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The potential to generate solar hydrogen for cooking applications: Case studies of Ghana, Jamaica and Indonesia

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ABSTRACT

This paper evaluates one option to replace traditional cooking fuels in developing economies with a flexible, modular and clean solution of solar hydrogen, based on a numerical and experimentally tested system to address technical and safety issues. The study focuses on Ghana, Jamaica and Indonesia as examples of developing economies using fossil fuels for domestic cooking. Statistical analyses are performed and the domestic cooking demand profiles are created for these countries based on available data and a specific quantitative study in Ghana. The derived cooking demand profiles are used to size solar hydrogen plant case-studies for rural communities based on a TRNSYS numerical model. The results indicate that hydrogen plant sizing and management satisfy annual cooking demands of the communities which are 621.6 kg H_2 for Jamaica, 631 kg H_2 for Indonesia and 785 kg H_2 for Ghana. The effect of the weather data on the simulation is estimated by comparison between TMY and recent weather data for Jamaica. Finkelstein-Schafer statistics indicate differences between the composite and recent weather data, but these prove to have minor effect on simulation results, with 0.9% difference in hydrogen generation. The potential to establish solar hydrogen plants in the countries is further evaluated by creating novel solar hydrogen potential maps.

1. Introduction

Energy security in developing economies is an important factor towards the improvement of the living and social standards. Household energy use in the developing world represents 10% of the world's primary energy demand, according to the International Energy Agency [1] and the main use of domestic energy (90%) is for cooking.

Almost 2.7 billion people depend on the burning of biomass as their primary cooking fuel [1,2] and most of them live in Asia and sub Saharan Africa. This number is predicted to rise further in the future; a fact that will have consequences in the increase of deforestation rates, greenhouse gas emission and health problems related to indoor air pollution [3]. Improving currently used cooking systems and replacing them with renewable based ones can have multiple advantages: reduced rates of respiratory problems, time saving due to less time spent on fuel collection and cooking and environmental benefits [4].

At the beginning of the 21st century the United Nations (UN) Organisation launched the Millennium Project that sets the target of reducing by 50% by the year 2015 the number of households that use biomass as a primary source of fuel [5]. Moreover, the 17 sustainable development goals set in 2015 further promote access to affordable, reliable and sustainable energy for all, with a focus on the cooking fuels and energy [6]. Solar powered electric cooking [7], improved wood stoves [8] and solar cooking projects [9] have been implemented by the UN in many developing economies as sustainable, clean and emissions free cooking methods. Beneficial outcomes have been reported by the use of solar cooking in refugee camps in Africa and multiple locations in Asia and South America where energy poverty was forcing people to use animal and agricultural waste [10,11]. Solar cooking and modified charcoal stoves are also highly promoted through the Global Alliance for Clean Cookstoves [12] and in 2013 11.7 million modified stoves were distributed in seven countries. The solar cooking projects however,

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which were the most ambitious, have not reported particular successes. Their dependency on sunlight availability, as the energy storage option is rarely combined, their low efficiency which makes cooking time-consuming and the large space demand, especially in the case of parabolic or solar panel cookers [13,14], pose hindrances for their use. Furthermore, solar cookers have not been widely accepted due to adverse social and cultural perceptions. This is because originally solar cooker projects targeted extreme energy poverty tackling which created a strong association with social discrimination and therefore have met with reluctance and criticism by local societies [15]. Moreover, they limit the cooking place to specific areas outside the house and are difficult to cook at high temperatures to prepare traditional fried meals, to correspond with traditional cooking habits and meals [15,16].

It is suggested that a successful alternative cooking system should be easy to adopt and should not pose disruption of the daily habits and cooking schedule of local residents that traditionally cook in stoves [1,2]. A study for the investigation of such a system was funded in 2010 by the European APC Caribbean & Pacific Research Programme for Sustainable Development programme to develop and test experimentally the application of solar-powered proton exchange membrane (PEM) electrolysers for the sustainable production of hydrogen gas a fuel for domestic cooking [17]. Within the scope of this project, this paper presents results on the evaluation of the potential to apply the developed system using a case-study country approach. The developed solar hydrogen system consists of a photovoltaic panel array which powers a proton exchange membrane (PEM) electrolyser plant. Hydrogen gas is generated and distributed to households for use as an alternative clean and sustainable cooking fuel in modified gas stoves with a simple adaptation to burn hydrogen. The current cooking systems in countries selected for this study consist mainly on LPG, charcoal and firewood stoves and therefore the introduction of a modified gas stove is a solution that can be easily accepted by a wide range of the society in these countries. The system operation is evaluated through a numerical model in TRNSYS developed by the authors, [18].

