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A review of renewable energy based cogeneration technologies

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ABSTRACT

A major focus of the current energy debate is how to meet the future demand for electricity. Conservation in buildings and industry, and conversion of utility central station capacity to alternate fuels will play a major role in meeting this demand. But cost-effective conservation measures can only go so far, and the industrial and commercial sectors ultimately will have to seek alternative sources of energy. Moreover, electric utilities may face financial, environmental, or other constraints on the conversion of their existing capacity to fuels other than oil, or on the construction of new alternate-fuelled capacity. A wide range of alternate fuels and conversion technologies has been proposed for the industrial, commercial, and electric utility sectors. One of the most promising commercially available technologies is cogeneration. Cogeneration systems produce both electrical (or mechanical) energy and thermal energy from the same primary energy source. This paper reviews the present day cogeneration technologies based on renewable sources of energy. Study of novel methods, existing designs, theoretical and experimental analyses, modeling and simulation, environmental issues and economics and related energy policies have been discussed in this paper.

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1. Introduction

Cogeneration is the combined production of two forms of energy – electric or mechanical power plus useful thermal energy – in one technological process. The electric power produced by a cogenerator can be used onsite or distributed through the utility grid, or both. The thermal energy usually is used onsite for industrial process heat or steam, space conditioning, and/or hot water. But, if the cogeneration system produces more useful thermal energy than is needed onsite, distribution of the excess to nearby facilities can substantially improve the cogenerator's economics and energy efficiency. Cogeneration is an old and proven practice. But, due to current energy crisis, there has been a resurgence of interest in recent years in cogeneration for industrial sites, commercial buildings, and rural applications. A cogenerator could provide enough thermal energy to meet many types of industrial process needs, or to supply space heating and cooling and water heating for a variety of different commercial applications, while supplying significant amounts of electricity to the utility grid. Because cogenerators produce two forms of energy in one process, they will provide substantial energy savings relative to conventional separate electric and thermal energy technologies. The principal technical advantage of cogeneration systems is their ability to improve the efficiency of fuel use. A cogeneration facility, in producing both electric and thermal energy, usually consumes more fuel than is required to produce either form of energy alone. However, the total fuel required to produce both electric and thermal energy in a cogeneration system is less than the total fuel required to produce the same amount of power and heat in separate systems. Hence, Cogeneration is most likely to be competitive with conventional separate electric and thermal energy technologies when it can use relatively inexpensive, plentiful fuels, and where there are large thermal energy needs or it can meet on-site energy needs while supplying significant amounts of electricity to the utility grid. In this paper, renewable energy based cogeneration technologies have been reviewed and presented.

2. Biomass based cogeneration technologies

Biomass based cogeneration systems are becoming widely popular and various researches have been carried out in this area. In this section such technologies are classified and presented based on study, design, modeling and simulation, environmental issues, energy policies.

2.1. Study

Hessami [1] described three electricity and/or heat generation applications fuelled by biogas or landfill gas produced from organic waste material and noted that cogeneration is currently the most suitable energy management strategy for applications requiring both heat and power simultaneously. Murphy and Mckeogh [2] investigated four technologies, which produce energy from municipal solid waste (MSW): incineration, gasification, generation of biogas and utilization in a combined heat and power (CHP) plant, generation of biogas and conversion to transport fuel. Dong et al. [3] carried out a review on the development of small- and micro-scale biomass-fuelled combined heat and power systems concentrating on the current application of organic Rankine cycle (ORC) in small- and micro-scale biomass-fuelled CHP systems and compared ORC with other technologies such as biomass gasification and micro-turbine based biomass-fuelled CHP systems. Gustavsson [4] observed that new technologies for biomass gasification are being developed which increase the potential to cogenerate electricity and may reduce costs compared with steam turbine technology and discussed its potential to cogenerate electricity in the Swedish district-heating systems. Larson [5] reviewed biomass integrated-gasifier/gas turbine combined cycle (BIG/GTCC) designs and ongoing demonstration and commercial projects and presented estimates of the performance of two different BIG/GTCC plant configurations integrated into sugar or sugar-and-ethanol factories and concluded with an assessment of the potential impacts on the Cuban energy sector of the introduction of BIG/GTCC cogeneration systems in that country's sugarcane industry. Uddin and Barreto [6] analyzed biomass-fired cogeneration plants based on steam turbine technology (CHP-BST) and integrated gasification combined cycle technology (CHP-BIGCC) and estimated the CO_2 mitigation costs of large-scale biomass-fired cogeneration technologies with CO_2 capture and storage. Prasad [7] explored potential for using biomass sources in Fiji for the generation of industrial process steam and rural electricity. Bianchi et al. [8] studied the utilization of the organic wastes from an existing poultry industry as fuel, considering different plant configurations, in order to make use of the oil and of the meat and bone meal, which are the by-products of the chicken cooking process. Tillman and Jamison [9] carried out a review on four basic cogeneration cycles: the steam turbine topping cycle, the gas turbine topping cycle, the diesel topping cycle, and the bottoming cycle and found that the steam turbine topping cycle is most appropriate for wood. Sipila [10] has given an overview on how combined heat and power production is widely used and is an efficient way to reduce CO_2 emissions in Scandinavia, as well as to some extent elsewhere in Europe and discussed several basic and applied research as well as pilot activities has been carried out in research organizations and in industry in Finland in the area of solid-biomass IGCC technology. Shuying et al. [11] described a project that is being co-funded by the Jilin Provincial Government and the United Nations Development Program to demonstrate the technical, economic and market viability of a modern biomass gasification system to provide cooking gas, heat and electricity to village communities in China. Pellegrini et al. [12] presented a comparative thermoeconomic study of biomass integrated gasification combined cycle systems for sugarcane mills. Gustavsson and Johansson [13] addressed the potential for bioenergy in Sweden and compared different means of using bioenergy in the electricity, heat, and transportation sectors.

