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The zero waste index: a performance measurement tool for waste management systems in a 'zero waste city'

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ABSTRACT

Waste is the symbol of inefficiency of any modern society and a representation of misallocated resources. Significant progress has been achieved in reducing waste but it varies from city to city. Currently, cities use their waste diversion rate as a tool to measure the performance of their waste management systems. However, diversion of waste from landfill does not give a holistic picture of zero waste performance. This paper conceptualises the concept of the 'zero waste city' and proposes a new tool to measure the performance of waste management systems called the 'zero waste index'. The zero waste index forecasts the amount of virgin materials, energy, water and greenhouse gas emissions substituted by the resources that are recovered from waste streams. Three high consuming cities (Adelaide, San Francisco and Stockholm) were analysed using the zero waste index. The zero waste indexes in Adelaide, San Francisco and Stockholm were found to be 0.23, 0.51 and 0.17 respectively (i.e. around 23%, 51% and 17% of resources were recovered and potentially substituted for virgin materials). In addition, the zero waste index estimated the potential energy, greenhouse gas (GHG) and water savings due to resource recovery from municipal solid waste in each of the three cities. It is evident that the zero waste index is an innovative tool to assess waste management performance and materials substitution by waste management systems in different cities.

1. Introduction

In 1962 it took 0.7 years for the earth's annual biological harvest to regenerate and now it takes 1.25 years (Smith, 2005). Global ecosystem services have been over-used significantly in parallel with world economic growth. Global economic growth has increased 5 times since the mid-twentieth century and 60% of the world's ecosystem services have been degraded during the same period (Jackson, 2009: 13). It is estimated that by 2050 we will have 9 billion people on earth. If every person achieved affluence similar to the OECD nations then the global economy would need to be 40 times bigger than it is today (and 200 times bigger than in 1950) by the end of this century (Jackson, 2009: 13–14).

Global non-renewable resources are depleted as a result of over-consumption. Continuous depletion of natural finite resources by urban populations is leading to an uncertain future. Therefore, to prevent further depletion of global resources, we need sustainable consumption and strategic waste management systems based on (1) waste avoidance, (2) material efficiency and (3) resource recovery (Lehmann, 2010).

Waste is the symbol of inefficiency of any modern society and a representation of misallocated resources. More than 50% of the world's population live in urban areas (UN-HABITAT, 2010), and some estimates have suggested that 80% of the human population will dwell in urban areas by 2030. Cities cover only around 2% of the world's surface, consume over 75% of the world's natural resources and generate 70% of all the waste produced globally (UN-MEA, 2006; Ramsar, 2012). Creation of any waste depletes natural resources, uses energy and water, places pressure on land, pollutes the environment and, finally, creates an additional economic cost for managing the waste. We need to move to a position where there will be no such thing as waste, merely transformation; this position is called zero waste.

'Zero waste' is one of the most visionary concepts for solving waste problems. Many cities around the globe such as Adelaide, San Francisco and Stockholm have declared their zero waste vision and these cities are working to be the world's first zero waste city. But how to transform our existing cities into zero waste cities and how to measure the performance of a zero waste city are the prime questions to answer in zero waste research.

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The products that we consume every day are primarily produced using virgin materials, energy and water. From resources extraction to waste generation, consumption depletes the environment by contributing greenhouse gases (GHG) to the atmosphere. The aim of this paper is to conceptualize zero waste based on material flow analysis. The paper also aims to develop a measurement tool to account for the performances of waste management systems in cities and to forecast the potential demands for virgin materials, energy and water, and reductions in GHG emissions. This paper therefore proposes a 'zero waste index' (ZWI) as a new tool to measure waste management performance. The comparative performance of the waste management systems in Adelaide, San Francisco and Stockholm will be studied using the proposed zero waste index.

2. Development of the zero waste concept

From outer space to the bottom of the ocean, generations of waste is accumulating over time. On one hand, the estimated amount of debris put into space by humans and no longer in function has increased from 14,000 pieces in 2007 to 18,000 pieces in 2008 (SSN, 2011). On the other hand, accumulation of waste in the great Pacific Garbage Patch (currently 1,760,000 sqkm, 12 times bigger than Bangladesh) is getting larger every day (MNN, 2010; PPC, 2011).

Currently, the world's cities generate about 1.3 billion tonnes of solid waste per year and the volume is expected to increase to 2.2 billion tonnes by 2025 (Hoornweg and Bhada-Tata, 2012). Waste generation rates will more than double over the next twenty years in lower income countries. However, this current trend of generating waste is not a recent practice; it comes from the very early stages of modern society. So how would it be possible to transform current society into a zero waste society?

2.1. Background of hyper-consumption

According to Strasser (1992), households did not produce much trash in the late nineteenth century by today's standards. Disposable products such as canned foods, safety razors and many more were introduced in the early twentieth century, designed to be thrown away after a brief use. They constituted a new kind of waste (Strasser, 1992), imposing enormous pressure on city authorities, which had to manage it properly.

Scholarly interest in the history of consumption first emerged during the Cold War, when the issue of consumption became a vehicle in the political and ideological clash of capitalism and communism. Consumerism satisfied in the capitalist West but not the socialist East (Strasser et al., 1998). Consumption was seen as a driver of economic growth from then on. Increasing economic growth until the global economic boom in the late 1990s led developed societies to become hyper-consuming societies. Disposable product design and never-ending market expansion were firmly established well before the beginning of the Great Depression (Strasser, 2000: 9).

