International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: # 794

OPTIMAL SIZING FOR OFFSHORE WIND-BASED PUMPED HYDRO STORAGE SYSTEM IN CONNECT TO THE MAIN GRID NETWORK

Xiaoyu Liu[1], Nan Li[1], Hailin Mu[1*], Miao Li[2], Xinxin Liu[1]

1 Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian 116024, China

2 School of Mechanical Engineering, Dalian Polytechnic University, Dalian 116024, China

ABSTRACT

The hybrid wind-based pumped hydro storage system that absorbs the wind curtailment due to grid limitations is considered to be a solution to improve wind energy penetration and the cost-effectiveness of wind farms. An offshore wind-pumped hydro storage hybrid power system connected to thermal supplied main grid is proposed in this paper. The contribution of this paper can be summarized as follows: (1) a multi-objective dynamic economic optimization model for the proposed system based on evolutionary algorithms is established to optimize size for offshore wind-based pumped hydro storage system; (2) design parameters include the capacity of pump, turbine and reservoirs, and the key financial parameters such as wind power feed-in tariff and capacitor price of pumped hydro storage power station are also taken into account; and (3) examine the attainability of various objectives to analyze the influence on the operation and economic effectiveness. The results show that the optimizing size study is importance to test the economic feasibility of the system. The case study presented in this paper provides decision makers with the flexibility to choose the appropriate capacity installation under different expectations.

Keywords: pumped hydro storage, hybrid power system, wind curtailment rate, capacity optimization, cost-effectiveness

NONMENCLATURE

Abbreviations

NPV	Dynamic Net Present Value
PHS	Pumped Hydro Storage
HPS	Hybrid Power System
MG	Main Grid

Symbols

PU	Pump Capacity
NT	Turbine Capacity
VR	Capacity of Reservoir
t^{oc}	Operation Cycle Time of PHS
T^{oc}	Length of Each Operation Cycle of PHS
η_p	Pump Efficiency
η_g	Turbine Efficiency
A_1	Annual Electricity Sales Revenue of Wind Farm
A_2	Annual Penalty for Failing to Meet the Guaranteed Load
A_3	Annual Capacity Price Revenue of PHS Station
A_4	Annual Electricity Sales Revenue of PHS Station
C_0	Initial Investment of HPS
α	Decision-maker's Share of C_0
β	Loan Capital Share of C_0
i	Discount Rate
δ_i	Loan Depreciation Rate
g	Inflation Rate
m	Annual Cost Expenditure
y	Ratio of Electricity Purchasing Price to Selling Price of PHS Station to MG
n	Year
¥	China Yuan (CNY)
R_C	Reduction Ratio of Wind Curtailment

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

R_T	PHS Station's Dependence on Thermal Power

1. INTRODUCTION

Renewable energies are declared by policy makers as one of the pillars to combat climate change [1]. In recent years, offshore wind energy is receiving more concerned because it is abundant and consistent in many regions to provide reliable energy production [2]. Chinese installed offshore wind power capacity is expected to reach 10GW to 12GW by 2020 [3] during the 13th 5-year plan (2016-2020).

However, the remarkable wind curtailment—mainly caused by the instability of wind resources, leads to serious financial losses to wind farm owners, which affects the enthusiasm of future investment in wind energy [4, 5]. Energy storage technology is considered as an effective way to absorb wind curtailment and increase the income of wind farm. And the use of PHS station to absorb surplus rejected wind power from the grid is currently a measure advocated by the Chinese government to reduce the curtailment rate. In recent years several studies have been carried on utilization of PHS facilities with the wind power system connected to MG [1, 6-11] and island electrical networks [12-18]. These studies mainly studied the role of PHS in improving wind power penetration and increasing the income of wind farms through simulation, optimization, scheduling and other methods. In this study, another very important function of PHS—modulating peak for thermal power based grid will also be considered and analyzed. An economic optimization model is presented based on the NPV method which could reflect both investment cost and future revenue to optimize size for offshore wind-based PHS system and examine the economic feasibility under different functional objectives of PHS station. Two operating scenarios are set according to the two functions of PHS station (reducing wind curtailment rate and filling valley and modulating peak). The optimization model includes three decision variables of PHS system configurations—pump size, turbine size and the capacity of reservoirs.

