exploitation term of the unit [years]
v	water flow [m^3/s]
v_0	initial water flow [m^3/s]
v_n	nominal water flow [m^3/s]
W	energy produced in average year [kWh/year]
ρ	density [kg/m^3]

INTRODUCTION

Ukraine is an energy dependent country which imports 62% of natural gas, and 70.5% of consumed oil and oil products, and nuclear material[1, 2, 3, 4]. At the end of 2013 over 60% of electricity was generated from natural gas and coal on CHPs (combined heat and power plants) and TPPs (thermal power stations), about 25% was generated from nuclear and about 10% from large-scale hydropower[5]. As energy price is steadily growing both individual consumers and industry are highly concerned on decreasing their grid energy dependence.

Energy carriers have a significant influence on the gross domestic product (GDP) level and economical development of the state[6, 7]. When analyzing the vulnerability of consumers to energy resources' price change, it appeared that the population's consumption is partially subsidized, while industry is highly vulnerable to any fluctuations of energy tariff. The most energy consuming industries are iron & steel, non-ferrous, chemical and petrochemical industries. In 2011 chemical and petrochemical industry consumed 6,248.5 millions kWh, which is 4.1% of the total electricity consumption[8].

According to the goals of the Energy Strategy of Ukraine the country is focusing on diversification of energy sources and wide implementation of renewable energy sources (RES), which should provide 10% of total electricity generation[9] by 2030. This goal will also meet the agreements Ukraine signed on mitigating climate change and pollution[10], since Ukraine has one of the highest levels of air pollution in Europe[11]. Producing green house gases (GHGs) emissions during both technological processes, and consuming energy industry has a significant carbon footprint, which is hardly regulated by governmental policies.

In this article the case of a fertilizer plant is considered as a typical example for a chemical industry in Ukraine. An ammonia plant mainly uses two types of energy carriers: natural gas and electricity[12]. Energy use, especially for ammonia production, has been growing since the 1960s due to expansion of production[13].

Energy price takes a large share in the prime cost formation of produced goods, thus affecting the market position and the ability to be internationally viable for the producers. Nowadays industrial plants in Ukraine obtain electricity from the Unified Electricity Grid of Ukraine (the UEG). Ammonia production has a high potential for energy saving via modernization of technological processes[14]; the article does not consider them because of high investment costs and region peculiarities. To raise the reliability and decrease the dependence on a single supplier the following actions are suggested:

- improving energy efficiency of local energy system (equipment modernization, energy saving measures);
- diversification of suppliers and tariff's change;
- modeling combined supply system.

Such energy systems are combined from renewable and alternative energy sources with or without connection to unified grid. They allow to use energy more fully and optimize energy flows via close interaction between different parts of energy complex. They are widely implemented for households and resorts in remote areas [15, 16, 17]; however, an explicit mechanism for modeling combined energy supply system for industrial plants is not yet developed.

DIVERSIFICATION OF POWER SUPPLY

In industry traditionally the supply from other sources has not been considered as it has not been proven to be profitable. Resources for implementation, accurate demand forecast, grid requirements and holistic benefit are hard for intrinsic estimation. However, diversification of energy sources for local energy systems, especially industrial plants, can lead to significant decrease of energy expenses. In its turn, it will decrease the energy intensity of production and energy expenses share in final goods price[18]. This will lead to higher competitiveness on the market. In fact, including "green energy" in energy supply can raise social acceptance and attract the "smart-consuming" customers[19]. Developed methodology includes analysis of ecoclimatological conditions, possibility for connection to the secondary service and technological processes analysis. The considered renewable energy sources are wind, solar PV energy (which are intermittent sources) and hydro-power (which is more reliable). The plant is located in industrial region. Due to lack of available biomass such electricity plant was not considered in this case study. As an alternative energy source improving general efficiency of energy use a turbogenerator is considered.

The localization of energy suppliers can have positive influence on decreasing the number of current long distance electricity transmission. The consumption was growing through years and the transmission capacity did not bringing the exhaustion of equipment. The distribution of energy sources can help to lessen the load on the transmission lines and decrease transmission losses. In this article a model for electricity supply is worked out for a fertilizers plant with potential ability for alternative sources connection. The following questions are discussed:

- Which configuration of combined system is the most effective?
- Can a combined system lead to economical benefits?
- What environmental effect will be gained if a combined system is installed?
- What is the payback period for such system?

