Can we get more out of our roads?

Ling Qin
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by

Ling Qin

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Thesis Assessment Board

Chair:	Prof. Dr. Andrew Skidmore
External Examiner:	Prof. Dr. Petter Pilesjö
First Supervisor:	Dr. Alexey Voinov
Second supervisor:	Dr. Iris van Duren

ITC UNIVERSITY OF TWENTE.

FACULTY OF GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

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Abstract

Under the pressure of increasing the share of renewable energy, the Netherlands is looking for available land to develop bio-energy, among which the road verge is a good option. This land is managed by Rijkswaterstaat and municipal authorities, and the verge grass is mown twice a year without any energy utilization. The opportunities and constraints of cultivating energy crops on road verge are fully discussed. The assumption of this study is to produce biomass from short rotation coppice (SRC) of willow on available road verge, and generate electricity from direct combustion at the Twence biomass power plant in the study area of eastern Overijssel. The entire production chain is assessed by a productivity index of Energy Return on Investment (EROI). Due to the constraints on land availability (land use conflicts, road safety and ecological concerns), available road verge for willow along A1, A35, N18 & N35 is calculated as 0.71-2.39 km^2. If some marginal land other than road verge is spared for natural conservation, higher value in the range would be achieved. An empirical model is developed, which connects the amount of available road verge with length of roads and number of junctions. It is estimated that about 3.88 km^2 road verge along all the A & N roads is available for willow in the study area, 1.15 km^2 of which can be used without ecological concerns. Six management options (reference option, reference potential option and four willow cultivation options) of bio-energy production on estimated available road verge are developed, the EROI comparison of which shows that willow cultivation on conditionally available (three land availability constraints considered) road verge without any application of fertilizer or herbicide has the best energy performance, but not as competitive as common commercial cultivation of willow. However, if the energy input of reference system (mowing and transporting verge grass twice a year) is considered, it would actually become a saving of energy and costs. Although the available road verge, biomass production, electricity generation, and reduction of greenhouse gases (GHG) emission from the best willow cultivation option are not significant comparing to national or even provincial level, the idea of making use out of our roads is definitely feasible as the currently unused road verge is turned into a feedstock for biomass and some extra energy, financial gain and reduction of GHG emission can be expected.

Key words: road verge, constraints, willow, SRC, verge grass, EROI, electricity, feasibility

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1. Introduction

1.1. Need for biomas

At present, coal and gas account for more than 50% of EU's electricity supply and will remain an important part of EU's energy mix (European Commission, 2007). The speeding process of global warming, a growing demand for energy, the medium-term depletion of petroleum and political concerns have highlighted the significance of renewable energy (Luque et al., 2008).

According to the report *Renewable energy in the Netherlands 2008* (Central Bureau of Statistics, 2009b), over sixty percent of renewable energy in the Netherlands comes from biomass, which makes it the most popular and reliable renewable energy source in this country. Besides reducing the emission of greenhouse gases (GHG) (McKendry, 2002a, Demirbaş, 2005), a common benefit shared by all the renewable energy sources, biomass derived fuels are especially attractive because it can be stored and used as a non-variable energy, which is exactly missing in solar power and wind power (Ölz et al., 2007).

The collective term of biomass refers to a wide range of organic materials, such as wood from biomass industry, sewage sludge from wastewater treatment plants, organic waste from households, oils and fats from food industry, manure from dairy farms and crops specifically grown for bio-energy such as rapeseed *(Brassica napus),* willow (*Salix*) and *Miscanthus* (Basu, 2010). Among all the sources, energy crop is the most promising because the production of which can be controlled.

The European Council of March 2007 endorsed a mandatory target of a 20% share of energy from renewable sources in overall Community's energy consumption by 2020 (European Parliament and European Council, 2009). For the Netherlands, the percentage of renewable energy in final energy consumption has to be increased from 3.4% in 2008 to targeted 14% in 2020, with 10.6% to cover (Europe's Energy Portal, 2010b). Under this pressure, the Netherlands should fully embrace every opportunity to develop bio-energy, starting by looking for available land for energy crop cultivation.

1.2. Exploration of potential land

Until recently, most practice on energy crop cultivation is based on plots of arable land. However, lack of free arable land is exactly the major limitation for the Netherlands in extracting energy from biomass. In a country famous for dense population and limited land, the Dutch application of fertilizer and pesticide on per hectare of arable land is among the highest in the EU, and delivers high yields (Dyson, 1996, FAOSTAT, 2010). This fact makes using arable land for bio-energy generation in the Netherlands less competitive than food production (Faaij et al., 1998). Moreover, for reason of food security, it is preferable to leave agricultural land untouched (Londo, 2002, Faaij et al., 1998). Therefore, researchers are inspired to look for idle land, among which the vicinity of roads is a good option. This land is maintained as the transition zone between different land uses (A. Reuver, personal communication, 7 October 2010) and in most occasions it appears as stripes on both sides of the road (Figure 1).