An enormous amount of natural resources are depleted every day due to the high demand for new products. Globally 120–130 billion tonnes of natural resources are consumed every year and produce around 3.4 to 4 billion tonnes of municipal solid waste (Giljum et al., 2008; Chalmin and Gaillochet, 2009).

2.2. The concept of zero waste and the zero waste city

Zero waste means designing and managing products and processes systematically to avoid and eliminate waste, and to recover all resources from the waste stream (ZWIA, 2004). Working towards zero waste has become a worldwide movement that motivates changes in design that make it possible to disassemble and recycle products. To put it simply, zero waste means no unnecessary and unwanted waste from a product at any stage of its life cycle. The scope of zero waste comprises many concepts that have been developed for sustainable waste management systems, including avoiding, reducing, reusing, redesigning, regenerating, recycling, repairing, remanufacturing, reselling and re-distributing waste resources. Hence, a zero-waste strategy is growing in popularity as best practice. It not only encourages recycling of products but also aims to restructure their design, production and distribution to prevent waste emerging in the first place (UNECE, 2011).

Most modern societies have been implementing integrated waste management systems to recycle and recover resources from waste. However, the concept of zero waste is not limited to optimum recycling or resource recovery; in addition to that zero waste requires elimination of unnecessary waste creation at the first stage of designing a product. Therefore, zero waste design principles go beyond recycling to focus firstly on avoidance and reduction of waste by innovative product design and then recycling and composting the rest (City of Austin, 2008).

Fig. 1 shows the key principles of the zero waste city. With proper implementation of all these principles, current cities could be transformed into zero waste cities. The key drivers are based on short-term and long-term implementation strategies. Awareness and education, behaviour change and systems thinking are long-term strategies, whereas innovative industrial design, legislation and 100% recycling are the short-term strategies to implement in a city. One of the important aspects of the zero waste city is the conversion of the linear city metabolism to a circular city metabolism.

This transformation requires a series of holistic strategies based on key development principles. Education and research is on the top of the zero waste hierarchy. Without proper environmental awareness and advanced research on waste, it would not be possible to achieve zero waste goals. Sustainable consumption and behaviour is placed second in the zero waste hierarchy. As the current trend of consumption is unsustainable and can not be continued for ever, it is important to understand the reality and act accordingly. The next on zero waste hierarchy is transformed industrial design for example, cradle-to-cradle design, eco-design or cleaner production combined with extended producer responsibility. It is important to have specific zero depletion legislation and incentive policies as part of the strict environmental legislations. If products are designed in such a way that everything can be recycled, then achieving optimum recycling and resource recovery will not be impossible in the long run. Finally, a new system thinking approach and innovative technologies are needed to transform current cities into zero waste cities.

2.3. Linear to circular city metabolism

Urban metabolism may be defined as 'the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste' (Kennedy et al., 2008: 44). If we can measure a city's material flow then it is easy to analyse the efficiency of the resource management systems in a city. Many studies have measured the material flow in cities. However, the concept of zero waste directs the linear city metabolism to a circular city metabolism.

Most cities have a linear metabolism, where materials, energy and water are consumed as inputs and, after this consumption, they produce solid waste, wastewater and emissions to the atmosphere. In a zero waste city material flow is circular, which means the same materials are used again and again until the optimum level of consumption. No materials are wasted or underused in circular cities. Therefore, at the end of their lives products are reused, repaired,

Fig. 1. Drivers for transforming current cities into zero waste cities.

sold or redistributed within the system. If reuse or repair are not possible then they are recycled or recovered from the waste stream and used as inputs, substituting the demand for the extraction of natural resources. Fig. 2 shows the symbolic material flow of a circular city, where the end–of-life product or output waste are treated as resources and used as inputs in the city's metabolism.

From Fig. 2, it is clear that a city's performance is reflected by its waste management systems. Material flow in a zero waste city should be circular and resources should be used efficiently. The performance of waste management systems therefore symbolizes the performance of a zero waste city. Hence, it is important to development a zero waste measurement tool for cities.

2.4. Similar studies of waste management and urban metabolism

Many researchers have studied waste management systems in different cities. A UN-Habitat recent study of waste management systems in 20 cities is one of the important works in this area. The study was further analysed and presented by Wilson et al. (2012). However, materials substitution by the recycling and recovery activities of the cities was not reflected in these studies. The World Bank also recently published a report on current waste management

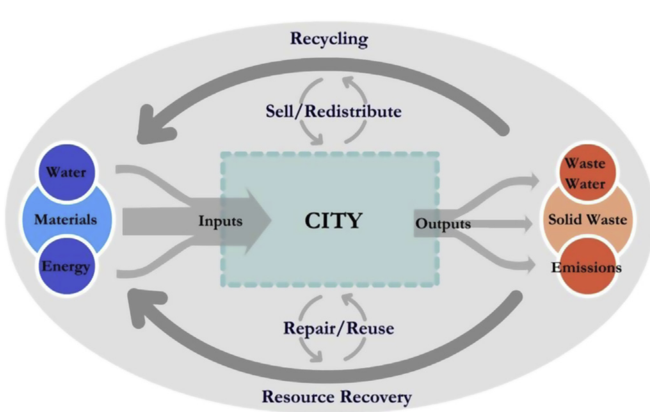

Fig. 2. Material flow in a zero waste city (adapted from Girardet, 1992, 1999).