The software used for modeling and analyzing the hybrid system is RETScreen 4 software[20]. RETScreen is a free tool for modeling, simulation and pre-feasibility study of energy effective and environmental-friendly systems. It provides eco-climatological and meteorological data for most regions of the world (from NASA data) and also uses an extensive database for equipment (solar panel collector, pumps, pipes etc), making it an excellent tool for pre-feasibility and environmental studies. The software was adapted to the case of the industrial plant, however, hand calculations can also be applied. Alternative software to RETScreen like HOMER or Hybrid2 can be also used[21].

THEORY AND CALCULATION

While modeling a local supply system, the following aspects should be considered: reliability and conditions of energy sources, transmission capacity and environmental impact. Considering intermittent availability of some sources it is necessary to provide accurate forecasting on both demand and supply sides. Establishing combined energy system requires simultaneous to power curve fluctuations demand-side management (DSM) for decreasing network risks[22, 23]. DSM is required for further optimization of combined system functioning via attribution an optimization target function. The majority of big enterprises operate with constant electricity demand with no peak or minimum load as they have normalized product output per hour. The energy supply should be constant and reliable, as it can lead to money loss.

When reviewing the energy system of the fertilizers plant in the Rivne region a possibility for connecting alternative sources was found. The analyzed fertilizers plant uses mostly two energy carriers: natural gas and electricity, which cannot be substituted. Combination of renewable and alternative energy sources with the UEG can create a stable and diverse energy system able to provide the cheapest available energy at every moment of time. The fertilizers plant does not produce bio-waste, thus potential for developing biogas utility is low. Eco-climatological conditions and available territory should be scrutinized to evaluate if they are potentially good for installing large wind or solar PV stations. In technological processes natural gas is used not only for energy, but as a raw material. During the ammonia production(fig.) natural gas, water and electricity are used; and, heat is produced. Ammonia is obtained from natural gas after carbon monoxide conversion and gas purification from CO_2. Ammonia synthesis in the fertilizers plant happens in reactors under pressure 280–330 bar. To compress syngas four-stage compressor with a nominal capacity of 32 MW and a productive capacity of 1360 t NH_3 per day is used. Its turbine consumes 350–370 t of vapor received after reforming with parameters 100 bar and 482 °C per hour. This turbine produces and the compressor consumes the biggest amount of mechanical energy/work. Energy losses under exhaust steam condensation are about 1.465–1.675 GJ/t NH_3. Analyzing technological processes [13] of fertilizers plant the following conversion takes place:

$$N_2 + 3H_2 = 2NH_3 + heat \quad (1)$$

The compression energy during the process converts into heat, which is transferred further with the vapor. This vapor at 105 atm does not perform useful work. According to Ukrainian legislative framework the high-temperature vapor cannot be released into atmosphere. Thus, the enterprise should waste additional energy on compressors and pumps for cooling purposes. During the cooling processes water obtained from the nearby river is used. The river has a high energy potential according to its head and flow, besides, it is affluent enough to be used during all year.