Figure 1 Strip land of road verge
Source: Wysowski (2010)

Currently, municipal authorities are responsible for more than 90% of the Dutch roads while the national government is only responsible for 4% (Central Bureau of Statistics, 2011). However, the 4% roads include all the motorways (A-road) and a few national highways (N-road), and have more mowing practices occurring than other roads. Vegetation along these roads is currently managed by Rijkswaterstaat (Public Works Department), the executive body of the Ministry of Transport and

Water. Reasons of carrying out mowing practice include to ensure visibility along roads in case of accident, to ensure visibility of road signs and constructions (e.g., electricity box), to get rid of nutrients in the soil and thus reduce the work demand of removing biomass waste (A. Reuver, personal communication, 7 October 2010). The policy for mowing is basically twice a year, with a maximum 20 cm high of grass allowed at the end of the 26th and 45th weeks (mowing weeks). During the rest time of the year, there is no restriction on the height of vegetation. Usually, the grass can grow as high as 70-80 cm. Mowing practice can be carried out in the evening to have less negative effect on transportation (Rijkswaterstaat, 2008).

According to the *Overview of the vegetation along National Road* (Rijkswaterstaat, 2008), verge management chooses between different species types, and varies between manual pruning, mowing, chipping and cutting. However, in reality, grass is the main target vegetation and a combined cutting and suction method is used to mow verge grass, as shown in Figure 2. The Dutch *Environmental Management Act* (2004) states that the removed grass must be delivered to and processed by a waste processor which has a valid license. Usually, the grass is either deposited to waste landfill or composted (J. W. Slijkhuis, personal communication, 5 November 2010; H. Nieuwenhuis, personal communication, 19 January 2011). If more cultivation of suitable energy crops occurs on available road verge, it will be a really promising way of increasing bio-energy supply in the Netherlands.

Figure 2 Existing practice of mowing verge grass
(Copyright: I.C. Iris van Duren)

Before further analysis, it is necessary to fully understand both the opportunities and constraints of utilizing road verge in the Netherlands for biomass feedstock.

1.2.1. Opportunities

The Netherlands ranks among the top 10 countries in the world with high road density (Encyclopedia of the Nations, 2007). With a total of more than 137 000 km of roads, it has an average road density of 5 000 m per km^2 of surface area (Visser, 2010). This indicates that there might be large areas of available road verge in this country. Easy access to this land is another advantage as the logistics costs of transporting biomass might be reduced. Third, Haines-Young et al. (2000), Truscott et al. (2005) prove that vehicular activities can actually elevate the nitrogen concentration of road verge, which benefits the growth of roadside vegetation and reduce potential application of fertilizer. Furthermore, Huang's study (1987) has confirmed that planting of shrubs in the median and road verge could stop the errant vehicle in case of accident and absorb the impact, without doing much damage to the car. Last but not least, the shrub barrier could reduce traffic noise and headlight glare (van der Heijden and Martens, 1982), benefiting sound environment and road safety.

Other benefits in utilizing roadside biomass include providing carbon sequestration, encouraging technological development and innovation, and providing opportunities for employment and regional development, especially in rural and isolated areas where more road verge is available (Vollebergh, 1997, Volk et al., 2004)

1.2.2. Constraints

There are also several constraints on road verge being a type of land resource for biomass production. The most important concern is road safety.

Road safety concerns

To ensure road safety, certain road verge must be free of obstacle, such as buffer zone of junction and area inside horizontal road curve. According to *International Sight Distance Design Practices* (Harwood et al., 1995), "*Intersection Sight Distance is intended to provide drivers at or approaching an at-grade intersection with an unobstructed view of the entire intersection and sufficient lengths of the intersecting highways to permit the approaching drivers to anticipate and avoid potential collisions.*" The Clear Sight Triangle is defined by sight distances along each approach of an intersection (Figure 3). For the Netherlands, policies of Intersection Sight Distance design are explicitly addressed in some official guidelines (Staatsuitgeverij, 1986), which are based on the prevailing 85th percentile of design speed. The Intersection Sight Distance along the major-road leg is decided according to different design speeds (Table 1) and the Intersection Sight Distance along the minor-road leg is defined as the distance from edge of major road to the driver's eye, which is 5m in the Netherlands.

