Chapter 2
Investigation of a Renewable Energy-Based Integrated System for Baseload Power Generation

Mehdi Hosseini, Ibrahim Dincer and Marc A. Rosen

Abstract A renewable energy-based integrated system is proposed for baseload power generation. Wind, solar, and biomass options are considered. The electric power produced by wind turbines, a photovoltaic (PV) system, and fuel cells is fed to the power grid. The surplus electricity produced by the integrated energy system is stored in forms of compressed air and hydrogen. When required, the compressed air is heated in a combustion process and expanded in a gas turbine for further power generation. The hydrogen produced by the electrolysis process is fed to a solid oxide fuel cell (SOFC) system for electricity generation. The system is analyzed with energy and exergy methods, and results are presented for monthly power generation, compressed air energy storage (CAES) and compression, and hydrogen production and consumption rates. Moreover, exergoeconomic analyses are performed based on the unit exergy cost of the electricity produced by the integrated system. The round-trip efficiency of the CAES system is 60 % without considering heat recovery potentials. The overall energy and exergy efficiencies of the integrated system are 37.0 and 31.9 %, respectively. Results of the exergoeconomic analyses show that the unit cost of electricity generated by the Wind-CAES system is 7 ¢/kWh, while it is 89 and 17 ¢/kWh for the photovoltaic-hydrogen-solid oxide fuel cell and the biomass-solid oxide fuel cell-gas turbine systems, respectively.

Keywords Renewable · Integrated energy system · Energy · Exergy · Solar · Wind · Biomass · Fuel cell

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2.1 Introduction

Renewable energy resources (e.g. wind and solar) cannot produce steady electric power, due to their intermittent characteristics. Wind speed and direction change almost constantly due to weather conditions, and solar irradiance reaching the surface of the earth is dependent on geographical location, time of the day, and clearness of the sky. However, proper design of wind turbines (variable speed power generators, appropriate pitching and tilting) makes them capable of producing a fixed-rated power over a course of wind speed range. No matter how sophisticated are the wind turbine control systems, the power output of a wind park depends on the wind speed. Therefore, when utilizing wind turbines in a baseload power plant, the intermittent power output of the wind park must be compensated. One solution is using energy storage systems, and example of which is compressed-air energy storage (CAES). During the period of excess power generation by the wind park, a CAES system can convert and store the surplus electricity in the form of compressed air.

Another option for overcoming the intermittent behavior of wind energy in generating constant rated power is hydrogen storage. According to Yang and Aydin [1], the excess power output of wind turbines can be utilized in water electrolysers for hydrogen production and storage. Once the hydrogen is stored in an appropriate high-pressure vessel, it can be used in a combustion engine, fuel cell, or water-cooled burner to produce high-quality steam for space heating, or to drive a turbine to generate electric power. In large scale baseload power generation, the size of the hydrogen tanks will be significantly large, and work of compression will be considerable.

Batteries, as small scale power generation systems, could be a good option to store the excess generated electricity by the wind turbine(s) and meet the demand when needed. However, in large scale scenarios (baseload power), batteries are very bulky, expensive, and require continuous maintenance. CAES seems promising, since the compressed air is stored in abandoned mines or underground salt caverns. CAES utilizes the familiar gas turbine cycle, with a simple modification. When integrated with wind turbines, excess generated electricity by the wind turbines is consumed by the compressors to compress ambient air, which is stored in the salt cavern or the abandoned mine.

Solar energy systems can also benefit from energy storage. The surplus electric power output of a solar photovoltaic (PV) system can be utilized for hydrogen production, which can be stored in hydrogen tanks for later use. Integrated wind and solar energy-based systems can help reduce greenhouse gas emission rates, if designed for baseload power production. This is achieved through diminishing the use of fossil fuels for electricity generation. Further, Ashraf, et al. [2] report that solar photovoltaic systems have great potential in grid-connected power generation, due to their simplicity of installation, operation and maintenance, and being carbon emission free electricity generation systems.

However, not all the renewable energy resources are emission free. Unlike wind and solar that produce almost no greenhouse gases (GHGs), biomass is a renewable energy resource that releases carbon containing gases when used. For example, a solid-oxide fuel cell-micro gas turbine (SOFC-GT) system integrated with biomass gasification releases 741 g/kWh of CO_2 [3]. This level of gross emission is comparable to the carbon dioxide emission by a fossil fuel power plant, 617 g/kWh.