The case study presented in this paper provides decision makers with the flexibility to choose the appropriate capacity installation under different expectations. This paper is organized as follows: Section 2 presents the offshore wind-pumped hydro storage HPS examined in the model in more detail. In section 3, the mathematical formulations of models are presented. The multi-objective optimization results and discussion in Section 4, followed by the main conclusions in Section 5.

2. DESCRIPTION OF HPS SYSTEM

The HPS used as a study case in this paper is located in the northern part of the Yellow sea, where the offshore wind farm (2×3MW, 49×3.3MW and 21×6.45MW) already constructed in 2019 and interest for the installation of PHS station already exists. The MG that wind farm connected to is primarily supplied by thermal power station. The schematic representation of HPS is shown in Fig 1.

The wind farm provides committed wind power to the MG at constant capacity rate (60%) per hour and a penalty for losing to meet the committed power would be charged. The PHS station absorbs surplus wind power to pump water to upper reservoir for storage and the MG would provide supplementary power if the absorbed wind power is inadequate. In operating scenario Ⅰ (S-Ⅰ), pumping operating condition is available within the

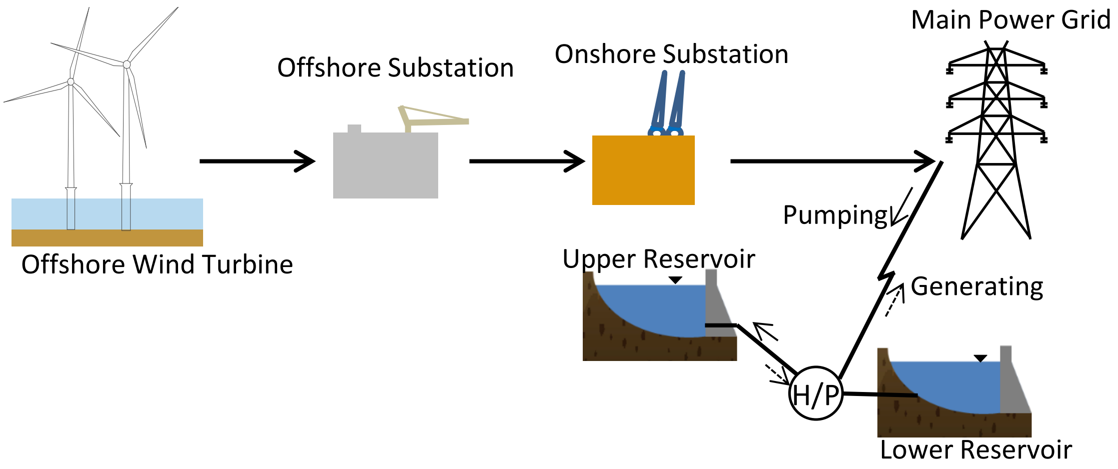

Fig 1 The schematic representation of HPS

24-hour period to minimize the wind curtailment rate. While pumping operations are carried out only at valley load demand time (from 1.am to 5.am) in operating scenario Ⅱ (S-Ⅱ), achieving effect of valley fling. The PHS station delivers guaranteed energy at full capacity on a daily basis during the peak load demand periods (from 10.am to 12.pm and 18.pm to 20.pm) to MG. Separate pumps and turbines are applied to provide the capacity to storage and generate electricity simultaneously in S-Ⅰ.

3. MODEL

3.1 Energy model

The expected wind power is modelled according to the wind energy model in Li Wang [19]. And the 90-meter offshore wind speeds input into the wind energy model could be obtained according to Zhang [20] and Chen [21] ignoring any dynamic stability and network constraints.

