Optimal Design of Hybrid Energy System with PV/ Wind Turbine/ Storage: A Case Study

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Main Reference

- Rui Huang; Low, S.H.; Ufuk Topcu; Chandy, K.M.; Clarke, C.R., **"Optimal design of hybrid energy system with PV/wind turbine/storage: A case study,“** *Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on* , pp.511,516, 17-20 Oct. 2011

Outline

- Introduction
- System Model
- Admissible Design [HOMER simulation]
- Optimal Design
- Discussion and Conclusion

1. Introduction

- Remote area power networks: Diesel engine and high cost (fuel transportation, environmental)
- Replacing diesel generation with renewable generation supplemented with batteries and use diesel engine as back up.
- Case study of Santa Catalina Island in California (electricity generated by diesel and transported by ship from the mainland, peak demand 5.3 MW in 2008)

1. Introduction: Objective

- To determine the size of energy resources (PV, wind turbine, batteries) that assures a maximum risk level of supply and demand mismatch
- Then choose a minimum-cost design among all the designs satisfying given maximum risk level

2. System Model

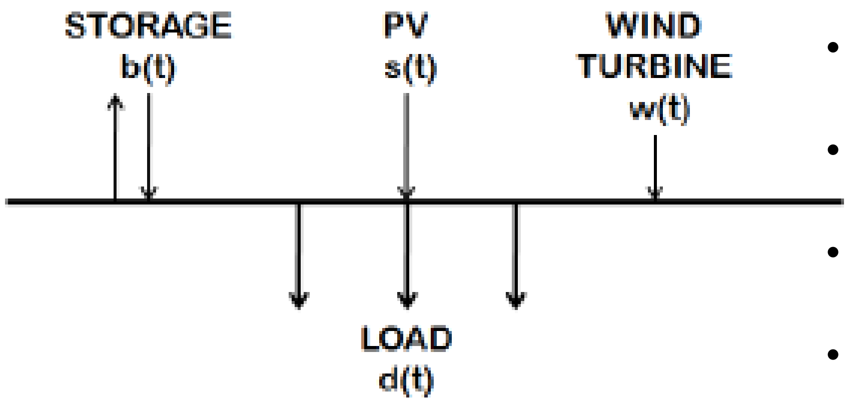
- Model of a hybrid energy system consists of PV arrays, wind turbines and battery storages – using them to define admissible design

- Using empirical whether data in HOMER simulator to compute admissible designs

[alternatively analytic model can be built to compute admissible designs]

HOMER: Hybrid Optimization for Electric Renewable
Energy modeling software for designing and analyzing hybrid power system
developed by National Renewable Energy Laboratory (NREL)

2. System Model: load-shedding model



- b(t): The amount of energy stored at battery at time t. or state of charge of battery.
- s(t): The amount of energy generated by PV array of 1 kW at time t.
- w(t): The amount of energy generated by Wind turbine of 1kW at time t.
- d(t): the amount of demand at time t.

Fig. 1: The hybrid energy system for Catalina Island.

Total generation by renewable resources: $$g(t) := \gamma_1 s(t) + \gamma_2 w(t)$$

γ_1 # of PV array

γ_2 # of Wind Turbine

Load shedding event: When d(t) > g(t) + b(t)

2. System Model: Battery Model

Simple deterministic battery model:

$$b(t+1) = b(t) + f\left(b(t), g(t) - d(t); \underline{b}, \overline{b}\right)$$

$$f\left(b(t), g(t) - d(t); \underline{b}, \overline{b}\right) \geq 0 \quad \text{for} \quad g(t) > d(t)$$

$$f\left(b(t), g(t) - d(t); \underline{b}, \overline{b}\right) \leq 0. \quad \text{for} \quad g(t) < d(t)$$

$$b(t+1) = b(t) + [g(t) - d(t)]_{-r_2(t)}^{r_1(t)},$$

where $[x]_a^c = \max\{\min\{x, c\}, a\}$, $a < c$, and

Charging $r_1(t) := \alpha_1(\overline{b} - b(t))$,

Discharging $r_2(t) := \alpha_2(b(t) - \underline{b})$,

where $\alpha_1, \alpha_2 \in (0,1)$

$$f = \begin{cases} \min\{\epsilon_1(g(t) - d(t)), r_1(t)\}, & \text{if } g(t) \geq d(t) \\ \max\{\epsilon_2^{-1}(g(t) - d(t)), -r_2(t)\}, & \text{otherwise.} \end{cases}$$

