COSEM RESEARCH PAPER

Evaluation of the energy potential of organic waste in Havenstad : From a systems modelling and behavioural perspective

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ABSTRACT
High waste separation rate may result in a higher energy yield of a Waste-to-Energy (WtE) system. But the influence of the factors determining waste separation, on energy extracted from organic waste is not thoroughly examined. By studying the influence of factors such as presence of Pro-environmental behaviour & increased bin size, their importance in the design of a Waste to energy system can be highlighted. To examine the role of these factors an Agent-Based Model (ABM) is created that captures the behavioural and system aspects of a WtE system.Experiments are carried out in the model to examine the influence of these factors. Based on the results, it is concluded that presence of Pro-environmental behaviour & a large bin size increased the energy obtained per tonne OFMSW. Recommendations for future research include the examination of other factors such as bin hygiene and socio-demographic factors such as age.

KEYWORDS
Agent-based Modelling; Pro-environmental behaviour; Waste to energy; Circular economy; Waste management

1. Introduction

Waste-to-Energy (WtE) can play an important role in fulfilling the growing energy demands of the world in a sustainable way. WtE is the process in which Municipal Solid Waste (MSW) is utilized to generate useful energy in the form of electricity, heat, or transport fuels (Barik, 2019; Cleveland & Morris, 2005). MSW is the waste generated by households, institutions and Small-Medium Enterprises (SMEs). In the Netherlands, Organic Fraction of Municipal Solid Waste (OFMSW) account for more than one-third of the MSW generated (Goorhuis et al., 2012).

WtE from OFMSW can help in the reduction of Greenhouse Gases (GHG) from conventional fossil fuel based power plants such coal power plants and Combined Cycle Gas Turbine (CCGT). It can do so by generating electrical power or steam, instead of fossil fuel based electrical generation that emits CO_2 (Johnke, 1996; Michael, 2013). Furthermore, energy generated in the form of heat or electricity from OFMSW or organic waste has the potential to result in zero net CO_2 emissions (European Compost Network, 2016; Jingura & Matengaifa, 2009).

Source separation of waste plays an important role in the process of WtE. Source separation is the segregation of different types of MSW at its point of generation. The segregation of the OFMSW may determine the WtE technological route employed to extract energy out of it. The source separated OFMSW may end up in the *Anaerobic digester* that produces bioogas out of it. If it is not separated and ends up in the residual waste stream then it ends up in the *Waste incinerator*. Between the two WtE technologies, anaerobic digestion is more sustainable and environmental friendly. It is the most promising technology for intensive bio-degradation of organic matter (Saadabadi et al., 2019).

Source separation of organic waste maximizes the energy recovery from organic waste by providing high quality OFMSW for anaerobic digestion (Al Seadi et al., 2013). It can also influence the potential of energy generated from it (Rousta & Bolton, 2019). This makes source separation of organic waste important step in the WtE process. It aids in providing feedstock for anaerobic digestion, which is the preferred technology over waste incineration. Due to which it is crucial for the development of a circular economy involving WtE (European Commission, 2018; Nainggolan et al., 2019).

Source separation of waste, particularly MSW, is dependent on certain internal and external factors. *Internal factors* are intrinsic to each individual, who is carries out the waste separation. They effect an individual's participation in the waste separation scheme.These factors help describe the Pro-environmental behaviour of the individuals. Individuals showing Pro-environmental behaviour are likely to engage in waste separation (Barr, 2007; Nainggolan et al., 2019). Internal factors include the individual's values, knowledge about organic waste, attitude and personal beliefs & norms towards recycling or waste separation(Meng et al., 2019; Minelgaitė & Liobikienė, 2019; Rousta & Bolton, 2019). *External factors* is about the availability of a waste collection infrastructure (or bin), involving its size or convenience of use (Meng et al., 2019).

Although the influence of these factors on the waste separation rate is well documented, but there is not enough research on the influence of these factors on the potential of energy generated from OFMSW. Therefore, based on this knowledge gap the following research question is proposed to analyse the influence of Pro-environmental behaviour & bin size.

