Developing and identifying sustainability indicators in the Singapore context

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Abstract

Singapore's geographical setting, being a highly industrialized city-state, with limited natural resources have placed it in a unique position to deal with key issues in its commitment to sustainable development. Evolving sustainability science and assessment tools that underpin sustainability efforts are instrumental in guiding decisions and policies in the drive towards achieving sustainable development. Practical sustainability methods or indicators are viewed as imperative to determine the successful implementation and outcome of sustainable strategies and policies.

We propose the preliminary development of sustainability indicators for four main important subjects for Singapore: i) carbon footprint; ii) energy; iii) water; and iv) waste management and landfill. For carbon footprint, a preliminary model was introduced to estimate the greenhouse gas (e.g. CO_2) emissions considering the manufacture of resources to (value-added) products. Limitations and potential performances of "clean energy" will be discussed, as well as, water supply and demand. In the fourth indicator development, the limited land area of Singapore (718.3 km^2) and its total dependence on an offshore landfill for the disposal of MSW (municipal solid wastes) is investigated.
Keywords: sustainable indicators, carbon footprint, energy, water, landfill.

1 Introduction

As the rise in population, resource depletion and climate change continue to become global concerns, many cities around the world have developed sustainable

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development plans. Singapore's geographical setting, being a highly industrialized city-state, with limited natural resources have placed it in a unique position to deal with key issues in its commitment to sustainable development [1]. Evolving sustainability science and assessment tools that underpin sustainability efforts are instrumental in guiding decisions and policies in the drive towards achieving sustainable development [2]. Practical sustainability indicators are viewed as imperative to determine the successful implementation of sustainable strategies and policies. Different indicators have been developed to serve various needs, and are carefully selected based on specific elements deemed important to a country [3]. This work describes the development of sustainability indicators for four main important issues in Singapore.

2 Carbon footprint

A few methods have been proposed to generate national carbon footprints (CF). Schulz [4] illustrated the challenges in CO_2 accounting for the city-state of Singapore as vibrant economic system. Hertwich and Peters [5] performed national CF analysis using a combined multi-regional statistical model considering input-output factors, consumption trends, and other variables. While life cycle assessment (LCA) is inarguably the most systematic and accurate way to derive product carbon footprints [6], such thorough assessment is time consuming to be performed on a national scale. Here, we propose a systematic, yet simplified, method to estimate the nation's CF for the manufacturing sector, which can help in gauging CO_2 in target reduction policies [7].

2.1 Carbon footprint of manufactured products

In this section, we consider Singapore's global strategic position as a manufacturing hub, and propose a model to generate the carbon footprint (CF) considering the inflow of resources that are processed into (value-added) products. As an easy and quick analysis, the following equation is proposed:

$$\text{Total CF}_{(\text{manufacture})}/\text{year} = \{ [\text{CF}_{(\boldsymbol{P})}] - [\Sigma[(\text{CF}_{(\boldsymbol{r})}) \text{ x } af\,]_i] \} \text{ x } \boldsymbol{P}_{\text{year}} \tag{1}$$

where $CF_{\boldsymbol{P}}$: total life cycle CO_2 of value-added Product **P**, including resource extraction, processing, and final manufacture (in kg/tonne P); $\boldsymbol{P}_{\text{year}}$: total production of ***P*** in a year (in tonne per year or tpy); $CF_{\boldsymbol{r}}$: CO_2 from extraction and processing of main resources (in kg CO_2/tonne $\boldsymbol{r}_i$) to make ***P**; i*: 1, 2, 3…..(number of main resources ***r***) to make ***P*** and af_i (*allocation factor*): CO_2 fraction from CF_P assigned according to the conversion/transformation (according to mass) of $\boldsymbol{r}_i$ to ***P***.

The overall method is illustrated in Fig. 1.