2.2. Design

Wahlund et al. [14] investigated a new approach for improving the performance of biomass-based cogeneration plants, a bioenergy combine and developed a conventional biomass-based combined heat and power plant with integrated pellet production, where part of the CHP plant's heat is used for drying biomass feedstock for producing pellets which enables increased annual operational hours and an increased use of biomass because the upgraded pellets as an energy carrier can be economically and technically transported from regions with a surplus biofuel to regions with demand for biofuel. Williams and Larson [15] developed a technology integrating gasifiers with gas turbines, aeroderivative gas turbines in particular, makes it possible to achieve high efficiencies and low unit capital costs in modest-scale biomass power generating facilities. De Holanda and Balestieri [16] proposed two cogeneration schemes for the burning of municipal solid wastes, associated or not with natural gas, and examined their technical and economic feasibilities. Syred et al. [17] designed an inverted cyclone gasifier with a vortex collector pocket (VCP) and a central collector pocket (CCP) to maximise particle and ash separation from the flow, and remove alkali and other heavy metal traces that agglomerate with the ash particles and also developed a cyclone combustor which produces a strong swirling flow with good mixing and burnout patterns, creating stable combustion conditions. Riccio and Chiaramonti [18] designed an innovative small scale polygeneration system (BIO_MGT), which combines biomass and natural gas in a micro gas turbine. Bannai et al. [19] developed a gas-turbine cogeneration system that makes effective use of calorific value of the volatile organic compound (VOC) gases exhausted during production processes at a manufacturing plant. Jou et al. [20] enhanced the performance of a high-pressure cogeneration boiler (max 280 tons/h boiler capacity) that burnt fuel oil (FO) and natural gas (NG) in a full-scale petrochemical plant by partially replacing the NG with a waste hydrogen-rich refinery gas (RG), a by-product from catalytic reforming and catalytic cracking operations. Drescher and Brüggemann [21] designed a power plant, which is based on organic Rankine cycle and this design influences the selection criteria of working fluids. Steinwall [22] examined the feasibility of integrating drying and gasification of biomass with the evaporative gas turbine cycle (EvGT) and designed and evaluated different power plant systems for cogeneration. Badami and Mura [23] presented the preliminary design and theoretical analysis of a small-scale Rankine cycle (RC) operating as a combined heat and power unit and fed by wood waste. Kuo [24] designed a conceptual power generation system configuration considered here includes a mass burning furnace-boiler system which can use the blend of bagasse and woody waste as fuel, and a gas turbine, coupled with a HRSG, firing on natural gas and/or biomass gasification products.