Renewable energy-based systems can be integrated to increase renewable energy utilization. Depending on the available renewable resources, different configurations can be proposed. In this study, an integrated renewable energy-based system is proposed to supply baseload electric power. The system utilizes wind, solar, and biomass as the renewable energy resources. Basedload wind energy is the subject of the work by Greenblatt, et al. [4]. The economic feasibility of a wind-CAES system is investigated and compared with gas and wind-gas power plants. The CAES system is used to store the surplus generated electricity by the wind turbines. For one set of input assumptions, i.e. $ 5/GJ effective natural gas price and 650 W/m^2 wind resource, the wind-CAES is the most expensive (6 ¢/kWh) system. This result is obtained for a compressed air energy storage system with a 169 h storage capacity.

Residential applications of photovoltaic electricity generation systems can be grid-connected and grid-independent. In both cases energy storage systems may be required to increase renewable energy utilization and/or to achieve higher power reliability. Widén, et al. [5] present options for improving PV capability in load following scenarios, considering the following options: PV array orientation, demand-side management (DSM) and electricity storage. They apply the available methods to a PV system for residential applications, and conclude that energy storage is more efficient than DSM and photovoltaic orientation methods if high PV penetration is desired. Castillo-Cagigal, et al. [6] present active demand-side management (ADSM) analysis for a grid-connected residential PV system in Spain. The ADSM method basically controls the power load variations between the electricity generation/supplying systems and the demand. The presented experimental set up is connected to the local electricity grid, and takes advantage of lead-acid battery storage.

Solar PV systems also can be used for large-scale, baseload power generation, as pointed out by Radchik, et al. [7].They state that intermittency of solar power output is a major factor in economic development of baseload PV systems. They propose market-based solutions for baseload PV electricity generation systems integrated with virtual non-intermittent generators, i.e. gas-fired power plants. This provides a financially attractive option for integrating a solar generator into existing electricity markets.

Solid oxide fuel cells are capable of operating with such fuels as natural gas, hydrogen, and syngas. The latter is produced with biomass gasification, and can be directly used after post-processing in SOFCs [3]. Colpan, et al. [8] investigate effects of gasification medium on systems integrating biomass gasification and SOFCs. Steam gasification is found to have a higher exergy efficiency, relative to air gasification. Also, the results show that a higher electricity generation rate (in the SOFC) is achieved with steam as the biomass gasification medium. Exergy, a measure of the quality of energy, is a concept that helps with identifying sources of irreversibility in a system or a process flow [9]. Exergy combines with economics to form exergoeconomics, which is used for evaluating the costs related to unit exergy flows and system products [9].

In the present study an integrated renewable energy-based system is investigated for baseload power generation. The integrated system utilizes wind, solar and