$\epsilon_1 \in (0,1]$ Charging Efficiency

$\epsilon_2 \in (0,1]$ Discharging Efficiency

Load shedding event: $\epsilon_2^{-1}(d(t) - g(t)) > r_2(t) := \alpha_2(b(t) - \underline{b})$,

i.e. the energy shortfall exceeds the maximum possible discharge rate.

2.System Model: Risk Measures

- **Ft :** fraction of time when a load-shedding event occurs over horizon [1,T]: T=8760 hrs (1 yr)
- **Fe** : fraction of energy not served when a load-shedding event occurs over horizon [1,T]

$$F_t := \frac{|L|}{T} \qquad L := \{\, t \mid \text{Load shedding events} \,\}$$

$$F_e := \frac{\sum_{t \in L} d(t) - g(t) - \epsilon_2 \alpha_2 (b(t) - \underline{b})}{\sum_t d(t)}$$

Ft and **Fe** depends upon System Size $(\gamma_1, \gamma_2, \overline{b})$

A design $(\gamma_1, \gamma_2, \overline{b})$ **is admissible if** $F_t \leq \epsilon$ **or** $F_e \leq \epsilon$ **For risk limit** $\epsilon \in [0,1]$

2. System Model: Empirical data for solar and wind output

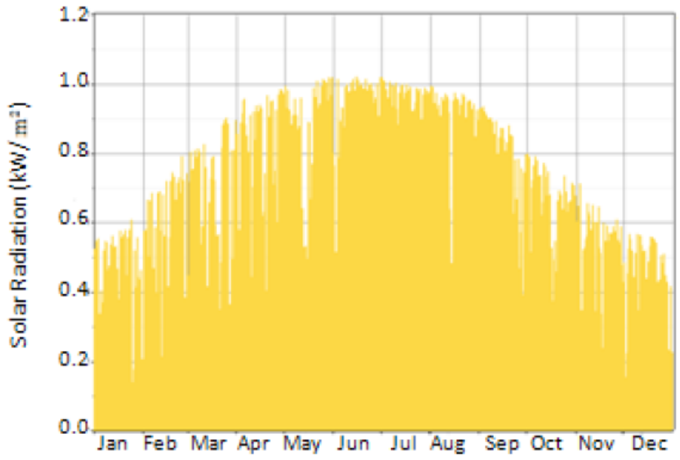


Fig. 2: Hourly solar radiation in one year on Long Beach, CA, USA

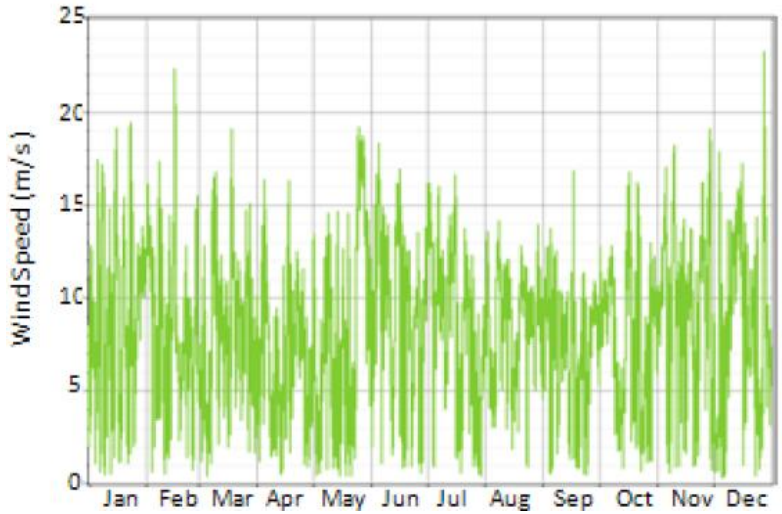


Fig. 3: Hourly wind speed in one year on an island off the coast of Santa Barbara, CA, USA.