The PHS energy model is based on the principle of conservation of mechanical energy, which is described in detail in Tao Ma [22]. In order to meet the full capacity demand of PHS station, the PHS energy model needs to meet the constraints of electric power balance in every operation cycle- 24 hours and starts at 8 p.m. (for the last hour of daily electricity generation is 8 p.m.). Thus,

$$\sum_{t^{oc}=1}^{T^{oc}} NT_{t^{oc}} + \eta_p \times \eta_g \times \sum_{t^{oc}=1}^{T^{oc}} PU_{t^{oc}} = 0 \qquad (1)$$

3.2 Optimization model

In this paper, the HPS system is assumed to owned by the same owner. The dynamic economic optimization model is established based on J.S. Anagnostopoulos [23], combining the development situation of China's offshore wind farm and PHS stations:

$$NPV = \sum_{t=1}^{n}[A_1 - A_2 + A_3 + \sum A_4(1 - R_T y)] f_{\ I} - C_0 \times \left[\alpha + \beta \left(1 - \frac{\delta_i}{1+i}\right)^n + \sum_{t=1}^{n} m(1+g) f_{\ I}\right] \qquad (2)$$

$$f_{\ I} = \frac{1}{(1+i)^n} \qquad (3)$$

Energy tariffs in the model are shown in Table 1. And the HPS investment cost are provided in Table 2.

This paper assumes that the investment capital is shared by investors and loans: the α is set at 30%, while the β is 70%. According to current economic situation, the value of i, δ_i and g are 8%, 3.25% and 7.5% respectively. Annual cost expenditure m is estimated at 3% of C_0. The parameter y is 75% according to China's currently pumped storage power station electricity policy. The study period n is 20 years.

Table 1

A summary of energy tariffs in the model.

Items	Unit	Tariffs (CNY¥)
Offshore wind energy	kW•h	0.8
Penalty	kW•h	0.029
Capacity of PHS	kW-year	800
PHS energy	kW•h	0.3749

Table 2

A summary of HPS investment cost.

Items	Unit	Cost (CNY¥)
Offshore wind farm	303MW	5.1×10^9
Pump	kW	1000
Turbine	kW	3000
Reserviors	m^3	40
Others for PHS	/	20% of the total PHS station cost

The reduction degree of wind curtailment rate by PHS station while meeting the modulating peak function as well as the economic benefit of HPS after increasing investment in PHS station are the concern of decision makers. Thus, maximize the NPV / C_0 and R_C represent the economic objective and the absorption objective of surplus rejected wind energy, respectively. R_T is the ratio between the thermal power absorbed by PHS station from the MG and the power output from PHS station. Minimize R_T is the third objective which represents the degree of PHS station's dependence on thermal power.

4. RESULTS AND DISCUSSION

Together with the *PU* ranging from 20000 kW to 1000000 kW in steps of 1000 kW and the *NT* from 100000 kW to 900000 kW in steps of 50000 kW. The reservoirs (*VR*) range from 6 million m^3 to 15 million m^3 according to the local geography. MATLAB function *gamultiobj* has been applied to get the Pareto frontiers of multi-objective in different configuration schemes for S-Ⅰ and S-Ⅱ. The key objectives that affect the investment intentions of decision makers-the economic feasibility, reduction degree of wind curtailment rate and the dependence of PHS station on thermal power during operation of different configuration schemes for S-Ⅰ and S-Ⅱ are intuitively shown in Fig 2 and Fig 3.

It is obvious that the cost-effectiveness of HPS in S-Ⅰ is higher which could absorb 100% of surplus rejected wind energy in theory when *PU* exceeds the rejected wind power. While on the other hand, the supplementary thermal power is inevitable when the absorbed wind curtailment is insufficient to meet the pumping load. Even in S-Ⅰ, the R_T is approximately

60% when R_C first reaches 100% (*NT* is 700000kW, *PU* is 155000kW, *VR* is 10719024 m^3). Based on the optimization results in Fig 2 and Fig 3, it turns out that different strategies for absorbing rejected wind power lead to two distinct pareto frontiers of the three objectives. It can be seen that the two functions of PHS station-to reduce wind curtailment rate and increase the thermal power valley filling regulation, have different effects on the cost-effectiveness.