What is the influence of pro-environmental behaviour & bin size on the waste separation rate and the energy obtained per tonne of OFMSW generated by households & SMEs ?

The purpose of this paper is to answer the above research question. The paper is structured in the following manner: In Section 2 the literature needed to answer this research question is discussed. In Section 3, the ABM is described. Section 4 presents the results of the model constructed to answer this research question. In Section 5 the results are discussed and validated with the help of literature & expert opinion. In Section 6, the answer to the research question is presented, along with recommendations for future research.

2. Literature review

Electricity can be generated from OFMSW by waste incineration or by converting the organic waste into an fuel source (such as biogas or biomethane).

Waste incineration is used in developed nations, including the Netherlands, to generate heat and electricity from the residual waste fraction, including the organic waste that is not separated properly (Gemeente Amsterdam - Afval Energie Bedrijf, 2007; Mubeen & Buekens, 2019). As compared to other waste fractions (glass, plastics etc.), the incineration of OFMSW results in lower CO_2 emissions (Astrup et al., 2009). But at same time it has a lower calorific value and high moisture content and it requires a fuel source (like natural gas) to incinerate (Di Maria & Micale, 2015; Mubeen & Buekens, 2019; Mutz et al., 2017).

Anaerobic digestion is a process of generating biogas from organic waste, in the absence of oxygen. The biogas obtained can be used to generate heat & electricity or can be upgraded to biomethane (GasTerra, 2009; German Biogas Association, 2016; Rousta & Bolton, 2019). Using gas turbines electricity can be generated from biogas and biomethane. Although the electricity generation from biomethane can be more economical than biogas due to a higher power output at lower cost (Achinas et al., 2017; Carvill, 1993; IEA, 2015; Lantz, 2012; Leme et al., 2014).

Furthermore, lower separation rate of organic waste can decrease the energy output from anaerobic digestion. Although it is possible to recover the organic waste from residual waste through a Material Recovery Facility (MRF), it is costly and does not completely recover the organic waste (Rousta & Bolton, 2019). Moreover, source separation is preferred over it (Bennagen et al., 2002) .

Thus, source separation of organic waste may determine the WtE technology that processes this waste and subsequently the energy generated from organic waste.

According to Rousta and Dahlen (2015), household waste separation can be influenced by three factors: *socio-demographic, internal and external factors. Socio-demographic factors* include individualistic variables such as culture, age, gender, level of education and income. Although socio-demographics factors play a role in waste separation, but it is still unclear how influence it (Meng et al., 2019).

Internal factors are intrinsic to each individual and affect an individual's participation in the waste separation scheme.These factors include the individual's behaviour values, knowledge about organic waste, attitude and personal beliefs & norms towards waste separation(Meng et al., 2019; Minelgaitė & Liobikienė, 2019; Rousta & Bolton, 2019). These variables can also determine an individual's pro-environmental or waste separation behaviour, that is if an individual is willing to separate waste.

Value-Belief Norm (VBN), a social theory , presents the relationship between behaviour values, beliefs, personal norms and pro-environmental behaviour. On the basis of these internal factors, the VBN theory can help predict the waste separation behaviour of an individual and subsequently help determine waste separation activity carried out.

Furthermore, VBN theory has been used in prior studies to predict waste minimization (Van der Werff et al., 2019), travel choice (Lind et al., 2015), purchasing intent (Davis, 2014) and the acceptability & expected effects of a car pricing policy (Hiratsuka et al., 2018).

But having a high waste separation behaviour is not enough to carry out the activity. *External factors* such availability of the waste collection infrastructure, feedback mechanisms- in form of social norms and transmission of information are important as well.

The waste collection infrastructure can play an important role in enabling waste separation. It's availability is considered crucial for the success of recycling of organic waste (Barr, 2007; Gellynck et al., 2011; Meng et al., 2019). Also, other aspects involving the collection infrastructure such as its proximity to households (Chalkias & Lasaridi, 2009; Nithya et al., 2012), convenience & hygiene (Bernstad, 2014; Ipsos, 2016; Meng et al., 2019) and size (WRAP, 2008) are important as well.

