Applied Energy 196 (2017) 18–33

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimisation of stand-alone hybrid energy systems supplemented by combustion-based prime movers

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HIGHLIGHTS

- Solar systems hybridised with Internal Combustion Engines and Micro Gas Turbines.
- Genetic Algorithms are used to derive single objective function sizing.
- Hardware Effects: start-up threshold, prime mover type, single vs tandem engines.
- Modelling Effects: start-up transient, temporal resolution.
- Analyses for Cost of Energy, waste heat, duty factor, and Life Cycle Emissions.

ARTICLE INFO

Article history:
Received 23 December 2016
Received in revised form 23 March 2017
Accepted 24 March 2017

Keywords:
Hybrid energy system
Internal Combustion Engine
Micro Gas Turbine
Cost of Energy
Waste Heat
Duty factor

ABSTRACT

A comparative analysis is undertaken between a baseline PV/Batt system, meeting a dynamic load profile, and systems hybridised with supplementary combustion-based prime movers such as Internal Combustion Engines (ICEs) or Micro Gas Turbines (MGTs) of 30–65 kW rating. This study sheds light for the first time on a number of research questions not addressed in earlier studies. The main contributions of the work are namely to: (i) analyse the effects of the start-up threshold and the type of supplementary prime mover on the Cost of Energy (COE, \$/kW h), lifetime CO_2 emissions, and (unrecovered) waste heat for a specified reliability (Loss of Power Supply Probability-LPSP); (ii) investigate the effects of including the transient start-up periods of prime movers on systems sizing; and (iii) look into the effects of using two smaller sized (tandem) supplementary prime movers versus a single larger one on the operational characteristics. The research also analyses (iv) the effects of the methods used (e.g. temporal resolution of simulations, Genetic Algorithm (GA) population size) on the COE, lifetime CO_2 emissions, and (unrecovered) waste heat.

The results of this study indicate that PV/Batt and PV/Batt/ICE systems have comparable COEs but are preferable to PV/Batt/MGT. The minimum starting thresholds of supplementary devices (ICE or MGT) have significant effects on renewable energy penetration, genset running hours, waste heat generation, and Life Cycle Emission (LCE, kg CO_2-eq/yr), but insignificant effects on the COE. The results also show that the transient start-up of supplementary devices has a negligible influence on overall system sizing. The COE resulting from the use of larger capacity prime movers (60 kW ICE or 65 kW MGT) is comparable to deploying two smaller capacity prime movers (30 kW) but results in higher renewable energy penetration, an improved duty factor with lower LCEs. Additionally, the COE increases slightly ($2 \sim 5\%$) when the models run at 15 min temporal resolution compared to 60 min.

1. Introduction

Global energy demand is rising steadily as a consequence of population growth and higher living standards. Around 1.2 billion people (17% of the global population) live without electricity: of those, 22% are in developing countries where a grid connection is not readily available [1]. The continuous depletion of fossil fuel reserves, growing awareness of the environmental impact of power generation solely reliant on combustion [2,3], and the remoteness of many communities [4–7] are driving the development of more sustainable energy supply options. Photovoltaic (PV), solar thermal power plants, wind energy, as well as generators driven by

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http://dx.doi.org/10.1016/j.apenergy.2017.03.119
0306-2619/

