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Exploring bioenergy potentials of built-up areas based on NEG-EROEI indicators

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ABSTRACT

The production of bioenergy is dependent on the supply of biomass. Biomass production for bioenergy may cause large land use conversions, impact agricultural production, food prices, forest conservation, etc. The best solution is to use biomass that does not have agricultural or ecological value. Some of such unconventional sources of biomass are found within urban spaces. We employed Geographic Information System (GIS) and quantitative Life Cycle Assessment (LCA) methodologies to identify and estimate bioenergy potential of green roofs and other bioenergy options within urban areas. Net Energy Gain (NEG) and Energy Return on Energy Invested (EROEI) were used as indicators to assess the bioenergy potential of urban spaces within the Overijssel province of the Netherlands as a case study. Data regarding suitable areas were geometrically extracted from available GIS datasets, and used to estimate the biomass/bioenergy potential of different species with different yields per hectare, growing under different environmental conditions. We found that potential net-energy gain from built-up areas can meet 0.6–7.7% of the 2030 renewable energy targets of the province without conflicting with socio-ecological concerns, while also improving human habitat.

1. Introduction

The search for and discovery of renewable energy sources has increasingly gained momentum since the turn of the 21st century. This can be attributed to humanity's race against time, in its bid to slow down global warming effects, through meeting of emission reduction targets and other climate change obligations (Firrisa et al., 2014; Voinov and Filatova, 2014). Globally speaking, bioenergy is by far the most widely used renewable energy source, supplying about 10% of the world's primary energy consumption (IEA, 2013). It accounts for nearly 80% of the yearly global renewable energy production (Climate Consortium Denmark, 2011). In theory, assuming that no energy from fossil fuel is used in its production process (which is usually not the case in reality but technically possible), bioenergy can be referred to as a CO_2-neutral energy source; this is because the amount of CO_2 absorbed during photosynthesis equals the amount emitted when biomass is converted to energy (McKendry, 2002). Certainly, the continuous use of biomass, especially from forest floors, grasslands, croplands etc. for bioenergy may lead to the decline in valuable storages of soil organic carbon (Lippke et al., 2011; Holtsmark, 2012). This may lead to an annual change in carbon stocks, and the lengthening of environmental payback time of bioenergy; with carbon emissions taking longer to approach zero before becoming carbon negative (i.e. a change from carbon emissions to removal) as the ecological system establishes a new dynamic equilibrium (Sathre and Gustavsson, 2011; Böttcher et al., 2012). However, carbon is lost from soils anyway due to natural decomposition and recycling of waste materials from bioenergy production (e.g. the use of digestates from biogas produced from wastes as fertilizers) may help reduce carbon loss from soils (Arodudu et al., 2013; Hudiburg et al., 2011). Therefore we can still think of bioenergy as a major contributor to meeting emission reduction targets, and as a source of renewable energy that is a direct replacement of cheap oil (Dincer, 1999; McKendry, 2002; Read and Lermit, 2005; Zanchi et al., 2012). Despite the speculated high potentials of bioenergy for meeting future energy demands and climate change obligations, global concerns regarding its socio-environmental consequences

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remain dubious for sustainability scientists and policymakers around the world (de Fraiture et al., 2008; McLaughlin and Walsh, 1998; Muller et al., 2008; Lovett et al., 2011).

The European Union (EU) contributed about 24.3% (3326 MT out of 21,400 MT) of the 1990 global CO_2 emissions (Oberthür and Ott, 1999). As a major player in global policy making, and one of the world's worst polluters, the EU accepted responsibilities under the Kyoto emission reduction protocol treaty aimed at slowing global warming effects, by pledging a mandatory 30% reduction of its 1990 CO_2 emissions by the year 2020, and placing economic transition towards renewable energies on its political agenda (European Commission, 2009; Rosende et al., 2010). In line with achieving these objectives, the EU set mandatory renewable energy targets for all its member countries, specifically a minimum of 20% of its overall energy needs, and 10% of its total transport fuel needs from renewable energy sources by the year 2020 (European Commission, 2010). In order to meet its renewable energy targets, Netherlands as an EU Member state reviewed its renewable energy directive in 2007 based on present realities at that time. This was because, although consumption of renewable energy in the transport sector grew rapidly from 0.3% in 2006 to about 2% by the year 2007 (Rosende et al., 2010); the Netherlands national share of energy from renewable sources only grew from 2.4% in 2005 to 4% in 2010. Going by this statistics, meeting the 2020 renewable targets for the Netherlands would have been quite elusive, this forced the Government to set a new minimum target of 14% total energy from renewable sources by the year 2020 (54.5% of it from biomass sources) (European Commission, 2010; IEEP, 2010).

Despite widespread optimism and speculations on the potential role of biomass in meeting renewable energy targets globally, there are still conflicts and controversies ranging from indiscriminate land cover/use change to effects on food prices and social equity (Dale and Beyeler, 2001; Clarke and Lawn, 2008; Lovett et al., 2011; McBride et al., 2011; Bagstad and Shammin, 2012). However, the socio-ecological burdens constituted by these constraints become quite passive and harmless if bioenergy is produced from by-products, or harvested in areas that are of least ecological value or agricultural importance (Dale et al., 2013; Arodudu et al., 2013). Such sources may include: crop residues, algae, animal waste, domestic and commercial organic waste (food, fruits and vegetables), as well as biomass produced in urban or residential settings (Kapdan and Kargi, 2006; Murphy and Power, 2008; Shilton et al., 2008; University of York, 2011).

In this paper, we focused on available and prospective (unconventional) sources of biomass, whose exploitation do not conflict with the socio-ecological functions of urban landscapes. Prospective or unconventional sources of biomass are those sources that are not associated with biomass production conventionally, while available sources are those already harnessed for bioenergy production. The sources we considered in the course of this study included: rooftops, construction sites, recreational parks, seasonal leaf-fall, garden wastes and domestic organic wastes (e.g. food, vegetable, fruit wastes etc.). Aside energy production, there are many other socio-economic and environmental benefits of producing biomass within human dominated urban spaces and ecosystems, which makes it even more attractive and desireable. Examples of such socio-economic and environmental benefits include: enhancement of biodiversity by serving as habitats for birds, bees, reptiles, insects etc.; more efficient management/use of urban waste; urban flood prevention through reduction of runoffs; reduction of medication costs through improvement of air quality and human health; saving energy costs for cooling and/or heating by reducing urban heat island effects and regulating the urban climate; reduction of urban greenhouse effects through carbon sequestration functions; minimization of urban fire disasters and sometimes for aesthetic purposes (ACC, 2010; ARDEX TPO Membranes, 2009; CFFA, 2001; Peck and Kuhn, 2003; Safeguard Europe Limited, 2010).

Although urban spaces ocuppy a very small portion of the total Earth's land surface (about 3%), it remains the most populated human dominated ecosystem (houses over 50% of human beings on planet Earth), and therefore has disproportionate effects on the global environment (Millennium Ecosystem Assessment, 2005). Despite its small size in comparison to other human dominated ecosystems (e.g. arable land, managed forestlands etc.), it harbours most biomass flow activities, and uses most of the biomass produced on the Earth's land surface (Seto et al., 2011). Consequently, the search for renewable energy (especially biomass sources) should not be restricted to the remaining 97% amendable human dominated and natural ecosystems alone, but also to the less amendable, 3% urban spaces that account for more than 50% of the world's economic activities and biomass flows (Chalmin and Gaillochet, 2009). Since global population and urbanization trends is projected to continue to rise unabatedly, exploring biomass flows within urban ecosystems has the potentials to contribute significantly to future global renewable energy and carbon emission reduction targets if properly harnessed (IEA, 2013).

In this age of transition from fossil fuel to renewables, there is need to bear in mind the fact that producing bioenergy also requires energy, which at present is mostly available in form of fossil fuel. Estimation of bioenergy potentials and consequent decision making regarding the feasibility and viability of exploiting bioenergy sources ought to factor in energy used in the process of growing, collecting, drying, fermenting, and converting biomass into energy. In order to take all that into account it is improtant to use the appropriate indicators (Clarke and Lawn, 2008; Bagstad and Shammin, 2012). Within the context of assessment and comparison of bioenergy potential of different bioenergy options within built-up spaces and its significance for set renewable energy targets, we employed a combination of Geographic Information System (GIS) and quantitative Life Cycle Assessment (LCA) methodologies. The bioenergy potential of different biomass sources within urban spaces were assessed using two indicators: Net Energy Gain (NEG) and Energy Return on Energy Invested (EROEI). NEG on the one hand is an indicator of the actual amount of energy added by a particular biomass source to the set renewable energy targets, while EROEI on the other hand analyzes the energy efficiency (i.e. energy gained per unit energy invested) of exploiting a particular biomass source for bioenergy production (Berglund and Borjesson, 2006; Correia et al., 2010).

