



## Research paper

## The potential role of waste biomass in the future urban electricity system

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## ABSTRACT

The share of intermittent renewable electricity (IRE) in the future urban electricity system is expected to increase significantly. Sufficient back-up capacity is needed in the period when IRE output is low. Bioenergy is both dispatchable and carbon-neutral, and can hence be a promising option to back up IRE. The objective of this study is to explore the potential of urban waste biomass in backing up IRE in an urban electricity system. An urban electricity system model is developed to project future electricity generation configurations. Given the projected electricity generation configuration, the potential demand for bioenergy as back-up capacity is estimated by simulating hourly electricity demand and the supply of IRE for a whole year. The estimated potential demand for bioenergy is then compared with the potential supply of bioenergy from the urban waste stream. We apply our model using data for the city of Amsterdam, the Netherlands. The complementarity of wind and solar energy is found to reduce the demand for back-up capacity from bioenergy. An extreme weather day with hardly any wind and solar energy supply requires about 2800 tonne waste biomass per day in an emission reduction scenario and 1300 tonne waste biomass per day in a renewable energy quota scenario, respectively. The average daily waste biomass generated in the city is about 1400 tonne. Bioenergy storage as a buffer is found to be necessary due to the monthly fluctuations in both the supply and demand of waste biomass.

## 1. Introduction

The Paris Agreement set a target of achieving a global net-zero carbon economy within this century [1]. The transition of urban electricity systems, as part of the low-carbon city development, is essential in cutting carbon emissions, since cities account for 75% of global energy consumption and 80% of global greenhouse gas (GHG) emissions [2]. An urban electricity system can be defined as a system that combines different processes of electricity production to meet the electricity demand of a given urban area [3,4]. Megacities in the world are leading the transition and taking actions to reduce GHG emissions (e.g. the formation of C40 Cities, which is a network of the world's megacities taking actions to reduce the emissions), to achieve sustainability, self-sufficiency and climate-resilience. The share of intermittent renewable energy (IRE) is expected to increase significantly in a decarbonized urban electricity system. The consequence is that in the period when the IRE output is low, sufficient back-up capacity is required to meet the demand. According to [5], the increasing penetration of intermittent renewable energy will lead to an increasing demand for grid balance. Flexible bioenergy supply has the potential to contribute to grid balance and decarbonization considering its advantages in being both dispatchable and carbon-neutral [6–8].

An open question is how much bioenergy will be required as back-up capacity in the future electricity system of cities. It is of high interest to answer this question in order to make robust energy policies and strategies. The future demand for flexible bioenergy will be affected by renewable energy policy measures. Currently, in some regions inconsistency between the renewable energy policy ambitions and biomass availability exists [9]. Furthermore, strategies for securing a sustainable biomass supply are absent from most national strategies [10]. A related question is how much back-up capacity can be obtained from the urban waste stream. There is an increasing interest in developing biomass feedstock from the urban waste stream to avoid the food versus fuel trade-off [11] and the sustainability disputes of first generation bioenergy [12,13]. Furthermore, using biomass from the waste stream for electricity generation can contribute to more effective urban waste management. In this paper, biomass feedstock from the waste stream will be addressed as "waste biomass". Waste biomass in cities includes the organic part of municipal solid wastes, urban green residues, food processing wastes and manures.

The objective of this paper is to develop a framework to assess the low-carbon electricity system for cities and the potential role of waste biomass in backing up intermittent renewable energy. We apply the

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framework using data for the city of Amsterdam, the Netherlands. The research questions studied in this paper include: (1) What are low-carbon electricity generation configurations in Amsterdam in 2050? (2) What is the required back-up capacity in the urban electricity system for these low-carbon scenarios? (3) How much of this back-up capacity can be obtained from the urban waste stream in the city?

This paper contributes to the biomass and bioenergy literature by using an energy system modelling approach to provide insights into the potential of bioenergy from urban waste streams in balancing the future electricity system. The novelty added is the focus on the city level, and the linking of demand for bioenergy to the biomass availability in the urban waste stream. The methodological framework and analysis can support policy-makers in cities in making robust policies and strategies and in avoiding inconsistencies between urban bioenergy policy ambitions and local biomass availability.

From the biomass resource availability perspective, a number of studies have estimated the bioenergy potential at the global level [14–17]; the regional level, such as the EU [18]; or the national level [19–21]. Only a few focused on the city level [22–24]. The link to the demand for bioenergy from the urban electricity system has not yet been studied. The potential of bioenergy has been analysed using a cost-supply analysis [25,26] or an energy system modelling approach [27–29] at regional level (e.g. the EU) or national level. To the best knowledge of the authors, no study has investigated the bioenergy potential from the waste stream on a city level using an energy system modelling approach.

The rest of this paper is structured as follows: Section 2 introduces the research method. Section 3 gives an overview of the data required and introduces the case study of Amsterdam. Sections 4 and 5 introduce the model scenarios and present results. Section 6 and section 7 give the discussion and the conclusions, respectively.

## 2. Methodology

### 2.1. Methodological framework

Fig. 1 shows an overview of the methodological framework. First, a cost minimization electricity system model is developed to project the future electricity generation configuration for cities. The structure of

the developed model shows strong similarities to other long-term energy system investment models such as MARKAL [30], HOMER [31], Balmorel [32], and LIME-EU [33]. Our model can be applied for the questions at stake because it focuses on cost minimization from a social planner's perspective. It has limitations because the setting of energy provision in Amsterdam, and in cities in general, is currently much more complex than the setting of the model. Despite this, our paper contributes to understanding the potential role of biomass in the energy system. Our model adds the vintage concept to indicate the effect of embodied and disembodied learning on the cost parameters of the electricity generation technologies. The learning effect is given exogenously in the model.

Second, three scenarios are developed to analyse the effects of different climate and energy policy goals on future electricity generation configurations with our electricity system model. A detailed introduction of the scenarios is presented in section 4.

Third, given the projected electricity generation configurations, the daily demand for bioenergy as back-up capacity for extreme weather days is estimated by simulating the hourly electricity demand and hourly supply of intermittent renewable energy in the future, using data for the city of Amsterdam, the Netherlands. Similarly, the annual demand for bioenergy as back-up capacity is estimated by simulating the hourly electricity demand and the supply of intermittent renewable energy for a whole year.

Finally, waste biomass flow data have been collected for the city of Amsterdam. We use the higher heating value (HHV) to calculate the bioenergy supply potential from the urban waste stream. The estimated potential demand for bioenergy is then compared with the bioenergy supply potential from the urban waste stream.

### 2.2. Model description

The urban electricity system model generates the optimal electricity technology investment and generation configuration by minimizing the urban electricity system cost. The system cost includes the investment cost, operation and maintenance cost, fuel cost, and the trade cost of importing and exporting electricity. We assume that the salvage value of the energy generation infrastructure can offset the dismantling cost of the old power plants. Therefore, the decommissioning cost is not