Equation 1 is applicable to a wide range of manufactured products to generate the CF of value-added goods, especially where:

- the process of dealing with – or lack of – massive amounts of data (statistical information) can be eliminated

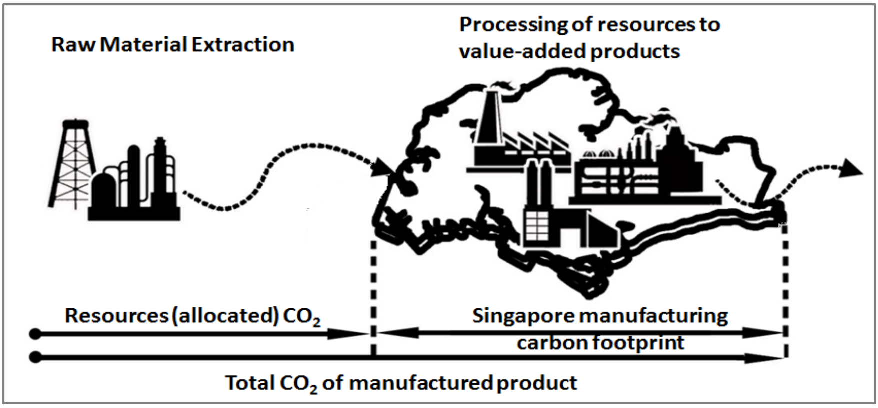

Figure 1: Life cycle approach for estimating carbon footprint.

- a life cycle approach is required
- quick and easy calculations are needed based on data obtained from widely available LCA databases (e.g. [8]).

2.2 CO_2 adjustment factor for Singapore

In order to adjust the total CF to the case of manufactured products in Singapore, an "*emission adjustment factor*" or "*ef*" is introduced. The amount of "*ef*" is estimated according to the type of fuel mixed for combustion or electrical energy required in the manufacture/processing of ***P***. Therefore:

$$\text{Total CF}_{(\text{national\_manufacture})}/\text{year} = \text{Equation (1)} \times [(\chi)ef_{(\text{fuel})} + (1-\chi)ef_{(\text{elec})}] \quad (2)$$

where χ = amount of process energy supplied by fuel combustion (in-situ) and $ef_{(\text{fuel})} = \frac{\text{kg CO}_2 \text{ per MJ energy use (home country)}}{\text{total kg CO}_2 \text{ per MJ energy (reference country)}}$

$$ef_{(\text{elec})} = \frac{\text{kg CO}_2\text{ /MWh (home country's fuel mix for electricity generation)}}{\text{total kg CO}_2\text{/MWh (reference country's fuel mix for electricity generation)}}$$

A few CO_2 emission examples, based on a country's specific fuel mixes for electricity generation, are: 390 kg CO_2/MWh for Singapore (fuel mix of 95% natural gas, 1% oil, 4% waste-to-energy), 457 kg CO_2/MWh for China [9] and 715 kg CO_2/MWh for US [10]. The aggregated European electricity mix is reported as 462 kg CO_2/MWh [11]. By default, $ef_{(\text{fuel})}$ = 1 in the case where there is lack of information.

2.3 CF example: resources to petrochemicals

The manufacture of polypropylene (PP) is taken as an example. The APME European average data [12], for PP production on a cradle to gate basis, is taken as representative to obtain CF_P of polypropylene. Emissions of CO_2 due to crude oil and natural gas extraction can be sourced from same database [12] (Table 1).

Table 1: Data for polypropylene (PP) manufactured from raw materials.

Life cycle data of CF_P		
Total CO_2 emissions from life cycle of resources to 1 tonne PP (main input: r_1 = 940 kg crude oil; r_2 = 586 kg natural gas; 0.44 MWh electricity)		CF_P = 1852 kg CO_2 per tonne
Life cycle data of resources (r_i)		
CF_{r_1} = 560 kg CO_2 per tonne crude oil CF_{r_2} = 138 kg CO_2 per tonne natural gas	Allocation factor	
	$af_1 = \frac{940}{1000}$	$af_2 = \frac{586}{1000}$

The annual PP produced in Singapore was reported to be 370,000 tpa [13]; hence the total CF of Singapore for PP can be deduced by equation (1): Total $CF_{(manufacture)}$/year = {[1852] – [(0.94 × 560) + (0.586 × 138)]} (kg/tonne) × 370,000 tpy = 461 million kg CO_2/year. With $ef_{(elec)} = \frac{390}{462}$ and $\chi = 0$; $CF_{(national\_manufacture)}$ is adjusted to ~ 389 million kg CO_2/year for the manufacture of polypropylene. By similar calculations steps (via equations 1 and 2), the total CF for the manufacturing of polyethylene, xylenes and benzene are: 657, 366, and 325 million kg CO_2/year respectively.

