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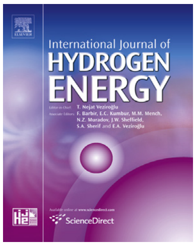

# Decentralized power and heat derived from an eco-innovative integrated gasification fuel cell combined cycle fuelled by waste

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A B S T R A C T

The suitability for fuel cells to run on synthesis gas coming from the gasification of waste is determined by the sensitivity of the fuel cell to run on contaminated fuel. Out of the available fuel cell technologies solid oxide fuel cells (SOFCs), because of their ceramic construction and high operating temperatures, are best suited for syngas operation. Their high operating temperature (>650 °C) and the presence of nickel at the anode means that it is possible to reform hydrocarbons to provide further hydrogen [1].

Numerical simulations representing all aspects of the proposed system have been developed to understand the energy performance of the system as a whole as well as the financial and environmental benefits. Taking into account variations in the waste composition and the wholesale electricity price the proposed system, scaled to process 100,000 tonnes of waste per year (40,000 removed for recycling), has a simple payback period of 7.2 years whilst providing $CO_2$ savings of 13%. Over the year the proposed system will provide enough electricity to supply more than 23,000 homes and enough heat for more than 5800 homes.

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## Introduction

Escalating energy demands, energy security issues and the current political drive to reduce carbon emissions have created an overwhelming need for innovative and future-proof decentralised energy production and management solutions to tackle the area of sustainable energy production. Over the past century there has been an exponential growth in energy consumption of which 80% is derived from fossil fuels [2]. Current estimations see coal as the only fossil fuel to be available after 2042 and will only be available up to 2112 [3]. At the same time there is growing concern surround the emission of greenhouse gasses which contribute to global warming disrupting the current climate rhythm.

This has led to substantial interest and deployment of solar powered renewable technologies such as wind turbines, photovoltaics (PV), and biomass. As an energy resource the potential for wind energy in the UK is very strong and is considered to the best wind resource in Europe [4]. Whilst wind turbines and PVs are fundamentally sustainable with relatively short energy payback periods they are inherently

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intermittent which means the electricity grid will struggle to support their deployment at large scale. Therefore, further technologies dealing with the dynamic relationship between demand and supply will be required to support the large-scale penetration of any intermittent energy sources.

There is also a need for effective and sustainable waste management at a time when households are producing ever more waste. In some cases this waste is sent to large centralised waste incinerators which are unable to make full use of the waste heat (which is >65% of the total energy content) and therefore unable to fully re-capture the embodied energy. They also have disadvantages in terms of emissions and solid by-products which are often classified as hazardous.

In order to maximise efficiency and to bring these waste-to-energy (WtE) systems closer to the end users – where waste heat can be utilised in intelligent building-to-building thermal energy networks – new technologies must be introduced [1].

Currently only 20% of the municipal waste produced in Europe is sent to incineration plants [5], and of the waste generated in the UK it is estimated that 40% is considered to be bio-waste [6,7]. Therefore there is a large potential to provide carbon emissions savings by diverting waste away from landfill to WtE plants that can efficiently recover the embodied energy within the waste to produce energy. The biofraction of the waste stream is considered as a renewable source of energy thereby providing carbon savings.

### *The waste, hydrogen, heat and electricity (WHHE) concept*

This concept and research relies on the successful integration of proven cutting-edge fuel processing, energy production and energy storage technology in a new and innovative manner to achieve a highly efficient and flexible decentralized energy system for the building industry. These technologies include: thermal plasma gasification, gas filtering, hybrid fuel cell/heat engine combined cycle, hydrogen production (electrolysis), hydrogen storage (nanostructured high capacity metal hydrides), enhanced heat exchange and effective thermal management systems, Fig. 1. This system represents an ambitious step in the direction of energy decarbonisation and security by providing decentralised clean and efficient energy centres for the long term, comprehensive management of heat, electricity, hydrogen and waste.

## Modelling theory and methodology

In this research Simulink®, which is an interactive graphical block programming tool that integrates with MatLab®, is used to carry out selective modelling of several of the energy processes (Fig. 2). The algorithms used to describe the various processes are based on static and dynamic equations that are either derived from experimental results or obtained through literature.

For those processes where Simulink modelling is not best suited ChemCad has been used. ChemCad is ideally suited to modelling of the chemical processes such as gasification, gas filtration and separation, and heat management.

## SOFC modelling

Due to the complexity and importance of the SOFC the modelling goes into details which are well suited to the functionality and capabilities of Simulink's modelling environment.

The performance of the SOFC is defined by the Nernst equations which describes the reversible voltage as a function of the partial pressure of product ($H_2O$) and the reactants ($H_2$, $O_2$):

$$E = E^o + \frac{RT}{nF} ln\left[\left(\frac{p_{H_2}}{p_{H_2O}}\right)\left(\frac{p_{O_2}}{p_0}\right)^{½}\right]$$

Therefore, in order to accurately simulate the interaction of the various gases, introduced via the syngas composition, mass transport calculations are carried out for Knudsen, ordinary and effective diffusion coefficients which are applied to the Maxwell–Stefan diffusion model for binary mixtures. The Maxwell–Stefan model is then manipulated to calculate the partial pressures to be used in the Nernst equation [8]:

$$p^*_{H_2} = p_{ch,H_2} - \frac{jRTt_a}{2FD_{H_2,H_2O}};$$

$$p^*_{H_2O} = p_{ch,H_2O} + \frac{jRTt_a}{2FD_{H_2,H_2O}};$$

$$p^*_{O_2} = P_{ch,c} - \left(P_{ch,c} - p_{ch,O_2}\right)\exp\left(\frac{jRTt_c}{4FP_{ch,c}D_{O_2,N_2}}\right)$$

Losses at the fuel cell come from; activation losses (activation energy required to overcome the charge double layer), concentration losses (restricted transportation of reactants and products to/from the reaction site), and ohmic losses (losses due to resistance – imperfect conduction).

Activation losses are calculated using the cell's current density and exchange current density:

$$\eta_{act} = \frac{RT}{\alpha nF}\log\left(\frac{j}{j_0}\right)$$

Where the exchange current density is calculated according to the Arrhenius law – which is again a function of the partial pressures of the product and reactants at the anode and cathode [9]:

$$j_{0,a} = \gamma_{an}\left(\frac{p_{H_2}}{P_{ref}}\right)\left(\frac{p_{H_2O}}{P_{ref}}\right)\exp\left(-\frac{E_{act,a}}{RT}\right)$$

$$j_{0,c} = \gamma_{cat}\left(\frac{p_{O_2}}{P_{ref}}\right)^{0.25}\exp\left(-\frac{E_{act,c}}{RT}\right)$$

Concentration losses are most noticeable at high current densities where the cell is starved from insufficient reactants reaching the reaction site and where the product is struggling to move away from the reaction site. Therefore by manipulating the Nernst equation the concentration losses can be defined by a limiting current density [10]:

$$\eta_{conc} = \frac{RT}{nF}\ln\frac{j_L}{j_L - j}$$

where

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