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Integrating renewable energy sources into energy systems for the reduction of carbon footprints of buildings and building complexes

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Energy use continues to rise and with it the emissions of CO_2. Energy efficiency methods have been applied across sectors, and efficiency gains and energy use per manufactured unit has fallen, particularly in relation to the processing industry. Residential, work place, leisure, and service sectors still use large amounts of energy and produce large emissions of CO_2 despite efficiency gains. The use of renewables in meeting these demands is still comparatively small, and if the carbon footprint is used as a measure of CO_2 reduction, some "zero" or low carbon emission technologies have a measurable effect on overall CO_2 production. Successful strategies used in the processing industry for integrating energy systems and increasing efficiency can be applied to this non-industry sector, which allows integration of renewable energies on a scale that allows demands to be satisfied and carbon footprints to be minimised.

1. Introduction

Although energy prices have risen considerably in the last few years, and energy efficiency measures have been introduced to deal with greenhouse gas emissions, since 1995 the energy consumption of the EC countries has risen by 11 %, to the value of 1637Mt of oil equivalent (Eurostat, 2006). In the UK domestic energy consumption has risen from 35.6 Mt of oil equivalent to 48.5Mt in the period 1971 to 2001, an increase of 36%, despite energy efficiency increases (DTI, 2006). In the UK it is proposed that the number of houses built over the next 10 years should increase by 200,000/y, to account for the smaller number of people per household, and the demand for housing (UK Government, 2005). This is likely to have serious implications for energy consumption and consequently greenhouse gas emissions if carbon based energy sources are not replaced more rapidly by non-carbon or renewable sources of energy. For example, renewables only contribute, in the UK, 1.0 Mt of oil equivalent towards total domestic energy use compared to a total use of 47.0 Mt of oil equivalent. Although the release of CO_2 from carbon based fuels has become the prime driving force to reduce energy use, the simple measure of CO_2 emissions related to fuel use is only part of the potential production of CO_2 from buildings. A "carbon footprint" (CFP) is defined by (POST, 2006) as the total amount of CO_2 and the other greenhouse gases emitted over the full life cycle of a process or product. There have been many studies (e.g. Albrecht, 2007, Fiaschi and Carta, 2007) stressing the carbon neutrality of renewable sources of energy. Even renewables make some contribution to the CFP. The assessments of renewable technologies applicable in the domestic sector can assist in making the correct selection and consequently reduce the release of CO_2. Electricity and heating/cooling needs of the residential sector can be partially satisfied by the use of renewable energy related to low and zero-carbon technologies on the local scale. Such sources include community CHP (combined heat and power), µCHP (at the household level), heat pumps, biomass, PV, solar heating and cooling, wind turbines etc. Many examples exist of how this can be achieved with individual dwellings. Remaining electrical and heating/cooling duties have to be met by either local sources (e.g. boilers) using carbon based fuels, such as gas, or from the national grid. Rarely investigated was the possibility of integrating local renewable energy with district renewable energy sources, supplemented by carbon based systems at times of high demand or low production. This paper will attempt provide an overall framework for an integration based on existing studies of integrated energy systems for industrial scale processes.

2. Local renewable energy sources

2.1 µCHP

In the main, as the minimum required temperatures in building applications vary between 40 °C and 80 °C, an output temperature of approximately 100 °C should be designed for a CHP system. Several competing technologies in the µscale can be used for combined heat and power generation: reciprocating engines, µturbines (electricity below 250 kW), Stirling engines, and fuel cells.

2.2 Reciprocating engines

A typical reciprocating engine (diesel, gas, multiple fuel) and a generator linked to the engine are quite efficient in producing electricity, have a large power range and a versatile of fuels. The applicability of gas engines is at its best in back-up systems, diesel engines are recommended for continuous use. The relatively noisy operation makes them unattractive for residential applications. The moving parts require regular maintenance which further adds to the CFP. CO_2 and SO_2 emissions are dependant on the type of fuel used. CHP based on reciprocating engines are more applicable to larger buildings with less peaked electricity and heat consumption profiles (Alanne and Saari, 2004).

2.3 Stirling engines (StE)

The StE is a reciprocating engine with its cylinder closed and combustion taking place outside of the cylinder. StE are characterised by low emissions (especially NO_x) and lower noise. External combustion causes a decreased maintenance level which reduces the CFP. Various fuels are suitable, including biomass. This type of CHP has rather low electrical efficiency, about 25–30 % when natural gas is used as a fuel. When solid fuels (e.g. biomass) are used, the efficiency can be as low as 15 %. The total efficiency is not significantly lower than that of other CHP applications. StE engines are applicable to residential buildings, due the electricity/heat ratio. Their low efficiency supports their use as backup supplies rather in continuous use (Peacock and Newborough, 2005).