3 Energy

With lack of fossil resources, Singapore imports natural gas and oil from other countries [1]. One of the policies aimed at increasing energy security for the country is in diversifying energy sources. Here, we focus on the potential of solar energy, with the target of 5% of energy delivered by solar by 2020 [14], which is a total ~ 2.5 TWh. equation (3) presents the potential energy delivered by solar:

$$\mathrm{SI}\left(\frac{\mathrm{MWh}}{\mathrm{m}^2}\right)\times \mathrm{area}(\mathrm{m}^2)\times \mathrm{E}(\%)\times \mathrm{PR}(\%)](\mathrm{MWh/year}) \quad (3)$$

where SI (Solar insolation): Amount of solar energy received per square meter; for Singapore, ($\frac{\mathrm{MWh}}{\mathrm{m}^2}$)/year = recorded as 1,627.9 ($\frac{\mathrm{MWh}}{\mathrm{m}^2}$)/year [15]. Area: Potential area available for installation. E(%): Efficiency of solar panel, i.e. ratio of solar cell output to the incident energy in the form of sunlight (recommended range of 16% to 20% according to crystalline and concentrated photovoltaic or PV) [16]. PR (%): Performance ratio, i.e. portion of energy available for export to electrical grid after losses (e.g. thermal or conduction losses).

The available areas for solar panel installations are on building rooftops. The possible usable areas for solar installation in future are reported to be 27–47 km^2 [16]. However, a moderate 10–30 km^2 was applied, along with PR = 67% to 77% [17], to generate the potential TWh/year. The results are shown in Fig. 2.

With E = 16% and PR = 67%, around 5 TWh is readily achievable if an area of 10 km^2 is dedicated to solar installation. A potential 20 TWh/year can be realized if a total area of 30 km^2 is installed with PV. Another issue is the costs of solar. Fig. 3 illustrates the efficiency (%) of solar vs. costs/m^2 according to thin film solar technology, crystalline or concentrating photovoltaics (in 2008), as reported

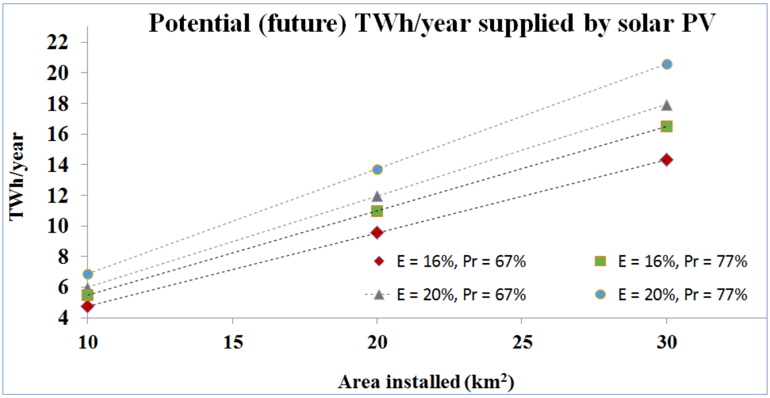

Figure 2: Potential energy from solar according to various scenarios.

by Doshi *et al.* [18]. As an additional sustainability dimension for solar indicator, costs can be factored in according to the types of technology employed to give:

$$\frac{\text{Equation (3)}}{\left[\frac{\text{Costs of solar tech}}{\text{m}^2}\right] \times \text{area}(\text{m}^2)} \tag{4}$$

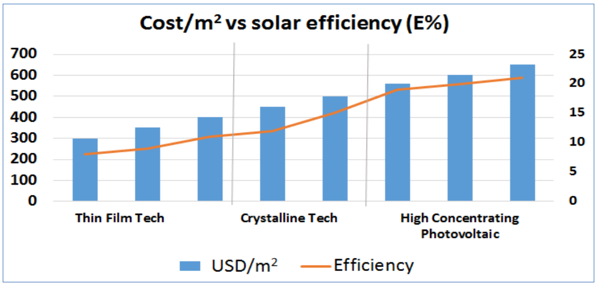

Figure 3: Costs/m^2 vs efficiency of solar.