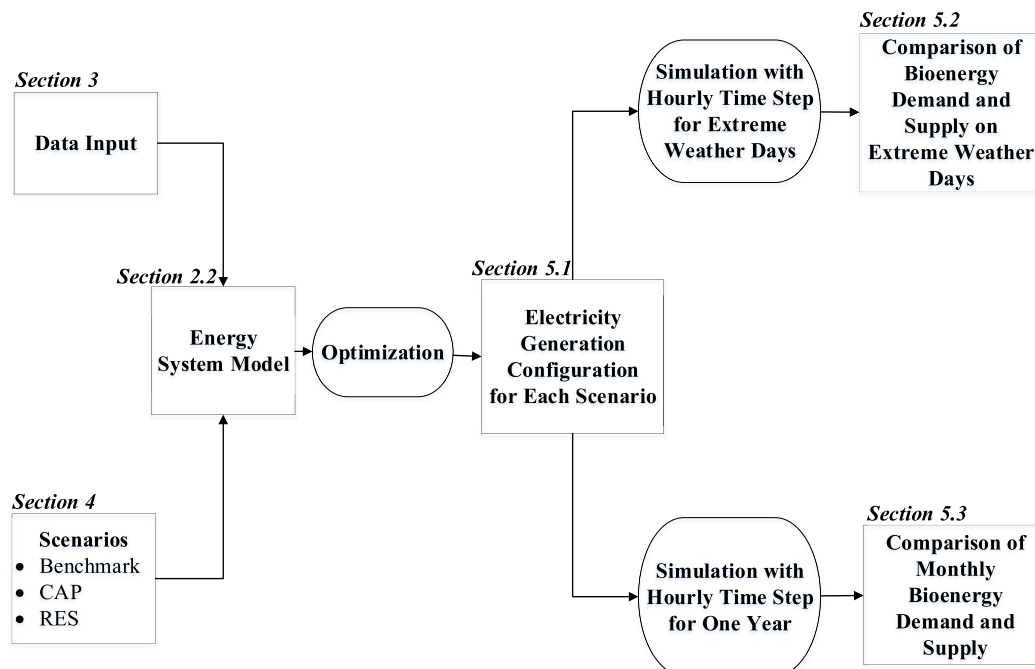


Fig. 1. Overview of the methodological framework.

explicitly considered in this paper. The spatial heterogeneity of the investment cost within the city of Amsterdam is taken into account to allow for location-dependent investment decisions, therefore, the city is divided into several districts to reflect spatial heterogeneity. The investment and generation decisions are based on perfect foresight. Transmission and distribution costs between the districts, however, are ignored. The constraints of the model include the electricity supply and demand balance, the electricity generation capacity constraint and the environmental policy constraint reflected in the scenarios.

The dynamics of the electricity demand and the fluctuations of the wind and solar electricity generation are reflected in the model by using a time slices approach, where one year is divided into four seasons. A representative day of each season is selected and then divided into six time slices to take the daily temporal dynamics into consideration. Electricity supply and demand should balance at each point in time. The time horizon for the evaluation is set from 2010 through 2050. To avoid an end-of-time-horizon effect, the model planning horizon is extended to 2150. The investment and model time step is 5 years. The investment in each period occurs at the beginning with the resulting installed capacity available throughout the entire period. The model has been written in the General Algebraic Modelling System (GAMS Version 24.6) and solved by the CPLEX solver.

Equation (1) describes the objective of the cost minimization model, which is to minimize the discounted system cost of the urban electricity system. The decision variables of the model are  $Q(t)$ , the electricity generation capacity expanded in year  $t$  in MW and  $G(t)$ , the active electricity generation capacity in year  $t$  in MW. We suppress technology and district subscripts here to ease notation. The cost variables in the objective function at the right-hand side of Equation (1) are all determined by the decision variables.

$$\begin{aligned} \text{minimize}_{Q(t), G(t)} \text{NPV} = & \sum_{t=T_0}^T (1+\rho)^{-(t-T_0)} (C_{\text{inv}}(t) + C_{\text{om}}(t) + C_{\text{fuel}}(t) \\ & + C_{\text{trade}}(t)) \end{aligned} \quad (1)$$

NPV is the net present value of urban energy system cost in M€;  $t$  is time in years;  $T_0$  is the start of the investment time horizon;  $T$  is the end of the investment time horizon;  $\rho$  is the discount rate;  $C_{\text{inv}}(t)$  is the investment cost in M€ in year  $t$ ;  $C_{\text{om}}(t)$  is the operation and maintenance (O & M) cost in M€ in year  $t$ ;  $C_{\text{fuel}}(t)$  is the fuel cost with unit M€ in year  $t$ ;  $C_{\text{trade}}(t)$  is the import cost minus export revenue in M€ in year  $t$ . All variables are positive except  $C_{\text{trade}}(t)$ , which may be negative.

The investment cost function is given by

$$C_{\text{inv}}(t) = \sum_r \sum_i (\alpha_{(r,i)}(v) \cdot Q_{(r,i)}(v)) \quad \forall t = v \quad (2)$$

where  $\alpha_{(r,i)}(v)$  is the unit investment cost of technology  $i$  of vintage  $v$  in district  $r$  in M€/MW; and  $Q_{(r,i)}(v)$  is the expanded electricity generation capacity of technology  $i$  of vintage  $v$  in district  $r$  in MW.

The O & M cost function is given by

$$\begin{aligned} C_{\text{om}}(t) = & \sum_r \sum_i \sum_{v=0}^t (\beta_{(r,i,v)}(t) \cdot K_{(r,i,v)}(t)) \\ & + \sum_r \sum_i \sum_{v=0}^t \sum_{\tau} (\gamma_{(r,i,v)}(t) \cdot (l_{\tau} \cdot G_{(r,i,v,\tau)}(t))) \end{aligned} \quad (3)$$

where  $\beta_{(r,i,v)}(t)$  is the unit fixed O & M cost for technology  $i$  of vintage  $v$  in period  $t$  in district  $r$  in M€/MW;  $K_{(r,i,v)}(t)$  is the total installed capacity of technology  $i$  of vintage  $v$  in period  $t$  in district  $r$  in MW;  $\gamma_{(r,i,v)}(t)$  is the unit variable O & M cost of electricity generation technology  $i$  of vintage  $v$  in period  $t$  in district  $r$  in M€/MWh;  $l_{\tau}$  is the length of time slices in hours;  $G_{(r,i,v,\tau)}(t)$  is the active capacity of technology  $i$  of vintage  $v$  in time slice  $\tau$  in period  $t$  in MW in district  $r$ . This equation calculates the sum of fixed O & M cost and variable O & M cost. As we consider a city system, transmission and distribution costs are ignored in our model.

The fuel cost function is given by

$$C_{\text{fuel}}(t) = \sum_r \sum_j \sum_v \sum_{\tau} \sum_f \sigma_{(f)}(t) \cdot P_{(r,j,v,\tau,f)}(t) \quad (4)$$

where  $\sigma_{(f)}(t)$  is the fuel  $f$  price in period  $t$  in M€/GJ; and  $P_{(r,j,v,\tau,f)}(t)$  is the primary energy consumption of technology  $j$  of vintage  $v$  that uses fuel  $f$  in time slice  $\tau$  in period  $t$  in district  $r$  in GJ.

The trade cost function is given by

$$C_{\text{trade}}(t) = \sum_r \sum_{\tau} (p_i(t) \cdot I_{(r,\tau)}(t) - p_o(t) \cdot O_{(r,\tau)}(t)) \quad (5)$$

where  $p_i(t)$  is the import price of electricity in period  $t$  in M€/MWh;  $I_{(r,\tau)}(t)$  is the imported electricity from outside of the city territory into district  $r$  in time slice  $\tau$  in period  $t$  in MWh;  $p_o(t)$  is the export price of electricity in year  $t$  in M€/MWh;  $O_{(r,\tau)}(t)$  is the exported electricity from district  $r$  to outside of the city territory in time slice  $\tau$  in period  $t$  with unit MWh. This equation calculates the positive or negative net income of trading electricity in the city.

The electricity supply and demand balance equation is given by

$$D_{(r)}(t) \cdot l_{\tau} + \sum_r O_{(r,\tau)}(t) = \sum_r \left( \sum_i \sum_{v=0}^t (G_{(r,i,v,\tau)}(t) \cdot l_{\tau}) + I_{(r,\tau)}(t) \right) \quad (6)$$

where  $D_{(r)}(t)$  is the power load in the city in time slice  $\tau$  in period  $t$  in MW.