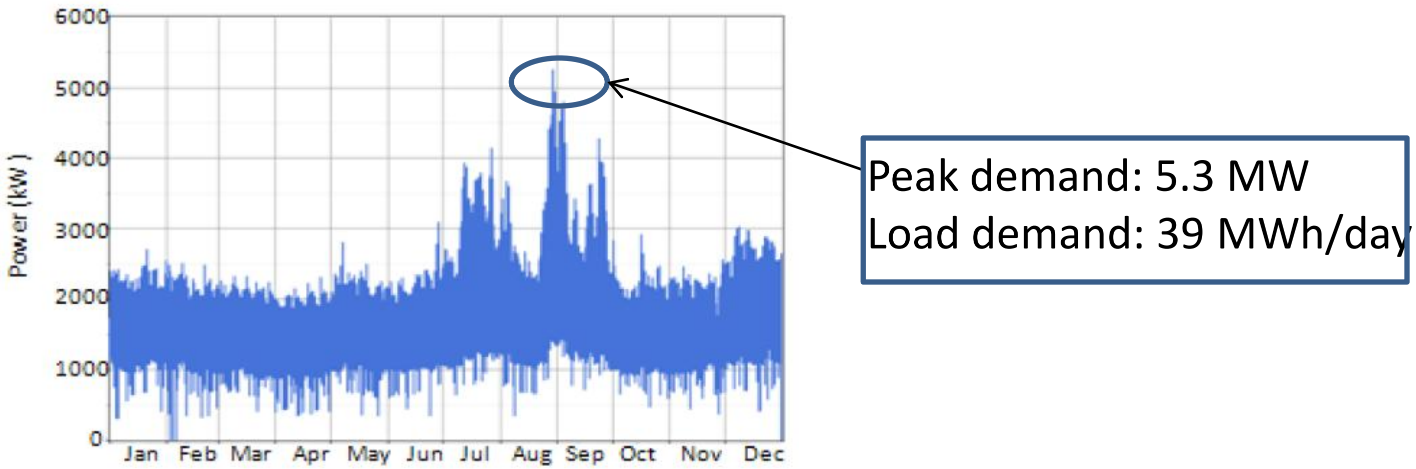


Fig. 4: Hourly load demand in one year on the Catalina Island, CA, USA.

3.Admissible Design: HOMER Simulation

✓ **Set of admissible designs for given risk level**

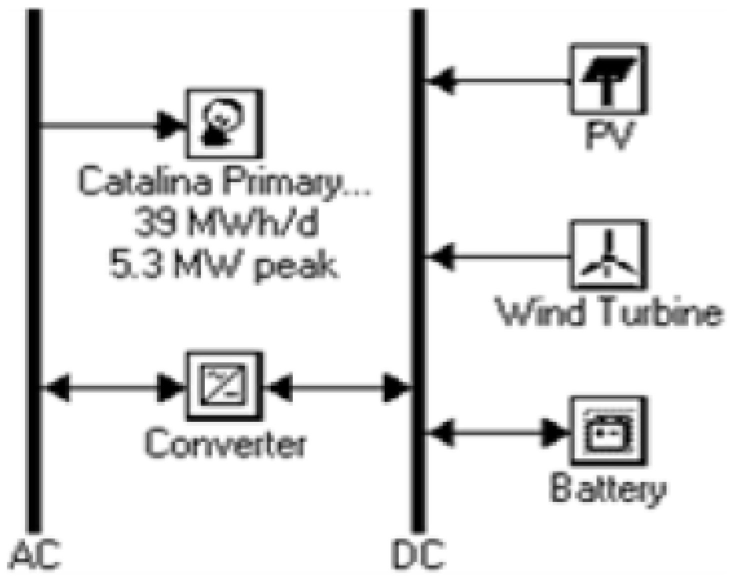


Fig 5. The Hybrid energy system with for Catalina Island in HOMER.

Input:
Hourly solar radiation, Hourly wind speed, and Load data

Built in modules to simulate solar and wind Power output, various battery dynamics.

Output:
Risk level Ft and Fe for each design set.
Set of admissible designs for given risk level.