4 Water

With a land area of 718.3 km^2, it is essential for Singapore to maximize the use of water catchment areas resourcefully [1]. The small city-state currently uses two-thirds of the main island for local water catchment. Plans are on-going to increase this capacity to 90% by the employment of variable salinity water treatment by 2060 [19]. In the aim to reduce the reliance of water imports (which is 40% of demand [20]) and be self-sufficient, investments into water reclamation (known as NEWater) and desalination are also underway. Currently NEWater and desalination systems provide 30% [1] and 25% of total water demand respectively [21].

Several indexes have been developed to measure water sustainability, each with slight variations based on different needs and scales, with Watershed

Sustainability Index (WSI) [22] and Water Provision Resilience (WPR) [23] being the most relevant to Singapore. Such indexes (Table 2) attempt to describe the multi-faceted state of the studied water system.

Table 2: Water indicators: issues considered.

Watershed Sustainability Index (WSI)	Water Provision Resilience (WPR)
• Hydrology • Policy • Quality of Environment and Life	• Supply • Finances • Infrastructure • Water Quality • Provisions • Governance

As Singapore is known to provide safe potable water to its population, indicator developments would aim towards self-reliance (reduced water imports), described by the Self-sufficiency index introduced as equation (5) [24]. The index takes into account the economic and social aspects of sustainability:

$$\text{Self-sufficiency Index} = \frac{\text{Total water supply - Imported water}}{\text{Total water demand}} \tag{5}$$

4.1 Targets and indicator recommendations

The supply of water in year 2014, and planned future projections, for years 2016 and 2060, are compiled in Table 3 from various reports [1, 19–21, 25, 26].

Table 3: Present and future water capacities.

Capacity (Mm^3/day)	**2014**	**2016**	**2060**
Imported water	1.14	1.14	0
Catchment water	0.68	0.68	0.95*
NEWater	0.54	0.77	1.75*
Desalination	0.45	0.45	0.80*

*Based on demand of 3.18 Mm^3/day in 2060 [27].

In order to assist in water supply planning and monitoring, three water sustainability indicators are proposed for Singapore:

$$\text{Long-term Sufficiency} = \frac{\text{Local capacity } (\frac{Mm^3}{year})}{\text{Local water demand } (\frac{Mm^3}{year})} \tag{6}$$

$$\text{Water Resilience} = \frac{\text{Local unused capacity (NEWater + Desalination)}(\frac{Mm^3}{year})}{\text{Amount of imported water + Variability of local catchment water}(\frac{Mm^3}{year})} \tag{7}$$

$$\text{Catchment Efficiency} = \frac{\text{Catchment water production } (\frac{Mm^3}{year})}{\text{Catchment Area} \times \text{Rainfall} \times \text{Surface Run-off Coefficient } (\frac{Mm^3}{year})} \tag{8}$$

While equation (6) measures the self-reliance of the country's ability to supply water without the input (import) of external sources; equation (7) introduces a buffer against non-controlling sources. It also attempts to capture any forms of risks associated with the continuation of imported water supply and fluctuations in local catchment water production which can be affected by weather. A variability of catchment water of 0.23 Mm^3/day was estimated. Equation (8) encapsulates the productive use of land areas dedicated for water catchment systems. Plans are currently underway to obtain 90% area coverage for water catchment [19]. With a high portion of space purposed for water catchment, it is important to measure its overall efficiency. For the Catchment Efficiency sustainability index, a value closer to 1 is desired.