The fuel consumption equation is given by

$$\sum_f \eta_{(j,f)}(v) \cdot P_{(r,j,v,\tau,f)}(t) = \varepsilon \cdot G_{(r,j,v,\tau)}(t) \cdot l_{\tau} \quad \forall v \leq t \quad (7)$$

where  $\eta_{(j,f)}(v)$  is the fuel conversion efficiency ( $0 < \eta_{(j,f)}(v) < 1$ ) of technology  $j$  of vintage  $v$  that consumes fuel  $f$ ;  $\varepsilon$  is the unit conversion scalar to convert electricity consumption (MWh) to fuel consumption (GJ) and has a value of 3.6. Fuel conversion efficiency is defined as the total delivery of electricity to the grid divided by the fuel consumption.

The capacity constraint equation is given by

$$G_{(r,i,v,\tau)}(t) \leq w_{(i,\tau)} \cdot K_{(r,i,v)}(t) \quad (8)$$

where  $w_{(i,\tau)}$  is the availability factor ( $0 < w_{(i,\tau)} < 1$ ) of technology  $i$  in time slice  $\tau$ . This equation introduces the constraint for each energy generation technology of each vintage.

The GHG emission equation is given by

$$E(r, t, e) = \sum_i \sum_{v=0}^t \sum_{\tau} \zeta_{(i,e)} \cdot l_{\tau} \cdot G_{(r,i,v,\tau)}(t) \quad (9)$$

where  $E(r, t, e)$  is the quantity emitted of pollutant  $e$  in district  $r$  in period  $t$  in kt;  $\zeta_{(i,e)}$  is the emission coefficient in kt/MWh. The emission coefficient uses the results of life cycle assessment of various energy technologies.

In one of the scenarios we introduce a CO<sub>2</sub> emission target. The emission constraint equation is given by

$$\sum_r E(r, t, e) \leq E_{\text{max}}(t, e) \quad (10)$$

where  $E_{\text{max}}(t, e)$  is the emission ceiling of emission type  $e$  (e.g. CO<sub>2</sub> emission in our case study) in kt.

Capacity degradation varies by vintage and develops as follows:

$$\begin{aligned} \text{for } v = t, & \quad K_{(r,i,v)}(t) = Q_{(r,i)}(v) \\ \text{for } t - \psi(v, i) \leq v < t, & \quad K_{(r,i,v)}(t+1) = (1 - \kappa) \cdot K_{(r,i,v)}(t) \\ \text{for } v \leq t - \psi(v, i), & \quad K_{(r,i,v)}(t) = 0 \\ & \quad K_{(r,i,v)}(T_0) \quad \text{given.} \end{aligned} \quad (11)$$

$\psi(v, i)$  is the life time of technology  $i$  of vintage  $v$ . When vintage  $v$  is installed,  $v = t$  and  $K_{(r,i,v)}(t)$  is equal to the capacity invested,  $Q_{(r,i)}(v)$ .

The vintage concept is used to indicate when a certain amount of generation capacity is deployed. Combining the vintage concept with the technology life time parameter, the decommissioning and new capacity investment are calculated. Investment in new capacity of the technology will take place if it leads to the optimal solution of the cost minimization model. When the technology is within the physical life time of its vintage, the technology capacity decreases at rate  $\kappa$ . When physical life time is reached, the technology is decommissioned. Installed capacity at the start of the planning horizon is given.

### 3. Case study and data collection

Amsterdam, the capital of the Netherlands, is selected as the city for our case study, as the city is pursuing to become a sustainable, self-sufficient and climate-resilient city [34]. In 2015, Amsterdam had a population of 821 752 [35]. It is located 52.3702°N, 4.8952°E, and has a temperate maritime climate. The city has set ambitious goals in reducing GHG emissions. In addition, it aims at increasing the amount of renewable energy production per capita with 20% relative to 2013 by 2020 by producing more wind and solar energy [34].

In this paper, we assume that the electricity system for Amsterdam is isolated from its surrounding electricity network and operated in an island mode. This specific setting reflects the vision and the local determination of the city of Amsterdam to become energy self-sufficient in the future. This specific setting is also useful to many other cities, such as Barcelona, that are taking steps towards energy self-sufficiency. Self-sufficiency is a political issue emerging as a key energy policy goal as it would help reduce electricity transmission loss, improve local electricity supply security, stimulate the local economy, and strengthen the local control of energy production, which gives all stakeholders a stronger local identity.

The data of the electricity demand, with a temporal resolution of 15 min, were obtained from Alliander, a Dutch energy network company. These electricity demand data are from two transformer stations in Amsterdam and do not represent the total electricity demand of the whole city. The total electricity demand of Amsterdam in 2014 was therefore collected to scale up the electricity demand data from the two transformer stations to the whole city. A scaling coefficient was obtained by dividing the total electricity demand in 2014 by the sum of the electricity demand of the two transformer stations in 2014. Then the scaling coefficient was used to scale up the electricity demand data from two transformer stations to the city scale, assuming that the pattern of the two transformer stations are representative for the city. In further studies this assumption can be relaxed if more detailed energy demand data are available. Based on the demand pattern, 24 time slices are used in a year to represent the temporal dynamics.

Energy technologies selected include pulverized coal, natural gas based combined cycle gas turbine (CCGT), onshore wind turbines, and solar PV. The techno-economic details of these technologies that are used as the model inputs are shown in Table S1 in the supplementary material. The projected fuel cost is shown in Table S2. Our model allows for cost decreases for new vintages through exogenous learning. The parameters affected by the learning effect are the unit investment cost for each electricity generation technology in this case study (see Equation (2)). They are calculated by  $\alpha_{(r,i)}(v+1) = (1 - CR_{(i)}) \cdot \alpha_{(r,i)}(v)$ , where  $CR_{(i)}$  indicates the relative cost reduction per vintage for technology  $i$ .

In this study, flexible biogas supply is selected to represent the flexible bioenergy technology as back-up capacity. Instead of biogas, it is also feasible to use solid biomass and liquid biofuels [36]. The benefit of using biogas compared with using other back-up renewable electricity sources is cost saving as existing natural gas pipelines in the city infrastructure to transport biogas to the power plant can be used. This choice still requires a certain level of biogas cleaning and upgrading with corresponding costs. Sun et al. (2015) recently reviewed the state-of-the-art of the biogas cleaning and upgrading technologies and the

associated costs [37]. We assume a 36% efficiency rate to represent the performance of biomass gasification technology [38,39].

Apart from studying the back-up capacity, the storage of the surplus electricity produced by wind and solar energy on an extreme weather day is also considered. The emerging power-to-gas technology is selected for storage of electricity on those extreme weather days.

In order to compare the potential supply of bioenergy from the urban waste stream with the estimated demand, we collected data about organic waste flows in Amsterdam from AEB, a waste-to-energy company in Amsterdam. The share of organic waste in the total waste flow is 36% [40]. We use a HHV of 7.65 GJ/t to calculate the potential energy in the waste biomass [41]. Currently, a part of the waste biomass is also used for heat generation. The share of the waste biomass that goes into electricity production is assumed to be 30%, based on literature [42]. Furthermore, the waste biomass data that we collect do not cover all the waste biomass in the city. Some waste biomass (e.g. food waste) is currently not fully collected in Amsterdam. A discussion of the effect of waste policy on waste biomass quantity is presented in Section 6.

### 4. Scenarios

We used our urban electricity system model to find the optimal electricity generation configuration for three different scenarios. These scenarios allow us to analyse the effect of different climate and energy policy goals on the potential for waste biomass in the electricity system of cities. The policies of Amsterdam are used for illustration purposes.

The benchmark scenario is developed to present the electricity generation configurations in Amsterdam in the absence of climate and energy policies. The presently existing wind and solar energy capacities are small compared to the other generation capacities. In this scenario, there will be no investment in wind and solar energy due to relatively high costs and lack of investment incentives. Therefore, the presently existing wind and solar energy capacities are ignored for simplicity.