conditions globally (Hoornweg and Bhada-Tata, 2012). Both studies identified the potential platform of knowledge sharing between developed and developing counties around the globe. There are many examples of best practices that can be modified based on the local needs and applied in the different parts of the world. Many studies have been conducted on urban metabolism. A few of the significant studies are Girardet (1992) on Hong Kong, the European Environment Agency (1995) on Prague, Alberti (1996) on measuring tools and indicators, Newman and Kenworthy (1999) on Sydney, Australia, Sviden and Jonsson (2001) on Stockholm, Sweden, Hammer and Giljum (2006) on Hamburg, Germany, Vienna and Leipzig, Schulz (2007) on Singapore, and Browne et al., 2009 on Limerick, Ireland. Researchers worked on different contexts to understand urban metabolism such as material flow, energy flow, nutrients flow, water flow. However, there is no evidence that studies have been done on materials substitution by the waste management systems in a city.

Recent research on the environmental performance of cities has been initiated by Siemens through a project called Green City Index (Siemens, 2012). The Green City Index measures and rates the environmental performance of cities from Asia, Europe, Africa and North America. In the study Siemens considers around 9 different environmental indicators including waste performance. Waste performance was primarily based on the waste diversion rate. This paper acknowledges the limitations of the diversion rate as a performance indicator of the waste management systems in a city and hence proposes a new tool to measure performance called the zero waste index. The proposed zero waste index measures waste management performance by considering the materials, energy, water and emissions substituted in the waste management systems.

3. Materials and methods

Practice-based built environment research includes case-based, evidence-based and performance-based research modes (Lee, 2011). In this study a waste management performance index called the zero waste index is developed based on the evidenced-based research methodology through peer reviewed literature, reports, the life cycle analysis (LCA) database and other secondary online sources. Finally, the proposed zero waste index is analysed by measuring the performance of waste management systems in the cities of Adelaide, San Francisco and Stockholm.

There are many ways to measure the waste management systems in a city. Decision makers and waste experts use various indicators such as the per capita generation rate, collection rate and recycling rate to measure the performance of the waste management systems. In the last decade, the waste diversion rate has been used as an important indicator to measure the performance of a city. Waste diversion from landfill has been widely accepted by local governments, waste authorities and city corporations. Therefore, a higher diversion rate from landfill has been considered as a benchmark of success.

3.1. Waste diversion rate

The waste diversion rate is one of the key indicators used by municipalities today to measure the performance of waste management systems. The diversion rate can be defined as the percentage of total waste that is diverted from disposal at permitted landfills and transformation facilities such as incineration, and instead is directed to reduction, reuse, recycling and composting programs (CalRecycle, 2012). The diversion rate can be measured by a generation-based measurement system or a disposal-based measurement system. In a generation-based measurement system, disposal and diversion are measured and added together to determine generation. In a disposal-based measurement system, the definition of waste generation is the same (disposal plus diversion), but what is measured changes. In the disposal-based measurement system, waste generation is estimated and then measured disposal is subtracted from generation to estimate diversion (IWMB, 2001). Therefore, traditional waste diversion rate can be formulated as in Equation (1).

Waste diversion rate

$$\text{Diversion rate} = \frac{\text{Weight of recyclables}}{\text{Weight of garbage} + \text{Weight of recyclables}} \times 100\% \tag{1}$$

Recyclables = waste that is reused, recycled, composted or digested

Garbage = waste that is landfilled or incinerated (City of Toronto, 2012).

Currently, many cities such as Adelaide, San Francisco and Stockholm are trying to be zero waste cities by achieving 100% diversion of waste from landfill. However, diversion from landfill and recycling are not sufficient for zero waste initiatives. The diversion rate as per Equation (1) does not consider waste avoidance through industrial design, effective policies and behaviour change; hence the diversion rate of waste is not sufficient to measure the zero waste performance of a city. The diversion rate is merely an indicator of recycling performance. It does not give the full picture of the recycling initiatives and does not tell us how much of the waste stream is recyclable, whether or not all recyclables are recycled, and how much less waste is generated overall (Marpman, 2011).

A holistic waste management performance tool is therefore needed. Waste avoidance is one of the key aspects that should be considered in measuring the performance of a waste management system. A new index is therefore needed that can measure more than the diversion rate to assess the performance of the waste management system. This paper presents a new index system called the zero waste index (ZWI) as an indicator to measure the waste management system holistically.

3.2. Zero waste index

The zero waste index is a tool to measure the potentiality of virgin materials to be offset by zero waste management systems. One of the important goals of the zero waste concept is zero depletion of natural resources. Therefore, measuring the performance of the zero waste city would eventually measure the resources that are extracted, consumed, wasted, recycled, recovered and finally substituted for virgin materials and offset resource extraction by the waste management systems. The zero waste index can be formulated as in Equation (2).

However, the waste diversion rate does not indicate the virgin material replacement efficiency of the waste management system, which is very important in conservation of global natural resources. Thus, the zero waste index is a cutting-edge tool to measure virgin material substitution by waste management systems. By introducing the zero waste index globally, we could measure the virgin material offset potentiality and the potential depletion of natural resources.