Specifically, we compared rooftop biomass production with rooftop solar photovoltaic panels because of their rise in popularity, and anticipated competition between them (as alternative rooftop renewable energy technologies) in the emerging green era (Municipality of Enschede, 2010). The comparison was done in terms of their energy potentials (using NEG and EROEI) and considering the environmental benefits. The case study area chosen for this research was the Overijssel province of the Netherlands (Fig. 1). The Netherlands because it is one of the most urbanized countries in the world, and the Overijssel province because it can be considered as a model of the whole country, since the mix of its land use types is close to what is estimated for the country as a whole (built-up – 10% in Overijssel vs. 14% in NL, agriculture – 79.8% vs. 74.3%, and forest – 10.2% vs. 12.1%) (CORINE, 2006). This makes the outcome of this study inferable for the whole country. In line with the new minimum target set by the Government of the Netherlands, in order to meet its EU Kyoto Protocol renewable energy obligations, the role of biomass in Overijssel Province's energy-mix as extrapolated from PGG's (Platform Groene Grondstoffen) estimate by the year 2030 is expected to rise to 60 PJ (Rabou et al., 2008). This study

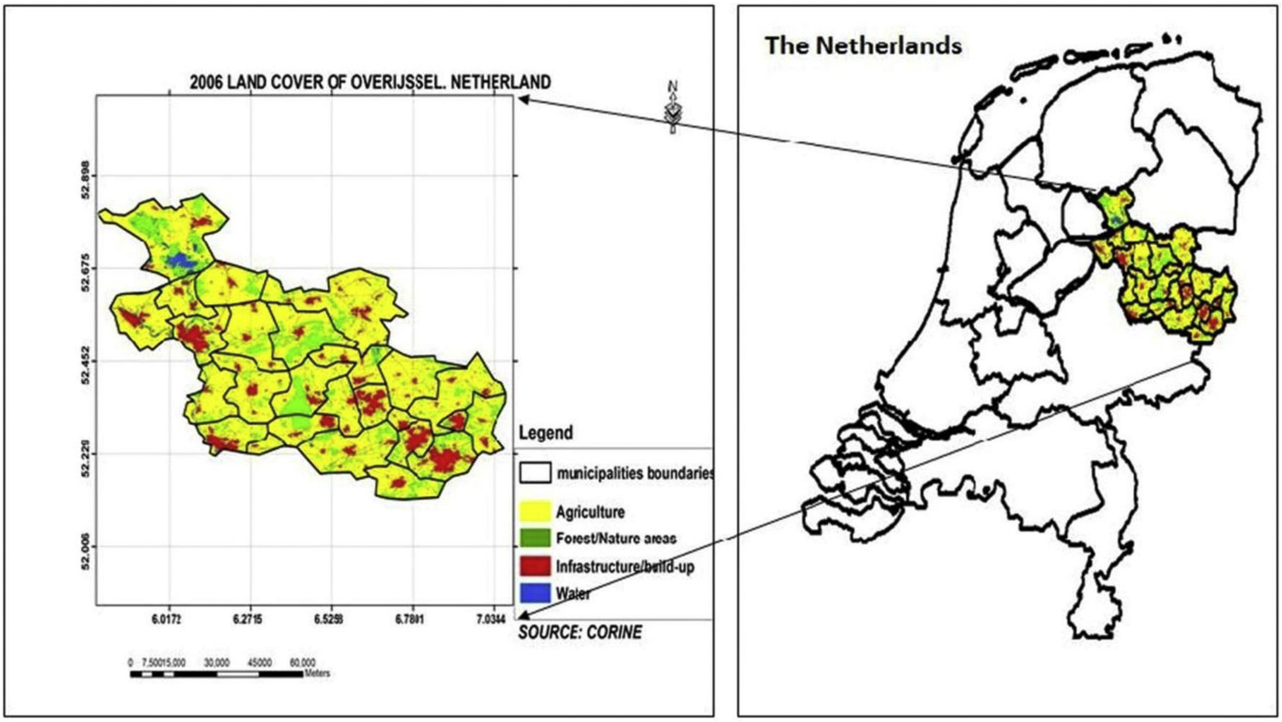


Fig. 1. Location and the municipality boundaries of the study area (Overijssel province) as part of the Netherlands.

Source: CORINE (2006).

will therefore attempt to compare the overall obtainable NEG from the different urban biomass sources it considered to the set share of biomass in future renewable energy targets.

2. Methodology

The methodological framework adopted by this study combined GIS with quantitative LCA analysis. These two methodological approaches were combined for the estimation of the bioenergy potential of different prospective and available biomass options within urban ecosystems using the Overijssel Province of the Netherlands as a case study.

In order to estimate the NEG and EROEI of different biomass sources within the urban environment, this study conducted an LCA (Life Cycle Assessment). This involved an inventory (stock-taking) of the energies, materials and processes associated with exploiting the different urban biomass sources for bioenergy production, from their cradle to their grave, i.e. across the full production chain.

As part of the LCA inventory, the spatial dimensions of the some urban biomass sources were captured from various remote sensing and GIS datasets, namely CORINE (2006) and Google Earth map, 2011 (both covering the entire Overijssel Province) as described in Sections 2.1 and 2.2. Data regarding point biomass sources (e.g. domestic organic wastes) were obtained from the Central Bureau of Statistics (CBS) database. Conversion factors for the estimation of the biomass potentials of the different urban biomass sources and their respective embodied energies were obtained from various literature sources as documented in Sections 2.3 and 2.4. The data collected above were used in calculating the total energy inputs to be invested into exploiting the different urban biomass sources, and the total energy output obtainable from them. The values of the two indicators for measuring bioenergy potential (NEG and EROEI) as proposed by this study were then estimated using the values of total input and output energies for the different urban biomass sources considered.

Equations representing these two indicators are as follows:

$$\text{NEG} = \text{output energy} - \text{input energy}$$

$$\text{EROEI} = \frac{\text{output energy}}{\text{input energy}}$$

EROEI is a measure of the energy efficiency as well as the capacity of a biomass/bioenergy production activity to support continuous socio-economic activity in the face of externalities such as soil degradation, water pollution, biodiversity impacts, price fluctuations etc. Using NEG and EROEI indicators together further adds scientific rigour to the analysis of bioenergy potential by assessing how much a particular activity will add to set renewable energy targets (Hall et al., 2009).

While NEG of biomass/bioenergy production activities is assessed in terms of their contribution to set renewable energy targets, for EROEI, the factor of 3 is considered as indicative. An energy production activity or a source with EROEI values of 3 and above (i.e. final energy output is at least three times more than the initial energy invested) is generally considered as stable and sustainable in the face of externalities that are hard to quantify in purely energy terms e.g. soil degradation, water pollution, biodiversity impacts, price fluctuations etc. (Hall et al., 2009). Otherwise, production of energy with EROEI < 3 is likely to be unsustainable, damaging for the ecosystems in the long run and therefore should be avoided.

The five major steps involved in the implementation of this methodological framework are however discussed in the following sections.

2.1. Locating prospective and available biomass sources within the urban space

The first major step in the implementation of this study involved an inquiry into prospective and available biomass sources within the urban settings of the study area. A cursory look at available GIS based land cover/use datasets, and an extensive field study which involved walking and biking around, as well as consultation

Table 1
An overview of the criteria and assumptions used for the biomass estimations.