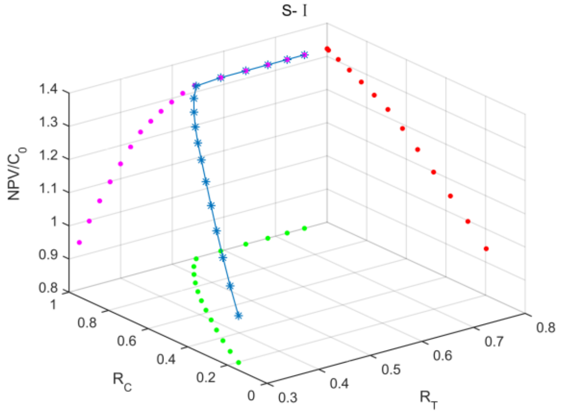

Fig 2 The Pareto optimization results of S- Ⅰ

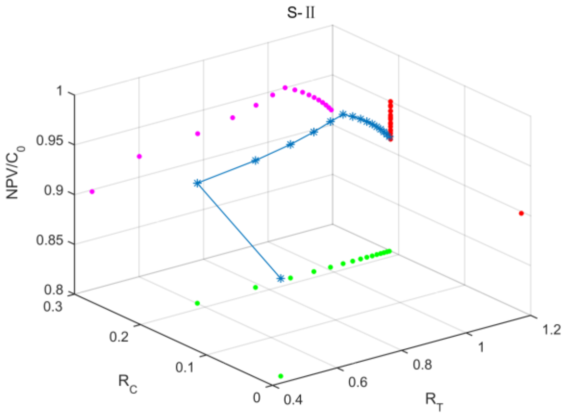

Fig 3 The Pareto optimization results of S- Ⅱ

In order to analyze the impact of *NT* on NPV/C_0 more intuitively, Fig 4 and Fig 5 show the relationship between NPV/C_0 and *NT*. In S- Ⅰ, there are three distinct regions of change for NPV/C_0: fast growth region *A*, moderate growth region *B* and maintain region *C*. R_C and R_T basically maintain a constant growth rate with the increase of *NT* when *NT* is less than 700000kW, respectively. When *NT* is less than 400000kW, the daily water demand for PHS station generating electricity is less than the minimum *VR*. Therefore, the unit installation cost of PHS station decreases rapidly in region *A* with the increase of *NT* which leads to a rapid increase in NPV/C_0. While the unit installation cost basically remains the same at ¥3,400 in region *B* for the *VR* becomes compatible with the *NT* after *NT* reaches 400000kW, leading to moderate growth trend of NPV before R_C reaches the peak. In region *C*, the increase of pumping load caused by the continuous increase of *NT* is all supplemented by thermal power for R_C is already at 100%, leading a rapid increase in R_T. But the imbalance of purchasing and selling electricity to the MG could not cause economic losses basically for the y value is set based on the mechanical energy conversion efficiency of PHS station. According to the economic optimization model in section 3.2, it can be seen that the increased capacity price revenue due to the increase of *NT* basically offsets the additional cost input, resulting in the NPV / C_0 maintaining around 1.323. Region *C* shows that there is no need for further investment when R_C reaches the peak if the decision makers are more focused on the wind curtailment rate reduction — continued capital input only increase the modulating peak effect of the PHS station, has no effect on the cost- effectiveness.