The ZWI is also a useful tool to compare different waste management systems in different cities and it gives a broader picture of the potential demand for virgin materials, energy, carbon pollution and water in a city. The ZWI is thus a performance indicator to assess the overall performance of waste management systems.

Zero waste index (ZWI)

$$\text{Zero waste index} = \frac{\sum \text{potential amount of waste managed by the city} * \text{substitution for the systems}}{\text{Total amount of waste generated in the city}}$$

$$\text{ZWI} = \frac{\sum_1^n \text{WMSi*SFi}}{\sum_1^n \text{GWS}} \tag{2}$$

WMSi = amount of waste managed by system i (i.e. $i = 1, 2, 3 \ldots$ n = amount of waste avoided, recycled, treated, etc.)

SFi = Substitution factor for different waste management systems based on their virgin material replacement efficiency

GWS = Total amount of waste generated (tonnes of all waste streams)

The zero waste index is based on the value of material that can potentially replace the virgin material inputs. The substitution of energy, water and greenhouse gas emissions is also considered with the material substitutions. Substitution values for material, energy, water and GHG emissions have been extracted from the life cycle database of different life cycle assessment tools and database sources. The amount of materials and resources substituted is positively related to the advancement of technology used in the material recovery process; therefore, the substitution value varies for different materials and for different waste management systems. Even though, waste prevention is one of the core components in the zero waste concept, but quantitative measurement of waste prevention by behaviour change has not been considered in this research due to limited scientific quantitative measurement data.

Table 1 shows the substitution values for waste streams for different waste management systems. Six major waste streams are considered based on waste data availability in Adelaide, San Francisco and Stockholm. Due to high dissimilarities in waste streams and data collection systems only six waste streams – paper, glass, plastic, metal, organic and mixed municipal solid waste – are considered for this study. Table 1 (adapted from Clean Energy Future, 2011; DECCW, 2010; DTU Environment, 2008; Grant and James, 2005; Grant et al., 2001; Larsen et al., 2012; Massarutto et al., 2011; Metro Vancouver, 2010; Morris, 1996; US-EPA, 2006; Van Berlo, 2007; Zaman, 2010; Zaman and Lehmann, 2011) presents the waste volume managed in these cities and the respective potential substitution value for different waste management systems.

4. Case study cities

4.1. Adelaide, Australia

Adelaide is the capital city of South Australia where a total of 1,089,728 inhabitants live in an 841.5 km^2 urban area (UN-HABITAT, 2010). Australian per capita GDP was US $41,300 in 2010 (CIA, 2011). Almost 85% of South Australia's population live within the Adelaide metropolitan area. Zero Waste SA is a South Australian state government organization established by legislation called the *Zero Waste SA Act* (2004) to improve waste management systems and to foster zero waste South Australia (ZWSA, 2011). Banning plastic shopping bags has been one of the key initiatives to avoid creation of waste in Adelaide.

The composition of municipal solid waste varies widely, both within and between countries and between different seasons of the year (UN-HABITAT, 2010). Municipal solid waste in Adelaide includes a significant amount of construction and demolition waste. Container deposit legislation was adopted in 1977; therefore, certain packing containers have been recycled for more than three decades in Adelaide. The average person generated around 681 kg of MSW in Adelaide in 2008–2009. Around 46% of all MSW was recycled, 8% was composted and the remaining 46% was disposed to landfill. Fig. 3(a) shows the composition of MSW in Adelaide and Fig. 3(b) shows the waste management systems.

4.2. San Francisco, USA

The city and county of San Francisco is quite small for a large city, covering 122 km^2 with a population of 835,364 (UN-HABITAT, 2010). It is located on a hilly peninsula separating San Francisco Bay from the Pacific Ocean. San Francisco has a long history in waste collection systems from informal waste recycling in the early twentieth century to the modern collection systems today. The initiator of the United Nations Environment Programme (UNEP) Urban Environmental Accords, San Francisco is a national and international environmental leader.

San Francisco is one of the leading cities in the USA and it has considered zero waste as a waste management manifesto. The zero waste challenge is reflected in solid waste system support for reducing consumption, maximizing diversion and encouraging reuse, repair and green purchasing. Banning troublesome goods such as plastic bags and superfluous packaging, and promoting alternatives such as recyclable or compostable take-out food packaging and reusable transport packaging are the prominent initiatives for achieving zero waste goals (UN-HABITAT, 2010). A total of

Table 1
Substitution values for the zero waste index.[d]