Source	Species	Yield	References	Criteria and assumptions
Green roof	*Festuca gautieri* *Bouteloua gracilis* *Carex nigra* *Rudbeckia fulgida* *Schizachyrium scoparius*	2.6–5.4 tonnes/ha	Tewari et al. (2008)	All large buildings (public/commercial) were included in the biomass estimation, since most of them are flat or less than 30° in inclination, and therefore suitable as green roofs.30% of residential roofs were assumed to be flat or have roof slopes below 30°, and therefore included in the biomass estimations together with large buildings. The estimated yield of 2.6 tonnes/ha and 5.4 tonnes/ha was used for biomass estimation
Recreational areas	*Trifolium repens* (white clover grass)	10 tonnes/ha	Davis et al. (1999); Smyth et al. (2009)	Perennials grass species that can grow under trees in recreational parks
	Dactylis glomerata (cocksfoot grass)	10 tonnes/ha		Due to presence of trees within the parks which may obstruct 12 tonnes/ha yields an estimated 10 tonnes/ha was used for biomass estimations. Based on the observation that some parts of that layer are grasses and road verges, only 50% of the total area was considered in the biomass estimations
Construction sites	*Phleum pretence* (Timothy grass) *Lolium perenne* (perennial Ryegrass)	12 tonnes/ha	McKendry (2002); Smyth et al. (2009)	All the calculated areas were included to obtain as much details as possible from the coarse resolution of the data used
Domestic waste	Food waste (GFT)	97.7 kg per capita (0.1 tonnes per capita)	Central Bureau of Statistics (2011)	All organic domestic waste collected within the province are used for bioenergy
	Bulky garden waste	24.9 kg per capita (0.03 tonnes per capita)		
	Wood waste	16 kg per capita (0.02 tonnes per capita)		
Seasonal leaf-fall		1.3 tonne/tree annually	Rowntree and Nowak (1991)	Deciduous trees shed their entire leafs between autumn to winter annually

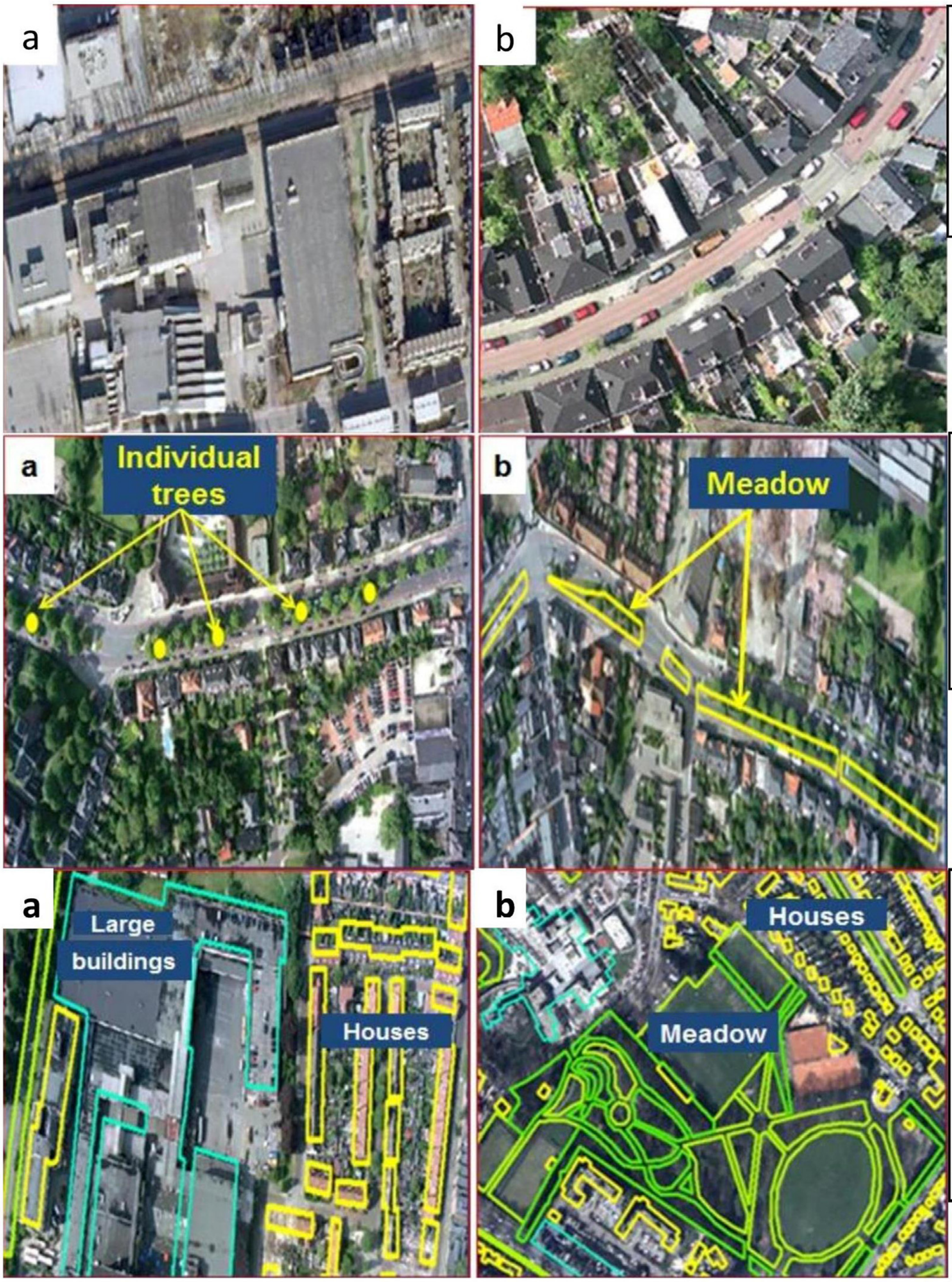
with relevant authorities within the province was done. Relevant authorities (stakeholders) with respect to bioenergy issues within the province included municipality council officials, waste management agency officials, responsible staffs of the provincial government, BE (Bioenergy for Overijssel) 2.O Researchers etc. The sustainability of these urban biomass sources against relevant criteria was also examined (Table 1).

The following were identified as prospective biomass sources within the urban built-ups of the study area: roof tops, recreational parks, deciduous trees (seasonal leaf-fall) and vacant construction sites (Table 1). Information regarding areas or features of interest was extracted from GIS layers using the extract function of the ArcGIS 12 software. Information regarding roof tops, recreational parks and seasonal leaf-fall from deciduous trees were extracted from the highly detailed Top 10 vector map of the Netherlands (1–10 m); while information regarding construction sites were extracted from a relatively coarser CORINE Land cover map of the Netherlands (100 m × 100 m) (CORINE, 2006). All the extracted layers were converted to Keyhole Mark-up Language (KML) data format, and over-laid on the Google Earth for visual analysis and cross-validation of the dimensions of the urban features under investigation. The features of interest on the Top 10 vector map were sufficiently cross-validated using several samples taken from the Google Earth map of the province. Estimates of the area available for biomass production from prospective sources (e.g. roof tops, recreational parks and vacant construction sites) were then extracted for the entire province. It was also observed that most of the small residential buildings have steep roofs (greater than 30° in inclination) that are quite unsuitable for biomass production, while the large buildings have flat roofs which are potentially more suitable for biomass production (flat or less than 30° in inclination). Also, it should be noted that estimates for recreational areas included vegetation planted at the verges of roads. Find below screenshots of GIS operations performed to extract information on prospective urban biomass sources (Fig. 2).

Also included in this assessment are other available sources within the urban built-up space; they include bulky garden wastes, wood wastes, and the so-called GFTs (Groente (vegetables), Fruit (fruits) en Tuinafval (garden)-wastes. Information regarding the biomass available from these sources was obtained from the Central Bureau of Statistics (CBS, 2011).

2.2. *Estimating prospective areas available for biomass production*

The second major step after identifying prospective and available biomass sources was to estimate the area coverage of three out of the four prospective sources (roof tops, recreational parks and vacant construction sites), and calculate the corresponding proportion that can be made available for biomass production, based on information obtained from stakeholders during the field survey. A new field was created in the database view of the extracted GIS data layers for construction sites, buildings and recreational areas, in order to calculate the estimated prospective areas for biomass production in hectares. This was done using the calculate geometry function of the ArcGIS 12 software. However, the fourth prospective biomass source (seasonal leaf-fall from deciduous trees) was not measurable in areas, but only recordable individually as numbers of trees.



A google orthomap showing the aerial view of rooftops of large commercial buildings, residential houses and meadows in parts of the study area.

Layers of individual trees and meadow extracted from Top 10 vector maps overlaid on a google orthomap of parts of the study area during the cross validation exercise.

Layers of large commercial buildings, residential houses and meadow (within recreational parks) extracted from Top 10 vector maps overlaid on a google orthomap of parts of the study area during the cross validation exercise.