2.3. Analysis

Husain et al. [25] determined boiler and turbine efficiencies, energy utilization factor, oil extraction rate and heat/power ratio for various palm oil mills working under similar conditions and adopting same processes. Prasad [26] investigated the theoretical performance of a biomass-fuelled boiler/steam power cogeneration system based on the known or assumed properties of the biomass fuel (its size, elemental composition, moisture content), energy content of the combustible constituents of the fuel, actual performance of a piston-operated-valve (POV) reciprocating engine and an alternator from earlier studies, and load profiles. Möllersten et al. [27] investigated the impact of combining CO_2 capture and storage with alternative systems for biomass-based combined heat and power production in Kraft pulp and paper mills and compared heat, power, and CO_2 balances of systems with alternative configurations of the CHP and CO_2-capture systems. Gustavsson [28] analyzed the costs and primary energy use required for producing one unit of electricity and one unit of heat, as well as the CO_2 emissions involved, for different biomass- and fossil-fuel-based systems. Holmgren [29] analyzed a municipal DH system, which uses waste heat from industries and waste incineration as base suppliers of heat and is currently investing in a natural-gas fired combined heat-and-power plant. Kamate and Gangavati [30] presented the exergy analysis of a heat-matched bagasse-based cogeneration plant of a typical 2500 TCD sugar factory, using back-pressure and extraction condensing steam turbine and found that at optimal steam inlet conditions of 61 bar and 475 °C, the backpressure steam turbine cogeneration plant perform with energy and exergy efficiency of 0.863 and 0.307 and condensing steam turbine plant perform with energy and exergy efficiency of 0.682 and 0.260, respectively. Ram and Banerjee [31] carried out an energy balance for an actual 5000 TCD plant and a Sankey diagram was drawn and a pinch analysis was done for the sugar factory which revealed that the minimum hot utility requirement is lower than the actual by 9% and consequently, modified evaporator designs were proposed as it has been found that the existing plant was not optimum with regard to the surface area of the evaporators and the amount of steam being consumed.

2.4. Modeling and simulation

Papadopoulos and Katsigiannis [32] presented a developed general computer program, which is a flexible computational tool for biomass energy surveying of an interested wide geographical area (w.g.a.) and its properly selected interior zones for the purpose of identifying possible cogeneration or combined heat and power unit installations in proper site locations, which in turn are fully assessed in techno-economic terms. Stehlík [33] presented a number of recent advances in technologies and improvements in units for the thermal processing of municipal solid waste and various other types of waste and outlined a new concept for a regional Waste-to-Energy Centre (WTEC), the design of which is based on a combination of experience, know-how and a sophisticated approach and utilized computational methods such as computational fluid dynamics (CFD) for design optimisation and/or for troubleshooting. Prasertsan and Krukanont [34] developed mathematical models of fuel cost incorporating various fuel parameters and power plant operating parameters and the maximum affordable fuel cost was found to depend on the fuel moisture content, area-base annual availability, the required financial return, size of the power plant, and the operation of the power plant. Zsigraiová et al. [35] proposed a model that integrates waste transportation optimisation and incineration with energy recovery combining production of heat and power, the heat being used for drinking water production and found that the extraction condensing steam turbines are more suitable when power production is a priority (5.0 MW with 4000 m^3/d of drinking water), whereas back-pressure turbines yield 5540–6650 m^3/d of drinking water with an additional power production of 3.3–4.7 MW. Jurado et al. [36] reported results of detailed full-load performance modeling of cogeneration systems based on gasifier/gas turbine technologies. El-Halwagi et al. [37] developed a systematic methodology for the quick targeting of power cogeneration potential in steam systems ahead of designing the power generation network and hence, devised an approach that makes effective utilization of combustible wastes and reconciles the use and dispatch of process fuel sources, heating and non-heating uses of steam, and power generation.