The setup of a Waste Management System (WMS) can determine these factors. The WMS is responsible for collection and management of MSW and its transportation to the WtE plants.

Therefore, the waste separation activity is dependent on a combination of internal & external factors and not solely on a single factor.

With the help of these factors the waste separation rate can be improved and possibly increase the output of certain WtE technologies.

3. Model description

To answer the research question an Agent-Based Model(ABM) is constructed. ABM is a type of a simulation model (Macal & North, 2005). It used to study complex socio-technical systems from a bottom-up approach (Ding et al., 2018). It helps analyse the complex interactions of individuals with external variables such as the organic central bin more closely. Furthermore, it can aid in depiction of emergent behaviour, which is not possible in other research methods. In this research, the ABM simulates the waste separation activity of households & SMEs for a period of 7 months and calculates the waste separation rate & energy obtained per tonne of OFMSW generated by households and SMEs. Using literature, case study reports & expert opinion, the ABM and its accompanying experiments are designed. Furthermore, the steps provided by Van Dam et al. (2013) to construct an ABM are employed here.

The conceptual model can be explained with the help of Figure 1. The diagram is divided into two parts. *Part 1* involves the interaction of the agents with the objects and external variables. The waste separation rate is the resultant output based on the agent's waste separation behaviour and interactions. *Part 2* includes the WtE technologies used to process organic waste into usable energy. The resultant output in this part is the energy obtained (kWh) from per tonne of OFMSW generated by the agents.

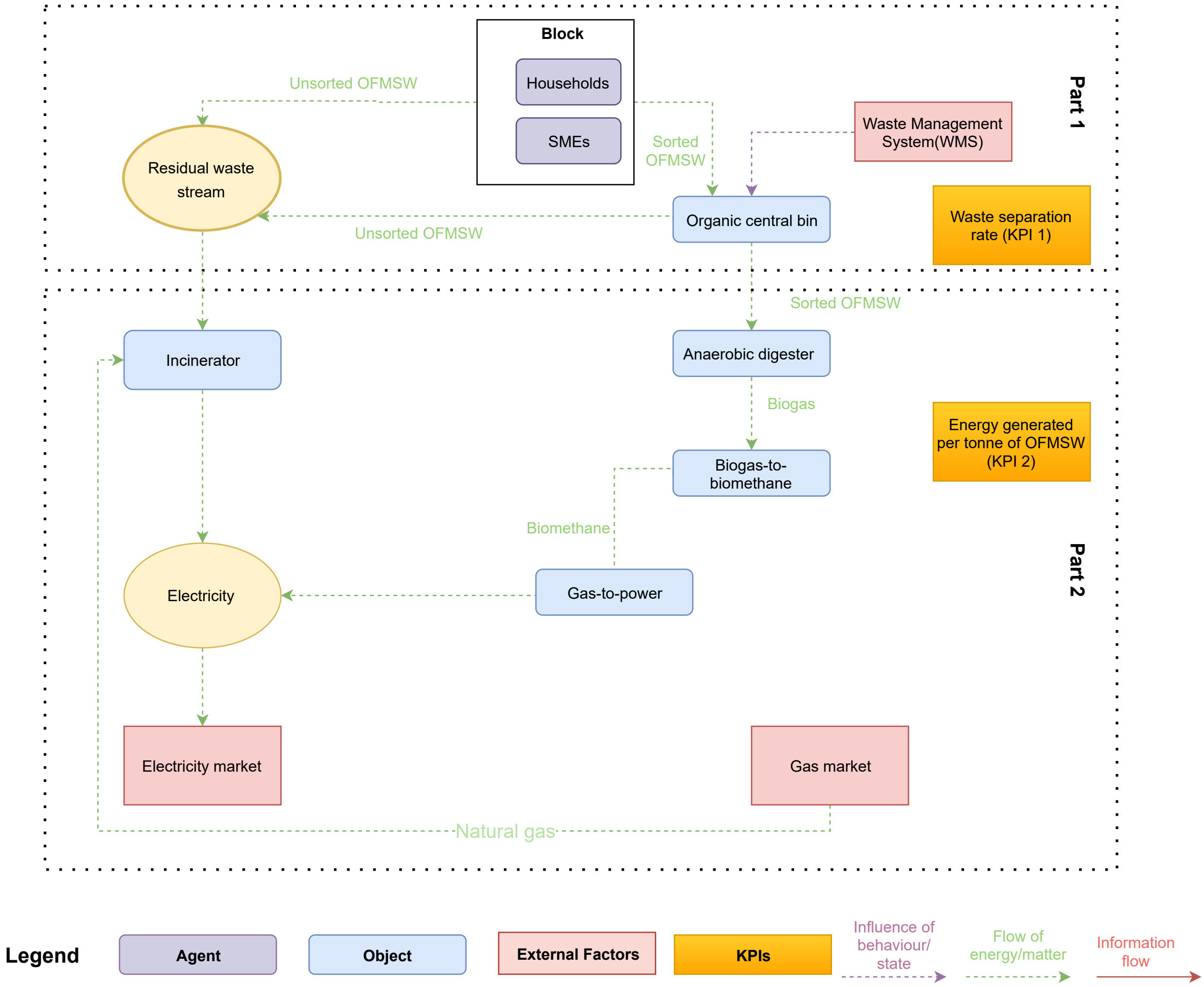
In the model, pro-environmental behaviour or waste separation behaviour is predicted based on behaviour values, based on the VBN theory. Agents that are pro-environmental have high altruistic & biospheric values. But in case of the default model conditions, the values of the agents represent that of Dutch households. According to a survey conducted by Namazkhan et al. (2019), Dutch households have shown to have equal amount of biospheric, altruistic, hedonic values and slightly lower egoistic values.