Table 1: Range and type of simulation components

Components	*Range*
PV Arrays	
Size	0-10,000 kW
Wind Turbine	
Number	0-10,000
Type	Generic standard 1 kW turbine
Battery	
Energy Capacity $\overline{b}$	15, 20 MWh
Minimum State of Charge $\underline{b}$	10 %
Fraction α_1	0.8
Fraction α_2	0.8
Charging Efficiency ϵ_1	90%
Discharging Efficiency ϵ_2	90%

3. Admissible Design: Simulation Results

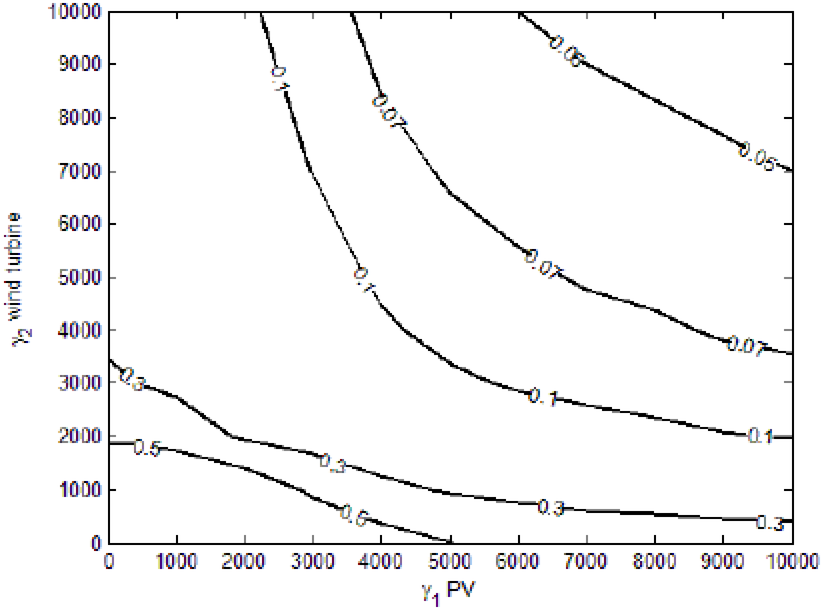


Fig. 6: Ft in one year as a function of γ_1 and γ_2 with $\overline{b}$ = 15 MWh.

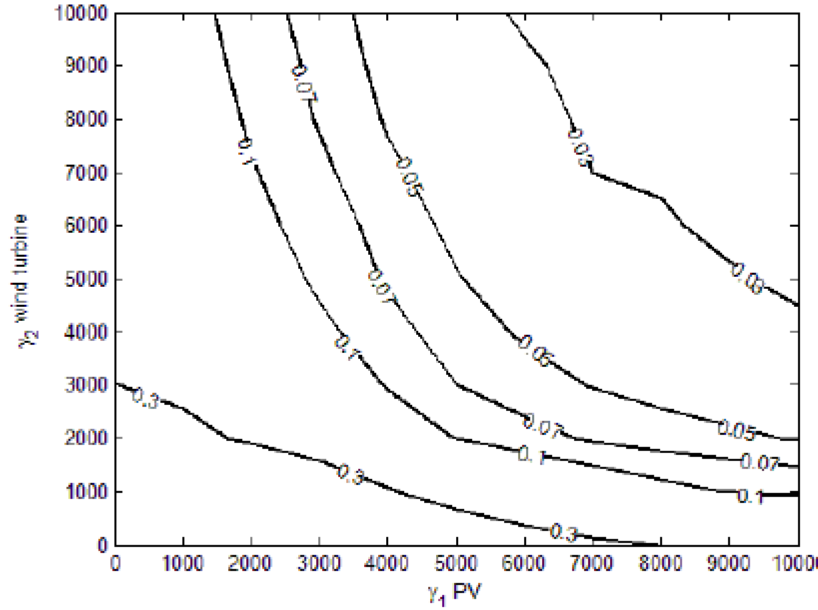


Fig. 7: Ft in one year as a function of γ_1 and γ_2 with $\overline{b}$ = 20 MWh.