2.4 Fuel Cells (FC*)*

A FC produces electricity electrochemically, by combining hydrogen and atmospheric oxygen. The electrical efficiency of these systems can be as high as 45–55% (Alanne and Saari, 2004). If pure hydrogen is used, the only emission is water. If reformation is used, CO_2 and a minimal amount of SO_X and NO_X are formed, depending on the fuel. Other benefits are noiselessness, reliability, modularity, and rapid adaptability to load changes. The important drawback is the investment cost. FCs are more demanding in respect of fuel production, storage, and transportation. Peacock and Newborough (2005) assessed the CFP of some of the CHP, namely the StEs and FCs applied for a single dwelling in Central England (Table 1). The StE yields daily savings of 2.5+ kg CO_2 in winter and less than 1 kg CO_2 in summer. The reduced thermal output of the 1 kW FC system causes significantly less seasonal variation and yields daily savings of 3+ kg CO_2 in winter and 2+ kg CO_2 in summer. μCHP systems can offer considerable CO_2 emissions reduction compared to a condensing boiler and network electricity.

Table 1 Carbon performance of μCHP systems (Peacock and Newborough, 2005)

μCHP	**Reduction in CO_2 emissions**
Stirling engine – unrestricted thermal surplus	-145 $kgCO_2$/y(+3%)
Stirling engine –restricted thermal surplus	+574 $kgCO_2$/y (-10%)
Stirling engine –restricted thermal surplus and part-load	+512 $kgCO_2$/y (-9%)
Fuel cell (1 kW)	+892 $kgCO_2$/y (-16%)
Fuel cell (3 kW)	+2247 $kgCO_2$/y (-40%)

2.5 Biomass

The use of biomass is considered as a 'carbon-neutral' process because the carbon dioxide released during the generation of energy is balanced by that absorbed by plants during their growth (CCAP, 1998). There are three main groups of biomass: dependent resources (co-products and waste generated), dedicated energy crops: (short-rotation crops) and multi-functional crops. Domestic applications mainly involve pelletised biomass for use in CHP generation. In the UK, the CFP of biomass vary widely depending on the kind of the feedstock: 25 gCO_2/kWh for high-density wood gasification to 93 gCO_2/kWh - combustion of low density miscantus (POST, 2006).

2.6 Solar cells (SC)

Electricity and heat produced from SC has a far smaller impact on the environment than traditional methods of electrical and heat generation. It has been estimated that for building integrated SC systems, the total life cycle emissions of CO_2 are between 13-731 gCO_2/kWh produced (depending on PV cell technology) (British Energy, 2005). The EMINENT software tool (EMINENT, 2005) analysed the solar film SC potential. It shows that the application of 3rd generation SC in the household sector can become economically viable and contribute to the reduction of the CFP. The details are given in (Klemeš et al, 2005). Further analysis of applications in the domestic sector is given by the SOLARSTORE system (Masruroh et al, 2006).

2.7 Wind

Wind generated electricity has one of the lowest CFP. Manufacturing and construction account for almost all of the carbon emissions, the rest being maintenance. In the UK, a typical wind generation CFP is about 4.64 gCO_2eq/kWh (POST, 2006). The availability should be also taken into consideration, and in most cases is rarely above 20 % (UCTE, 2004). Back-up systems increase the effective CFP.

3. Integrating Micro Renewable Energy Sources

The Centre for Process Integration, The University of Manchester, has extended concepts and methodologies in the design of energy based systems from the established Pinch Technology (Linnhoff and Hindmarsh, 1982, Linnhoff and Vredeveld, 1984) for single chemical processes to analysis, understanding, and design of integrated site systems (Klemes et al, 1997). These developments have included Network Pinch for the retrofit of Heat Exchanger Networks (Asante, 1996), Cogeneration and Site Utility system modelling, simulation, and design (Varbanov et al, 2004a, Varbanov et al, 2004b, Varbanov et al, 2005), and HEN optimisation (Zhu and Asante, 1999). The new concepts and methodologies have combined thermodynamics and mathematical modelling into an integrated systematic approach to the design and analysis of small and large energy based systems. The conceptual understanding of these energy-based systems and the tools developed to exploit these new design methodologies have been extensively covered in many papers.