In *Part 1*, the households & SMEs form a part of a neighbourhood. These agents generate organic waste and based on their waste separation behaviour they decide if they are going to separate their organic waste in their individual local bins (not shown in the diagram). Incase they don't then the waste is disposed off in the residual bin or the residual waste stream.

Once their local bins are full, the households & SMEs walk to dispose (& separate) their waste in the central bins. Based on factors intrinsic to these entities (or agents) and the interactions with the central bin, they decide if they are going to separate their organic waste in the organic central bin. If they decide not to separate their waste, then they dispose the waste in the residual central bin (not shown in the diagram) or the residual waste stream.

In *Part 2*, the different technological routes are depicted with help of WtE technologies. The technological route chosen is determined based on whether the organic

Figure 1. Model conceptualisation



waste is sorted correctly.

From the organic central bin, the sorted organic waste is transported to the anaerobic digester, while the unsorted organic waste ends up being transported to the waste incinerator. The incinerator, with a supply of natural gas, generates electricity from unsorted fraction of organic waste. The separated fraction of organic waste is processed by the anaerobic digester into biogas. The biogas obtained ends up be converted into biomethane. Biomethane is used as a fuel source to generate electricity, which is traded in the energy markets.

The ABM is primarily created to examine Part 1 because it helps capture the typical waste separation activity of households & SMEs and their interactions with other objects. In the second part, only the calculations of the energy obtained per tonne OFMSW are taken place.

4. Results

4.1. Experimental setup

A set of experiments are carried out in the model to study the influence of Pro-environmental behaviour & bin size. The results of these experiments are the two KPIs shown in Figure 1. In order to study the influence of Pro-environmental behaviour and bin size, the results of the experiments involving these variables are compared with the baseline scenario.

A baseline scenario is constructed of Havenstad, which is a planned city in Amsterdam region. The baseline scenario represents the real time values of the different variables within the ABM. The baseline scenario and the other two experiments are defined with help model variables in the table below.