Although there is an energy conservation program in Amsterdam, the increasing electrification, due to the penetration of heat pumps and electric vehicles, population growth [43] and rebound effects [44], may lead to an increase in electricity demand. Considering the large uncertainties associated with the future electricity demand in Amsterdam, it is assumed that the electricity demand will be constant until 2050 in all three scenarios. This assumption will be relaxed in a sensitivity analysis.

The CAP scenario was developed to compute the electricity generation configuration in the presence of a city-level cap on CO<sub>2</sub> emissions. The city of Amsterdam has set a goal of emitting 40 and 75% less CO<sub>2</sub> by 2025 and 2040, respectively, compared to the 1990 level [34]. The emission reduction goal for the electricity sector is usually more ambitious than the economy wide objective. For example, a GHG emission reduction of 80% for 2050 would imply an emission reduction of 93–99% for the EU electricity sector [45]. Therefore, the CO<sub>2</sub> emission reduction goal of the Amsterdam electricity system is assumed to be more ambitious than the general goal stated in the agenda of the Municipality of Amsterdam [34]. The official agenda of Amsterdam only mentioned the emission reduction goals for 2025 and 2040. Since the time horizon in this study is until 2050, we assume that the goal in 2050 is higher than that in 2040 based on the trend of Dutch national policy targets. The Dutch national targets are to reduce GHG emission by at least 40% by 2030 and by 80–95% by 2050 [46]. The specific assumptions on emission reduction goals in the CAP scenario are presented in Table 1.

The RES scenario was developed to present the electricity generation configuration under the influence of the ambition to increase the capacity of renewable energy in Amsterdam. The official agenda in Amsterdam [34] specified an energy policy goal of increasing renewable energy capacity in the city until 2040, which is also shown in Table 1. In this paper, the policy-driven Solar-PV capacity in 2050 is



**Table 1**  
Summary of the characteristics of the three scenarios.

Scenario name	Installed capacity	CO <sub>2</sub> emission reduction goals <sup>a</sup>	Urban electricity demand
Benchmark	–	–	Constant
CAP	–	50 by 2025 85% by 2040 95% by 2050	Constant
RES	<i>Solar-PV</i> 9 MW in 2015 160 MW in 2020 1000 MW in 2040 1300 MW in 2050 <i>Wind-Turbine</i> 67 MW in 2015 85 MW in 2020 250 MW in 2025 400 MW in 2040 400 MW in 2050		Constant

<sup>a</sup> The CO<sub>2</sub> emission level in 1990 is used as the baseline in the policy goal.

assumed to be the technical potential of solar energy in Amsterdam, which is 1300 MW [34]. Since no data have been found on the technical potential of wind energy capacity in 2050 and considering the limited space for building wind turbines in Amsterdam, the policy-driven wind turbine capacity in 2050 is assumed to be the same as in 2040. Table 1 summarizes the characteristics of the three scenarios.

## 5. Results

In this section, we first present the constrained cost-minimizing electricity generation configurations for the three scenarios. Subsequently the results for the demand for bioenergy back-up capacity on extreme weather days are presented. This is followed by the results of monthly requirements for back-up capacity in a whole year and the comparison with potential supply from the urban waste stream.

### 5.1. Future electricity generation configurations

Fig. S1 in the supplementary material shows the electricity generation configuration in the benchmark scenario. In this scenario, the urban electricity system is planned based on the cost minimization principle without consideration of environmental aspects or the policy goal of increasing the use of wind and solar energy.

As shown in Fig. S1 (a), initially there is overcapacity in the system because our model considers the existing capacity of the coal (630 MW) and CCGT (435 MW) in Amsterdam. The phenomenon of overcapacity in the city of Amsterdam is also stated in a report by energy company Nuon [47]. The installed capacities of coal and CCGT are almost the same. As shown in Fig. S1 (b), coal power generation is functioning as baseload, and CCGT power generation is functioning as peakload.

Fig. 2 (a) and Fig. 2 (b) show the electricity generation configuration in the CAP scenario. Installed capacity of Solar-PV is zero in this scenario. This can be explained by the high investment cost of Solar-PV, in the absence of subsidies. The share of wind turbines in the system increases over time, which is driven by the CO<sub>2</sub> emission reduction target. Its share in total installed capacity grows from 45% in 2025 to 81% in 2050. The generation share of wind energy increases to 95% in 2050 in Fig. 2 (b). Coal energy is phased out by 2030.

Fig. 2(c) and (d) show the electricity generation configuration for the RES scenario. In this scenario policy targets impose minimum capacity for solar and wind energy. The installed capacity of Solar-PV takes a 53% share of total installed capacity in 2050. However, the generation share of Solar-PV in 2050 is only 23%. This is due to the fact that the solar irradiance in Amsterdam is low and hence the capacity factor of the Solar-PV is low as well, with an average value of 9%. The

capacity factor is defined as the ratio of an energy generation technology's actual electricity output over a period of time to its potential output if it operates at a full capacity continuously over the same period of time. The capacity factor is calculated using the meteorological data in the region of Amsterdam. We use the method in Haller et al. [48] to convert the meteorological data into the capacity factor.

### 5.2. Demand for bioenergy back-up capacity on extreme weather days

In order to explore the demand for bioenergy back-up capacity on a day with extreme weather conditions, we developed two extreme weather scenarios for each season. The assumptions for the extreme values of wind speed and solar irradiance are based on historical meteorological data from 2005 to 2015 from the Schiphol weather station in Amsterdam [49]. The electricity generation configurations from section 5.1 are used here for the simulation. Winter days have the highest demand for back-up capacity, therefore only the results of the winter season are presented here, the results of other three seasons can be found in the supplementary materials.

Fig. 3 (a) and Fig. 3 (b) show the hourly power flow in the extreme weather scenarios on a winter day in the CAP scenario. Fig. 3 (a) shows the situation of a winter day with extremely strong wind and solar irradiance, but a low demand for electricity. The result of the power-to-gas conversion shows that there is a large excess of electricity in the system. Assuming a power-to-gas technology efficiency of 55% [50], a total of 0.1 PJ can be stored. Fig. 3 (b) shows the situation of a winter day with extremely low wind and solar irradiance, but a high demand for electricity. As can be seen from the demand for biogas, a total of 0.021 PJ net bioenergy is required as flexible back-up supply.

Fig. 3 (c) and Fig. 3 (d) show the hourly power flow in the extreme weather scenarios on a winter day in the RES scenario. Fig. 3 (c) shows the situation of a winter day with extremely strong wind and solar irradiance, but a low demand for electricity. As in the CAP scenario, the result of the power-to-gas conversion shows that there is also a large excess of electricity in the system. A total of 0.053 PJ energy can be stored by power-to-gas technology. Fig. 3 (d) shows the situation of a winter day with extremely low wind and solar irradiance, but a high demand for electricity. The result shows that there is a total of about 0.002 PJ excess electricity from midnight to 6 a.m. After 6 a.m., there is a requirement for a total of about 0.01 PJ biogas back-up capacity in the system.