2.5. Economics and environmental issues

Lian et al. [38] formulated a calculation process, based on the second law of exergy, for evaluating the thermoeconomic potential of a steam-turbine plant for trigeneration and evaluated its cost effectiveness with varying economic and operating parameters', because only the fuel price and electricity price are varied and found that exergy destruction is most extensive in the furnace, amounting to nearly 60% and also observed that the overall production cost decreases with steam pressure and increases with steam temperature. Warren and El-Halwagi [39] assessed the technical and economic feasibility of a new process based on incorporating recent experimental data on plastic/coal liquefaction within a conceptual process framework and compiled the data on plastic-waste availability, disposal and economics and identified from the economic analysis, the profitability criteria for gross profit and thus return on investment based on variable conversion, yield and tipping fee for plastic waste was processed. Gustavsson and Johansson [13] analyzed the costs for district heat production with various technologies and fuels, as well as the impact of a carbon tax on these costs are also analyzed. Lybæk [40] explored opportunities for efficient supply of district heating to the industrial sector and through a case-study conducted in small and medium enterprises (SMEs) in Thailand, he showed how this can be established technically, and be financially supported in practice through the clean development mechanism (CDM) and further analyzed options for local manufacturing of CHP technologies, etc., in countries in the South (exemplified by Thailand), to support the implementation of biomass-based CHP with supply of district heating in the future energy supply of Asia. Duval [41] evaluated the environmental benefits associated with the adoption of modern biomass cogeneration technologies in South-east Asia. Holanda and Balestieri [42] presented results of environmental analyses based on two configurations proposed for urban waste incineration; the annexation of integer (Boolean) variables to the environomic model makes it possible to define the best gas cleaning routes based on exergetic cost minimisation criteria and the results for steam cogeneration system analysis associated with the incineration of municipal solid wastes are also presented. Holanda and Balestieri [43] presented an environomic analysis of a cogeneration system comprising a combined cycle composed of a gas cycle burning natural gas with a heat recovery steam generator with no supplementary burning and a steam cycle burning municipal solid wastes to which will be added a pure back pressure steam turbine (another one) of pure condensation. Madlener and Bachhiesl [44] provided a detailed case study on Austria's by far largest biomass cogeneration plant and deduced the main socio-economic drivers and success factors for the realisation of large bioenergy projects in urban settings. Mastro and Mistretta [45] presented a thermoeconomic analysis of a cogenerative system with steam bleedings produced starting from the thermal energy recovered in a municipal solid waste thermovalorization plant an economic analysis of a hypothetically coupled MSW thermovalorization–multi stage flash (MSF) desalination plant was carried out to estimate the capital and operating costs and the gain derived from the sale of distilled water. Mbohwa [46] examined the potential for cogeneration in Zimbabwe's sugar industry on the basis of state of the art technology in bagasse energy cogeneration implemented in Mauritius and Reunion Islands and found that it is technically feasible to implement such a project. Holmgren and Gebremedhin [47] analyzed the economic effect of building a waste incineration plant in a Swedish municipality, Skövde, to produce electricity and heat, on the energy system as well as environmental effects in terms of carbon dioxide emissions. Hassler and Jones [48] examined the magnitude and scope of the Tax Reform Act of 1986, which drastically altered the business tax structure of the United States, and their impact on three basic types of investment in biomass energy systems: (1) a replacement facility, (2) a retrofit, and (3) the addition of a cogeneration turbine and also examined the economic feasibility of these three biomass projects (adapted from real case studies) before and after implementation of the Tax Reform Act of 1986 using the effects on net present value and internal rate of return criteria C. Ram and Banerjee [31] performed a cost analysis to determine the variation of the average cost of generation of power with the generation temperature of the steam in an Indian sugar plant.

2.6. Energy policies

Tsai and Chou [49] summarized energy policy relating to MSW-to-energy in Taiwan and also presented the regulatory system including Air Pollution Control Act, Energy Management Law and Statute for Upgrading Industries, which is not only to establish the environmental standards on MSW incineration facility, but also to provide economic and financial incentives to promote the use of MSW-to-energy. Smouse et al. [50] stated the objective of the Advanced Bagasse Cogeneration ABC Component of the GEP Project which is to promote year-round cogeneration in Indian sugar mills with power export using only biomass as a fuel and reviewed the structure and activities of the ABC Component, which is implemented through technical assistance and investment subcomponents. Teixeira and Carvalho [51] reviewed the PROINFA program, a regulatory mechanism to incentivize renewable electricity generation and analyzed the best economical option for cogeneration using one of the biomass resources available in Brazil-Babassu. Holmgren and Gebremedhin [47] studied the consequences of two different policy instruments, green electricity certificates and a tax on waste incineration in a Swedish municipality, Skövde, to produce electricity and heat.

3. Solar energy based cogeneration technologies

Solar energy can be significantly utilised for cogeneration and various such technologies have been proposed. In this section, presentation of such technologies has been made by classifying them under study, design, analysis, modeling and simulation, economics and environmental issues.

3.1. Study

Rheinländer and Lippke [52] studied the cogeneration of electricity and potable water utilizing solar energy, assuming solar tower power plants with the open volumetric PHOEBUS receiver and the results for alternative plant configurations show that the water production cost is about the same or even lower than the cost of water produced by conventionally fired systems. Pearce [53] investigated the potential of deploying a distributed network of PV–CHP hybrid systems in order to increase the PV penetration level in the U.S and the temporal distribution of solar flux, electrical and heating requirements for representative U.S. single family residences were analyzed and the results clearly showed that hybridizing CHP with PV can enable additional PV deployment above what is possible with a conventional centralized electric generation system. Prengle et al. [54] discussed, in detail, a 100 MWe central receiver–AHS cycle cogeneration power plant and cycle analysis, preliminary cost estimates, and unit energy costs are also discussed. Moustafa et al. [55] described a 100 kW_e/700 kW^{th} distributed receiver; solar-thermal power plant, that was installed in remote desert location 35 km south-west of Kuwait City in the country of Kuwait, designed to supply the electric power and fresh water, needs of a small agricultural desert settlement.