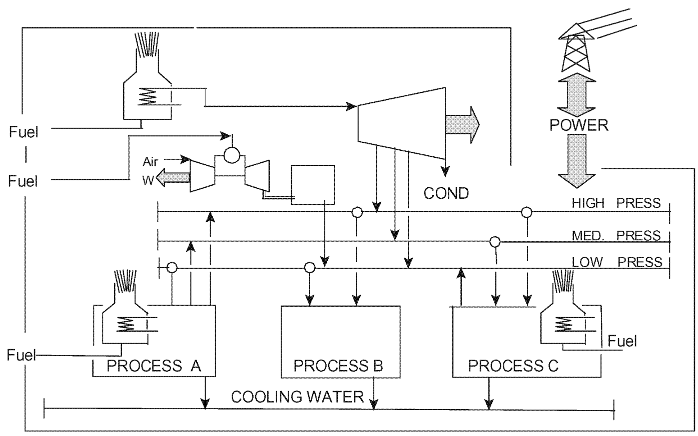

Figure 1. Integrated Energy Systems for Total Sites

A typical industrial site comprises different process production units linked to a common utility system (Fig. 1). The centralised utility system meets the demands for heat and power, creating indirect links between the processes. High temperature heating demands within process units may require furnace heating. The cooling demands of the processes can be met by a cooling water system, air cooling, a refrigeration system, or a combination of these. The concept of an integrated energy system for the production of heat and power meeting local needs can be applied to systems involving demands produced by individual buildings and building complexes (Fig. 2). In this case demands for heating/cooling and electricity in units (e.g. dwelling, offices, hospitals, or schools) can be met locally by renewable energy sources such as wind, solar cells, or heat pumps. Additionally locally installed boilers, consuming traditional fossil based fuels or biomass, can also help to meet these requirements, when demand is high or other sources are unavailable. Heating/cooling and power not required by one unit can be fed to a grid system, and then passed to another unit that is unable to meet its demands locally. The grid system can distribute power (electricity) and heating in the form of hot water or steam. In geographic locations where air conditioning is required, a cooling distribution main could also be provided. If local sources are unable to provide the demands for all of the units in the system, then district renewable sources can be provided. These again would include larger scale wind turbines, solar cell systems, large scale heat pumps, and combustors using waste provided by the units or fossil or bio-fuels. The sources at this level would include power generating equipment such as steam turbines or gas turbines.

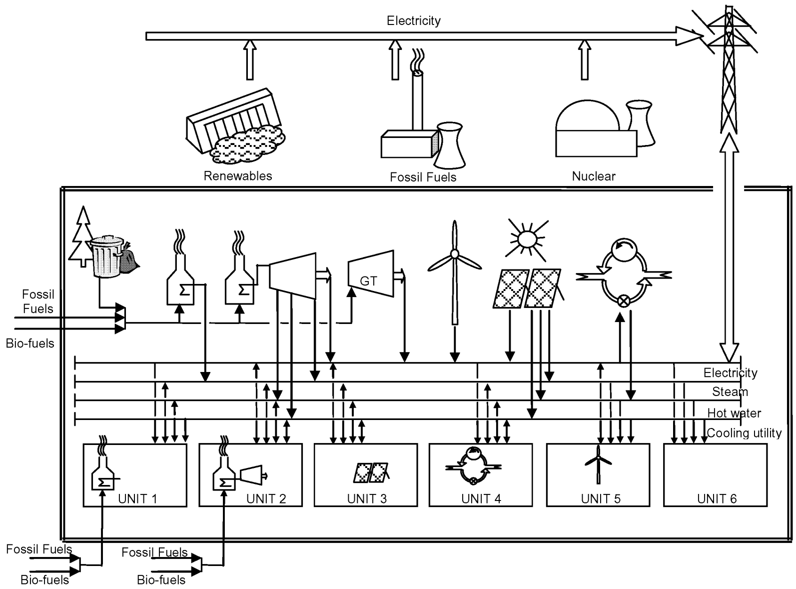

Figure 2. Integrated Energy Systems with Renewables for Buildings and Building complexes for Total Sites

4. Conclusions

Buildings and building complexes, such as individual dwellings, offices, leisure facilities, and service providers, have large energy demands in the form of electrical power and heating/cooling. Some of these demands can be met by small local renewable energy providers, although it has been shown that their CO_2 contribution may be larger than initially realised and better estimates can be made through the application of carbon footprints. However, the use of integrated energy systems, including renewables, incorporating supply and demand at both the local and district level, would likely produce overall better energy efficiencies and consequently reduced emissions and carbon footprint. The application of proven design strategies adopted from the chemical process industry could provide the key to successful reductions.

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