To cover the biogas supply using urban waste, an extreme weather day in 2050 requires about 2800 tonne waste biomass per day in the CAP scenario and 1300 tonne waste biomass per day in the RES scenario, respectively. The average daily waste biomass generated in

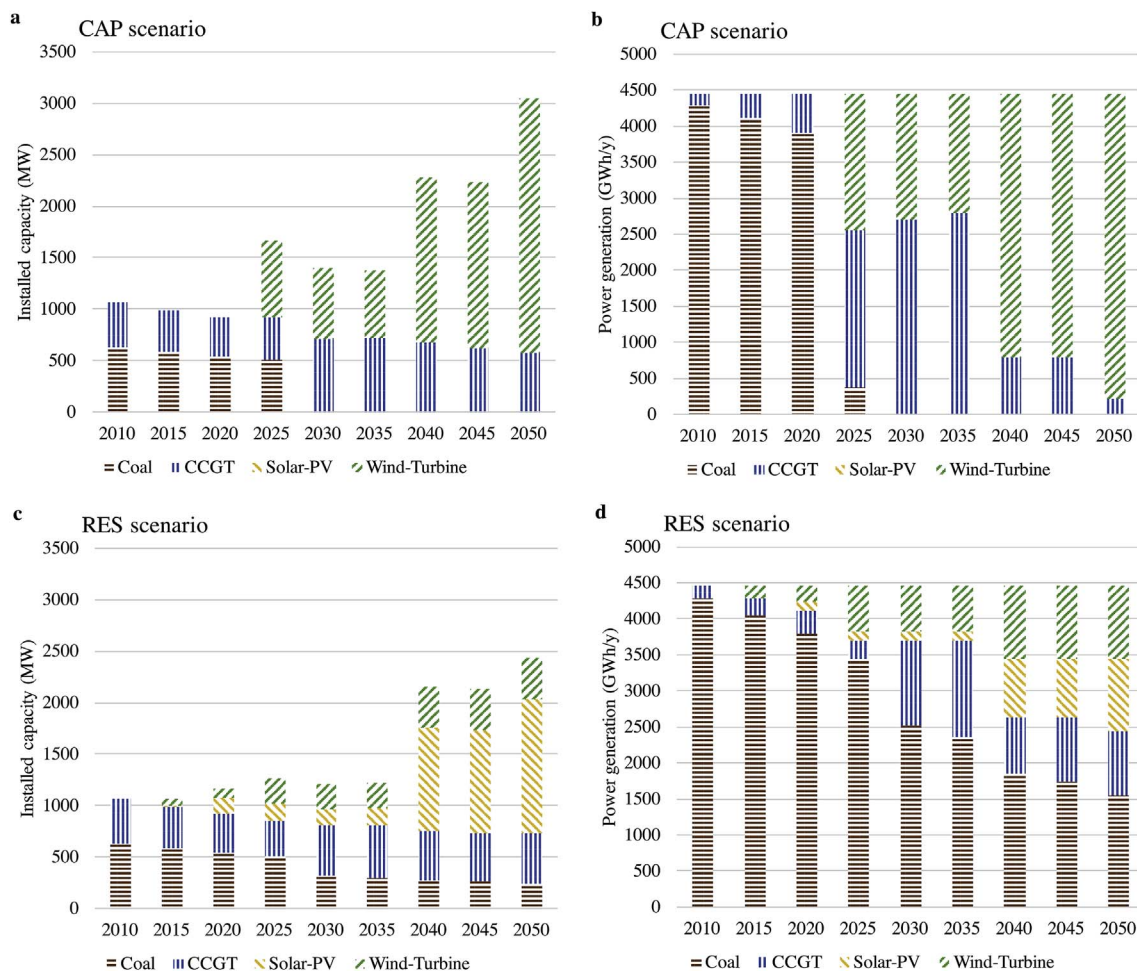


Fig. 2. (a) Urban electricity generation configuration in the CAP scenario; (b) Yearly urban power generation in the CAP scenario; (c) Electricity generation configuration in the RES scenario; (d) Yearly power generation in the RES scenario.

Amsterdam is about 1400 tonne [51]. This implies that import or storage of waste biomass is necessary for the CAP scenario. The demand for waste biomass in the RES scenario can be self-sufficient in the city.

### 5.3. Comparing monthly bioenergy demand and supply

Section 5.2 presented bioenergy demand and supply on extreme weather days. In this section we analyse the monthly bioenergy demand and supply. We use data from 2014, the latest year for which relevant data are available for our simulation. Since the temporal resolution of the waste flow data is monthly, the estimated demand for biogas back-up capacity is aggregated to the monthly level to compare demand and supply.

As shown in Fig. 4, the estimated demand for the bioenergy back-up capacity in the CAP scenario (panel (a), dashed and dotted lines for 2030 and 2050, respectively) is found to be much higher than that in the RES scenario (panel (b)), both for the 2030 and 2050 energy system configurations. This can be explained by the wind and solar resource synergy (e.g. Ref. [52]). Since wind and solar energy complement each other, the system needs less back-up capacity in the RES scenario, in which both technologies are installed, as compared to the CAP scenario, in which only wind turbines are installed and the complementarity between the wind and solar energy does not exist. Moreover, as the 2050 configuration has a higher renewable energy capacity share than the 2030 configuration, it can be concluded that when the intermittent renewable energy capacity increases in the system, the demand for the back-up capacity also increases. The demand and supply curves for bioenergy intertwine with each other and fluctuate. To provide a stable

supply of bioenergy from waste, bioenergy storage is needed as a buffer to meet the electricity demand when the supply is lower than demand, as shown in Fig. 4.

### 5.4. Sensitivity analysis

Due to the high uncertainties associated with the cost parameters of the wind and solar energy technologies and the electricity demand trend, a sensitivity analysis is conducted by varying the parameters of the unit investment cost of the wind-turbine and Solar-PV technologies, and the annual growth rate of the electricity demand in the CAP scenario. CAP scenario is selected because the model results are affected more significantly by the cost parameters and demand growth rate in the CAP scenario than in the RES scenario. The range of the variation of the cost parameters are based on [53] and the range of the variation of the demand rate is based on own assumptions.

As shown in Fig. S2 (a) in the supplementary material, the required bioenergy increases when the unit investment cost of the wind-turbine technology is low. This is reasonable because an increase in the capacity of the wind-turbine is expected when the unit investment cost is low, which results in a higher demand for back-up capacity. When the unit investment cost of Solar-PV is very low, it is expected that the capacity of the Solar-PV will increase in the system. Solar energy can then to a large extent back-up wind energy. Therefore, as shown in Fig. S2 (b), the required bioenergy sharply drops when the unit investment cost of the Solar-PV becomes smaller than 0.453 M€/MW. As shown in Fig. S2 (c), when the electricity demand growth rate increases, the required bioenergy also increases. This is because a higher back-up capacity is