The proposed cases for combined energy system for

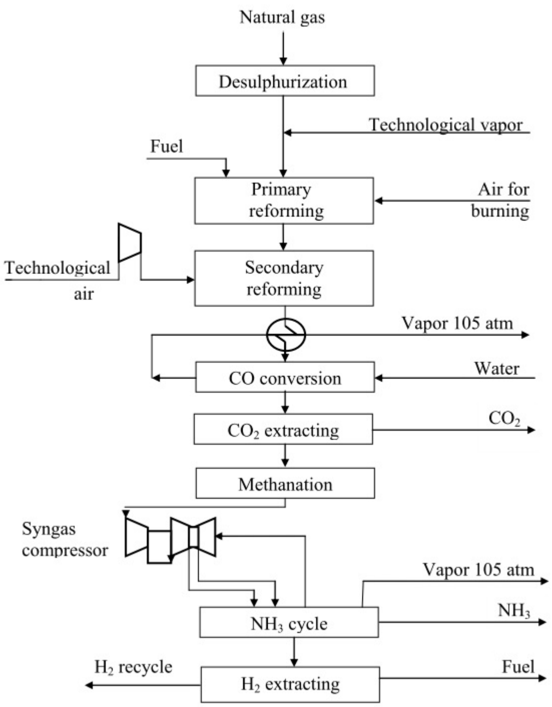


Figure 1: Technological scheme

the fertilizers plant operate on the UEG combined with 1) a turbogenerator on exhaust vapor; 2) a mini-hydropower plant; 3) a solar PV station and 4) a wind power station.

The following combinations can become more complex if interconnected and operating either in sequential or in parallel mode. To calculate the expenses from non-renewable energy sources eq. 2 can be used.

$$C = \frac{C_u}{T_u \cdot W} + c_m + c_f \cdot q \qquad (2)$$

where: C_u: cost of the turbogenerator unit, \$; T_u: exploitation term of the unit, years; W: energy produced in average year, kWh/year; c_m: maintenance cost, \$/kWh; c_f: cost of fuel unit, \$/m^3 (in the case of the turbo generator the price is already included as it has been used for ammonia production); q: fuel use per kWh, m^3/kWh. The expenses from renewable energy sources are obtained through eq. 3.

$$C = (\frac{C_u}{T_u} + \frac{C_u \cdot b_{eq}}{T_{eq}}) \times \frac{1 + b_m}{W} \qquad (3)$$

where C_u: cost of generating unit, \$; T_u: exploitation term of the unit, years; W: energy produced in average year, kWh/year; T_{eq}: exploitation term for auxiliary equipment, years; b_{eq}: specific cost for auxiliary equipment as a share from main; b_m: specific maintenance cost from the main funds.

Energy consumption

The energy model is typical for fertilizers plants in Ukraine. They have a constant energy consumption not much depending on day, season, year (fig.) with traditionally normalized production output. The average day load is 1656 MW, and the major consumers are compressors for NH_3–H_2 circulation, turbine, additional heater, filters, reformers etc.

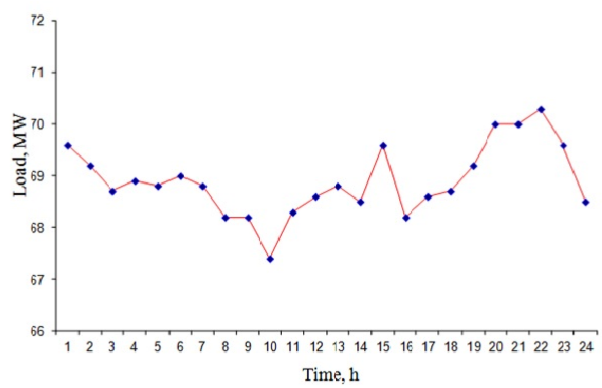


Figure 2: Load curve of the fertilizers plant

Turbogenerator

Cogeneration has proved itself cost-efficient in many industrial sectors [24, 25] with its short payback period and high energy potential. The input parameters for turbogenerator in table 1 are used to calculate energy saving from installation. A turbogenerator for the case perform work during all year (except for maintenance period) since waste vapor requires utilization. The theoretical capacity of the generator is 12,926 kW.

Hydropower

The plant uses water for technological processes from the nearest river. The characteristics of flow (5.2 m^3/s) and head (25 m) allow to calculate theoretical power capacity via eq. 4.

$$P_{th} = \rho \times v \times g \times h \qquad (4)$$

Table 1: Input data for the turbogenerator

Parameter	Value
Steam flow, kg/h	100,000
Operating pressure, bar	106
Superheated temperature, °C	500
Back pressure, kPa	7
Return temperature, °C	70
Steam turbine (ST) efficiency, %	35
Minimum capacity, %	98
Seasonal efficiency, %	90

where: P_{th}: power theoretically available, W; ρ: density, kg/m^3 (for water ~1000 kg/m^3); v: water flow, m^3/s; g: acceleration of gravity, 9.81 m/s^2; h: falling height, head, m.