3.2. Design

Mcdonald [56] proposed a simple hybrid solar–fossil cogeneration plant which utilizes the attractive sensible heat rejection characteristics of the Brayton cycle, the plant with a rating up to say 10 MWe, operating in a combined heat and power mode and would provide continuous total energy needs. Zhao et al. [57] recorded the process of calculating the performance of the nozzle applying homogenous equilibrium model, designing and testing the prototype of system, which uses solar energy to produce fresh water and electricity simultaneously, using three different types of the nozzles in static and rotary systems and some data were analyzed theoretically based on the test and the results found that the percentage of fresh water measured by experiment is consistent with the calculation using homogenous equilibrium expansion model (HEM), however, there is big difference in power generation between theory and experiments. Mittelman et al. [58] proposed a system for simultaneous production of electrical and high grade thermal energy with a concentrating photovoltaic/thermal (CPVT) system operating at elevated temperature. Qiu and Hayden [59] investigated power generation using InGaAsSb TPV cells in a gas-fired home heating furnace and the radiant power density and radiant efficiency of a gas-heated radiator were determined at different degrees of exhaust heat recuperation and the electric output characteristics of the InGaAsSb TPV devices were investigated under various operating conditions and an electric power density of $5.4 \times 10^3\,\mathrm{W\,m^{-2}}$ was produced at a radiator temperature of 1463 K for the small cogeneration system and furthermore, the design aspects of combustion-driven TPV systems were discussed.

3.3. Analysis

Göktun [60] investigated, by employing the energetic optimization technique, the optimal performance of a focusing collector-driven, an irreversible Carnot cogeneration system for air conditioning and refrigeration and a minimum value for the total solar insolation needed to overcome internal irreversibilities for start-up of the system is defined and the effect of the collector design parameters on this value was investigated.

3.4. Modeling and simulation

Oliveira [61] presented a new approach to express the long-term performance of general solar thermal systems based on the calculation of two utilizability values, related to the minimum and maximum temperature levels that regard the load and examples for solar cooling and solar cogeneration systems were shown. Pfeifer et al. [62] presented some part of the results of an investigation in which the dimensioning of an internal combustion engine under the special conditions of the combination with a solar-heating system was analyzed and the course of the yearly duration curve, which is an important criterion in dimensioning a BTP, was found out to be like a step. Vargas et al. [63] developed a simplified mathematical model, which combines fundamental and empirical correlations, and principles of classical thermodynamics, mass and heat transfer and was utilized to simulate numerically the system transient and steady state response under different operating and design conditions of a cogeneration system consisting of a solar collector, a gas burner, a thermal storage reservoir, a hot water heat exchanger, and an absorption refrigerator. Alrobaei [64] developed a detailed computational model to identify and investigate the effectiveness and thermodynamic performance of concentrating solar cogeneration power plants (CSCPP) schemes and implemented it on simulation computer code and hence, influence of the most important design parameters on the effectiveness of integrated gas turbine solar cogeneration power plant (IGSCP) were discussed. Lindenberger et al. [65] improvised the dynamic energy, emission, cost optimization model and applied them to the analysis of solar district heating systems with seasonal storage in a pilot project of the Bavarian Research Foundation and the optimum integration of condensing boilers, compression and absorption heat pumps, and cogeneration of heat and power was computed for 100 well insulated housing units with an annual total heat demand of 616 MWh and comparing with a reference case with individual condensing boilers and electricity taken from the public grid, it was found that the selected scenarios achieve (non-renewable primary) energy savings between 15% and 35% associated with cost increases between 220% and 140% and hence, it was concluded that cogeneration turns out to be quite attractive from an economical point of view. Göktun and Ökaynak [66] investigated the optimum value of overall effective utilization factor (EUF) of a solar cogeneration system and for optimum operation; primary performance parameters of the system were discussed. Ranade and Prengle [67] proposed a model for sizing an energy storage system for large utilization of solar energy and based on selection criteria and relevant data, two storage systems were investigated: an all sodium system and a molten salt system.

3.5. Economics and environmental issues

Mittelman et al. [58] investigated the performance and cost of a CPVT system with single effect absorption cooling in detail and the results showed that under a wide range of economic conditions, the combined solar cooling and power generation plant can be comparable to, and sometimes even significantly better than, the conventional alternative. Medrano et al. [68] developed a simplified model to assess the potential energy, economic and CO_2 savings of the building with non-conventional energy systems such as solar photovoltaic arrays, thermal collectors, an internal combustion engine cogeneration, and an absorption chiller. Also, parametric studies for natural gas and electricity prices as well as results for other possible combinations with only one or several of the installed systems in operation was carried out. Beccali et al. [69] presented a detailed analysis of the energy and economic performance of desiccant cooling systems (DEC) equipped with both single glazed standard air and hybrid photovoltaic/thermal (PV/t) collectors for applications in hot and humid climates and showed the results of detailed simulations conducted for a set of desiccant cooling systems operating without any heat storage.