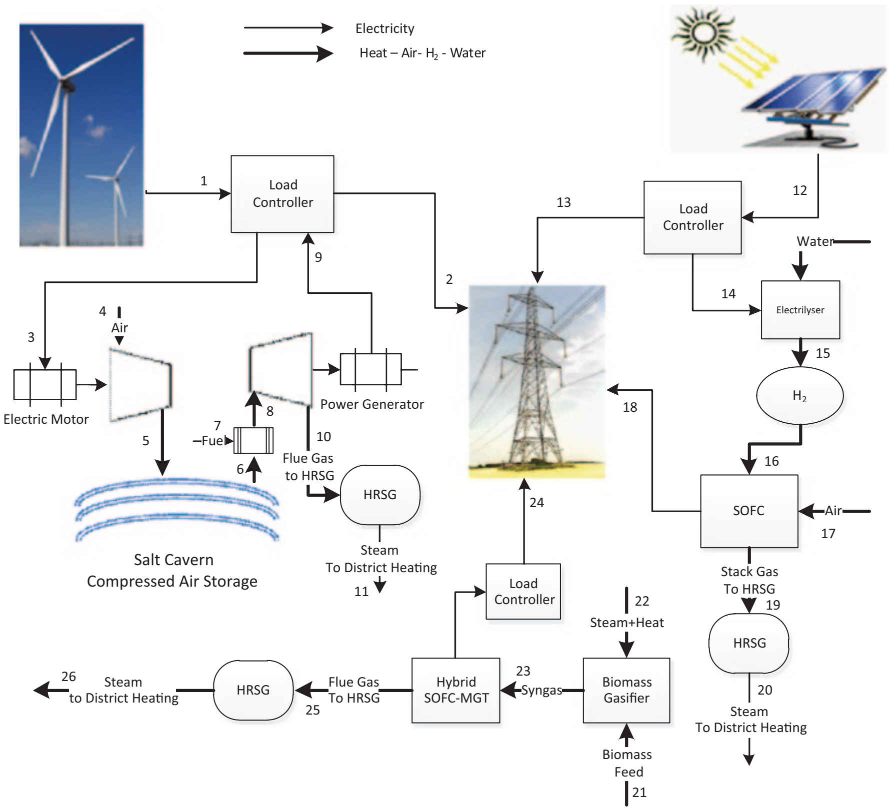

Fig. 2.1 Simplified schematic of grid-integrated renewable combined heat and power system for a district

biomass as the renewable energy resources. Energy and exergy methods are used to analyze the system electric power generation and thermal energy output. Moreover, carbon emission rates are calculated on a per kWh basis. Economic analyses are combined with exergy concepts to perform exergoeconomic analyses of the system, providing information regarding unit cost of electricity production of the electric power generation components.

2.2 System Description

The renewable-based integrated energy system contains three different power generation systems, each utilizing a renewable energy resource. As shown in Fig. 2.1, wind, solar and biomass are the renewable energy resources.

The integrated system is meant to supply the baseload electric power of a district, and the system components are selected so the wind park has the greatest share in meeting the power demand. The operation of each sub-system of the integrated system is described below.

Wind-CAES

The power output of the wind park (point 1) is fed to a load controller. The controller decides if the power output should be delivered to the grid (point 2) or to the CAES system (point 3). When the electric power output of the wind park is more than the demand, the surplus electricity is fed to the CAES system. The compressor consumes the surplus electricity to pressurize ambient air (point 4) in two steps. First, the ambient air is compressed to a medium pressure (pressure ratio of r_c), and is cooled in the heat-exchanger. The heat removed from the compressed air in the heat exchanger can be used for district heating, or can be stored in a thermal storage system. The medium pressure, low temperature air enters the next compressor for further compression. During the compression process it gains energy. To decrease the required volume for storage, the high pressure compressed air is cooled in the second heat exchanger, and stored in underground salt caverns (point 5).

If the power output of the wind park is less than the demand, the gas turbine operates, extracting compressed air (point 6) from the salt cavern. The compressed air enters a combustion process with natural gas (point 7), and is fed to the gas turbine (point 8) for electric power generation (point 9). To increase efficiency, the gas turbine exhaust gas (point 10) is fed to the heat recovery steam generator (HRSG) for low pressure steam generation (point 11). The generated steam is stored in a thermal energy storage system. Due to the intermittency of power generation by the gas turbine, an advantageous way to utilize the generated steam is energy storage, as it gives more flexibility in meeting part of the thermal demand of the district. The compressor must produce enough compressed air so there is a net positive amount of stored air in the salt cavern throughout the year, considering air consumption by the gas turbine.

PV-H_2-FC System

The photovoltaic-hydrogen-solid oxide fuel cell (PV-H_2-FC) is considered to supply a small part of the electricity demand (5 MW). This decision is made due to the high land use of the photovoltaic system (5.9 m^2/kWe). The electricity output of the PV system depends on solar irradiance, which is related to climate. It is possible to size the PV system so that electricity generated during day time exceeds demand, and surplus electricity can be harvested and stored as hydrogen gas. Thus the PV system generates as much electricity as needed to meet the electricity demand. The intermittent characteristic of solar energy is overcome by the hydrogen–fuel cell system. The electrolyser utilizes the surplus electricity of the PV system (point 13) during times of the day when PV output exceeds the electricity demand of the grid. The electrolyser splits water (point 14) into hydrogen and oxygen (point 15). Interest in the substitution of fossil fuels with hydrogen is growing; however hydrogen storage is a challenge in developing sustainable energy systems. Hydrogen can be stored and transported in bulk as a compressed gas or liquid, and new storage methods are under development. These storage methods require significant inputs through compression and liquefaction processes, and require high-tech storage tanks. In contrast, on-site utilization of hydrogen eliminates most of these difficulties. In the system illustrated in Fig. 2.1, hydrogen is produced in an electrolyser installed at the PV-H_2-FC site. Therefore, there is no need for long term storage of hydrogen, because it is consumed by the fuel cell system on demand. Moreover, with proper sizing of system components, high pressure compressed gas is not required. The stored hydrogen is fed (point 16) to the SOFC system for electricity generation (point 18).