Case study cities	Waste management systems	Waste category	Total waste managed in the city (tonnes)	Virgin material substitution efficiency (tonnes)	Energy substitution efficiency (GJLHV/tonne)	GHG emissions reduction (CO_2e/tonne)	Water saving (kL/tonne)
Adelaide	Recycling	Paper	23,918	0.84–1.00	6.33–10.76	0.60–3.20	2.91
		Glass	17,084	0.90–1.00	6.07–6.85	0.18–0.62	2.30
		Metal	17,084	0.79–0.96	36.09–191.42	1.40–17.8	5.97–181.77
		Plastic	17,084	0.90–0.97	38.81–64.08	0.95–1.88	−11.37
		Mixed	2,66,521	0.25–0.45	5.00–15.0	1.15	2.0–10
	Composting	Organic	59,424	0.60–0.65	0.18–0.47	0.25–0.75	0.44
	Landfill	Mixed MW[a]	3,41,692	0.00	0.00–0.84[c]	(−) 0.42–1.2	0.00
San Francisco	Recycling	Paper	1,21,997	0.84–1.00	6.33–10.76	0.60–3.20	2.91
		Glass	15,096	0.90–0.99	6.07–6.85	0.18–0.62	2.30
		Metal	20,332	0.79–0.96	36.09–191.42	1.40–17.8	5.97–181.77
		Plastic	55,915	0.90–0.97	38.81–64.08	0.95–1.88	−11.37
		Mixed	50,830	0.25–0.45	5.00–15.0	1.15	2.0–10
	Composting	Organic	1,01,665	0.60–0.65	0.18–0.47	0.25–0.75	0.44
	Landfill	Mixed MW[a]	1,42,331	0.00	0.00–0.84[c]	(−) 0.42–1.2	0.00
Stockholm	Recycling	Paper	3,6552	0.84–1.00	6.33–10.76	0.60–3.20	2.91
		Glass	10,083	0.90–0.99	6.07–6.85	0.18–0.62	2.30
		Metal	3781	0.79–0.96	36.09–191.42	1.40–17.8	5.97–181.77
		Plastic	8823	0.90–0.97	38.81–64.08	0.95–1.88	−11.37
		Mixed	66,805	0.25–0.45	5.00–15.0	1.15	2.0–10
	Composting	Organic	4065	0.60–0.65	0.18–0.47	0.25–0.75	0.44
	Incineration	Mixed MW[a]	2,39,891	0.00	0.972–2.995[b]	0.12–0.55	0.00
	Landfill	Mixed MW[a]	36,596	0.00	0.00–0.84[c]	(−) 0.42–1.2	0.00

[a] Average composition of municipal waste.
[b] Heat capture efficiency of WTE technology 15–30%.
[c] Energy from landfill facility. A positive value represents the savings and a negative value represents the demand or depletion.
[d] As site specific data may vary, the final outcome of the zero waste index may also vary in different sites. However, in this study site specific data variations are not considered due to unavailability of data in the site specific context. Sources: Morris (1996), Grant et al. (2001), Grant and James (2005), US-EPA (2006), Van Berlo (2007), DTU Environment (2008), DECCW (2010), Metro Vancouver (2010), UN-HABITAT (2010), Clean Energy Future (2011), Massarutto et al. (2011), Zaman (2010), Zaman and Lehmann (2011), Larsen et al. (2012).

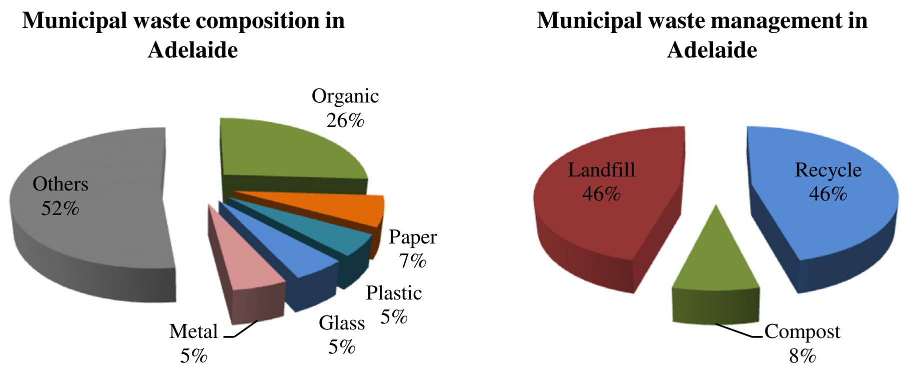

Fig. 3. Composition and waste management systems in Adelaide (UN-HABITAT, 2010).

508,323 tonnes of MSW was generated in 2008 (609 kg per person per year). MSW was managed by recycling (52%), composting (20%) and landfill (28%). Fig. 4(a) shows the composition of MSW in San Francisco and Fig. 4(b) shows the waste management systems.

4.3. Stockholm, Sweden

Stockholm is the capital city of Sweden with 847,073 inhabitants (2010) living in a 188 km^2 land area (Statistics Sweden, 2010; USK, 2011). Avfall Sverige is an organization that supports all municipalities in Sweden. The City of Stockholm started a project called "Vision Stockholm 2030" for Stockholm's sustainable development in the future (City of Stockholm, 2009). One of the key objectives of the 2030 vision is transforming Stockholm into a resource-efficient region (RUFS, 2010).

Stockholm is very prominent in regulations and policies in waste management systems. One of the most important waste management policies is the ban on putting combustible waste and organic waste in landfill (Avfall Sverige, 2008). A total of 4,06,596 tonnes of waste was generated in Stockholm in 2008–2009, which was around 480 kg per person per year (Stypka, 2007; Avfall Sverige, 2011). Fig. 5(a) shows the composition of MSW in Stockholm and Fig. 5(b) shows the waste management systems.

5. Results and discussions

A comparison of the waste management systems in Adelaide, San Francisco and Stockholm is presented below by considering both performance indicators, i.e. the diversion rate and the zero waste index.

5.1. Waste diversion rate

The diversion rate of municipal solid waste in Adelaide, San Francisco and Stockholm are given below based on Equation (1).