4. Fuel cells based cogeneration technologies

Fuel cells based cogeneration has a huge potential for future research works. Such cogeneration technologies have been reviewed and presented in this section by classifying them under study, design, analysis, modeling and simulation, economics, environment and energy policy.

4.1. Study

Dufour [70] studied the impact fuel cells could have on electrical grid management and control, for their voltage support and active filtering capabilities, for their response speed and for quick load connection capabilities. Alcaide et al. [71] presented a review of specific fuel cells (FCs) with ability to produce useful chemicals and also generate electricity at the same time and classified the chemical cogeneration processes according to the different types of fuel cells and it was shown that a flow alkaline FC (AFC) is able to produce hydrogen peroxide. Figueroa and Otahal [72] focussed on the strategy and experience of San Diego Gas and Electric with the development and demonstration of a proof of concept 250-kW internally manifolded heat exchanger (IMHEX®) carbonate fuel cell power plant and discussed the following topics: (i) SDG&E's involvement in the development of molten carbonate fuel cell (MCFC) technology; (ii) the active role in engineering and specification of the IMHEX® MCFC demonstration plant; (iii) responsibility for installation, commissioning, and operation; (iv) utility role in technology development and application of MCFC in a restructured and competitive environment.

4.2. Design

Al-Hallaj et al. [73] proposed a novel concept for integrating fuel cells with desalination systems and discussed two case studies – the first involving a hybrid system with a reverse osmosis (RO) unit and the second – integrating with a thermal desalination process such as multi-stage flash and showed that the system efficiency can be raised appreciably when a high-temperature fuel cell co-generates DC power in situ with waste heat suitable for MSF. Ishizawa et al. [74] developed a highly efficient system for recovering heat and water from the exhaust gases of a 200-kW rated power fuel cell, which is composed of a shell-and-tube type heat exchanger to recover high-temperature heat and a direct-contact cooler to recover the water efficiently and simply.

4.3. Analysis

Silveira et al. [75] relative fuel cell concepts are presented, followed by chemical and technical information on the change of Gibbs' free energy in isothermal fuel oxidation directly into electricity and a methodology for the study of a fuel cell associated with an absorption refrigeration system is developed, considering electricity and cold water production for the air-conditioning system of a computer centre building under Brazilian conditions, using energy, exergy and economic analyses. Yu et al. [76] presented a total energy system (TES) incorporating a solid oxide fuel cell (SOFC) and an exhaust gas driven absorption chiller (AC) to provide power, cooling and/or heating simultaneously and a steady-state mathematical model was developed to simulate the effects of different operating conditions of SOFC, such as the fuel utilization factor and average current density, on the performance of the TES by using the MATLAB software package and parametric analysis showed that both electrical efficiency and total efficiency of the TES have maximum values with variation of the fuel utilization factor; while the cooling efficiency increases, the electrical efficiency and total efficiency decrease with increase in the current density of SOFC. Obara and Tanno [77] investigated the exergy flow and exergy efficiency of a 3 kW proton-exchange-membrane fuel cell and the regional characteristic of the distributed energy system was considered and by examining how to improve the exergy efficiency of this system, certain improvement methods were proposed. Gariglio et al. [78] compared two similar experimental campaigns performed on the two SOFC prototypes with different nominal power, in order to investigate the performance of the two generator designs and factorial analysis was applied considering two factors: setup temperature of the generator and fuel utilization factor and the obtained data was analyzed by using the ANOVA of the experimental data of some dependent variables and then, the regression models was obtained for every dependent variable considered, and an optimization analysis was performed and the analysis showed that the stack voltage sensitivity to the fuel utilization of the two systems has nearly the same value; and the stack voltage sensitivity to the generator setup temperature was different for the two systems. Obara [79] examined the characteristics of the power quality of a fuel cell micro-grid, and the generation efficiency of the fuel cell using numerical analysis and as a result, the relationship between the parameter of the controller and power quality and a fall in generation efficiency by a partial load was clarified. Barrera et al. [80] investigated the performance and reliability level of the Acumentrics CP-SOFC-5000 Fuel Cell Generator, focused on continuous mode operation at half-power and low power levels and performed technical and economical assessment for future applications of small SOFC plants for distributed cogeneration. Dorer et al. [81] established a methodology for assessing the performance of such systems in terms of primary energy demand and the CO_2 emissions by transient computer simulations, and demonstrated for a natural gas driven solid oxide fuel cell and, to a lesser extent, a polymer electrolyte fuel cell (PEFC) home fuel cell cogeneration system and the systems were evaluated for different grid electricity generation mix types and compared to traditional gas boiler systems. Huang and Huang [82] studied the syngas cogeneration in direct-methane solid oxide fuel cells with Ni–yttria-stabilized zirconia (YSZ) anodes with temperature varying from 700 to 900 °C and a phenomenon of electrochemical promotion of bulk lattice-oxygen extraction from the YSZ electrolyte was observed. Riensche et al. [83] carried out an energetic and economic analysis of a decentralized natural gas-fuelled SOFC-power plant in the range of 200 kW and capacity and changes in costs of electricity (COE) and plant efficiency were determined for the variation of cell operation parameters. Verda and Quaglia [84] conducted the analysis of some possible improvements of a 100 kW SOFC system as well as possible applications considering both technical and economic aspects of decentralized power generation and cogeneration. Obara and Tanno [85] proposed the hybrid cogeneration system (HCGS) that uses a solid polymer membrane-type fuel cell (PEM-FC) and a hydrogen mixture gas engine (NEG) together to improve power generation efficiency during partial load of fuel cell cogeneration and HCGS was introduced into 10 household apartments in Tokyo, and the power generation efficiency, carbon dioxide emissions and optimal capacity of a boiler and heat storage tank were investigated through analysis.