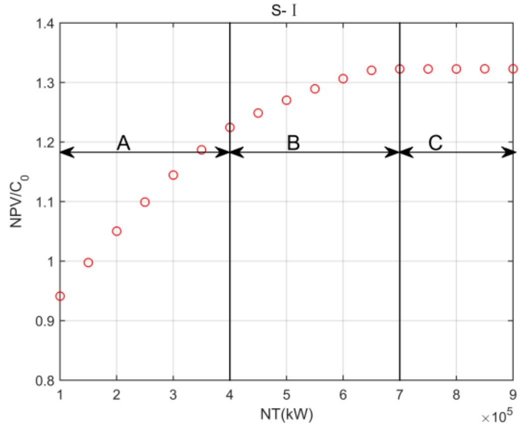

Fig 4 Relation with installed capacity of *NPV/C₀* in S- Ⅰ

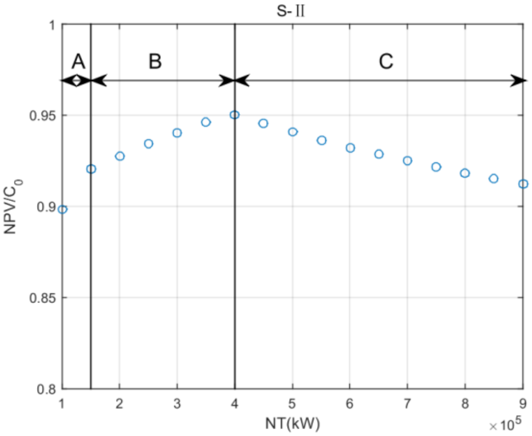

Fig 5 Relation with installed capacity of *NPV/C₀* in S- Ⅱ

It can be seen from the comparison of Fig 4 and Fig 5 that the NPV/C_0 in S-Ⅱ is lower than that in S-Ⅰ with the same PHS system configuration, which is mainly caused by the lower R_C (due to the pumping time) and higher unit installation cost (due to an increase in the *PU* matching the same *NT*) in S-Ⅱ. The trend of NPV/C_0 in S-Ⅱ is also divided into three parts: fast growth region *A*, moderate growth region *B* and moderate decline region *C*. The reasons for NPV/C_0 changes in region A are consistent with those in S-Ⅰ. Due to the limitation of pumping time, R_C reaches its peak (21.22%) when *NT* is 150000kW, *PU* is 159000kW and *VR* is 6000000 m^3. Although R_C has already reaches its peak in region B, the decreasing unit installation cost with the increase of *NT* still cause the continuous increase of NPV/C_0-reach the maximum 0.950 when *NT* is 400000kW, *PU* is 424000kW and *VR* is 6125157 m^3. However, in region C, the NPV/C_0 change trend of S-Ⅱ is completely different from that of the S-Ⅰ. When the unit installation cost basically remains at ¥4,407 in region *C*, the influence of absorbed surplus rejected wind energy on R_T is gradually weakened and R_T begins to show a slow growth trend towards the extreme value. And because the *PU* matched with the same *NT* increased significantly compared with the S-Ⅰ, the additional cost input has more impact on NPV/C_0 than the capacity price revenue, which cause a decreasing trend of NPV/C_0 with the increase of *NT*.

It can be seen from the above results that under different operation strategies, the cost- effectiveness, the reduction of wind curtailment rate and the dependence on thermal power of the HPS are all different. Therefore, it is necessary to analyze the operating benefits of each configuration scheme before investment, so as to choose the appropriate capacity installation that most consistent with expectations.

5. CONCLUSIONS

Even though the offshore wind farm is allowed to transmit wind power to the MG at a very high capacity, wind curtailment remains a major problem to be solved, which affects the economic returns of wind farm. Building HPS containing energy storage is considered as a measure to increase wind farm penetration. An offshore wind-pumped hydro storage hybrid power system connected to thermal supplied main grid which aims to provides committed wind power and store the surplus rejected wind energy, modulate peak for main grid is proposed in this paper. PHS system configuration is optimized by *gamultiobj* based on multi-objective dynamic economic optimization model. Multi-objective optimization results show that the proposed system could achieve considerable cost-effectiveness while realizing the functions of PHS station. The Multiple objects in this model are not linearly related to each other. The absorption of wind curtailment has an important impact on NPV/C_0 while an increase in R_C is necessarily accompanied by an increase in R_T. The configuration scheme (*VR*, *NT* and *PU*) has a certain impact on the NPV/C_0. In S-Ⅰ, when *NT* reaches 700000kW, the continued increase of *NT* has no effect on NPV/C_0 when R_C reaches the peak. On the other hand, the continuous increase of *NT* leads to the decrease of NPV/C_0 in S-Ⅱ when *NT* reaches 400000kW.

The case study provides decision makers with a variety of flexible choice on operating scenarios and device configuration. It can be seen that it is importance to test the economic feasibility of the system. However, the optimization results do not reflect the impact of external economic variables, such as wind power feed-in tariff, on the cost-effectiveness of the proposed HPS. Further studies on important economic parameters would be carried out to analyze the market adaptability of the proposed system.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (51976020, 71603039 and 71603035). This research has also been supported by China Postdoctoral Science Foundation (2015M571309), Doctoral Startup Funds of Liaoning Province (201601049) and the Fundamental Research Funds for the Central Universities (DUT18JC12).