Total waste generated = 7,42,807 tonnes, comprised of 59,424 tonnes composted (8%), 3,41,691 tonnes recycled (46%) and 3,41,691 tonnes disposed to landfill (46%). So the total diversion rate in Adelaide was 54%. Total waste generated = 5,08,323 tonnes, comprised of 1,01,665 tonnes composted (20%), 2,64,327 tonnes recycled (52%) and 1,42,330 tonnes disposed to landfill (28%). So the total diversion rate in San Francisco was 72%. Total waste generated = 4,06,596 tonnes, comprised of 4065 tonnes composted (1%), 1,26,044 tonnes recycled (31%), 2,39,891 tonnes incinerated (59%) and 36,593 tonnes disposed to landfill (9%). So the total diversion rate in Stockholm was 32%.

5.2. Zero waste index

Applying Equation (2) in Table 2, the zero waste index for Adelaide is 0.23. That means around 23% of resources were recovered from the waste management systems from the amount of waste generated. It is evident from Table 2 that the average person in Adelaide generated around 681 kg of waste every year and the resources recovered and potentially substituted for virgin material was 153 kg. Waste management systems in Adelaide potentially substitute the energy demand of 2.9 gigajoules (GJ), equivalent to 805 kilowatt hours (kW-h) per person per year. GHG emissions substituted were 387 kg CO_2e and total water savings from the waste management systems was 2800 L per person per year.

The zero waste index for waste management systems in San Francisco is 0.51, which means around 51% of materials were recovered and potentially replaced the demand for virgin materials from the waste generated in a year. From Table 2, the average person in San Francisco generated around 609 kg of municipal solid waste and around 307 kg of materials are recovered and substituted for virgin materials. Waste management systems in San Francisco potentially substituted 5.1 gigajoules (GJ), equivalent to 1417 kilowatt hours (kW-h) of energy demand, 672 kg of CO_2e GHG emissions and 3420 L of water per person per year.

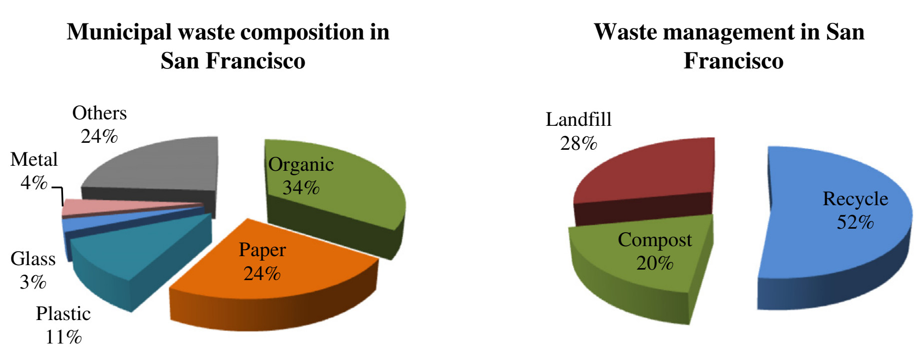

Fig. 4. Composition and waste management systems in San Francisco (UN-HABITAT, 2010).

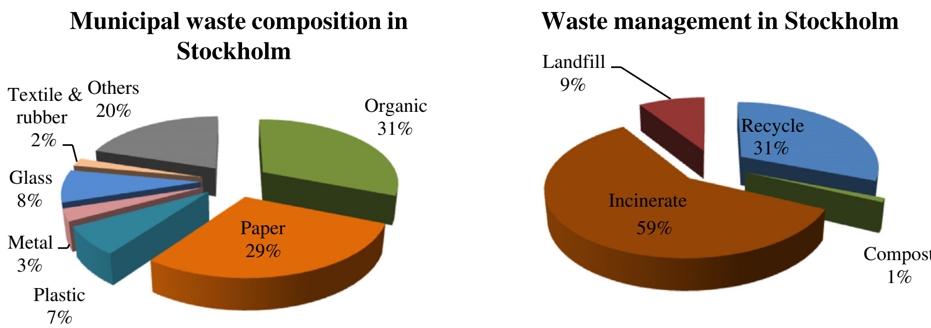

Fig. 5. Composition and waste management systems in Adelaide (Stypka, 2007; Avfall Sverige, 2011).

From Table 2, the zero waste index for waste management systems in Stockholm was 0.17 which means around 17% of materials were recovered and substituted for virgin materials from the amount of waste generated. The average person in Stockholm generated around 480 kg of waste in a year and from that amount around 79 kg of materials were recovered and replaced virgin materials. Waste management systems in Stockholm potentially substituted 2.83 gigajoules (GJ), equivalent to 786 kilowatt hours (kW-h) of energy demand, 330 kg CO_2e GHG emissions and 920 L of water per person per year.

5.3. Comparative zero waste indexes in Adelaide, San Francisco and Stockholm

The comparative analysis is not to rank the cities but to analyse the performances based on resource recovery and waste management systems. The following comparative study is done by considering the substitution of virgin materials from waste, energy, greenhouse gas emission and water savings.

5.3.1. Virgin material substitution

Virgin material substitution by reusing and recycling is one of the main goals of the zero waste concept. Current trends of hyper-consumption deplete an enormous amount of natural resources every day. Hence, substituting resources available from the waste that is produced every day would be the ultimate goal for achieving zero waste. As Fig. 6 shows, San Francisco recovered 51% (307 kg) of the municipal solid waste that is produced by every person each year. Adelaide and Stockholm recovered around 23% (153 kg) and 17% (79 kg) respectively from the municipal waste that is generated every year.