Fig. 2. Screenshots of GIS operations performed to extract information on prospective urban biomass sources.

2.3. Estimating the biomass potentials of the different biomass sources

After estimation of the area coverage/counting of the different prospective biomass sources (as applicable), the next step within the framework of this study was the estimation of the biomass potential of all the different urban biomass sources already identified. Estimations of the biomass potential of green roofs, recreational areas and construction sites were based on certain assumptions about the species to be grown and their yields (Table 1). The criteria for selecting the biomass to be grown included: high production yield, nativity/climatic adaptations of plants, reseeding of plants, and in some case their perennial nature or aesthetic values (where important e.g. for green roofs). The biomass potentials were calculated as products of the potential tonnes/ha yield of the respective species and the estimated available area for growing them in hectares.

The waste collection data obtained from the CBS expressed biomass wastes in kilograms (kg) per capita per year for all municipalities in Overijssel. Therefore, to calculate the total annual biomass potential from waste, the population of each municipality was multiplied by their per capita waste flows and added up to get the sum total for the whole province. The amount of biomass potentially available from waste (in kg) was however converted to tonnes to ensure uniformity and give room for comparison in the final analysis.

Based on the available data, we identified 4967 individual deciduous trees within the built-up areas in Overijssel, although during visual analysis and cross validation of the data layer using Google Earth information, this was observed to be highly under-estimated.

The final estimation is however considered to still be a fair estimate because of the possibility of counting of less, leaf-shedding soft trees with deciduous trees. According to Rowntree and Nowak (1991) a mature deciduous tree can produce biomass of as much as 1.3 tonnes of dry matter per year. This was multiplied by the number of trees in the built-up areas of Overijssel to obtain the biomass potential of seasonal fall from deciduous trees. This was done based on the assumption that they shed their entire leaf canopy annually.

2.4. Estimating input and output energies

The next step after the estimation of the biomass potential of the different urban biomass sources is to calculate the total input and output energies involved in their separate production chains. The potential input and output energies are used to obtain the NEG and EROEI values, which are both measures of the bioenergy potential of different biomass sources. This study estimated the total energy inputs used to produce bioenergy from the identified urban sources. Essential input energies required for the production of green roof biomass include:

- *Energy for construction and installation of green roof layers*: Previous life cycle analysis of roofs indicates that green roofs cost the same or even less than conventional roofs (Peck and Kuhn, 2003). Based on that assumption the least energy required to install a normal roof (ferro-concrete) was used to estimate the energy required per square metre of the green roof membrane (Reddy and Jagadish, 2003).
- *Energy for seedlings*: This is the energy required to produce grass seedlings for green roof biomass production (Smyth et al., 2009).
- *Fertilization*: Extensive green roofs require little fertilization every 6–12 months after installation with little necessity for watering; while the intensive green roofs require regular maintenance (Great lakes water institute, 2011). However, some fertilization is required for green roofs and this is done with controlled-release fertilizers in order to avoid polluting storm water (Emilsson et al., 2007). The approximated nutrient requirement of vegetated roofs is 5 g/m^2 and with substrate that does not contain too much nutrients (Landschaftsbau.e.v, 2009).
- *Harvest*: The assumed method of harvesting was mowing for flat roofs and manual harvesting using high lifts for steeper roofs. We used energy requirements for mowing similar to those on land though this is probably an underestimation (Down and Hansen, 2001).
- *Transportation of cultivation materials*: This was the energy required to transport fertilizers, seeds and other materials to the production sites (Correia et al., 2010).
- *Transportation of biomass*: The harvested biomass has to be transported to the digesters in order to be converted to energy. There are 21 digesters scattered around the province and a buffer analysis was performed to generate the suitable maximal, minimal and average distances to digesters. An estimated energy of 0.0002 GJ/tonne/km (Smyth et al., 2009) and the average distance to digesters was used to calculate the energy for the transportation of biomass from all potential production areas to digesters.
- *Biomass conversion*: The energy required for the conversion process depends on the method of conversion (Haq, 2001). Well-developed methods of conversion include gasification, pyrolysis, anaerobic digestion, or modular processes. Anaerobic co-digestion was however chosen as the conversion technology for this study, because of it can convert all the biomass types considered under this study (e.g. leafs, fruits, grasses, vegetables, food wastes, sewage etc.), while also providing a common reference system for all the biomass sources been compared (Uellendahl et al., 2008).

According to Table 1, since the potential annual yields of green roof biomass is between 2.6 and 5.4 tonnes/ha (Tewari et al., 2008), its corresponding energy output will therefore be between 3.1 MJ/m^2 and 6.2 MJ/m^2 (Smyth et al., 2009). The installation energy for green roofs, which is a one-time investment up-front was divided over the expected lifetime (LT) of the roof to make all estimates correspond to annual rates. Consequently, the input energy for green roofs can be calculated as follows:

$$
\begin{aligned}
&\text{Input energy for green roofs} = \text{energy for production of biomass}\\
&\quad + \text{conversion energy} = \frac{\text{Energy for installation membrane}}{\text{LT(Lifetime)}}\\
&\quad + \text{Energy for fertilization}\\
&\quad + \text{Energy for harvest}\\
&\quad + \text{Energy for transportation of biomass}\\
&\quad + \text{Energy for transportation of other inputs)}\\
&\quad + \text{Energy of conversion of biomass to energy}
\end{aligned}
$$

$$\text{While Output energy} = \text{the Energy produced}$$

The only input energies involved in biomass production from domestic organic waste and seasonal leaf-fall are the energies required to transport wastes from collection points to digesters and the energies for conversion of wastes to bioenergy (Uellendahl et al., 2008; Smyth et al., 2009). Input energy estimates were calculated based on coefficients reported by EUBIA (2011). The output energy per tonne of domestic organic waste and seasonal leaf-fall were estimated based on coefficients obtained from ETSU-Harwell Laboratory (1997) and EUBIA (2011).

Instead of calculating the input and output energies of biomass produced from vacant construction sites and recreational areas before getting their corresponding NEGs and EROEIs, their NEGs and EROEIs were estimated using coefficients from similar NEG and EROEI calculations done previously (Davis et al., 1999; Smyth et al., 2009). This is explained in the next Section 2.5. The NEGs where expressed in form of NEG/ha, NEG/tonne, NEG/m^2 or NEG/y (annually) for biomass produced within certain area or space (e.g. green roofs, vacant construction sites, recreational spaces etc.), and NEG/tonne or NEG/y for point-source biomass (e.g. domestic organic waste, seasonal leaf-fall etc.).

2.5. Calculating the bioenergy potential indicators (NEG and EROEI)

After estimating the input and output energies of the different urban biomass sources, the final step is to calculate their respective NEGs and EROEIs, analyze them with respect to set bioenergy/renewable energy targets, as well as compare them with other equally competitive renewable energy sources.

Unlike other urban biomass sources under this study, whose NEGs and EROEIs were estimated using results of input and output energies estimated by the study (green roofs, domestic organic wastes and seasonal leaf-fall from deciduous trees); the NEGs and EROEIs of biomass produced from vacant construction sites and recreational areas was calculated using coefficients from previous studies (Davis et al., 1999; McKendry, 2002; Smyth et al., 2009). The input energy and net-energy estimates of Smyth et al. (2009) were used for production within construction sites with the assumption that the same grasses (Timothy grass and Ryegrass) will be grown and all digestate produced from biomass will be utilized as fertilizers. All necessary input energy was considered, including field preparations, sowing, harrowing, rolling, fertilization, application of herbicides and lime, forage harvesting, silage transport, ensiling, digestate processing and biomass conversion.

The net-energy estimates of Smyth et al. (2009) were also used to estimate biomass production in recreational areas, assuming that cocksfoot grass (*Dactylis glomerata*) and white clover grass (*Trifolium repens*) will be grown and all digestate produced from biomass conversion will also be re-utilized for fertilization in the production (Smyth et al., 2009). According to Davis et al. (1999), the presence of trees in the parks inhibits grass growth and yield by 85%. It was therefore assumed that absorption of the different energy inputs and the final energy output from the grass yield will be 85% lower than the average estimates; this corresponds to an energy input and output of 38 GJ/ha and 104 GJ/ha annually.

In order to compare the energy production potential of rooftop biomass with rooftop solar PVs, the EROEI and NEG of rooftop solar PVs in the study area (Netherlands) was calculated based on estimates from Alsema and Nieuwlaar (2000) (energy production potential of 1700 kWh/m^2 i.e. 6120 MJ/m^2, payback time of 2 years and a life span of 30 years), and also compared to similar studies by Espinosa et al. (2011).