Safety of hydrogen use at home is an important issue considered in this project. Two alternative methods of storage were developed; (a) a relatively low cost cascading system where hydrogen is stored in high pressure cylinders outside the house and is cascaded to lightweight low pressure containers suitable for transportation in private vehicles and used inside homes and (b) metal hydride storage which is more expensive and under development at present but is considered as a safer option. The system described in this paper focuses on the metal hydride storage. In addition, cookers need to be modified for burning hydrogen to which odour and flame colour is added for safety. A prototype of the modified cooker has been constructed and being tested and will be reported in a separate paper. Some visual information of the developed system can be seen in the website of the sustainable hydrogen cooking gas project [19].

This paper is divided to four sections. Section 2 presents the country case studies examined for the application of the solar hydrogen system. The process to calculate the daily cooking profile of the typical household for each case is described. Section 3 presents the simulation results for each case study based on the TRNSYS solar hydrogen numerical model. Section 4 analyses the effect of weather data on the simulation results and, Section 5 visualises the potential of solar hydrogen generation on a country level in the form of maps.

2. Case studies presentation

Three countries were selected as case studies for the evaluation of the solar hydrogen system, Ghana, Jamaica and Indonesia. All three countries have developing economies [20] and geographically belong to the near equatorial region. In addition, their prime proportion of domestic energy demand comes from cooking and is dominated by fossil fuels, mainly firewood, charcoal and petroleum by-products. Poor ventilation and out-dated cooking methods result in numerous deaths every year directly related to the emissions of these cooking fuels [1]. Moreover, these countries can be pushed to finance instabilities being dependant on imports of petroleum products for their energy needs.

The purpose of this study is to determine the size of a solar hydrogen system to provide hydrogen as a cooking gas, that can replace the fossil fuel based cooking systems of selected communities in the three case study countries. The communities belong to rural areas and represent actual size small villages of 20 households. The evaluation of the cooking demand profile for the households is essential for the correct and optimised sizing of the solar hydrogen system, and this is done through quantitative studies, research and extensive literature review.

2.1. Article I. Ghana case study

Ghana is a West African country with tropical climate of a total land area of 238,500 km^2 and a population of 27 million [21]. It is positioned in the Gulf of Guinea and is a country well-endowed with water resources, which are essential for the generation of electrolytic hydrogen. The solar energy potential of the country is also very high, ranging from 4 to 6 kWh/m^2 providing excellent conditions for photovoltaic panel applications [22].

The greatest percentage of final energy use in the country corresponds to the residential sector with energy for cooking accounting for almost 95% of the household energy use [23]. The majority of the population -57%- lives in rural areas and statistics show that most Ghanaians rely completely on the use of biomass for cooking (firewood and charcoal) as well as a small percentage on LPG [24].

With an aim to create a cooking demand profile for a Ghanaian household and due to lack of available data in the literature, a questionnaire survey was conducted with a quantitative approach. Use and cost of fuels was evaluated as well as socio – economical relation of household and fuel use and the potential to introduce a solar hydrogen system. Local people from three communities were selected for the field study, Akatsi, Keta and Sogakope, which are located in the south-east part of the country, in the Volta region [25]. These communities were selected as they represent the typical rural households of Ghana.

Raw data were collected through interviews and standardised questionnaires. The questionnaires included factual questions with pre-determined answers and opinion based questions with an open-ended form where the participants had the liberty to give their own answers. The main subjects that were addressed are: sources of energy for cooking, socio-economic background of the households and cooking behaviour.

The sample population consists of 155 adults who belong to distinct professional and social groups. Cooking is a woman dominated activity in Africa [24], and most of the participants are females who were contacted through visits in the local fuel markets of the villages. The majority of the population forming the sample are engaged in trading and owning their own business (in total 64%). The second largest category is teachers, followed by clerks/secretaries, farmers and fishermen/fishmongers, bank workers and pensioners. The results of this survey are presented by Topriska et al. [26] and a summary is included in this paper for completeness and to facilitate comparison with Jamaica and Indonesian case-studies. The results of the survey are analysed in Sections 2.1.1 to