This formula results in theoretical capacity of 1,200 kW and with efficiency of 93% the power capacity will be of 1,186 kW. To complete the calculations for the hydropower plant a capacity factor defined by eq. 5 is required:

$$CF(\%) = \frac{W}{P \times 8760} \cdot 100\% \qquad (5)$$

where: W: energy generated per year, kWh/year; P: installed capacity, kW with 8760 hours per year. Knowing the capacity factor and installed capacity from table 2, the produced energy can be calculated from eq. 5.

Table 2: Input data for renewable powerstations

Parameter	Hydrostation	Wind	Solar PV
Power capacity of one unit, kW	1,186	2,000	0.32
Number of units	1	3	3000
Total power capacity, kW	1,186	6,000	960
Capacity factor, %	66	46	16

The Canyon Hydro Cross-flow turbine was chosen for medium-head torrent. Electricity delivered to load will be W=6,857 MWh per year. The electricity generated from the hydro-power station depends on energy potential of the flow; the generation mode can be described by eq. 6:

$$W(v) = \begin{cases} 0 & \text{if } v \leq v_0 \\ W & \text{if } v_0 \leq v \leq v_n \\ W_n & \text{if } v_n \leq v \end{cases} \qquad (6)$$

where: v_0: initial water flow speed; v_n: nominal water flow when the hydro station generates P_n: nominal capacity.

Meteorological Data input for wind and solar energy estimations

Table 3 shows the meteorological parameters to calculate wind and solar energy use potential for the selected region (Rivne), which are available in NASA database in RETScreen.

Wind

RETScreen has a good database of wind turbines which can provide highly accurate data input. For the calculation a simplified method was applied using parameters from table 2. There is theoretical possibility for installing wind powerstation of 3 turbines of about 70 m high on the plant's territory, however, such factors as shadowing objects, wind speed and wind rose should be scrutinized. Such wind powerstation will require high capital investments.

Solar PV

The estimated solar potential of Ukraine is 718.4 $\cdot 10^9$MWh per year (53.8$\cdot 10^5$ MWh per year are economically viable for extraction); the Rivne region in particular has a potential of 21.8$\cdot 10^9$ MWh per year (and 1.6$\cdot 10^5$ MWh per year respectively). While solar heaters can be applied in Rivne region only for 5 months in a year (since May till September), the PV station can provide energy output during all year. The combined system with solar PV uses the data in table 2. There is no big opportunity for developing a PV station by the plant since it would require a vast territory without shadowing objects, which is not available. However, the solar PV panels can reside on the roofs. For the calculation the mono-Si panels produced by Sunpower were considered. The frame area of such panel is 1.62 m^2 and efficiency is 19.62%. Total electricity delivered to the load will result in 1,346 MWh per year.

Hybrid system: hydropower station & turbogenerator

The possibility for interconnection several sources is considered via modeling hybrid supply system consisting of the grid, turbogenerator and a mini-hydro powerstation (fig.). Electricity from grid and turbogenerator is used to cover the base load, hydropower plant is used mostly in hours of semi-peak and peak

Table 3: Meteorological parameters for Rivne

Month	Air temperature, °C	Relative humidity, %	Daily solar radiation, kWh/m^2/d	Atmospheric pressure, kPa	Wind speed, m/s	Earth temperature, °C	Heating "degree-days", °C-d	Cooling "degree-days", °C-d
January	-3.4	83.9	1.01	99.2	5.0	−5.0	663	0
February	-2.9	82.1	1.81	99.1	4.7	−4.1	585	0
March	1.1	77.6	2.83	99.1	4.6	1.0	524	0
April	8.4	69.3	3.87	98.8	4.2	9.9	288	0
May	14.3	68.0	5.08	98.9	3.9	16.5	115	133
June	16.6	73.5	5.17	98.8	3.7	18.9	42	198
July	18.7	74.5	4.98	98.8	3.3	20.7	0	270
August	18.0	73.8	4.58	98.9	3.3	20.5	0	248
September	13.1	78.7	3.02	99.0	3.8	15.0	147	93
October	7.9	80.7	1.87	99.3	4.2	8.5	313	0
November	1.8	85.3	1.04	99.2	4.5	1.0	486	0
December	-2.1	86.2	0.81	99.3	4.8	−4.1	623	0
Annual	7.7	77.8	3.01	99.0	4.2	8.3	3,786	942