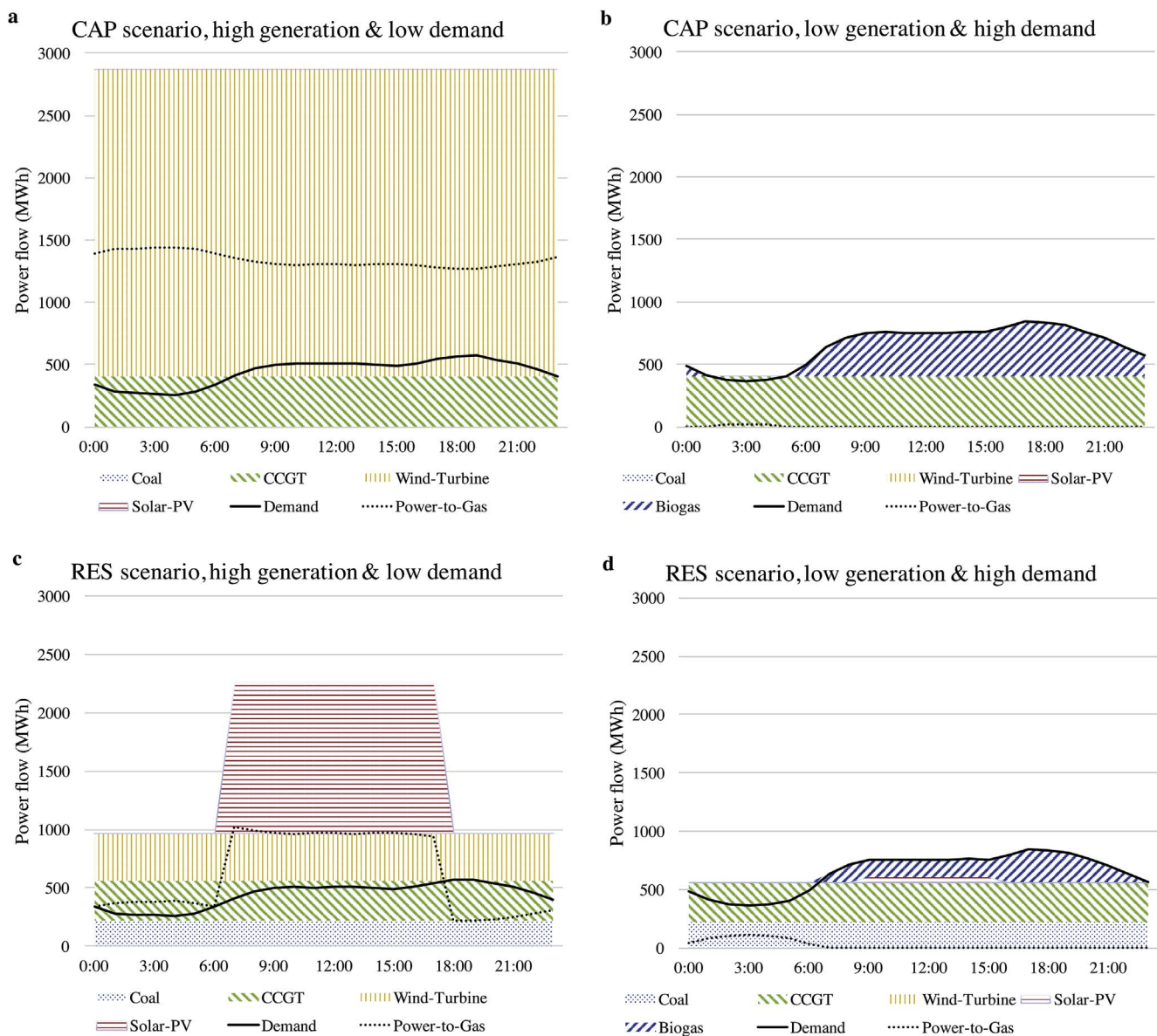


Fig. 3. (a) High urban renewable energy generation and low urban electricity demand on a winter day in 2050 in the CAP scenario; (b) Low urban renewable energy generation and high urban electricity demand on a winter day in 2050 in the CAP scenario; (c) High urban renewable energy generation and low urban electricity demand on a winter day in 2050 in the RES scenario; (d) Low urban renewable energy generation and high urban electricity demand on a winter day in 2050 in the RES scenario.

needed when both the electricity demand and the intermittent renewable energy capacity in the system are high.

## 6. Discussion

We calculated the theoretical potential supply of bioenergy from an urban waste stream, and evaluated whether this potential supply could meet the demand for back-up capacity in different scenarios. However, the economic aspect of waste biomass energy is not included in the analysis. Here we provide a discussion on the cost and benefit of the flexible biogas supply from urban waste biomass. The levelized cost of electricity (LCOE) is used as an economic indicator. We collected data from the literature and report them expressed in euros in constant values for 2016. The LCOE of a biogas plant with the flexible energy supply ((0.158–0.269) €/kWh) is lower than that of a battery system (above 0.2 €/kWh), but not as low as that of a natural gas system ((0.075–0.098) €/kWh) in the Netherlands [54–58]. The LCOE of flexible biogas supply using urban waste biomass is highly influenced by the waste pretreatment cost, storage cost and full load hours. Due to

the heterogeneous nature of the waste biomass, a pretreatment such as grinding for particle size reduction, separation for contaminants removal and alkali treatment is needed for efficient biogas production [59]. Waste pretreatment leads to extra cost compared with homogeneous substrates, but the homogeneous biomass feedstock costs (80–150) €/t [60]. Hence, the urban waste as a biomass feedstock can be cost competitive compared with a homogeneous biomass feedstock. Ariunbaatar et al. [61] suggested that the best options for waste biomass pretreatment are thermal pretreatment at low temperatures and two-stage anaerobic digestion. Making existing biogas plants more flexible will increase costs due to required larger storage capacities and reduced full-load hours [62,63]. Compared to non-flexible electricity generation, the flexibilization of biogas plants leads to further costs amounting to (0.020–0.050) €/kWh [58].

However, the extra costs mentioned previously can be compensated by the waste gate fee, which is about (15–60) €/t in the Netherlands [60]; by a renewable energy support mechanism such as feed-in premium, which is 0.055 €/kWh in 2016 under the subsidy scheme SDE+ in the Netherlands; by selling the digestate as a fertilizer; and by

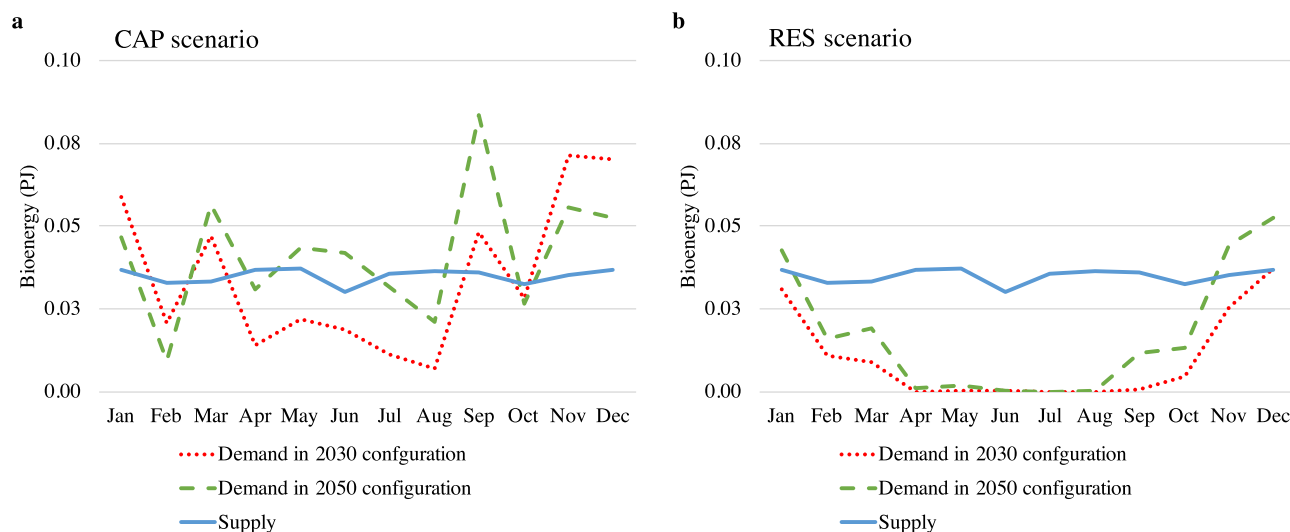


Fig. 4. (a) Estimated monthly demand for bioenergy compared with the monthly potential supply in the CAP scenario for 2030 and 2050; (b) Estimated monthly demand for bioenergy compared with the monthly potential supply in the RES scenario for 2030 and 2050.

avoiding the external cost from using natural gas. Furthermore, future policy measures that incentivize the flexible biogas supply could financially compensate the extra cost incurred by changing the operation mode of the biogas plant.

In this study we used historical data to represent the potential supply of the bioenergy from the waste stream. By doing this, we assumed that the waste generation will not change in the time frame from 2010 to 2050. However, waste generation can change under different policy drivers. Studies have shown that the decoupling of waste generation from economic growth is far from being reached in Europe [64,65], which implies that the increasing urbanization and economic growth will most likely lead to an increased waste generation. But on the other hand, waste prevention policy such as increasing efforts on food waste prevention may reduce the generation of waste biomass in the cities. Given these uncertainties, in further studies a quantitative forecasting of future urban waste biomass is needed, including explicit policy and technology scenarios.