Variable	Baseline conditions	Pro-environmental behaviour	Large central organic bin
Organic central bin size	240 L	240 L	240 L, 480 L and 3000 L
Frequency of waste collection	Once in two weeks	Once in two weeks	Once in two weeks
Biospheric value	0.4	0.8	0.4
Altruistic value	0.4	0.8	0.4
Hedonic value	0.4	0.2	0.4
Egoistic value	0.2	0.2	0.2

In case of the first experiment, *Pro-environmental behaviour*, the ratings of the four behaviour values is changed. In the model, different ratings for each behavioural values can be set from a scale measuring 0 to 1, with an increment of 0.2. A rating of 0.8 implies that the presence of that particular behavioural value is high for the agent. Conversely, a rating of 0.2 implies that the presence of that particular behavioural value is low for the agent.

In case of the second experiment, *Large central organic bin*, the bin size is varied. Apart from 240 L, two different sizes- 480 L and 3000 L are examined. The values of the rest of variables are same as the baseline conditions.

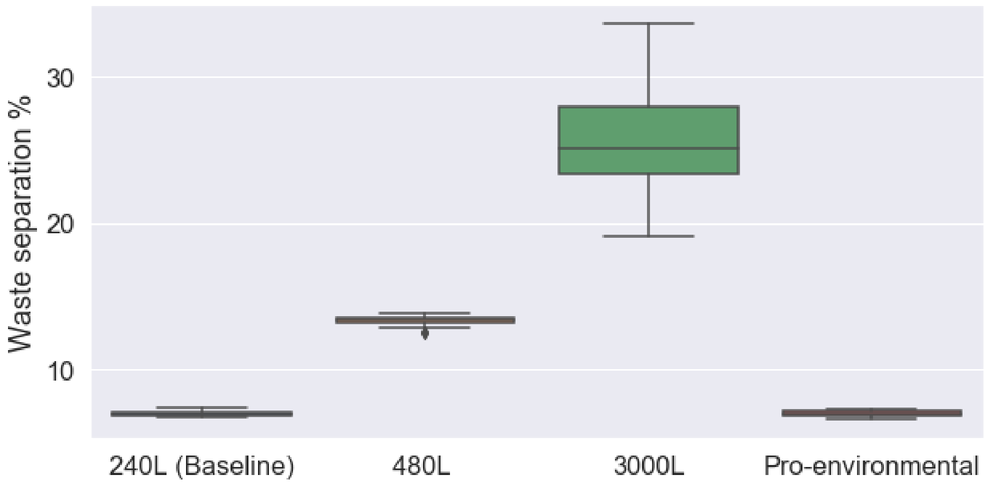
4.2. Waste separation rate

In this subsection the capacity of the central organic bin is varied in the x-axis and the waste separation rate is measured in the y-axis. Additionally, the waste separation rate of agents that are *Pro-environmental* is measured as well.

Based on the results presented in Figure 2, it is observed that the waste separation rate or KPI 1 increases with the increase in the capacity of the central organic bin. In case of a 3000 L bin, the waste separation rate is the highest. The reason for this observation is that the instances of the central organic bin being full may have decreased. Thereby, increasing its availabilty for the agents to separate their organic waste.