Table 4: Plant implementation and maintenance cost

Parameter	Turbo-generator	Hydro-station	Wind turbines	Solar PV
Incremental initial costs, thousand $	5,000	2,000	12,000	2,100
Project life, years	20	25	25	20
Other initial costs, thousand $	3,000	200	1,500	400
O&M annual costs, thousand $	20	10	30	50

grid load. This configuration allows the plant to obtain energy from different sources during the day. The input parameters for calculation vide supra (tables 1, 2).

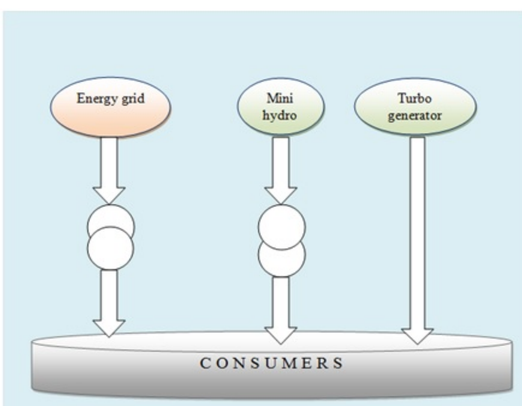


Figure 3: Electricity supply from grid, hydropower and turbogenerator

Financial data input

Table 4 reflects the input data for economic feasibility study. In the case if a loan is provided for the combined system implementation the financial parameters were input as: inflation rate: 2%, debt ratio: 80 %, debt interest rate: 4.5%, debt term is considered to be: 10 years. It is possible to make hand calculations, however, in this article further economical analysis was conducted in RETScreen.

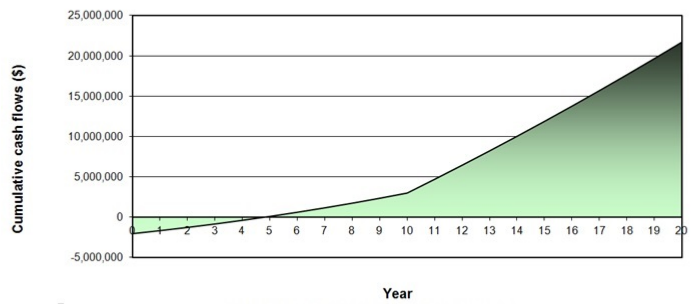


Figure 4: Cashflow for a hybrid system case (grid, turbogenerator and mini-hydropower plant)

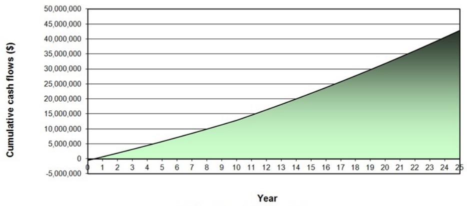
Station type	Maximum available capacity, kW	Simple payback period, years	Pre-tax IRR assets, %
Hydro	1,186	1.6	57
Turbogenerator	12,926	5.8	11
Wind	6,000	9.8	5.0
PV	960	1.8	47.7
Hybrid (hydro-, turbo, grid)	14,112	7.4	6.8

Table 5: Financial results

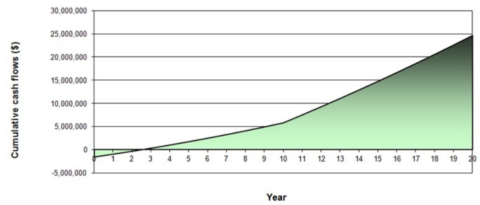
RESULTS

Economic analysis In the table 5 are shown obtained results for the systems to be compared. The combined systems were analyzed for the maximum available capacity, simple payback period and pre-tax IRR-assets.