5.3.2. Energy savings

One of the important resources that depletes with waste is energy. Sometimes, more energy is used to produce a product

Table 2
Potential substitution of resources in the zero waste index.

Cities	WMS (ii)	Waste category (iii)	Total waste managed in the city (tonnes) (iv)	Potential total virgin material substituted (tonnes) (v)	Total energy substituted (GJLHV)	Total GHG emissions reduction (tonnes CO_2e)	Total water saving (kL)	Zero waste index, (ZWI = v/iv)
Adelaide	Recycling	Paper	23,918	20,091	2,04,260	45,444	69,601	**0.23**
		Glass	17,084	15,375	1,10,362	6833	39,293	
		Metal	17,084	13,496	19,44,159	1,64,006	1,554,644	
		Plastic	17,084	15,375	8,78,800	23,917	−1,94,245	
		Mixed	2,66,521	66,630	26,65,210	3,06,499	15,99,126	
	Composting	Organic	59,424	35,654	19,609	29,712	26,146	
	Landfill	Mixed MW[1]	3,41,692	000	000	−1,43,510	000	
	Total value		7,42,807	1,66,621	3,157,190	4,21,901	30,94,565	
	Benefits per person per year		681 kg	153 kg	2.9 GJ	387 kg	2.8 kL	
San Francisco	Recycling	Paper	1,21,997	1,02,477	1,041,854	2,31,794	3,55,011	**0.51**
		Glass	15,096	13,724	98,508	6099	35,072	
		Metal	20,332	16,062	23,13,781	1,95,187	27,60,212	
		Plastic	55,915	50,323	2,83,691	78,281	−6,35,753	
		Mixed	50,830	12,707	5,08,300	58,454	3,04,980	
	Composting	Organic	1,01,665	60,999	33,549	50,832	44,732	
	Landfill	Mixed MW[1]	1,42,331	000	000	−59,779	000	
	Total value		5,08,323	2,56,292	42,79,683	5,60,868	28,64,254	
	Benefits per person per year		609 kg	307 kg	5.1 GJ	672 kg	3.42 kL	
Stockholm	Recycling	Paper	36,552	30,703	3,12,154	69,448	1,06,366	**0.17**
		Glass	10,083	9074	65,136	4033	23,190	
		Metal	3781	2987	4,26,863	36,297	3,44,071	
		Plastic	8823	7940	4,53,855	12,352	−1,00,317	
		Mixed	66,805	16,701	6,68,050	76,825	4,00,830	
	Composting	Organic	4065	2439	1341	2032	1788	
	Incineration	Mixed MW[1]	2,39,891	000	4,77,383	80,363	000	
	Landfill	Mixed MW[1]	36,596	000	000	−1536	000	
	Total value		4,06,596	69,844	2,404,782	2,79,814	7,75,928	
	Benefits per person per year		480 kg	79 kg	2.83 GJ	330 kg	0.92 kL	

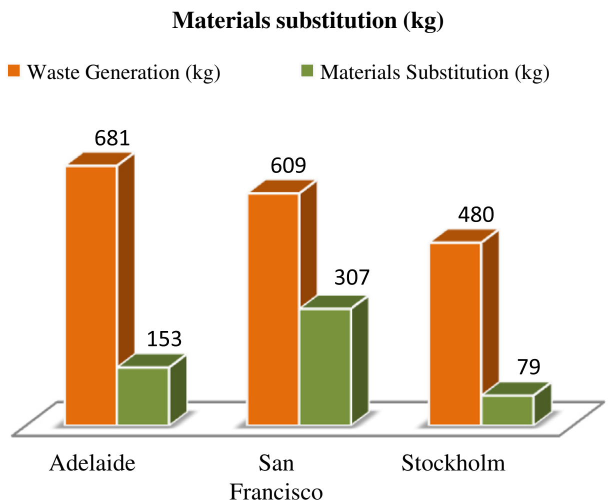

Fig. 6. Virgin material substitution in Adelaide, San Francisco and Stockholm.

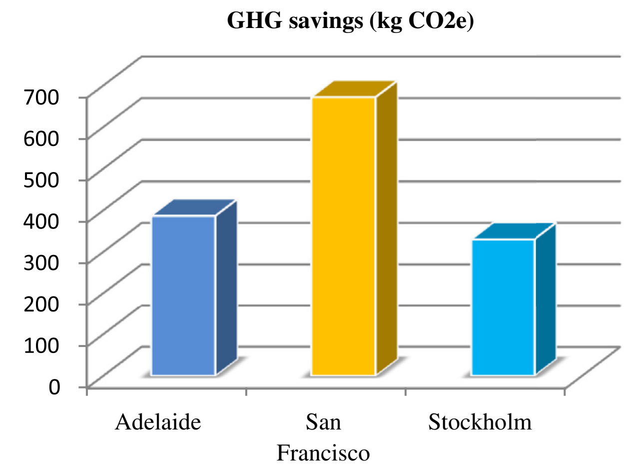

Fig. 8. GHG savings from waste management systems in Adelaide, San Francisco and Stockholm.

than when the product is used in its lifetime. Hence, recovering resources from waste potentially saves an enormous amount of energy. Comparing the energy savings in the three cities, San Francisco substituted the highest amount of energy demand from the resources recovered in waste management systems. The average person in San Francisco substituted around 1417 kilowatt hours (kW-h) of energy demand in a year. In Adelaide and Stockholm, the energy demand substitution value was 805 kilowatt hours (kW-h) and 786 kilowatt hours (kW-h) respectively. Even though the zero waste index for Stockholm was 0.17, which was lower than San Francisco (0.51) and Adelaide (0.23), overall energy saving was significantly higher in Stockholm. The key reason for the high energy savings from the waste management system in Stockholm was the energy generation from incineration of municipal solid waste. Fig. 7 shows the comparative energy savings in Adelaide, San Francisco and Stockholm.