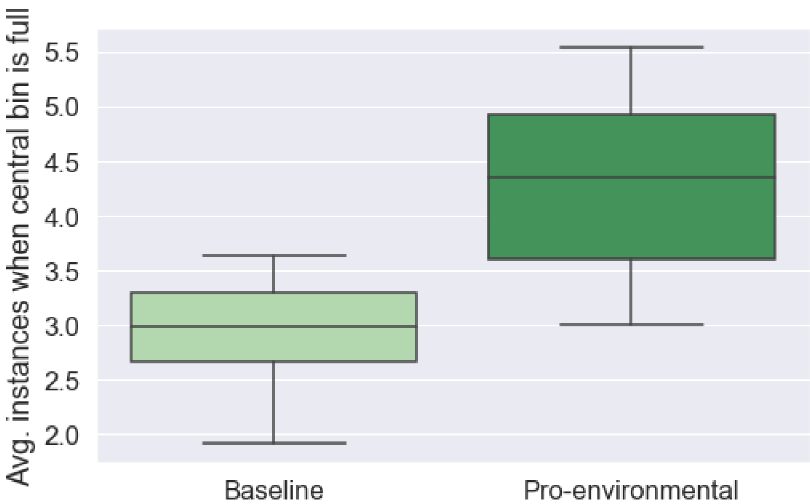
Additionally, it is observed from the boxplot that the presence of *Pro-environmental* behaviour did not increase the waste separation rate as compared to the baseline scenario. One of the reasons for this observation may be the decreased availability

Figure 2. Waste separation rate



of the central organic bin. This can be explained with the help of Figure 3. As seen from the plot, agents that are *Pro-environmental* tend to encounter a full organic bin more frequently than the agents in the baseline scenario. The reason being that *Pro-environmental* agents tend to engage in waste separation more often than the agents in the baseline scenario. This fills up the central organic bin faster. So when an agent comes back to separate its waste, the average instance of it encountering a full bin is higher, leaving it no choice but to dispose its waste in central residual bin. Thus, due to this decreased availability the waste separation rate is nearly the same (or even less) as the baseline scenario.

Figure 3. Average instances when central bin is full

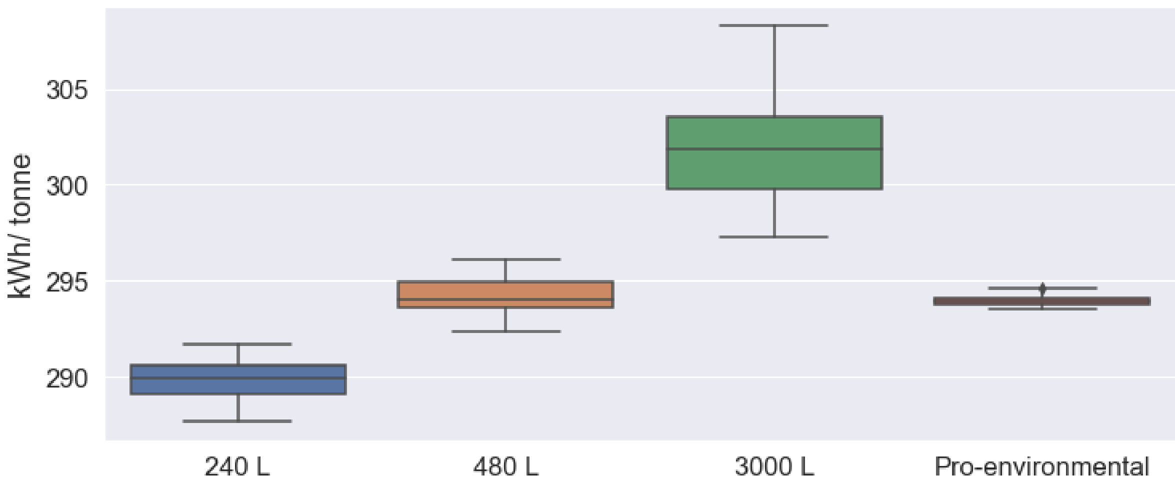


Although the waste separation rate in case of the 'Baseline' & 'Pro-environmental' runs is nearly the same at the end of 7 months, but in the case of the latter run, the waste separation rate may increase initially and then decrease, unlike the former.

4.3. Energy generated per tonne OFMSW

In this subsection, the Energy obtained per tonne of OFMSW generated or KPI 2 is measured in the y-axis instead of the waste separation rate.By observing Figure 4, the following analyses are made: *Firstly*, the increase in waste separation rate mostly results in an increase in the Energy generated per tonne of OFMSW. This is due to the fact that more waste ends up being converted into biomethane, which has a higher energy output compared to the incineration of waste.