4.4. Modeling and simulation

Akkaya et al. [86] developed a thermodynamic model of solid oxide fuel cell/gas turbine combined heat and power (SOFC/GT CHP) system under steady-state operation using zero-dimensional approach and compared the energetic performance results of the developed model with the literature concerning SOFC/GT hybrid systems for its reliability and exergy analysis was carried out based on the developed model to obtain a more efficient system by the determination of irreversibilities and the simulation results of the SOFC/GT CHP system investigated showed that a design based on exergetic performance coefficient (EPC) criterion has considerable advantage in terms of entropy-generation rate. Calì et al. [87] calibrated a mathematical model with the results acquired during the first CHP100 demonstration at EDB/ELSAM in Westerwoort and performed simulated tests in the form of computer experimental session, and the measurement uncertainties was simulated with perturbation imposed to the model independent variables and the effect of the main independent variables (air utilization factor U_{ox}, fuel utilization factor UF, internal fuel and air preheating and anodic recycling flow rate) was investigated using the ANOVA technique. Obara [88] considered an effective-use method of exhaust heat for a fuel cell energy network (FEN), in which fuel cells installed in two or more buildings are connected and developed a program for planning the path for the hot-water piping network, and it can be used to plan the route which minimizes the amount of heat released in the piping considering the difference in temperature of the open air and hot water. Ferguson and Ugursal [89] developed a steady-state model of a generic PEM cogeneration fuel cell system to accurately size fuel cell systems for houses which can be used for the following: (i) estimating system fuel use, and electrical and thermal production, (ii) investigating the suitability of fuel cell systems in different climates, (iii) sizing fuel cell systems and ancillary equipment, and (iv) evaluating different control strategies and the model was validated using empirical data and published estimates produced with other models. Liu and Leong [90] developed a steady-state mathematical model to simulate a cogeneration system that incorporates a natural gas fed internal-reforming solid oxide fuel cell (IRSOFC) and a zeolite/water adsorption chiller and the effects of fuel flow rate, fuel utilization factor, circulation ratio, mass of adsorbent and inlet air temperature on the performance were considered and the results showed that the proposed IRSOFC-AC cogeneration system can achieve a total efficiency (combined electrical power and cooling power) of more than 77%. Korsgaard et al. [91] developed a complete model of a system consisting of the high-temperature proton exchange membrane (HTPEM) fuel cell stack based on PBI membranes, steam-reforming reactor, burner, heat reservoir and other auxiliary equipment included in a typical reforming-based fuel cell system and implemented the model in the MATLAB® Simulink environment enabling both static system integration as well as dynamical control strategies to be evaluated and all results of the sub models correspond well with experimental results obtained. Lee and Strand [92] developed a thermal and electrochemical model for the simulation of solid oxide fuel cell cogeneration system in this study and the modeling algorithms of electrochemical and thermal models were described and as a result of the parametric study, fuel flow rate, cell voltage, fuel utilization and recycling rate of cathode gas turned out to improve system power output. Hawkes et al. [93] developed a detailed model of SOFC based on micro-CHP technical characteristics, considering a number of different heat demand profiles for a typical UK residential dwelling and also economic and environmental outcomes were modeled for each heat demand profile. Hubert et al. [94] performed the steady state modeling and optimization of a micro-cogenerator based on a natural gas reformer and a PEMFC using Thermoptim®, a software developed within Center for Energy and Processes (CEP) for applied thermodynamics. Beausoleil-Morrison and Lombardi [95] have demonstrated how a mathematical model for simulating the thermal and electrical performance of SOFC micro-cogeneration devices and which is suitable for use in whole building simulation programs can be calibrated to represent the performance of specific SOFC micro-cogeneration devices and this calibrated model was used to test a prototype 2.8 KW_{AC} SOFC micro-cogeneration system. Obara [96] examined the hot-water piping and heat release of two types of fuel cell energy network installations: a concentration installation FEN wherein a single fuel cell supplied power and heat to the entire network, and a partial distribution installation FEN wherein two fuel cells in two separate buildings were used and based on this analysis, as for heat release, the length of the hot-water piping was found to have greater significance than the order of the hot-water piping route and all the analytical results using a genetic algorithm indicated that the hot-water piping route with the shortest length was the optimal pathway. Verhaert et al. [97] developed a two-dimensional model for an alkaline fuel cell, using a control volume approach, in order to better understand the water, alkali and thermal flows and validated the model by experimental data from measured performance by VITO with their cell voltage monitor at a test case, where the AFC-unit is used as a cogeneration unit.