4.2 Present and projected indicator values

With a demand of 1.82 Mm^3/day in 2014 [19], Long-term sufficiency in 2014 is calculated (via equation (6)) as 0.92. And the current combined production output and spare capacity of NEWater and desalination plants is calculated out to be 1.09 Mm^3/day and 0.58 Mm^3/day respectively. Hence, Resilience is 0.61. In 2016, Singapore's 5th NEWater plant is expected to be operational, supplying 0.23 Mm^3/day of water [26]. By interpolation, the expected demand in 2016 is estimated as 1.88 Mm^3/day. This will result in a combined water production output, as well as, spare capacities of 1.13 Mm^3/day and 0.77 Mm^3/day coming from NEWater and desalination plants respectively, leading to an increased Long-term Sufficiency and Water Resilience of 1.01 and 0.79 respectively.

Singapore has plans to increase NEWater and desalination capacities up to 55% and 25% of future demands by 2060 [19]. Supposing a long-term sufficiency target of 1.10 by 2061 is achievable (with a safety-uncertainty factor of 10% applied to account for variability in weather and coastal conditions), the potential catchment water capacity will reach 0.96 Mm^3/day – a 40% increase of the current 0.68 Mm^3/day capacity. Water Resilience would then be 0.98.

Table 4 summarizes the indicator values in 2014, predicted values in 2016 due to the opening of a new NEWater plant, and suggested values for 2060.

Table 4: Indicator values.

Indicator/Year	2014	2016	2060
Long-term sufficiency (equation (6))	0.92	1.01	1.10
Water resilience (equation (7))	0.61	0.79	0.98

Catchment efficiency is not projected due to unavailable data

5 Waste, recycling and landfill

In this section, the limited land area of Singapore and its total dependence on an offshore landfill for the disposal of municipal solid wastes (MSW) is investigated. Semakau landfill covers 350 hectares and has a capacity of 63 million m^3. It is split into two phases. The capacity of Phase One is 11.4 m^3 and is projected to be full around 2015 [28]. The development of Phase 2 of Semakau landfill began in

2014 and is estimated to be completed by the first quarter of 2015. When completed, it is projected that the new landfill cell is capable of meeting the waste disposal requirements of Singapore up to 2035 or beyond. In order to prolong the lifespan of the landfill, only inert waste materials and incinerated by-products (bottom ash and fly ash) are sent to Semakau landfill. Therefore, the total waste occupying the landfill, and the corresponding lifespan of the landfill are related to the space taken up yearly by the waste volumes determined by the densities of inert wastes (ρ_{inert}) and ash (ρ_{ash}) after incineration (Fig. 4).

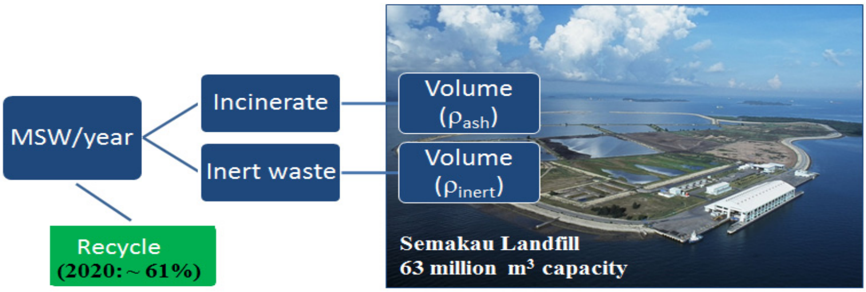

Figure 4: Overview of wastes sent to Semakau landfill.

5.1 Waste statistics and trends

Based on statistics [29], it can be observed that the total waste generated, total waste incinerated and total waste recycled all increase almost linearly during the past years, albeit at different rates. Therefore, the following equation was modeled to determine the rate of landfill volume occupied each year:

$$Vol_{landfill} = \sum_{1999}^{target\ year} \left[\frac{Mass_{inc} \times \phi_{waste\text{-}to\text{-}ash}}{\rho_{ash}} + \frac{MSW_{total} - Mass_{inc} - MSW_{rec}}{\rho_{inert}} \right] \quad (9)$$

where $Vol_{landfill}$: accumulated volume of total wastes which go to landfill (vol), which is set at < 63 million m^3 (Semakau fixed capacity); MSW_{total}: MSW generated (million tpy) = 0.362 × (year – 2006) + 5.154; MSW_{inc}: waste incinerated (million tpy) = 0.074 × (year – 2006) + 2.293; MSW_{rec}: waste recycled (million tpy) = 0.284 × (year – 2006) + 2.697 until year 2020; $\Phi_{waste\text{-}to\text{-}ash}$: mass ratio between waste-to-ash after incineration (%); ρ_{inert}: density of inert solid wastes, ca. ~ 1.5 to 2.0 tonne/m^3 [30, 31]; ρ_{ash}: density of ash, reported (average value) as 1.5 tonne/m^3 [32].