Figure 4. Energy generated per tonne OFMSW



Secondly, the increase in central organic bin capacity results in an increase in the KPI 2. This is due the fact that the presence of a large central organic bin results in a high waste separation rate.

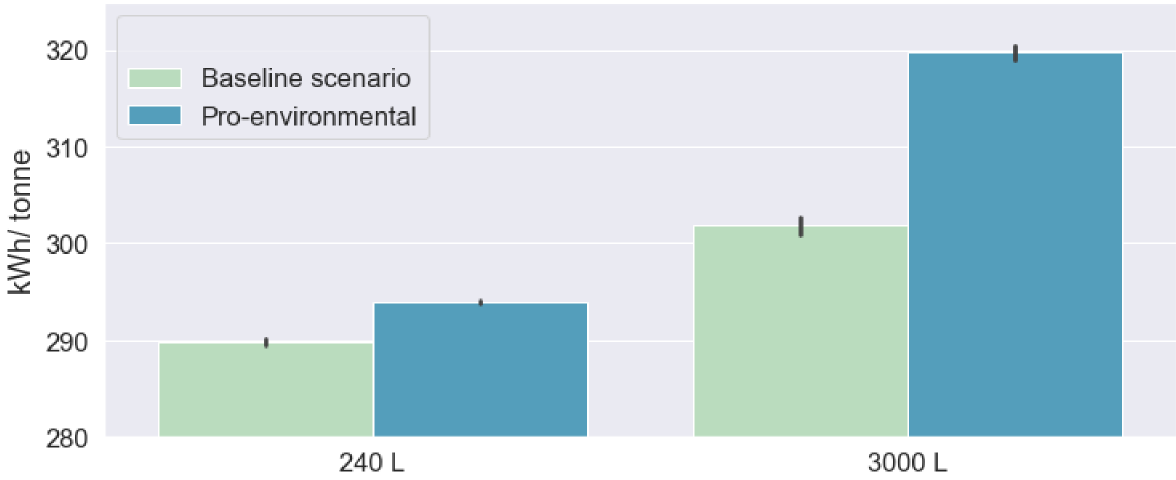
Thirdly, compared to the agents in the baseline scenario, the *Pro-environmental* agents gave a higher output for KPI 2, even though their waste separation rates are nearly the same. This may be because the waste separation rate during the initial stages of the model run is higher, resulting in more OFMSW ending up in the anaerobic digester instead of the waste incinerator. Thus, increasing the Energy obtained per tonne of OFMSW.

4.4. Pro-environmental behaviour & large bin size

In this subsection the combined influence of Pro-environmental behaviour & large central organic bin size is examined on the two KPIs. In Figure 5, the output values of KPI 1 are plotted for the two bin sizes in the x-axis. The green bars represent the agents in the baseline scenario and the blue bars represent the *Pro-environmental* agents.

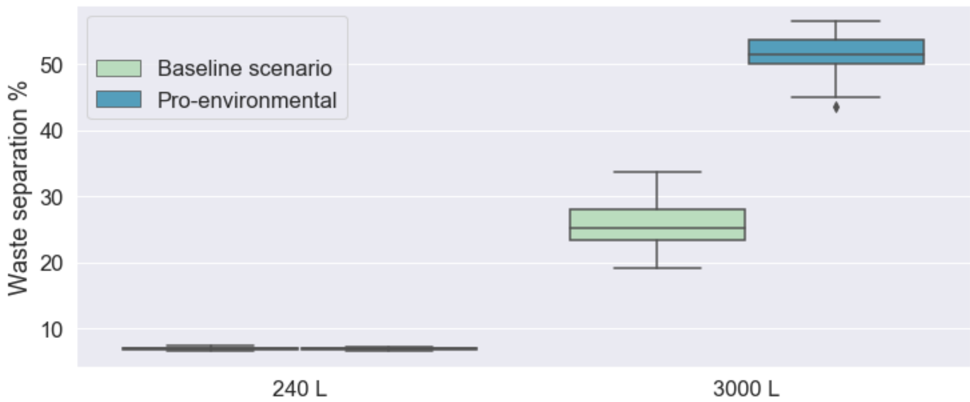
Based on the boxplot, it is observed that the *Pro-environmental* agents separate more waste than their counter parts in the baseline scenario, for a bin size of 3000 L. For that size, the waste separation rate drastically increases the agents are *Pro-environmental.* This is due to an increased availability of the central organic bin.