3. Results and discussion

3.1. Green roofs

Results obtained from this study indicated that up to 98.6% (102,561 ha) of the calculated building areas were small individual residential buildings, and only 1.4% were large public/commercial buildings (1493.1 ha). However, despite the spaces available from the residential buildings, visual analysis reveals that most of these buildings (especially small buildings) have steep roofs, which are not suitable for biomass cultivation. Green roofs require roofs with slopes below 30° in order to minimize potential risk of roof erosion (Mentens et al., 2003). If only large buildings were used for cultivation of rooftop biomass, the provincial biomass potential at 5.4 tonnes/ha yield (maximum) will be 8063 tonnes/y. However, if 30% of the small residential buildings are added to the large buildings, a biomass potential of 129,046 tonnes per annum becomes achievable (Table 2).

Calculated NEG was negative (−2.5 MJ/m^2) for rooftop biomass whose annual yield was 2.6 tonnes/ha, and only marginal (0.6 MJ/m^2) at a maximum annual yield of 5.4 tonnes/ha. This low NEG can be attributed to the exceptionally high requirements of input energy/m^2 of green roofs (Table 3). This low NEG corresponds to an EROEI of 0.6 and 1.1 for annual yields of 2.6 and 5.4 tonnes/ha, respectively. If all large buildings and 30% of the small residential buildings in Overijssel were used as green roof, the maximum achievable bioenergy potential (under maximum attainable annual yield of 5.4 tonnes/ha) is 183.7 TJ/y (Table 2).

The largest untapped potential of bioenergy production within built-up areas in Overijssel in terms of areas and total biomass productions are the roof tops, but they have an EROEI of 0.8–1.1, if we account for the energy costs of roof installation. Recall that EROEI below 1 makes a project thermodynamically meaningless, and when EROEI is less than 3 there are large concerns about its overall environmental sustainability. Retrofitting existing roofs also incurs extra input energies because repairs and reinforcement are required before planting of the roof grasses, and those can be even more expensive than new construction.

However there are many direct and indirect socio-economic and environmental benefits associated with green roofs, both to the building owners and the community at large (Taha, 1997; CFFA, 2001; Santamouris, 2001; Arnfield, 2003; Peck and Kuhn, 2003; Alexandri and Jones, 2004, 2005; ARDEX TPO Membranes, 2009; ACC, 2010; Safeguard Europe Limited, 2010). These include:

- Generating potential greenhouse gas emission-trading credits (carbon trading).
- Minimizing the impacts of fire disasters due to the presence of membranes and vegetation on roofs.
- Saving energy and reducing carbon footprints by reducing cooling and heating needs of building during summer and winter respectively. According the US Environmental Protection Agency, evapotranspiration may cool down the air temperature by several degrees (EPA, 2009). An estimated of 25.9 MJ (£4300) is saved per year in London using current electricity rates (Vinlyroofs.org, 2011).
- Reducing urban heat island effects and regulating urban temperature because of evapotranspiration (EPA, 2009), and via the distribution of heat that would normally have been absorbed or accumulated within lower albedo roof materials and surfaces (e.g. black asphalt roof) (Arnfield, 2003). The change in albedo occasioned by the installation of green roofs facilitates general cooling effects within urban spaces because green roofs reflect and scatter back (distribute) more incident heat energy from the sun than some lower albedo surfaces (Taha, 1997; Alexandri and Jones, 2005). Green roofs can therefore contribute to climate change mitigation and adaptation efforts, especially if adopted on a large scale (Santamouris, 2001).
- Easing planning permit because of its sustainability profile.
- Enhancing the aesthetic value of green roofs by turning roofs into part of landscape.
- Increasing the property value of a building because it maximizes building space for leisure and replaces land lost to the footprint of building.
- Reducing the impact of surface run-off by increasing storm water retention, thereby reducing the impact of rain water flows and eventual urban flooding.
- Lessening the need to expand or rebuild separate storm sewer system in a building.
- Reducing pollutant loads by plants on the rooftops.
- Reducing noise in high noise areas like areas close to airports or major urban centres.
- Improving air quality and human health, thereby reducing medication costs.
- Creating additional soil organic carbon pools that can build-up into substantial carbon stock over time (Zanchi et al., 2012). Soil carbon sequestration of green roofs seems however, lower than comparable vegetation types on ground level (Whittinghill et al., 2014).
- Serving as habitat to variety of plant and animal species, hereby improving biodiversity. Birds, bees, reptiles, insects etc. usually find a home on green roofs.

These considerations alone could be sufficient to justify green roof construction aside from bioenergy. Perceiving biomass produced from green roofs as a by-product, while putting a higher emphasis on its environmental and social benefits, changes the sustainability picture quite dramatically. If biomass from green-roofs is considered a by-product of this type of roofing, the NEG rises from −2.5 to 3 MJ/m^2 for an annual yield of 2.6 tonnes/ha, and from 0.6 to 6.1 MJ/m^2 for an annual yield of 5.4 tonnes/ha. The EROEI also experiences a significant leap from the initial extremely low values (0.6–1.1) to unexpectedly high values of 31 and 62 for 2.6 and 5.4 tonnes/ha yields, respectively. Similarly, the overall provincial annual NEG becomes 44.8 TJ/y under an annual yield of 2.6 tonnes/ha using only large buildings. The NEG obtainable rises to 960.7 TJ/y under an annual yield of 2.6 tonnes/ha using large buildings and 30% of the small residential buildings, and 1958.6 TJ/y if a maximum annual yield of 5.4 tonnes/ha yield applies (Table 3).

Despite uncertainties associated with the LCA for rooftop biomass (e.g. lack of common reference data for estimation of the

Table 2
Energy balance of producing bioenergy from green roofs.

Items	Energy per operation (5.4 tonnes/ha yield)[f]	Energy per operation (2.6 tonnes/ha yield)[f]	References
Membrane[a]	5.3 MJ/m^2 (30 years)	5.3 MJ/m^2 (30 years)	Reddy and Jagadish (2003)
Seeds[b]	0.0003 MJ/m^2 (10 years)	0.0003 MJ/m^2 (10 years)	Smyth et al. (2009)
Fertilization	0.2 MJ/m^2	0.2 MJ/m^2	Meisterling (2011)
Harvest	0.01 MJ/m^2	0.01 MJ/m^2	Down and Hansen (2001)
Transportation of other inputs	0.00001 MJ/m^2	0.00001 MJ/m^2	Correia et al. (2010)
Transportation of biomass[c]	0.0002 MJ/m^2	0.0002 MJ/m^2	Smyth et al. (2009)
Conversion[d]	0.1 MJ/m^2	0.1 MJ/m^2	Uellendahl et al. (2008)
Digestate[e]	0.03 MJ/m^2	0.02 MJ/m^2	McEniry et al. (2011)
Output energy[f]	6.2 MJ/m^2	3.1 MJ/m^2	Smyth et al. (2009)
NEG	0.6 MJ/m^2	−2.5 MJ/m^2	
EROEI	1.1	0.6	

[a] The energy required to install a normal roof was used to estimate the energy for installing a square metre of roof membrane (Reddy and Jagadish, 2003; Peck and Kuhn, 2003). Nevertheless green roofs are designed to last for 30 years (Greenroofs.com, 2011). The energy for installation of membrane was then divided by 30 to calculate the yearly membrane energy requirement.

[b] Reseeding grass species have a regeneration period of 10 years (McEniry et al., 2011). Therefore the energy required for seeds and planting was divided by 10 to calculate the yearly seeding and planting energy requirement.

[c] The energy requirement for transporting biomass per km is 0.0016, multiplied by the average distance to a digester in Overijssel (9 km) (Smyth et al., 2009).

[d] To convert a tonne of biomass, 192 MJ is required (Uellendahl et al., 2008) and potential annual biomass yields for green roofs is 2.6 tonnes/ha and 5.4 tonnes/ha respectively (Tewari et al., 2008).Therefore, the energy for conversion of 1 m^2 of rooftop biomass produced will be the equivalent of potential annual biomass yields per m^2 divided by 192 (Uellendahl et al., 2008).