5.2 Projected waste volume and Semakau landfill's lifespan

An estimated 75% is made for mass reduction rate ($\Phi_{waste\text{-}to\text{-}ash}$) by incineration. Based on the estimation through linear regression, in year 2020, the recycling rate ($\frac{MSW_{rec}}{MSW_{total}}$) would reach 61%. As a conservative assumption, we assume that after 2020, the recycling rate would not increase beyond 61%. Based on these parameters, equation (9) projected that by 2015, $Vol_{landfill}$ would reach 8.43 million m^3 of waste. This amount approximately matches Semakau's Phase One capacity. The graphical results – displayed in Fig. 5 – from equation (9) shows that total $Vol_{landfill}$ equaling to 61.06 million m^3 would be reached in year 2049, which is still within the landfill's total designed capacity of 63 million m^3.

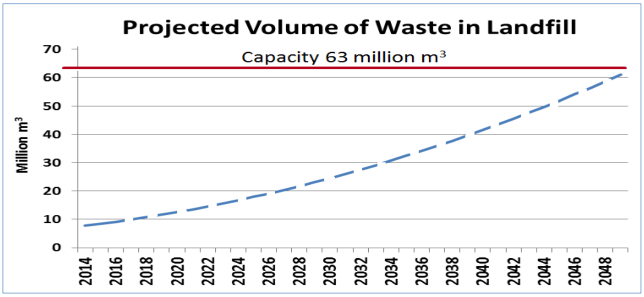

Figure 5: Projected total waste occupying landfill.

6 Summary

A summary of the indicators presented, uncertainties and national targets are compiled in Table 5.

Table 5: Summary of sustainability indicators.

Topics	Sustainability indicators/ measurements	Uncertainties/risks	National targets
CO_2	Simplified carbon footprint estimation tool for manufacturing sector	Data availability and reliability; future clean schemes on "clean" technology	Reduction of ~ 650 ktonne $CO_{2\text{-eq}}$ by 2020 for manufacturing sector
Energy	• Potential energy delivered by solar (TWh/year) • Potential energy vs costs × area installed	Weather, technological advancement, costs, area for installation	5% of energy delivered by solar by 2020 (2.5 TWh/ year)
Water	Indicators suggested: • Long-term sufficiency • Resilience • Catchment efficiency	Weather-related risks, land area for catchment, possible rise in demand	Capacity targets for 2060: Catchment water = 0.95* NEWater = 1.75* Desalination = 0.80* *All in Mm^3/day
Waste, landfill	Trend of waste sent to landfill relating recycling rate and waste densities	Uncertainty in population growth; MSW per capita	Capacity set at < 63 million m^3; Lifespan ≥ year 2045

Sustainability indicators or assessment tools play a crucial role in informing and guiding national policies [1, 2]. Methods to estimate national carbon footprint have been discussed in literature [4–6], with the need for substantial levels of data.

A simplified life cycle method focusing on resources-to-manufactured products was proposed to eliminate the amount of input-output coefficients required. With advanced PV solar technologies that can provide efficiencies of 20% or more, the nation's policy for solar energy (2.5 TWh/year by 2020) [14] can be made possible along with an installed area of ≥ 10 km^2 [16]. The development of three water indicators considered Singapore's water supply and demand mix, as well as, the ongoing efforts to secure the nation's water demands till 2060 [19, 20, 25]. However, the dynamic nature of water supply considering risks and weather-related factors were omitted. The final indicator (equation 9) provides some answers to the lifespan of Singapore's only offshore landfill [28]. Supposing recycling rates can be maintained at ≥ 61% in 2020 onwards, Semakau landfill will reach its full capacity around year 2049.

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