Solid oxide fuel cells are capable of generating baseload electric power. In addition, the high temperature exhaust gases leaving the fuel cell stack (point 19) can be used for space heating or hot water production in a heat utilization unit. Since the fuel cell is in operation only when required, the heat gained by the heat utilization unit is stored in a thermal energy storage system (point 20).

Biomass-SOFC-GT System

The integrated system includes a biomass gasification unit, an SOFC, a gas turbine and a heat recovery unit. Wood dust or crop waste is used as biomass in the biomass gasification unit (point 21). To improve the performance of the gasification process, the moisture content of the biomass feed is controlled via a biomass dryer. Various drying methods are available, among which direct steam biomass drying has the higher exergy efficiency. The superheated steam is supplied by the heat recovery steam generator. The gasification process occurs in the presence of pressurized steam (point 22). The product syngas (point 23) is fed to the fuel cell system for power generation (point 24). The gases leaving the fuel cell stack enter the combustion chamber of the micro gas turbine, and the gas turbine cascade for further electricity generation. The biomass-SOFC-GT system is assumed to supply a fixed portion of the electricity demand of the grid. This means that, in contrast to the wind-CAES and PV-H_2-FC systems, the biomass-SOFC-GT system has steady, not-intermittent, operation. The SOFC-GT exhaust gas feeds a heat recovery steam generator (point 25) for further renewable energy utilization. The generated steam is fed to the thermal storage system for thermal management (point 26).

Thermal Energy Storage

The heat recovered from the gas turbine flue gas of the CAES and SOFC-GT systems is stored in the form of hot water in thermal energy storage systems. The hot water is used for hot water usage or space heating.

2.3 Energy and Exergy Analyses

The main components of the integrated system are considered in the energy and exergy analyses. Their energy and exergy flows are illustrated in the following section.

Wind Park

Wind energy is a cubic function of wind speed. Therefore, any fluctuation in the wind speed leads to a significant change in its available energy. Wind turbines are usually in operation 80% of the year, and produce nearly 30% of their nominal power capacity throughout the year [10]. Wind power density (W/m^2) is an index quantifying the level of wind resource, and can be related to the cube of wind speed and the Weibull distribution function. The efficiency of wind turbines is limited to a maximum of 59%, known as the Betz limit [10].

Power output of the wind turbine is a function of wind speed, blade geometry and turbine efficiency, and can be expressed as

$$\dot{W}_{\mathrm{wt}} = \frac{\pi}{8} C_{\mathrm{p}} \rho D^2 v^3 \tag{2.1}$$

Here, C_{p} is the wind turbine efficiency, which is related to aerodynamics characteristics of the blades [11]. Due to the quality of electric power output of the wind turbine, the energy and exergy efficiencies are the same; therefore, the exergy destruction rate of the wind turbine is calculated using:

$$\dot{I}_{\mathrm{wt}} = \left(\frac{1}{C_p} - 1 \right) \dot{W}_{\mathrm{wt}} \tag{2.2}$$

Compressed Air Energy Storage System

Compressor

The energy and exergy balances for the CAES compressor and intercoolers, respectively, follow:

$$(\dot{m}_{\mathrm{air}} h_{\mathrm{air}})_{\mathrm{in}} + (\dot{m}_{\mathrm{air}} w_{\mathrm{C}})_{\mathrm{in}} = (\dot{m}_{\mathrm{air}} h_{\mathrm{air}})_{\mathrm{out}} \tag{2.3}$$

$$(\dot{m}_{\mathrm{air}} ex_{\mathrm{air}})_{\mathrm{in}} + (\dot{m}_{\mathrm{air}} w_{\mathrm{C}})_{\mathrm{in}} = (\dot{m}_{\mathrm{air}} ex_{\mathrm{air}})_{\mathrm{out}} + \dot{I}_{\mathrm{c}} \tag{2.4}$$

