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Challenges in Environmental Sustainability of renewable energy options in Singapore

Augustine Quek[a,*], Alvin Ee[a], Adam Ng[b], Tong Yen Wah[c]

[a] National University of Singapore, NUS Environmental Research Institute (NERI), Energy and Environmental Sustainability Solutions for Megacities (E2S2), Singapore
[b] National University of Singapore, Department of Industrial Systems Engineering and Management, Singapore
[c] National University of Singapore, Department of Chemical and Biomolecular Engineering, Singapore

ABSTRACT

Renewable and sustainable are often used synonymously. This study examines the sustainability of switching from fossil-based electricity generation to renewable energy systems. Life cycle assessment (LCA) of both fossil- and renewable-based electricity generation were modeled for four environmental impact categories, in the context of Singapore city. The LCA method followed the CML methodology. Four major environmental impacts were calculated: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and human toxicity potential (HTP). The cradle-to-gate analyses were done for various types of electricity supply sources: Solar photovoltaics (PV), biogas, municipal waste incineration, natural gas, coal and oil. The current mix of 95.2% natural gas, 3% incineration, 1% petroleum products and 0.8% coal was used as baseline for comparison with other mixes. The results showed that having a high proportion of electricity generated from solar PVs can produce ten times higher HTP than baseline scenario. Similarly, electricity from biogas can produce eight times higher AP and EP than baseline. Further analysis showed that HTP from solar PVs impacts locally, but mostly external to Singapore. AP from biogas impacts regionally, within and without Singapore. Policies about renewable energy in the overall electricity mix would thus be value- based, rather than purely economic or environmental.

1. Introduction

Electricity generation in most parts of the world currently depends heavily on fossil fuels. It is commonly understood that converting fossil fuels to electricity is environmentally unsustainable. The depletion of nonrenewable fossil fuels coupled with global warming from greenhouse gases releases implies that switching to renewable forms of energy is inevitable. While renewable energy systems are less pollutive in general than fossil fuels at their point of use, environmental impacts can be high at other stages in the life cycle of the system. Therefore, the environmental sustainability of renewable energy depends on many aspects in the entire lifecycle of the system, and not just in greenhouse gases emissions at the point of electricity generation. This paper considers multiple aspects sustainability of shifting from fossil fuels-based electricity generation to more renewable energy supplies for a developed, but small country like Singapore.

Singapore is unique in that it is both a city and a country. Hence, Singapore's political borders can also be considered as the city's limits. As a small city state, with a population of 5.6 million occupying just 710 km^2 of land, Singapore's has one of the highest population density in the world (National Environment Agency NEA, 2016). Like many high-income countries, its economic activities involves a high throughput of materials and resources, from inputs that originate both inside and outside the city. As the country is almost completely urbanized, many solutions have to be catered for urban areas, with small physical and environmental footprints. With no natural resources or environmental service provision, all negative environmental impacts arising from local urban activities would have to be prevented or mitigated through a number of political, social and technological instruments. Hence, an analysis of Singapore's activities and consequent environmental impacts can provide insights and lessons for other cities and countries.

One such urban activity that is fundamental to urban life is energy generation and consumption is not just in Singapore, but in cities throughout the world. Most, if not all urban economic and social activities require energy input of some form. For a city, the energy input is most likely in the form of electricity. Therefore, electricity generation and consumption is a key driver of urban life and prosperity. However, electricity generation uses a significant amount of energy in proportion to total urban energy use. In Singapore, electricity accounts for 26.5% of all energy use (Energy Market Authority EMA, 2017).

More than 95% of Singapore's electrical power is generated using natural gas supplied by Malaysia and Indonesia. The remaining installed capacity generates electricity from fuel oil and coal and incineration of solid waste. In meeting its energy demand, a conscious effort has been made to safeguard environmental interests. In recent years, significant progress has been made in the power generation sector to reduce greenhouse gases emissions. The proportion of

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* Corresponding author.
E-mail address: augustineq@gmail.com (A. Quek).

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electricity generated by gas in Singapore has grown from 19% in 2000 to 74% in 2005, one of the highest levels in the world. In addition, Singapore's renewable energy based electricity generation is mainly from the incinerators, and a tiny fraction (< 1%) from solar photovoltaics (PVs). The energy source for electricity generation is 95.2% natural gas, 3% incineration, 1% petroleum products and 0.8% coal (Energy Market Authority EMA, 2017).

Like the rest of the world, it is inevitable that Singapore would decarbonize and shift to more sustainable energy systems in the future. Unfortunately, Singapore lacks many renewable energy sources such as hydroelectricity, geothermal, wind, tidal and wave. Current state of nuclear power technology was also deemed to be too risky for a densely populated city like Singapore (National Environment Agency NEA, 2016). Thus, alternative renewable sources are limited to solar energy, specifically solar photovoltaics (PVs) and biogas generation of electricity. This paper analyses the sustainability of increasing the energy mix of these two sources for Singapore's electricity generation.