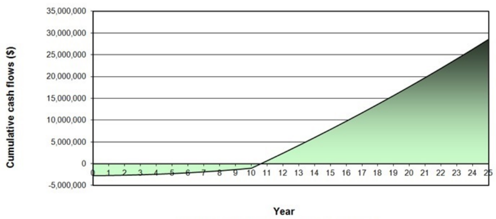
To compare the economic performance of combined energy systems the cash flows are shown on fig.4,5 , .



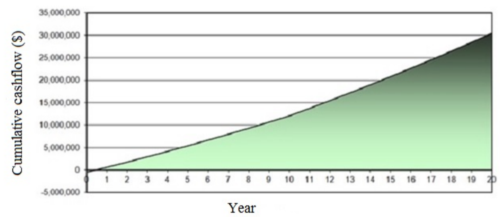
(a) Hydrostation



(b) Turbogenerator



(c) Wind station



(d) Solar PV station

Figure 5: Comparison of cashflows: Hydrostation, Turbogenerator, Wind station and solar PV station

Energy source	Net annual GHG emission reduction tCO_2	
	Coal substitution	Natural gas substitution
Hydrostation	3,966.1	2,766.2
Turbogenerator	-76,636.0	-94,865.7
Wind powerstation	13,984.5	9,753.5
Solar PV panels	778.3	542.8

Table 6: Emissions analysis

Emissions analysis Introduction of combined energy system does not lead to direct GHGs emissions reduction. Conventional emissions reduction takes place as less of electricity is taken from the UEG. The potential not delivered GHGs can be estimated by the volume of emissions from the UEG generating units. As the biggest GHGs emitters are coal and gas CHPs, the analysis was provided for both cases (table 6).

DISCUSSION

From the tables 4, 5 it is shown that implementation of the wind powerstation is the most expensive project, which requires the longest payback period (almost 10 years) and a big territory. The hydropower plant and the solar PV station have the shortest payback period (less than 2 years). Maximum available capacity is in a close range, however, the hydropower plant can provide with flexible in time energy output and energy accumulation while the solar power is intermittent and requires precise radiation forecasting system. The turbogenerator has the highest potential for energy utilization via available capacity (almost 13,000 kW) and less than 6 years of payback period, which makes it optional for installation. The environmental analysis pointed out a significant reduction in GHGs emissions while implementing any of before-mentioned combinations. As the GHGs reduction depends a lot on stations' capacity it is shown (table 6) that wind powerstation has the highest environmental potential. In case of the turbogenerator installation there is no GHGs reduction as it operates on vapor received during natural gas processing. However, almost complete utilization of natural gas and wastes allows to say that conditional decrease in emissions is taking place.

CONCLUSION

At the recent level of renewable technologies development complete refill of industrial energy supply from the grid to the RES is impossible. However, the partial generation is proven to be beneficial. RETScreen provided pre-feasibility studies to find the most viable supply system, which is combined from mini-hydropower plant, turbogenerator and the unified grid. The system can work in sequential or in parallel mode. Solar PV station and wind powerstation have lower potential performance. Introducing renewable sources in supply chain will slightly reduce energy dependency from ultimate supplier — the grid; improve reliability of supply and decrease the UEG load. The model is of ultimate interest for industrial plants in remote areas and for those with intermittent electricity supply from grid. Optimization of energy supply of chemical industry can lead to significant energy and resource-saving and have a huge impact on all energy sector of Ukraine. Overall, it has a potential for decreasing GHGs emissions from power generating units (via carbon footprint), creating 'green' workplaces, and reduction of local air pollution. The study opens further questions, i.e. what other factors influence on combined energy systems, what will be the contribution of state's energy policies, how to make the system work in the optimal mode and if the real life benefit will be close to pre-feasibility study. Consideration of other RES (like biomass, biogas etc.) will make a complete picture for a future research.

GLOSSARY OF ACRONYMS

CHP: combined heat and power plant.

DSM: demand-side management.

GDP: gross domestic product.

GHG: green house gases.

IRR: internal rate of return.

NASA: the National Aeronautics and Space Administration.

O&M: operation and maintenance.

PV: photovoltaic.

RES: renewable energy source.

toe: tons oil equivalent.

TPP: thermal power plant.

UEG: the Unified Electricity Grid.

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