The enthalpy of air is calculated as $\Delta h = c_p \Delta T$, where ΔT is obtained using the isentropic relations for the compressor:

$$T_{\text{out}} = T_{\text{in}} \left[1 + \frac{1}{\eta_{\text{c}}} \left(r_{\text{c}}^{\frac{\gamma_{\text{air}}-1}{\gamma_{\text{air}}}} - 1 \right) \right] \tag{2.5}$$

For a compression ratio r_c and a known inlet air temperature, the compressor outlet temperature is calculated. The specific work of compression can thus be calculated as follows:

$$w_{\text{c}} = (h_{\text{air}})_{\text{in}} - (h_{\text{air}})_{\text{out}} \tag{2.6}$$

In Eq. 2.4, exergy of the inlet air to the compressor is zero, considering the ambient conditions be the same as the reference environment. The balances for the air intercoolers are as follows:

$$(\dot{m}_{\text{air}} h_{\text{air}})_{\text{in}} + (\dot{m}_{\text{cw}} h_{\text{cw}})_{\text{in}} = (\dot{m}_{\text{air}} h_{\text{air}})_{\text{out}} + (\dot{m}_{\text{cw}} h_{\text{cw}})_{\text{out}} \tag{2.7}$$

$$(\dot{m}_{\text{air}} ex_{\text{air}})_{\text{in}} + (\dot{m}_{\text{cw}} ex_{\text{cw}})_{\text{in}} = (\dot{m}_{\text{air}} ex_{\text{air}})_{\text{out}} + (\dot{m}_{\text{cw}} ex_{\text{cw}})_{\text{out}} + \dot{I}_{\text{intercooler}} \tag{2.8}$$

where subscript cw in Eqs. 2.7 and 2.8 represents the cooling water, removing heat from the compressed air.

Gas Turbine

The energy and exergy balances for the gas turbine of the CAES system, respectively, follow:

$$(\dot{m}_{\text{air}} h_{\text{air}})_{\text{in}} + (\dot{m}_{\text{fuel}} LHV_{\text{CH}_4})_{\text{in}} = (\dot{m}_{\text{gas}} w_{\text{T}})_{\text{out}} + (\dot{m}_{\text{gas}} h_{\text{gas}})_{\text{out}} \tag{2.9}$$

$$(\dot{m}_{\text{air}} ex_{\text{air}})_{\text{in}} + (\dot{m}_{\text{fuel}} ex_{\text{CH}_4})_{\text{in}} = (\dot{m}_{\text{gas}} w_{\text{GT}})_{\text{out}} + (\dot{m}_{\text{gas}} ex_{\text{gas}})_{\text{out}} + \dot{I}_{\text{GT}} \tag{2.10}$$

The enthalpy of the combustion gases is calculated as $h = c_{p,g}T$, where T is obtained using the isentropic relations for the gas turbine:

$$T_{\text{out}} = T_{\text{in}} \left[1 + \frac{1}{\eta_{\text{GT}}} \left(r_{\text{T}}^{\frac{\gamma_{\text{g}}-1}{\gamma_{g}}} - 1 \right) \right] \tag{2.11}$$

The air and gas specific heats are functions of gas molar fractions, and temperature.

Energy and Exergy Efficiencies of the Wind-CAES System

The main output of the integrated renewable energy-based system is baseload electric power. The system takes advantage of heat recovery to increase renewable energy utilization. Since the energy resources are renewable, and therefore intermittent, the recovered heat is stored as hot water in thermal energy storage systems. The inputs to the Wind-CAES section of the integrated system are wind and natural gas. The overall energy and exergy efficiencies follow:

$$\eta_{\text{wind-CAES}} = \frac{W_{\text{demand}} + Q_{\text{HRSG}} + (\Delta m \cdot h)_{\text{stored air}}}{E_{\text{Wind}} + (m \cdot LHV)_{\text{CH}_4}} \tag{2.12}$$

$$\psi_{\text{wind-CEAS}} = \frac{W_{\text{demand}} + Ex_{\text{q,HRSG}} + (\Delta m \cdot ex_{\text{ph}})_{\text{stored air}}}{Ex_{\text{Wind}} + (m \cdot ex)_{\text{CH}_4}} \tag{2.13}$$

Here, $P_{\text{demand}}, Ex_{\text{q,HRSG}}, and\, \Delta m_{\text{stored air}}$ account for the total annual electric energy demand of the wind park, the total annual heat recovery from the overall CAES system, and the difference between production and consumption of compressed air on a yearly basis, respectively. The energy inputs in the denominator of the efficiency equations are also considered on a yearly basis. The notations in Eq. 2.13 explain the exergy terms using the same concepts.