Life Cycle Analysis (LCA), as described in ISO 14040:2006 (ISO, 2006a), is a good method for elucidating the potential environmental impacts from the life-cycles of different electricity options (Asdrubali et al., 2015; Masanet et al., 2013; Tan et al., 2010). LCA takes into account all inputs and outputs throughout the various stages in the lifecycle of the electricity generation process.

Analyzing and identifying the areas of high environmental impacts from electricity generation can shed light on possible key challenges for sustainable urban living. For example, one recent review of over 100 case studies on renewable electricity technologies (Asdrubali et al., 2015) found that solar PV had the highest overall environmental impacts. Overcoming these environmental challenges would then be necessary for long-term continuation of urban activities and growth. Thus, LCA of the most likely renewable energy systems would shed light on possible environmental impacts for Singapore in future. The objective is to elucidate major environmental impacts of possible sustainable electricity supply systems for Singapore.

This paper seeks to identify challenges in renewable energy opportunities for Singapore, through cradle-to-gate LCA studies of six different electricity generation methods: coal, oil, natural gas, solid waste incineration, solar photovoltaics (PVs) and biogas from organic waste. As Singapore's geographical features limit its access to geothermal resources, hydroelectricity, wind, tidal and wave power, these energy sources were not studied.

2. Methodology

The evaluation in this work was based on LCA methodology (ISO, 2006b), which consists of four phases: (1) defining goal and scope, (2) gathering inventory data, (3) classification of impacts and (4) interpreting the results.

2.1. Goal and scope

The goal of this study is to identify and quantify the potential environmental impacts of electricity generation from coal, fuel oil, natural gas, incineration, biogas and solar PVs in the context of Singapore, an urban city-state. The scope of this study is limited to the global warming potential, ecosystem damage and human health damage from the generation of electricity from biogas.

2.1.1. Functional unit

The environmental impacts were calculated based on the functional unit of 1kwh of low voltage electricity generated, ready further stepping down for redistribution. This functional unit was chosen so that the environmental impacts from generation of electricity from alternative source can be compared with current electricity generation sources in Singapore, natural gas and solid waste incineration.

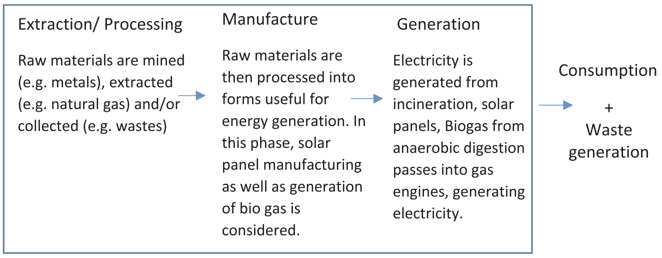

Fig. 1. Boundary conditions for the study.

2.1.2. System boundary

The system boundary encompasses four process stages, described below (Fig. 1).

1. Extraction, processing of raw materials (e.g. natural gas, minerals and metal ores) and cultivation of energy crops. This include mining for all types of metals and minerals, separation and refining. Impacts such as those from producing raw silicon crystals, and purifying rare metal ores are included. Avoiding the zero burden assumption, cultivation, collection and transport of agricultural product (horticultural waste) are considered in this phase as well.
2. Manufacture of solar PV panels and generation of biogas via anaerobic digestion. This stage calculates the impacts from combining the raw materials in the previous stage into solar PV panels, it includes impacts from necessary additional inputs of energy and materials, such as inorganic acids.
3. Electricity generation. Conventional anaerobic digestion using commercial best available technology (BAT) was used in the calculation of gas yield and operation environmental impacts. This include gas cleaning, solids residue recycling and microbial inoculum. Gas collection efficiency from the reactor was assumed to be 100%. Biogas is burned in gas engines at an efficiency of 40%. Biogas was converted to electricity by Combined Heat and Power (CHP) units for feeding into public grid. Heat from the CHP plants was used for heating digesters and where necessary, for pre-treatment of feedstock, whereas excess heat was assumed to be lost. In addition, incineration which generates electricity is being considered in this stage.
4. Electricity transmission and consumption. Electricity is assumed to be transmitted under high voltage and further step down to low voltage to consumers. Thus, subsequent stages of voltage step down for further distribution were not analyzed. Power plant, reactors and module end-of-life decommissioning and treatment were also not included.

Environmental impacts associated with plant construction and transportation were assumed to be insignificant when being distributed throughout the lifespan of such a plant, and therefore were not accounted for in this study. Lifetime of the PV panels, natural gas and biogas plants are assumed to be 20 years.

2.2. Inventory analysis

The lifecycle inventory phase include data collection and calculation in order to quantify inputs (energy, raw and ancillary materials and other physical inputs) and outputs (products, emissions and waste) of a product system.

The input data used to carry out this study was a combination primary and secondary sources published in previous peer-reviewed LCA studies carried out as well as information from established databases such as Ecoinvent and Gabi (Wernet et al., 2016; PE International, 2018). Input data selected and assumptions (e.g. efficiency of power generation from heat) used were based on current best available technology. Energy losses at each stage were accounted for using the actual