- With increase of γ_1 and γ_2 -- Ft decreases (Tradeoff relation)
- Trend is better for fixed value of PV -> irregularity and unpredictability of wind speed, compared with solar radiation

Gives set of admissible design.

4. Optimal Design

- Choose minimum-cost design among the set of admissible designs.
- Tradeoff between system size $(\gamma_1, \gamma_2, \bar{b})$ and risk level Ft or Fe.

Problem Formulation:

For set of admissible designs w.r.t $\epsilon \in [0, 1]$

$$\begin{aligned} X_t(\epsilon) &:= \{(\gamma_1, \gamma_2, \bar{b}) \geq 0 \mid F_t \leq \epsilon\} \\ \min_{\gamma_1, \gamma_2, \bar{b}} &\quad C(\gamma_1, \gamma_2, \bar{b}) \\ \text{subject to} &\quad (\gamma_1, \gamma_2, \bar{b}) \in X_t(\epsilon). \end{aligned}$$

or

$$\begin{aligned} X_e(\epsilon) &:= \{(\gamma_1, \gamma_2, \bar{b}) \geq 0 \mid F_e \leq \epsilon\} \\ \min_{\gamma_1, \gamma_2, \bar{b}} &\quad C(\gamma_1, \gamma_2, \bar{b}) \\ \text{subject to} &\quad (\gamma_1, \gamma_2, \bar{b}) \in X_e(\epsilon) \end{aligned}$$

4. Optimal Design

Cost Model:

$$C = C_{PV} + C_{WT} + C_{BA} + C_{CONV}$$

$$\begin{aligned}
&C_{PV} = C_{module} \times \gamma_1 + C_{O\&M1} \times \gamma_1 \times Life,\\
&C_{WT} = C_{turbine} \times \gamma_2 + C_{O\&M2} \times \gamma_2 \times Life,\\
&C_{BA} = C_{battery} \times \overline{b},\\
&C_{CONV} = C_{converter} \times S_{CONV}.
\end{aligned}$$

Design Process:

1) Obtain realistic solar radiation and wind speed data representative of the location of the design.
2) Obtain representative load data.
3) Specify the desired risk measure F_t or F_e and acceptable risk level ϵ.
4) Use a realistic simulator, e.g., HOMER, to characterize the feasible set $X_t(\epsilon)$ or $X_e(\epsilon)$ based on the weather and load data.
5) Determine the cost function $C(\gamma_1, \gamma_2, \overline{b})$.
6) Estimate a solution to the optimization problem for an optimal design $(\gamma_1^*, \gamma_2^*, \overline{b}^*)$

4. Optimal Design: Case Study

Focus on sizing PV arrays and wind turbines

Acceptable risk level $\epsilon = 10\%$

Fixed Battery Capacity

$$\bar{b} = 15 \text{ MWh and } \bar{b} = 20 \text{ MWh}$$

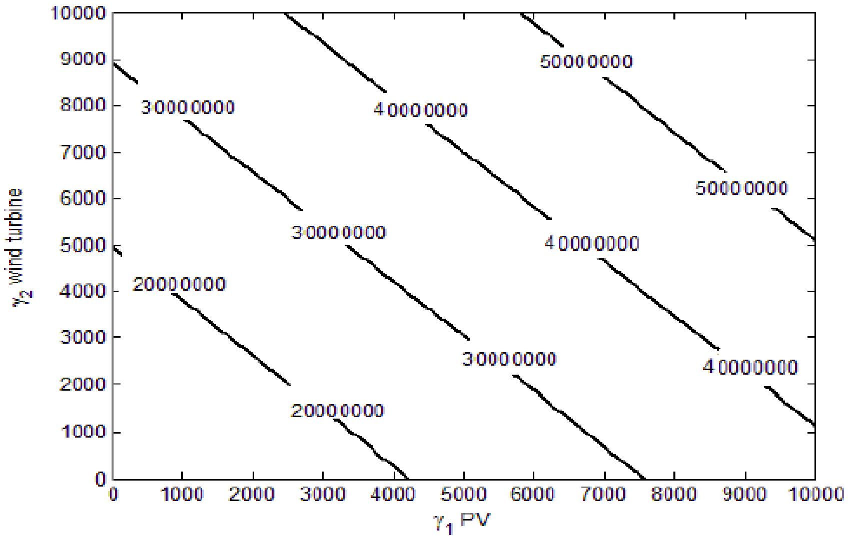


Fig 8. The variation trend of the total construction and operation cost with battery capacity of 15 MWh