[e] 90–96% of a tonne of grass biomass is digestate; it contains NPK, which was converted to energy value. The digestate nutrient content is 2.1 kg/tonnes, 0.087 kg/tonnes and 3.08 kg/tonnes for N, P and k respectively (McEniry et al., 2011) and the energy embodied in these nutrients is 48.4 MJ/kg, 32 MJ/kg and 10 MJ/kg for N, P and K respectively (Meisterling, 2011). This energy was summed and multiplied by 0.9 (90) to calculate the least energy value of digestate/tonne which can be added as the output energy (McEniry et al., 2011).

[f] An energy yield of 6.2 MJ/m^2 is expected at a biomass yield of 5.4 tonnes/ha, while an energy yield of 3.1 MJ/m^2 is expected at a biomass yield of 2.6 tonnes/ha (Smyth et al., 2009).

different items involved, the use of logical and reasonable assumptions due to non-availability of certain coefficients etc.), it should be noted that estimates from this study are fair assessments of what is obtainable in reality. While constructing green roofs specifically for bioenergy may be less attractive and thermodynamically useless, it still has the potential to contribute significantly to future renewable energy and carbon emission reduction targets if promoted for its socio-environmental benefits while its biomass is only used as a by-product. Of course some adjustment and modification of construction may be required when biomass productivity of a roof is expected to be maximized. This may potentially decrease the high EROEI value, but will probably increase NEG. Considering and analysing these trade-offs is a subject of further research.

3.2. Comparison of the energy efficiency of rooftop biomass and rooftop solar photovoltaic panels

Results obtained from comparing the energy potential and environmental benefits of two renewable energy technologies expected to compete for rooftop spaces in the emerging green era is as follows (Table 4).

While it appears that solar photovoltaic panels are a more energy efficient source of energy than green roofs; it should be noted that they are quite susceptible to monthly variations of output energies due to monthly weather variations (Celik, 2002). Besides, rooftop bioenergy also has another major advantage of being able to store and accumulate the energy it produces more easily when compared to solar PVs (Fadare, 2009).

The energy efficiency of producing energy from solar PVs is expected to keep rising, and it has repeatedly been reported that, the energy embedded in the input materials of solar panels has constantly been declining over the years and is expected to continue to decline (Branker et al., 2011; Celik, 2002). While the NEG of rooftop bioenergy is still far less than that of solar PVs (5712 MJ/m^2), its EROEI (i.e. its energy efficiency factor) becomes higher than the highest estimates for solar PV panels (Espinosa et al., 2011), if biomass is perceived as by-product of green roofs. Under such an arrangement, when the energy cost of green roof installation is excluded, the estimated CO$_2$ emitted during the production of bioenergy therefore becomes less than 0.02 kg/kWh, compared to rooftop emissions caused by solar PVs (0.05–0.06 kg/kWh) or fossil fuels (0.4–1 kg/kWh) (Harro and Curran, 2007; Thamsiriroj and Murphy, 2009). The amount of CO$_2$ saved from replacing fossil fuels can be estimated using these values. Based on the above analysis, we can safely infer that using by-products of green roofs for bioenergy production represents a more effective way of reducing CO$_2$ emissions than the installation of rooftop solar PVs.

It could also be noted that PV production relies on certain rare elements (indium and tellurium) (NREL, 2005), which reserves are limited and which availability can become constraining in case of

Table 3
Energy balance of producing bioenergy from by-product of green roofs.

Items	Energy per operation (5.4 tonnes/ha yield)	Energy per operation (2.6 tonnes/ha yield)	References
Harvest	0.01 MJ/m^2	0.01 MJ/m^2	Down and Hansen (2001)
Transportation of biomass	0.0002 MJ/m^2	0.0002 MJ/m^2	Smyth et al. (2009)
Conversion	0.1 MJ/m^2	0.1 MJ/m^2	Uellendahl et al. (2008)
Total input energy[a]	0.1 MJ/m^2	0.1 MJ/m^2	
Output energy	6.2 MJ/m^2	3.1 MJ/m^2	Smyth et al. (2009)
NEG	6.1 MJ/m^2	3 MJ/m^2	
EROEI	62	31	

[a] The energy required for green roof's installation, seeding and biomass fertilization was excluded from the calculation. Only the energy for biomass harvest, transportation and conversion was included.

Table 4
A comparison of energy efficiency of solar PV and green roof bioenergy.

Items	Life span	Energy efficiency (EROEI)	References
Solar PV (67% active area)	15 years	4–37	Espinosa et al. (2011)
Solar PV (85% active area)	15 years	5–47	Espinosa et al. (2011)
Solar PV (The Netherlands)	30 years	15	Alsema and Nieuwlaar (2000)
Green roof (mainly for bioenergy)	30 years	1.1 (5.4 tonnes/ha)	
Green roof (used as by-product)	–	54 (5.4 tonnes/ha)	
Green roof (mainly for bioenergy)	30 years	0.8 (2.6 tonnes/ha)	
Green roof (used as by-product)	–	51 (2.6 tonnes/ha)	

mass transition to solar generated power. While other research (Candelise et al., 2011) lays these concerns at rest, it still admits that supply-demand perturbations can result in volatile prices for these elements and that production can be impacted. Compared to this, bioenergy seems like a more stable source limited only by the available area for production.

However, despite the promise green roof bioenergy holds for the future, it is still an evolving option, which requires lots of research, developmental efforts and funding (CFFA, 2001; GLWI-UoWM, 2011). There still exists the need to identify the most suitable and productive soil mixture formula and green roof species for optimum rooftop biomass production (Peck and Kuhn, 2003; Safeguard Europe Limited, 2010). Also, the actual potential green-roof condition yields are not known (Reddy and Jagadish, 2003; ARDEX TPO Membranes, 2009). This study only assumed the use of grassland species and yields of grasses under grassland conditions, which in reality may be different under green roof conditions. Other green roof biomass related issues also include concerns related to its high construction energy and envisaged future disturbance of the urban life as a result of in-flocks of birds, bees, insects, reptiles etc. around built-up areas (homes, workplaces etc.) (Tewari et al., 2008; ACC, 2010).

3.3. Recreational areas

Results obtained from the study revealed that the total area covered by recreational sites was 4792 ha and an estimated 23,960 tonnes of biomass can be produced if perennials are grown there using 50% of the total area (Table 5). The coefficients for calculating the output energies for producing biomass on recreational parks were obtained by lowering previous estimates from Smyth et al. (2009) by a factor 0.85 (the output energy of 122.4 GJ/ha/y was also lowered to 104 GJ/ha/y), while the input energies remain the same (44.7 GJ/ha/y); this is because the shadowing effects of tree covers often inhibit the growth of grass species to 85% of their potential yield (Davis et al., 1999). As a result of this, the NEG was 59.3 GJ/ha/y while the EROEI was 2.3 (Table 5). Consequently, the estimated provincial NEG from this source was 120.8 TJ/y.

However, some fast-growing perennial grasses are capable of very high energy yield, as much as 139 GJ/ha/y for switch grass and up to 225–555 GJ/ha/y for miscanthus (McKendry, 2002). While we did not consider these two species (switch grass and miscanthus) under this study because they are less visually appealing, invasive and non-native to the study area, cultivating them in recreational parks for bioenergy can improve the NEG and the EROEI by factors ranging from 1.2–7.8 and 1.2–5.1 respectively (i.e. NEG, EROEI and total obtainable NEG per annum of 462.5 GJ/ha, 11.7 and 942.2 TJ/y respectively).

Table 5
Energy balance of producing bioenergy from recreational parks.

Items	Energy per operation	References
Total input energy	44.7 GJ/ha	Smyth et al. (2009)
Total output energy	0.1 GJ/ha	Smyth et al. (2009)
85% of the total output energy[b]	104.0 GJ/ha	Davis et al. (1999)
NEG	59.3 GJ/ha	
EROEI	2.3	

[a] Refer to description “e” in Table 2.

[b] Due to the presence of trees in the park only 85% of the total output energies are usable and obtainable respectively (Davis et al., 1999).