## 7. Conclusion

This study is driven by three main questions: (1) What are the future electricity generation configurations in Amsterdam in 2050 with and without policy interventions? (2) What is the demand for back-up capacity in the urban electricity system of Amsterdam in 2050? (3) How much of this back-up capacity can be obtained from the urban waste stream in the city?

- We find that, in the absence of climate and energy policy targets, renewable energy is dominated by conventional energy in the urban electricity system. In the CAP scenario, in which we cap CO<sub>2</sub> emissions, coal-fired power plants are phased out by 2030 while the wind energy capacity increases from 45% in 2025 to 81% in 2050 and the generation share of wind increases to 95% in 2050. In the RES scenario, in which we impose a target on installed capacity for wind and solar, the generation share of the Solar-PV is found to be low despite its high share in the installed capacity because of its low capacity factor.
- Our main finding is that on extreme weather days in 2050 with hardly any wind and solar energy supply, about 2800 tonne waste biomass per day is required in the CAP scenario to back up the intermittent renewable electricity using urban waste. In the RES scenario 1300 tonne waste biomass per day is required. The average

daily waste biomass generated in the city of Amsterdam is about 1400 tonne [51]. This implies that import or storage of waste biomass is necessary for the CAP scenario. The demand for waste biomass in the RES scenario can be self-sufficient in the city.

- Analysis from the comparison of monthly demand and supply of bioenergy shows that the demand for the bioenergy back-up capacity in the CAP scenario is higher than that in the RES scenario due to the synergies of wind and solar energy in the RES scenario.

Our analysis has shown that the flexible bioenergy supply from the urban waste stream has a high potential in backing up intermittent renewable energy in cities. The methodological framework and analysis presented in this paper can support policy-makers in exploring the potential of bioenergy from urban waste streams in balancing the future sustainable urban electricity system and avoiding inconsistencies between urban bioenergy policy ambitions and local biomass availability.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.biombioe.2017.10.001>.

## References

- [1] UNFCCC, Adoption of the Paris Agreement, Report No. FCCC/CP/2015/L.9/Rev.1 (2015) <http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>.
- [2] U.N. Habitat, Cities and Climate Change: Global Report on Human Settlements, Earthscan, London, 2011.
- [3] A. Ramaswami, A. Chavez, J. Ewing-Thiel, K.E. Reeve, Two approaches to greenhouse gas emissions foot-printing at the city scale, *Environ. Sci. Technol.* 45 (10) (2011) 4205–4206.
- [4] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: approaches, challenges and opportunities, *Renew. Sustain. Energy Rev.* 16 (6) (2012) 3847–3866.
- [5] H. Kondziella, T. Bruckner, Flexibility requirements of renewable energy based electricity systems—a review of research results and methodologies, *Renew. Sustain. Energy Rev.* 53 (2016) 10–22.
- [6] J. Fargione, J. Hill, D. Tilman, S. Polasky, P. Hawthorne, Land clearing and the biofuel carbon debt, *Science* 319 (5867) (2008) 1235–1238.
- [7] R. Kothari, V. Tyagi, A. Pathak, Waste-to-energy: a way from renewable energy