Figure 5. Energy generated per tonne OFMSW



Furthermore, it is observed that a combined influence of a large bin size & Pro-environmental behaviour results in a higher waste separation, as compared to their individual influences. A similar analysis can be made by observing Figure 6. The combined influence of a large bin size & Pro-environmental behaviour results in an increase in Energy obtained per tonne of OFMSW, due to an increase in the waste separatin rate.

Figure 6. Waste separation rate



5. Discussion

In most of the results presented in the previous section, it is observed that the waste separation rate increased the energy obtained per tonne of OFMSW. Therefore, the model results highlight the importance of source separation on the WtE process. This is in-line with the literature & societal developments, which have highlighted the benefits of source separation on the WtE process.

Secondly, the results show that increasing the bin size (external factor) results in a higher waste separation rate as compared to the presence of Pro-environmetal behaviour (internal factor). This is observed in literature as well. According to Meng et al. (2019), the effect of external factors (such as interventions) on household's waste separation is twice that of internal factors.

Thirdly, according to a study conducted in the UK, increasing the bin size is shown maximize the waste collection (WRAP, 2008). A waste management expert in the Municipality of Amsterdam stated something similar. According to the expert, the size could matter incase of a quick overflow- (when there is low capacity and high frequency of disposal) (Personal communication with expert, February 28, 2020). In the model results, a quick overflow is observed when the agents are *Pro-environmental* & the bin size is 240 L. Furthermore, it is seen that increasing the bin size could prevent the quick overflow and increase waste separation rate. Therefore, model results are shown to be validated based on literature and expert opinion.

Although, according to the same expert increasing the bin capacity comes may make the bin more unhygenic and smelly. This may decrease the instances of an agent separating its waste. But this concept is not addressed within the scope of this study.

6. Conclusion

In this research, an Agent-Based Model (ABM) is used to study the influence of Pro-environmental behaviour & bin size on the waste separation rate and the energy generated from OFMSW. Based on the analysis of the model results, the following conclusions are made:

Firstly, Pro-environmental behaviour & a large bin size increased the waste separation rate and subsequently the energy obtained from OFMSW generated by households & SMEs.

Secondly, the combined influence of Pro-environmental behaviour & increased bin size on the waste separation rate and the energy obtained from OFMSW is higher than their individualistic presence.

6.1. Recommendations for future research

In the research, using VBN theory, the Pro-environmental behaviour or waste separation behaviour is predicted. But there are other social theories (like Theory of Planned Behaviour) that may give a different result. Therefore, it is recommended to construct an ABM based on a different social theory.

Apart from internal & external factors, there is third factor that influence the source separation of waste. According to Rousta and Bolton (2019), that is the socio-demographics of an individual such as age, education, income, gender or culture. As per Meng et al. (2019), the influence of these factors on the source separation of waste is still unclear. Therefore, in future research it is recommended to examine the influence of these factors in combination with the other two factors. Additionally, it is recommended to identify and examine more sub-factors within the three main factors and compare their influence on the waste separation rate. For example, bin hygiene & convience (external factors) should be examined, especially in case of a large bin

Other kinds of interventions, such as monetary incentives individuals to separate waste should be examined by conducting a field study and carrying out surveys. Additionally the use of persuasive games to incentivise individuals should be examined as well.

Lastly, the losses during the different processes such as presence of contaminants, loss of organic waste or mechanical/electrical losses should be addressed in the future research. Especially the link between the pro-environmental behaviour and waste contamination and its subsequent influence on the energy obtained from OFMSW.

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