4.5. Economics

Alanne et al. [98] conducted a comparative assessment of the SOFC system vis-à-vis heating systems based on gas, oil and electricity using the simplified model for a single-family house located in Ottawa and Vancouver and the energy consumption of the house was estimated using the HOT2000 building simulation program and a financial analysis was carried out to evaluate the sensitivity of the maximum allowable capital cost with respect to system sizing, acceptable payback period, energy price and the electricity buyback strategy of an energy utility.

4.6. Environment and energy policy

Williams et al. [99] discussed several major programs for clean and efficient power generation, funded by U.S. Department of Energy – Office of Fossil Energy, which include high temperature solid oxide and molten carbonate fuel cells and the combinations of these with gas turbines in highly efficient hybrids and outlined about the SECA program which is expected to provide SOFC systems that cost about $400 per kW by 2010.

5. Cogeneration technologies based on waste heat recovery

The effective utilization of waste heat from various systems has formed a new area of research. Cogeneration technologies based on waste heat has been presented here by classifying them under study, design, analysis, modeling and simulation.

5.1. Study

Al-Rabghi et al. [100] presented a review of waste heat recovery and utilization and discussed the potential for re-using the otherwise wasted heat in different branches of industry and traditional and new ways to recover the discharged heat from industrial equipment were illustrated and it was concluded that there exist numerous opportunities for recuperating and using waste heat.

5.2. Design

Satyamurthy et al. [101] proposed a novel conceptual scheme for utilizing the heat released during interim storage of the vitrified nuclear waste for electrical power generation by using a liquid metal magnetohydrodynamic energy converter (LMMHDEC) and the basic design details of the LMMHD gravitational type energy converter was presented, and based on this model, various important parameters of the LMMHDEC system, suitable for coupling to the nuclear waste, were obtained. Budin et al. [102] introduced some methods for improving energy management in energy intensive polyethylene production (LDPE) and usually used conventional system with separate heat and power production, CHP satisfying thermal energy needs was proposed and secondary sources i.e. condensate and flue gases utilization were also examined. Maidment et al. [103] proposed the use of a novel barometric flash-type desalinator, driven by otherwise waste-heat from the island of Cyprus' power-stations, as a means of increasing freshwater supplies and investigated the thermodynamic performance and economic viability of the proposed system using mathematical models.

5.3. Analysis

Kalinowski et al. [104] analyzed a potential replacement of propane chillers with absorption refrigeration systems and it was found that recovering waste heat from a 9 MW electricity generation process could provide 5.2 MW waste heat produced additional cooling to the LNG plant and save 1.9 MW of electricity consumption.

5.4. Modeling and simulation

Descombes and Boudigues [105] studied the waste heat recovery aiming to increase the availability of the combined cycles and cogeneration and non usual depressurised and over-expansion cycles were studied and calculations showed that thermal efficiency of the engine is increased by 4–5 points on its optimum working condition.

6. Conclusion

A detailed literature survey of cogeneration technologies based on renewable energy sources like biomass, solar energy, fuel cell, and waste heat was performed. Various designs, numerical and simulation models, key development areas, economic and environmental considerations were focused in this review. This paper will be useful for the researchers in cogeneration technologies to make effective decisions and generate more ideas. Thus the paper explicitly points out the areas in cogeneration technologies where there is scope for future research.

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