- sources to sustainable development, *Renew. Sustain. Energy Rev.* 14 (9) (2010) 3164–3170.
- [8] M. Kranert, R. Gottschall, C. Bruns, G. Hafner, Energy or compost from green waste?—A CO<sub>2</sub>-based assessment, *Waste Manage* 30 (4) (2010) 697–701.
- [9] E. Özcan, M. Arentsen, Nonconformity of policy ambitions with biomass potentials in regional bioenergy transition: a Dutch example, *Energy Policy* 65 (2014) 212–222.
- [10] L. Staffas, M. Gustavsson, K. McCormick, Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches, *Sustainability* 5 (6) (2013) 2751–2769.
- [11] M.W. Rosegrant, S. Msangi, Consensus and contention in the food-versus-fuel debate, *Annu. Rev. Environ. Resour.* 39 (2014) 271–294.
- [12] T. Searchinger, R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Song, D. Hayes, T.-H. Yu, Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change, *Science* 319 (5867) (2008) 1238–1240.
- [13] D. Tilman, R. Socolow, J.A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville, R. Williams, Beneficial biofuels—the food, energy, and environment trilemma, *Science* 325 (5938) (2009) 270–271.
- [14] H. Haberl, T. Beringer, S.C. Bhattacharya, K.-H. Erb, M. Hoogwijk, The global technical potential of bio-energy in 2050 considering sustainability constraints, *Curr. Opin. Environ. Sustain.* 2 (5) (2010) 394–403.
- [15] M. Hoogwijk, A. Faaij, B. Eickhout, B. de Vries, W. Turkenburg, Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios, *Biomass Bioenergy* 29 (4) (2005) 225–257.
- [16] R. Offermann, T. Seidenberger, D. Thrän, M. Kaltschmitt, S. Zinoviev, S. Miertus, Assessment of global bioenergy potentials, *Mitig. Adapt. Strategies Glob. Change* 16 (1) (2011) 103–115.
- [17] E.M. Smeets, A.P. Faaij, I.M. Lewandowski, W.C. Turkenburg, A bottom-up assessment and review of global bio-energy potentials to 2050, *Prog. Energy Combust. Sci.* 33 (1) (2007) 56–106.
- [18] N.S. Bentsen, C. Felby, Biomass for energy in the European Union—A review of bioenergy resource assessments, *Biotechnol. Biofuels* 5 (1) (2012) 25.
- [19] L.P. Koh, H.T. Tan, N.S. Sodhi, Biofuels: waste not want not, *Science* 320 (5882) (2008) 1419.
- [20] N. Scarlat, J.-F. Dallemand, O.J. Skjelhaugen, D. Asplund, L. Nesheim, An overview of the biomass resource potential of Norway for bioenergy use, *Renew. Sustain. Energy Rev.* 15 (7) (2011) 3388–3398.
- [21] J.J. Roberts, A.M. Cassula, P.O. Prado, R.A. Dias, J.A.P. Balestieri, Assessment of dry residual biomass potential for use as alternative energy source in the party of General Pueyrredón, Argentina, *Renew. Sustain. Energy Rev.* 41 (2015) 568–583.
- [22] J. Cai, R. Liu, C. Deng, An assessment of biomass resources availability in Shanghai: 2005 analysis, *Renew. Sustain. Energy Rev.* 12 (7) (2008) 1997–2004.
- [23] D.W. MacFarlane, Potential availability of urban wood biomass in Michigan: implications for energy production, carbon sequestration and sustainable forest management in the USA, *Biomass Bioenergy* 33 (4) (2009) 628–634.
- [24] F. Kraxner, K. Aoki, G. Kindermann, S. Leduc, F. Albrecht, J. Liu, Y. Yamagata, Bioenergy and the city—what can urban forests contribute? *Appl. Energy* 165 (2016) 990–1003.
- [25] E. Smeets, M. Junginger, A. Faaij, A. Walter, P. Dolzan, W. Turkenburg, The sustainability of Brazilian ethanol—an assessment of the possibilities of certified production, *Biomass Bioenergy* 32 (8) (2008) 781–813.
- [26] E.M. Smeets, A.P. Faaij, The impact of sustainability criteria on the costs and potentials of bioenergy production—Applied for case studies in Brazil and Ukraine, *Biomass Bioenergy* 34 (3) (2010) 319–333.
- [27] G. Berndes, J. Hansson, Bioenergy expansion in the EU: cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels, *Energy Policy* 35 (12) (2007) 5965–5979.
- [28] S. Jablonski, N. Strachan, C. Brand, A. Bauen, The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergy scenarios, *Energy Policy* 38 (10) (2010) 5799–5816.
- [29] V. Krishnan, J.D. McCalley, The role of bio-renewables in national energy and transportation systems portfolio planning for low carbon economy, *Renew. Energy* 91 (2016) 207–223.
- [30] L.G. Fishbone, H. Abilock, Markal, a linear-programming model for energy systems: technical description of the bnl version, *Int. J. Energy Res.* 5 (4) (1981) 353–375.
- [31] T. Givler, P. Lilienthal, Using HOMER Software, NREL's Micropower Optimization Model, to Explore the Role of Gen-sets in Small Solar Power Systems; Case Study: Sri Lanka, Tech. rep. National Renewable Energy Lab., Golden, CO (US), 2005.
- [32] K. Karlsson, P. Meibom, Optimal investment paths for future renewable based energy systems - using the optimisation model balmorel, *Int. J. Hydrogen Energy* 33 (7) (2008) 1777–1787.
- [33] P. Nahmmacher, E. Schmid, B. Knopf, Documentation of LIMES-EU a Long-term Electricity System Model for Europe, Potsdam Institute of Climate Impact Research (PIK), 2014, <https://www.pik-potsdam.de/members/paulnah/limes-eu-documentation-2014.pdf>.
- [34] Municipality of Amsterdam, Sustainable Amsterdam-Agenda for Renewable Energy, Clear Air, a Circular Economy and a Climate-resilient City, (2015) <https://www.amsterdam.nl/bestuur-organisatie/organisatie/ruimte-economie/ruimte-duurzaamheid/making-amsterdam/sustainability/>.
- [35] CBS, Population dynamics; birth, death and migration per region, (2015) <http://statline.cbs.nl>.
- [36] D. Thrän, Smart Bioenergy: Technologies and Concepts for a More Flexible Bioenergy Provision in Future Energy Systems, Springer, Leipzig, 2015.
- [37] Q. Sun, H. Li, J. Yan, L. Liu, Z. Yu, X. Yu, Selection of appropriate biogas upgrading technology—a review of biogas cleaning, upgrading and utilisation, *Renew. Sustain. Energy Rev.* 51 (2015) 521–532.
- [38] International Renewable Energy Agency, Renewable Power Generation Costs in 2014, (2015) <http://www.irena.org/menu/index.aspx?mnu=Subcat&PrMenuID=36&CatID=141&SubcatID=494>.
- [39] L.A. Hadidi, M.M. Omer, A financial feasibility model of gasification and anaerobic digestion waste-to-energy (WTE) plants in Saudi Arabia, *Waste Manage. Oxf.* 59 (2017) 90–101.
- [40] J. de Bruijn, Domestic Waste in Amsterdam, (2014) <http://www.municipalwasteurope.eu/sites/default/files/Benchmarking%20big%20cities%20-%20Amsterdam.pdf>.
- [41] ECN, Phyllis 2-Database for Biomass and Waste, (2016) <https://www.ecn.nl/phyllis2/>.
- [42] P. Tafarte, S. Das, M. Eichhorn, M. Dotzauer, D. Thrän, The potential of flexible power generation from biomass: a case study for a German region, *Smart Bioenergy*, Springer, Leipzig, 2015, pp. 141–159.
- [43] CBS, Population Growth Rate Major Cities above Average, (2011) <https://www.cbs.nl/en-gb/news/2011/28/population-growth-rate-major-cities-above-average>.
- [44] K. Gillingham, D. Rapson, G. Wagner, The rebound effect and energy efficiency policy, *Rev. Environ. Econ. Policy* 10 (1) (2016) 68–88.
- [45] EC, A Roadmap for Moving to a Competitive Low Carbon Economy in 2050, European Commission, Brussels, 2011 <http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0112>.
- [46] PBL, Monitoring Climate Targets in the Netherlands, (2014) <http://pubdocs.worldbank.org/en/123941484255893633/pbl-monitoring-climate-targets-netherlands.pdf>.
- [47] N.V. Nuon, Nuon Energy Annual Report 2014-Towards Sustainable and Flexible Energy, (2014) <https://www.nuon.com/globalassets/nederland/bedrijf/publicaties/nuon-annual-report-2014.pdf>.
- [48] M. Haller, S. Ludig, N. Bauer, Decarbonization scenarios for the EU and MENA power system: considering spatial distribution and short term dynamics of renewable generation, *Energy Policy* 47 (2012) 282–290.
- [49] KNMI, Hourly Data of the Weather in the Netherlands, (2016) <http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi>.
- [50] M. Götz, J. Lefebvre, F. Mörs, A.M. Koch, F. Graf, S. Bajohr, R. Reimert, T. Kolb, Renewable Power-to-Gas: a technological and economic review, *Renew. Energy* 85 (2016) 1371–1390.
- [51] M. Spiller, S. Stremke, URBAN PULSE: Understanding the Dynamics of Resource Flows in Amsterdam, (2015) <https://www.wur.nl/en/project/Urban-Pulse.htm>.
- [52] A.A. Prasad, R.A. Taylor, M. Kay, Assessment of solar and wind resource synergy in Australia, *Appl. Energy* 190 (2017) 354–367.
- [53] A.S. Brouwer, M. van den Broek, A. Seebregts, A. Faaij, Operational flexibility and economics of power plants in future low-carbon power systems, *Appl. Energy* 156 (2015) 107–128.
- [54] C. Kost, J.N. Mayer, J. Thomsen, N. Hartmann, C. Senkpiel, S. Philipps, S. Nold, S. Lude, N. Saad, T. Schlegl, Levelized Cost of Electricity Renewable Energy Technologies, Fraunhofer Institute for Solar Energy Systems ISE, 2013.
- [55] IEA/NEA, Projected Costs of Generating Electricity, International Energy Agency (IEA) and Nuclear Energy Agency (NEA), Paris, France, 2015.
- [56] IRENA, Renewable Power Generation Costs in 2014, International Renewable Energy Agency, Abu Dhabi, 2015.
- [57] N.B.D. Thi, C.-Y. Lin, G. Kumar, Electricity generation comparison of food waste-based bioenergy with wind and solar powers: a mini review, *Sustain. Environ. Res.* 26 (5) (2016) 197–202.
- [58] M. Lauer, D. Thrän, Biogas plants and surplus generation: cost driver or reducer in the future German electricity system? *Energy Policy* 109 (2017) 324–336.
- [59] R. Zhang, H.M. El-Mashad, K. Hartman, F. Wang, G. Liu, C. Choate, P. Gamble, Characterization of food waste as feedstock for anaerobic digestion, *Bioresour. Technol.* 98 (4) (2007) 929–935.
- [60] H. Balcazar, C.M. Fougret, K.P. Geigle, S. Gust, E. Hagen, A. Lappas, K. Lenz, J. Maier, E. Papadopoulou, R. Parton, Biomass based energy intermediates boosting biofuel production-bioboost, Proceedings of 21st European Biomass Conference, 2013.
- [61] J. Ariunbaatar, A. Panico, G. Esposito, F. Pirozzi, P.N. Lens, Pretreatment methods to enhance anaerobic digestion of organic solid waste, *Appl. Energy* 123 (2014) 143–156.
- [62] N. Szarka, F. Scholwin, M. Trommler, H.F. Jacobi, M. Eichhorn, A. Ortwein, D. Thrän, A novel role for bioenergy: a flexible, demand-oriented power supply, *Energy* 61 (2013) 18–26.
- [63] M. Lauer, M. Dotzauer, C. Hennig, M. Lehmann, E. Nebel, J. Postel, N. Szarka, D. Thrän, Flexible power generation scenarios for biogas plants operated in Germany: impacts on economic viability and GHG emissions, *Int. J. Energy Res.* 41 (1) (2017) 63–80.
- [64] M. Mazzanti, Is waste generation de-linking from economic growth? Empirical evidence for Europe, *Appl. Econ. Lett.* 15 (4) (2008) 287–291.
- [65] F. Monteverchi, Policy mixes to achieve absolute decoupling: a case study of municipal waste management, *Sustainability* 8 (5) (2016) 442.