Table 2: Cost Model parameters for Catalina

Name	*Cost Data*	*Sources*
Life	20 years	
PV Array		
C_{module}	2.80 $/W	[10] for utility-scale PV
$C_{O\&M1}$	15 $/kW-yr	[11]
Wind Turbine		
$C_{turbine}$	2,300 $/per turbine	[12] for 1 kW turbine
$C_{O\&M2}$	20 $/kW-yr	[10]
Battery		
$C_{battery}$	211 $/kWh	[13]
Converter		
$C_{converter}$	0.715 $/W	[13]

4:Optimal Design: Results

- Intersection of Risk curve and Cost curve

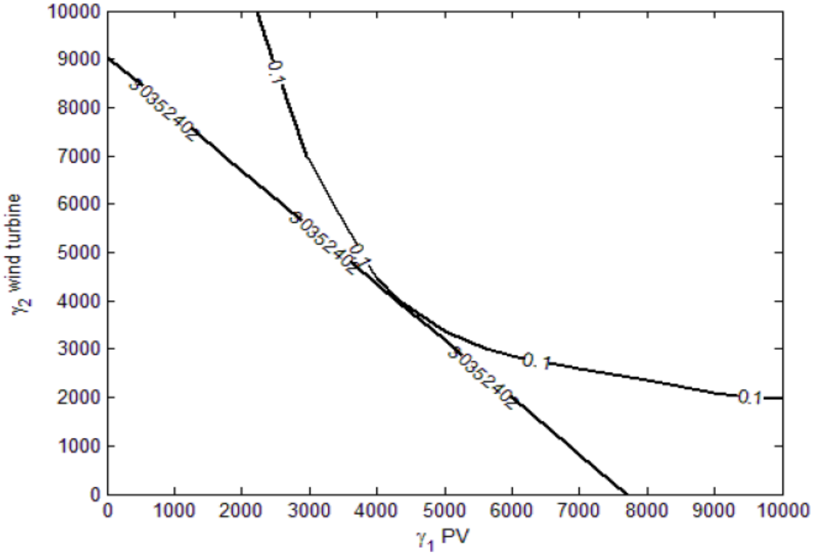


Fig 9. The optimal solution to the problem: minimize total cost subject to Ft ≤ 0.1 with $\vec{b}$ = 15 MWh

Table 3. Summary of optimal results

PV Arrays	Wind Turbine	Battery Capacity (MWh)	F_t	C (\$)	COE (\$/kWh)
4,300	4,000	15	10%	30,352,402	0.201
PV Arrays	Wind Turbine	Battery Capacity (MWh)	F_t	C (\$)	COE (\$/kWh)
3,930	3,000	20	10%	27,778,348	0.185
PV Arrays	Wind Turbine	Battery Capacity (MWh)	F_e	C (\$)	COE (\$/kWh)
3,650	3,000	15	10%	25,891,174	0.177
PV Arrays	Wind Turbine	Battery Capacity (MWh)	F_e	C (\$)	COE (\$/kWh)
3,000	3,000	20	10%	25,014,342	0.172

Comparable estimated renewable cost:
Conventional Power cost in U.S. is 9.48 cent/kWh (2009):

COE is less for battery capacity 20 MWh compared to 15 MWh

Discussion

- No consideration of effect of stochastic weather, load profiles, transmission and distribution of the power network on design results.
- Markov chain model (average behavior but with simple analytical approximations) [1] in contrast to HOMER simulation.

[1] Huan xu, Ufuk Topcu, S. low, C. R. Clarke and K. M. Chandy, “Load shedding probabilities with hybrid renewable power generation and energy storage”, Proc. 48th Annual Allerton Communication, Control and Computing, 2010.

Conclusion

- Tradeoff between the total construction cost and acceptable risk levels has been demonstrated.
- Cost of energy for renewable energy is fairly comparable with conventional generation cost.

Thank you !