5.3.3. Greenhouse gas (GHG) emissions

One of the major environmental impacts from waste is greenhouse gas emissions to the atmosphere, which intensifies global warming and climate change. Landfill is the main source of methane and other GHG emissions from waste management systems. Resource recovery from waste eventually substitutes the emissions that would otherwise reach the atmosphere if waste is managed by landfill. Each person in Adelaide, San Francisco and Stockholm saved 387 kg CO_2e, 672 kg CO_2e and 330 kg CO_2e of GHG each year, respectively, from the waste management systems. In countries like Australia where a carbon tax costs polluters a huge amount of money, waste management authorities can claim carbon credits that they have saved from waste recycling activities. Fig. 8 shows the GHG savings.

5.3.4. Water savings

Water is not an abundant resource anymore; rather it is already a scarce natural resource in many parts of the world. The relationship between water and waste is significant at the point of resource recovery because a significant amount of fresh water is used to process raw materials to produce products. Therefore, substituting virgin materials can save water. Fig. 9 shows the per capita water saved in the three cities. Adelaide, San Francisco and Stockholm saved around 2800 L, 3420 L and 920 L per person per year respectively.

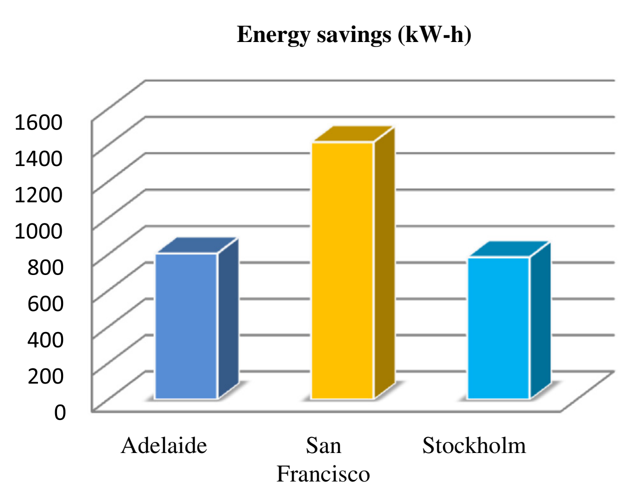

Fig. 7. Energy savings from waste management systems in Adelaide, San Francisco and Stockholm.

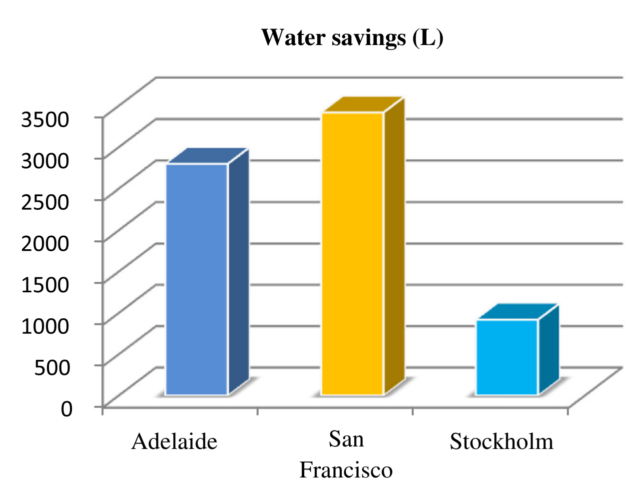

Fig. 9. Water savings from waste management systems in Adelaide, San Francisco and Stockholm.

6. Concluding remarks

From the previous discussion it is clear that the zero waste index provides a better picture of the overall waste management performance of a city than the diversion rate. Moreover, a 100% diversion of waste from landfill would obviously be a milestone for a waste authority but would not necessarily achieve zero waste goals. The diversion rate does not give an indication of resources that have been recovered and substituted, which eventually avoids extraction of further resources. The zero waste index forecasts the amount of resources that are recovered from the waste streams and substituted for virgin materials. In addition, the ZWI also forecasts the demand substitution of energy, water and emissions by the waste management systems.

The overall performance of waste management systems in Adelaide is higher compared to Stockholm. This difference is due to the virgin material recovery and energy substitution by the waste management systems. Adelaide substitutes more virgin materials than Stockholm. The overall performance of the three cities was analysed and San Francisco was found to be top among the three cities.

The study aimed to develop a holistic tool for measuring the waste management performance of a city. From the study results it is evident that San Francisco has a higher zero waste index than Adelaide and Stockholm. Virgin materials substitution, energy savings, emissions saving and water savings were also higher than the other two cities. This study was limited to the municipal waste management systems in 6 broad waste categories: paper, plastic, metal, glass, organic and mixed municipal solid waste. Further research is required to develop a zero waste index system for other types of waste such as commercial and institutional waste, industrial waste, and construction and demolition waste.

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