However, it should be noted that these areas are under heavy usage by the public for aesthetic purposes; this may have a high and overwhelming priority over bioenergy production in the sight of stakeholders and decision makers. While growing herbal and non-visually appealing species for optimization of biomass production may be difficult in recreational areas due to the need to preserve the aesthetic values (Walter, 1990), some changes may be possible if renewable energies is made a new priority and therefore becomes a factor of social preferences. Also, grasses in most recreational parks are now usually slow growing species. They were chosen to minimize the frequency of mowing. Changing priorities in favour of renewable energies and carbon stock build-up for emission reduction purposes may encourage the breeding of fast growing and/or high yielding species that can be mowed more than once in a year in some recreational facilities. This will maximize biomass production for bioenergy and build up more unconventional soil organic carbon stocks within urban spaces (Smyth et al., 2009). Fast growing species are, however, likely to deplete the soil nutrient stocks faster than slow growing species so in the selection of species the local ecosystem conditions need to be considered. When choosing alternative species, it also should be also taken into account that mowing operations can be a source of public nuisance, and therefore increasing its frequency may be unacceptable in these areas. Furthermore, in optimising biomass production from recreational parks, there might be a need to choose between higher yields of grasses or higher amounts of leaf-fall biomass to be collected. These multi-dimensional challenges however calls decision makers to seek innovative means of planning production in such a way that energy is produced, social values are respected, the landscape preserves its local features and attractions, and endangered species are conserved (Lovett et al., 2011).

3.4. Domestic organic waste

According to the 2004 data for domestic waste generation obtained from the Central Bureau of Statistics (CBS 2011), the amount of wood, garden and domestic organic waste collected in Overijssel was 1,584,086 tonnes (73.5% of this was from fruit, vegetable and food sources). The minimum, average and maximum per capita waste collected within the Overijssel Province was 39 kg, 133 kg and 245 kg respectively (minimum from Kampen, and maximum from Rijssen). Going by the 2004 CBS statistics above, we considered two scenarios in estimating the domestic organic waste generated (which is 73.5% of the total domestic waste generated-excluding wood waste) within the urban built-up spaces of the Overijssel Province. The first scenario included energy for the handling and pre-treatment of the waste materials while the second one did not. It should be noted that usually, wastes properly handled and pre-treated yields much more energy than those that were not (14 GJ/tonne against 1.1 GJ/tonne) (ETSU-Harwell Laboratory,

Table 6
Energy balance of producing bioenergy from organic domestic waste (maximum potential- energy for handling and pre-treatment of waste included).

Items	Energy per operation	Average distance from built-up areas to digesters	References
Energy for handling raw materials	0.6 GJ/tonne		EUBIA (2011)
Transportation energy[a]	0.0002 GJ/tonne/km	9 km	Smyth et al. (2009)
Conversion energy	0.2 GJ/tonne		Uellendahl et al. (2008)
Input energy	0.8 GJ/tonne		
Total output energy[a]	14 GJ/tonne		EUBIA (2011)
NEG	13.2 GJ/tonne		
EROEI	15		

[a] The coefficient for transport energy required per tonne of biomass was 0.187 MJ/tonne (Smyth et al., 2009). This was multiplied by 9, which was the average distance from built-up areas to digesters.

1997; EUBIA, 2011). Based on the above information, we estimated the NEG, total obtainable NEG per annum and the EROEI from domestic organic waste to be 0.9–13.1 GJ/tonne, 142.6–2075.2 TJ/y and 5.5–15 respectively (Tables 6 and 7). The NEG and EROEI values of domestic organic wastes that were properly handled and pre-treated were higher than those that were not (13.2 GJ/tonne compared to 0.9 GJ/tonne, and 15 compared to 5.5).

Despite the similarities in total income per service area, number of people per household, historical amount of waste generated, income per household, and collection of wastes by similar companies across the Overijssel province; it remains particularly unclear why there is a big difference in per capita waste collected from the different municipalities within the province (Central Bureau of Statistics, 2011; Twentemilieu, 2011). However, we assumed that it must have been as a result of the peculiarities of their collection schemes, different techniques of handling and the prevailing residential arrangement patterns i.e. (high density urban vs. low density residential). Estimated per capita waste generation is 1.2 kg/day in most developed countries and up to 1.7–1.9 kg/day in the US (Brian and Ni-Bin, 2005). This adds up to about 438 kg/y in developed countries, but of course this includes other types of waste not useful for bio-energy. This can explain the high waste collection of 245 kg per capita in Rijssen but not the 39 kg per capita collected in Kampen. The Australian Government estimated annual organic food waste collection in Australia as 2080 kg per capita (Australian Government, 2010). Despite the fact that Netherlands and Australia are both developed countries, the gap between per capita waste collected is very large. This gap may however not be unconnected with the fact that residents in the Netherlands (Overijssel Province inclusive) pay for organic waste collection. This arrangement has the potentials to incentivise a reduction in the amount of waste put up for collection, since it costs less to bury some organic wastes as composts in a bid to reduce monthly charges on waste collection. Consequently, the creation of right incentives aimed at increasing per capita waste collected can further increase the flow of biomass for energy production, since other factors seem fairly similar in most municipalities across the province (Central Bureau of Statistics, 2011). It could be noted that removal of domestic wastes for bioenergy may cause a reduction in soil organic carbon stock meant to be stored up in dumpsites (Hudiburg et al., 2011; Lippke et al., 2011). On the other hand, carbon stocks from domestic organic wastes in dump sites decompose and undergo oxidation in the process of its formation; this further emits greenhouse gases to the atmosphere and produces unpleasant odours around their locations (Hamilton et al., 2003; Keppler et al., 2006; Sathre and Gustavsson, 2011). A compromise between the two can however be attained if domestic organic wastes are used for bioenergy and returned back to the soil as fertilizers.

3.5. *Seasonal leaf-fall*

Results obtained from the study showed that there were 4967 trees within the built-up areas of the Overijssel province. The estimated potential leaf biomass based on conversion factors from Rowntree and Nowak (1991) stood at 6457 tonnes. Based on coefficients from domestic organic waste above, the corresponding minimum and maximum NEG estimates for seasonal leaf-fall was 5.8–84.6 TJ/y. Although, seasonal leaf-falls are usually collected by the waste companies in Overijssel and utilized for bioenergy. The collection process is far from being optimised and is not conducted to maximize the amount of leaves collected. Optimising biomass flows from seasonal leaf-falls is however important because leaf decay is considered to be one of the sources of ozone-layer degrading chloromethane (CH_3Cl) (Hamilton et al., 2003; Keppler et al., 2006). Like in the case of green roofs, collecting seasonal leaf-falls is worth considering as a biomass source for bioenergy production because of its additional environmental benefits. Also like in the case of domestic organic wastes, removal and continuous use of seasonal leaf-falls for bioenergy may cause a change in annual carbon stock by reducing soil organic carbon meant to be stored in soils (Hudiburg et al., 2011; Holtsmark, 2012). However, its use for bioenergy, followed by a return of its waste (e.g. digestate from biogas) back to the soil, may reduce (in part) incidences of further loss of carbon stock to the atmosphere, via emissions of greenhouse gases originating from oxidation and consequent decomposition

Table 7
Energy balance of producing bioenergy from organic domestic waste (minimum potential- energy for handling and pre-treatment of waste not included).

Items	Energy per operation	Average distance from built-up areas to digesters	References
Total output energy[a]	1.1 (GJ/tonne)		ETSU-Harwell Laboratory (1997)
Transportation energy	0.0002 (GJ/tonne/km)	9 km	Smyth et al. (2009)
Conversion energy	0.2 (GJ/tonne)		Uellendahl et al. (2008)
Input energy	0.2 (GJ/tonne)		
NEG	0.9 (GJ/tonne)		
EROEI	5.5		

[a] The energy required for transporting a tonne of waste from residential areas to digesters is 15 MJ/tonne (EUBIA, 2011). This was multiplied by 9 which is average distance from built-up areas to digesters.

Table 8
A summary of the bioenergy potential of urban built-up spaces/sources within the Overijssel Province.

Source	Area/source available for production (ha, kg, trees)	Biomass (tonnes/y)	NEG (GJ/ha, GJ/tonne)	Total obtainable NEG (TJ/y)	EROEI
Green roofs (retrofitting for bioenergy)	32,261 ha	8063–1,29,046	−2.5–0.6 GJ/ha	183.7	0.6–1.1
Green roofs (as by-product or in new construction)	32,261 ha	3882–83,878	30–60 GJ/ha	44.8–960.7	31–62
Organic waste	14,37,05,747 kg	158,409	0.9–13.2 GJ/tonne	142.7–2075.2	5.5–15
Seasonal leaf-fall	4967 trees	6457	0.9–13.2 GJ/tonne	5.8–84.6	5.5–15
Recreational areas	2396 ha	23,960	59.3 GJ/ha	120.8	2.3–11.7
Construction sites	955 ha	11,456	77 GJ/ha	74.1	2.7–13.8
Recreational areas (if switch grass or miscanthus is planted)	2396 ha	23,960	66–514.8 GJ/ha	120.8–942.2	2.7–13.8
Construction sites (if switch grass or miscanthus is planted)	955 ha	11,456	77–600.6 GJ/ha	74.1–578.3	2.7–13.8
Total bioenergy potential (total NEG obtainable)				388.1–4640.9	

of seasonal leaf-fall (Keppler et al., 2006; Sathre and Gustavsson, 2011).