Nomenclature

B_{SOC}	battery state of charge (%)
$B_{SOC,\ max}$	maximum battery state of charge (%)
$B_{SOC,\ min}$	minimum battery state of charge (%)
C_b	nominal battery capacity (kW h)
C_{fuel_ICE}	fuel consumption rate for ICE (l/h)
C_{fuel_MGT}	fuel consumption rate for MGT (l/h)
C_0	capital cost ($)
C_{pg}	specific heat of exhaust gas (kJ/kg K)
d	discount rate (%)
E_L	energy load demand (kW h)
E_S	useful energy production from the system (kW h)
E_{sup}	energy generation by supplementary prime movers (kW h)
G	solar irradiation (W/m^2)
G_{ref}	reference solar irradiation (W/m^2)
I_L	light current (A)
$I_{L,ref}$	short circuit current at reference temperature (A)
I_{mp}	maximum power point current (A)
I_o	diode reverse saturation current (A)
I_{PV}	saturation current (A)
I_{sc}	short circuit current (A)
$LPSP_{comp}$	computed loss of power supply probability
$LPSP_{max}$	maximum loss of power supply probability
$\dot{m}_g$	exhaust gas mass flow rate (kg/h)
n	component lifetime (yr)
N	number of values
N_{batt}	number of lead acid batteries
N_{PV}	number of PV module
$N_{s/s}$	number of start-stop for supplementary prime movers
P_B	power flow toward/out of battery (kW)
P_{ICE}	power generation by ICE (kW)
P_L	load demand (kW)
P_{MGT}	power generation by MGT (kW)
P_{Net}	net power generation (kW)
P_{PV}	power generation by PV (kW)
P_{sup}	power generation by supplementary prime mover (kW)
$P_{sup,max}$	maximum power generation by supplementary prime mover (kW)
$P_{sup,min}$	minimum power generation by supplementary prime mover (kW)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
s_{N-1}	standard deviation
T_1	inlet temperature of air into combustion engine (°C)
T_2	exhaust gas temperature (°C)
T_{amb}	ambient temperature (°C)
T_{PV}	cell temperature (°C)
T_{ref}	reference temperature (°C)
V	PV module voltage (V)
V_{oc}	nominal open circuit voltage (V)
V_{mp}	maximum power point voltage (V)
W_s	wind speed (m/s)
$\dot{W}H_{sup}$	waste heat generation from supplementary prime movers (kW)
x_i	load demand at any time step (kW)
$\bar{x}$	mean load (kW)
Δt	time step (min)
ΔT_s	transient start-up time (s)

Greek symbols

α	modified ideality factor
β	lifetime equivalent CO_2 emission (kg CO_2-eq/kW h)
K_t	temperature coefficient of short circuit current (/°C)
η_b	battery efficiency
η_{inv}	inverter efficiency

Abbreviations

ACC	annualised capital cost ($/yr)
AFC	annual fuel cost ($/yr)
AOM	annual operation and maintenance cost ($/yr)
COE	cost of energy ($/kW h)
CRF	capital recovery factor
DF	duty factor
EE	excess energy (kW h)
GA	genetic algorithm
ICE	internal combustion engine
IEA	international energy agency
LCE	life cycle emissions (kg CO_2-eq/yr)
LPS	loss of power supply (kW h)
LPSP	loss of power supply probability
MGT	micro gas turbine
PMS	power management strategy
WHSP	waste heat to supply power

combustion engines in hybridised power installations can be cost-effective choices in remote areas compared to grid connections [8–10]. However, amongst all the renewable energy systems, PV is the dominant configuration [11–15]. Wind energy may not be technically feasible at low wind speeds [16] and is more intermittent than PV [17], thus requiring the use of intelligent methods in many instances to predict availability [18] . PV systems are common in many stand-alone energy applications due to their lower maintenance requirements [19] and more straightforward applications [13]. However, with solar irradiance also being seasonal and intermittent [20–23], PV systems need supplementation to increase the reliability of meeting electric loads. Whilst storing surplus generated power in batteries over periods of low (electric) demand remains widespread [24], the environmental impact of such methods also needs to be considered [25,26]. Even so, energy storage media are routinely used alongside renewables to stabilize power output [27–29]. An alternative approach to solely relying on (long-term) energy storage via batteries in energy systems based on renewables only involves deploying hybridisation featuring other (backup) prime movers [17].

With the exception of distributed energy systems, which can also be supplemented by grid connections [30,31], the data presented in Table 1 clearly shows the lack of work done in integrating waste heat recovery into hybridised stand-alone systems. This has occurred even enough there are numerous hybrid systems in practice [44] and has led to these systems involving combustion processes which suffer from low thermal efficiency. Improving the sustainability of such hybridised systems can be achieved through increasing renewable energy penetration [45] and overall fuel utilisation efficiencies so as to reduce fossil fuel consumption [46]. In combustion-driven (supplemental) prime movers like Internal Combustion Engines (ICEs) or Micro Gas Turbines (MGTs), the recovery of waste heat to meet local heating and cooling loads can achieve higher overall power plant efficiency [47] and fewer environmental pollutants [48,49]. This results in stand-alone and distributed energy systems based on Combined Heat and Power