REFERENCE

[1] P. Cruz, H. M. I. Pousinho, R. Melício, et al. Optimal Coordination on Wind-Pumped-Hydro Operation. Procedia Technology 2014:17:445-451.
[2] X. Wang, L. Li, A. Palazoglu, et al. Optimization and control of offshore wind systems with energy storage. Energy Conversion and Management 2018:173:426-437.
[3] J. Yuan. Wind energy in China: Estimating the potential. Nature Energy 2016:1.
[4] J. K. Kaldellis. Investigation of Greek wind energy market time-evolution. Energy Policy 2004:32:865-879.
[5] J. K. Kaldellis, K. A. Kavadias, A. E. Filios, et al. Income loss due to wind energy rejected by the Crete island

electrical network – the present situation. Applied Energy 2004:79:127-144.

[6] M. W. Murage and C. L. Anderson. Contribution of pumped hydro storage to integration of wind power in Kenya: An optimal control approach. Renewable Energy 2014:63:698-707.

[7] L. Dinglin, C. Yingjie, Z. Kun, et al. Economic evaluation of wind-powered pumped hydro storage system. Systems Engineering Procedia 2012:4:107-115.

[8] A. M. Foley, P. G. Leahy, K. Li, et al. A long-term analysis of pumped hydro storage to firm wind power. Applied Energy 2015:137:638-648.

[9] M. Parastegari, R.-A. Hooshmand, A. Khodabakhshian, et al. Joint operation of wind farm, photovoltaic, pump-storage and energy storage devices in energy and reserve markets. International Journal of Electrical Power & Energy Systems 2015:64:275-284.

[10] M. Parastegari, R.-A. Hooshmand, A. Khodabakhshian, et al. Joint operation of wind farms and pump-storage units in the electricity markets: Modeling, simulation and evaluation. Simulation Modelling Practice and Theory 2013:37:56-69.

[11] Zhou, Y., J.A. Ferreira, P. Bauer. Grid-connected and islanded operation of a hybrid power system. 2007 IEEE Power Engineering Society Conference and Exposition in Africa – PowerAfrica:1-6.

[12] J. K. Kaldellis, M. Kapsali and K. A. Kavadias. Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks. Applied Energy 2010:87:2427-2437.

[13] T. Ma, H. Yang, L. Lu, et al. Pumped hydro storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization. Applied Energy 2015:137:649-659.

[14] D. A. Katsaprakakis, D. G. Christakis, K. Pavlopoylos, et al. Introduction of a wind powered pumped hydro storage system in the isolated insular power system of Karpathos–Kasos. Applied Energy 2012:97:38-48.

[15] M. Kapsali and J. S. Anagnostopoulos. Investigating the role of local pumped-hydro energy storage in interconnected island grids with high wind power generation. Renewable Energy 2017:114:614-628.

[16] A. Rathore and N. P. Patidar. Reliability assessment using probabilistic modelling of pumped hydro storage hydro plant with PV-Wind based standalone microgrid. International Journal of Electrical Power & Energy Systems 2019:106:17-32.

[17] A. Ghasemi and M. Enayatzare. Optimal energy management of a renewable-based isolated microgrid with pumped-storage unit and demand response. Renewable Energy 2018:123:460-474.

[18] S. V. Papaefthymiou and S. A. Papathanassiou. Optimum sizing of wind-pumped-storage hybrid power stations in island systems. Renewable Energy 2014:64:187-196.

[19] Li Wang Tai-Her Yeh, We-Jen Lee and Z. Chen. Benefit evaluation of wind turbine generators in wind farms using capacity-factor analysis and economic-cost methods. IEEE Trans Power Syst 2009:24:692-704.

[20] ZHANG Zeng-Hai, CAO Yue-Nan and Z. Wei. Wind characteristics and land-sea wind speed comparison in the Bohai Bay. Marine Forecasts 2011:28:33-39.

[21] Chen Yongli, Zhao YongPing and e. a. Zhang Bichen. The study of the relations of wind velocity at different heights over the sea. Marine Sciences 1989:3:27-31.

[22] T. Ma, H. Yang, L. Lu, et al. Optimal design of an autonomous solar–wind-pumped hydro storage power supply system. Applied Energy 2015:160:728-736.

[23] J.S. Anagnostopoulos and D. E. Papantonis. Simulation and size optimization of a pumped–storage power plant for the recovery of wind-farms rejected energy. Renewable Energy 2008:33:1685-1694.