3.6. Construction sites

Results obtained from the study revealed that about 955 ha of construction sites (corresponding to 11,456 tonnes of biomass annually) was available within the Overijssel Province (Table 8). Assuming an input energy of 44.7 GJ/ha/y and an output energy of 122.4 GJ/ha/y for biomass production on construction sites (Smyth et al., 2009), the NEG and EROEI values obtained was 77.7 GJ/ha/y and 2.7 respectively (Table 8). The estimated provincial net-energy gain was 74.138–171.838 TJ/y. However, it is worthy of note that the EROEI of poor sandy soil-tolerant and high yielding perennial grasses (Timothy grass and Perennial Ryegrass) selected as suitable biomass for cultivation on vacant construction sites will increase over the 5 years of cultivation because there will be no need for annual re-fertilization. This is because perennials are capable of producing biomass while also building up additional carbon stocks continuously for up to 12 years, the input energy may be wasted if cultivated for shorter periods of time (Murphy and Power, 2008; Smyth et al., 2009). Establishing the duration for which the vacant construction site will be available may be important for further re-evaluation of the implications of exploiting them, especially on the NEG and EROEI values. Also, like in the case of recreational parks, using fast growing/higher energy yielding species which have conflicts arising from non-nativity and invasiveness can improve the bioenergy potentials of vacant construction sites from 77 to 600.6 GJ/ha for NEG, from 2.7 to 13.8 for EROEI, and from 74.1 to 578.3 TJ/y for the total province wide obtainable NEG per annum respectively.

3.7. Contributions of prospective and available urban biomass sources to future bioenergy targets

In order to assess the contribution of prospective and available urban biomass sources to future bioenergy targets, there will be need to get a sum total of their total obtainable NEGs. Results obtained showed that 388.1–4640.9 TJ of NEG is obtainable from urban biomass sources for meeting Overijssel Province's future bioenergy targets (Tables 8 and 9). This represents 0.6–7.7% of Overijssel's 2030 renewable energy targets from bioenergy. The distribution of the NEG obtainable according to the different urban biomass sources is as follows: organic waste contributed 36.7–44.7% of the overall net-energy potential, the green roofs – 11.5–20.7%, recreational areas – 20.3–31.1%, construction sites – 12.5–19.1%, and seasonal leaf-fall – 1.5–1.8%.

Generally, the EROEI for bioenergy production within built-up areas was between 0.6 and 15. The calculated EROEI were comparable to the EROEI computed for some bioenergy crops. For example, the bioenergy potential of retrofitted green roofs was comparable to that of ethanol production from wheat (Murphy and Power, 2008) or bio-diesel produced from rapeseed (Firrisa et al., 2014), while the bioenergy potentials from recreational parks and construction sites was comparable to the production of biomethane from palm oil with both having similar NEGs, gross output energies and EROEIs (Smyth et al., 2009). However, it should be noted that in case of residential bioenergy production no additional and potentially negative land use and land cover conversions are necessary. On the contrary the only land cover conversion that may be envisioned (in case of green roofs) could be seen as largely positive.

While available biomass sources (domestic organic wastes) already been used represents about 38.2–46.5% of the bioenergy potentials within the urban landscapes of the Overijssel Province; 53.5–61.8% are prospective (yet to be explored) sources which can be gainful deployed to meet part of Overijssel's future renewable energy targets. However, despite the promising nature of this prospective sources, it should be noted that several subsisting management structures, policies, practices, arrangements, priorities and rules have to be changed or adjusted (bent) in favour of sustainable measures geared towards ensuring the meeting of future renewable energy targets. Such measures may include legislations promoting green roof for its socio-environmental benefits in order to use its by-products for bioenergy production, permission for cultivation of fast-growing species that can be harvested more than once annually on recreational parks and/or vacant construction sites (if renewable energy demands rise sharply) and improved collection of seasonal leaf-falls from deciduous trees around the urban vicinities to prevent further emissions of ozone layer degrading chloromethane gases.

Although the total obtainable NEG from urban biomass sources cannot meet future bioenergy targets for the Overijssel province, other bioenergy sources within the rural landscapes of the province (e.g. animal manure, crop residue, waste grasses from

Table 9
A Comparison of total NEG obtainable from urban spaces/sources to Overijssel's 2030 bioenergy targets.

Total bioenergy potential (total NEG obtainable)	388.1–4640.9	% component of urban biomass sources in 2030 bioenergy targets	0.6–7.7%
Bioenergy 2030 target (Rabou et al., 2008)	60,000	Actual 2030 bioenergy targets	100%

natural grasslands, growing energy crops on surplus pasturelands etc.) can also contribute substantially towards the achievement of this goal (Arodudu et al., 2013). In societies with lower energy demands and relatively unexplored bioenergy sector (especially developing countries), the potentials of urban biomass sources might be far more significant in meeting rising energy demands, renewable energy targets and earning of emission trading credits (where applicable) than it is in highly developed Netherlands. Also in the event of an acute future global energy crisis occasioned by rising energy demands (due to global increase in population, consumption, and associated global economic expansion), at the end to the cheap oil era, exacerbated by climate change adaptation needs on a global scale (Voinov and Filatova, 2014), tapping into every renewable energy source available (urban biomass sources inclusive), no matter their percentage contribution to the energy-mix, will become highly essential and inevitable.

Also, it should be noted that while most of the GIS techniques used by this study can be easily replicated on larger scales for more comprehensive studies, the capabilities of LIDAR (Light Detection and Ranging) remote sensing and advanced GIS information extraction methods can be further explored for more accurate mapping of urban aerial information, in order to obtain better estimates for studies of this sort (Nagendra et al., 2013).

4. Conclusion

From this study, we found that remote sensing and GIS tools are quite valuable for detailed identification, extraction and quantification of potential areas for biomass/bioenergy production within human dominated urban ecosystems and spaces. The use of NEG and EROEI indices as indicators of bioenergy potentials further opened up and deepened the discussion on the sustainability of bioenergy sources within urban built-up spaces by comparing their energy efficiencies and their contributions to set renewable energy targets in one frame. The conversion factors and assumptions used in the course of estimating the bioenergy potentials are quite promising for further use in other parts of Europe with similar urban patterns and social arrangements. Our findings are useful as guides for policy makers in decision making processes aimed at ensuring sustainable bioenergy production, meeting renewable energy targets, general energy demands and CO_2 emissions reduction obligations locally, nationally and globally. Due to the closeness of Overijssel Province's land cover to that of the whole Netherlands, deductions made regarding the bioenergy potential of its urban ecosystem can be inferred for the whole Netherlands as well as other parts of Europe that share more or less similar patterns of lifestyles, architectural designs and municipal planning patterns. However, bigger urban centres within the Netherlands such as Rotterdam, Den Haag and Amsterdam may have even greater bioenergy potentials considering the size of their urban agglomeration, population and the amount of economic activities they attract in comparison to urban centres within the Overijssel Province. Globally speaking, from the results of this study, we can also infer broadly (having used an area in one of the most urbanized country in the world as a case study) that although 3% portion of the Earth's total land surface (urban areas) houses more than 50% of the global population and therefore harbours a significant biomass flow, it is doubtful if it can harness enough of this biomass to meet future global bioenergy demands; even if there are significant structural and systemic changes aimed at maximizing its bioenergy potential. However, despite this fact, biomass flows from urban settings might still be capable of playing significant roles in meeting local energy demands, and renewable energy/carbon emission targets, depending on the peculiarities of the local or regional energy landscape in focus. Finally, irrespective of the bioenergy potential of urban biomass sources and their potential contribution to renewable energy and carbon emission targets, what is most important is that tapping this resource does not impact any natural ecosystems and only improves human habitat and livelihoods.

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