PV-H_2-FC system

The mathematical model and energy and exergy analysis equations for the PV-H_2-FC system are presented by the authors elsewhere [12].

The PV cell power output is a function of its terminal voltage and current, which are dependent on solar irradiance and ambient temperature:

$$\dot{W}_{\text{PV}} = IV \tag{2.14}$$

The difference between PV electric power output and the grid electric power demand is

$$\Delta \dot{W}_{\text{PV}} = \dot{W}_{\text{PV}} - \dot{W}_{\text{demand}} \tag{2.15}$$

If $\Delta \dot{W}_{\text{PV}} > 0$, the PV system produces more power than the demand, and the surplus electricity is fed to the electrolyser for hydrogen production. If $\Delta \dot{W}_{\text{PV}} < 0$, the SOFC produces power to make up for the power difference between the PV and the grid.

Energy and Exergy Efficiencies of the PV-H_2-FC System

The energy input to the hybrid PV-fuel cell system is solar irradiance. Although solar energy is not available during night hours and cloudy days, the system operates solely on solar energy, thanks to the storage options considered in the integrated system. The main output of the system is electricity, which is fed to the grid. Heat recovery from the SOFC stack gas is another output of the system. The integrated system is sized to supply the electricity demand throughout the year. Therefore, the storage tank size should always contain enough hydrogen to feed the fuel cell, when required. On a year round basis, hydrogen production is set to be more than hydrogen consumption. Thus, the remaining hydrogen in the storage tank is another output of the system. The overall energy and exergy efficiencies of the hybrid PV-fuel cell system can be written as follows:

$$\eta_{\mathrm{PV-fuel\ cell}} = \frac{W_{demand} + Q_{\mathrm{HRSG}} + \Delta m_{\mathrm{H_2}} LHV}{E_{\mathrm{solar}}} \tag{2.16}$$

$$\psi_{\mathrm{PV-fuel\ cell}} = \frac{W_{\mathrm{demand}} + Ex_{\mathrm{q,HRSG}} + \Delta m_{\mathrm{H_2}} ex_{\mathrm{ch,H_2}}}{Ex_{\mathrm{solar}}} \tag{2.17}$$

In Eq. 2.16, W_{demand} is the annual electricity demand in kWh, Q_{HRSG} is the total heat recovery from the fuel cell stack gas, Δm_{H_2} is the difference between production and consumption of hydrogen on a yearly basis, and E_{solar} is the annual solar energy received by the PV system. The notations in Eq. 2.17 apply to the exergy terms similarly.

Biomass Gasification and SOFC-GT

Details of the modeling and thermodynamic analysis of the hybrid SOFC-GT system integrated with biomass gasification are presented by the authors elsewhere [13]. The electric power output of the biomass-SOFC-GT system is expressible as

$$\dot{W}_{\mathrm{SOFC-MGT}} = \dot{W}_{\mathrm{SOFC}} \eta_{\mathrm{conv}} + \dot{W}_{\mathrm{MGT}} - \dot{W}_{\mathrm{airC}} - \dot{W}_{\mathrm{consumption}} \tag{2.18}$$

where η_{conv} is DC/AC power converter, and $\dot{W}_{\mathrm{airC}}$ and $\dot{W}_{\mathrm{consumption}}$ are air compressor and internal consumption, respectively.

The energy and exergy balances can be written as follows:

$$(\dot{m}ex)_{\mathrm{biomass}} + \dot{E}x_{\mathrm{steam}} + \dot{E}x_{Q} = \dot{W}_{\mathrm{SOFC-MGT}} + \dot{E}x_{\mathrm{out}} + \dot{I}_{\mathrm{biomas-SOFC-MGT}} \tag{2.19}$$

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