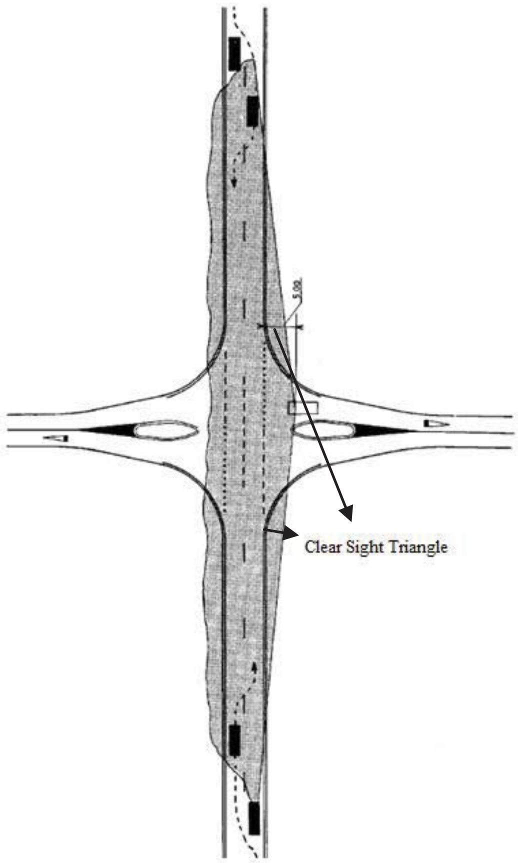

Figure 3 Typical Clear Sight Triangle used in Intersection Sight Distance design in the Netherlands
Source: Staatsuitgeverij (1986)

Table 1 Intersection Sight Distance along the major-road leg in the Netherlands

Design situation	***A-road***	***N-road***	***other road***
Design speed (km/h) (outside urban areas)	120	100	80
85th percentile of design speed (km/h)	102	85	68
Intersection sight distance along major road (m)	250	150	100

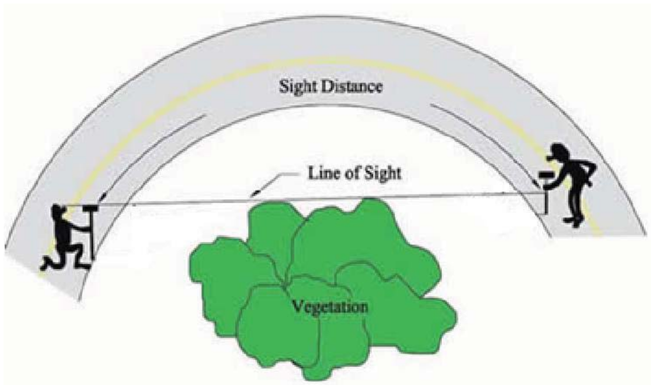

Figure 4 Stopping Sight Distance on horizontal road curves
Source: Eck and McGee (2008)

Furthermore, vegetation inside horizontal road curves may also obstruct the driver's line of sight (Figure 4). The value of stopping sight distance is the same as intersections (Table 1), because it takes the same distance to stop the vehicle under the same design speed (Eck and McGee, 2008).

According to Mr. J.W. Slijkhuis (personal communication, 5 November 2010), who is responsible for all the greenery in the province of Overijssel, the length of grass vegetation and crops within 1.20 m from the edge of asphalt pavements (roads, parallel roads and bike paths) and Clear Sight Triangle should never exceed 0.50 m. The 1.20m buffer zone of road edge should be kept clean for road sign.

Land use conflicts

According to the location of land use conflicts, there are two kinds of conflicts between bio-energy generation and other land use purposes on road verge. The first one occurs within the scope of road verge, where the land is occupied by business (e.g., advertisement and electricity pole), transportation (e.g., water area, side walk, cycle way, sandy path), or conservation (e.g., forest, nursery) purposes. The water area (e.g., open ditch) is usually considered sensitive habitats and the soils of bank need to be preserved (Perttu, 1999). Therefore, it is recommended to keep the water area in the road verge free of vegetation.

The second conflict appears on the border of road verge, where it is connected with different land uses in the surrounding, such as residence (e.g., building, garden), agriculture and recreation (e.g., play ground, park). Vegetation on the verge bordering these land uses should be carefully managed to avoid potential conflict.

For example, no tree-like vegetation is allowed to stand where the road crosses agricultural fields (A. Reuver, personal communication, 7 October 2010). Similar conflicts with residence area and recreation land should be eliminated.

These two conflicts can be solved by preserving the original land use, except for conservation purpose, which is discussed in ecological concerns.

Ecological concerns

Roadside vegetation should be managed under other constraints as well, such as landscape maintenance and ecosystem balance (Rijkswaterstaat and Dienst Weg- en Waterbouwkunde, 2006), which might limit the amount of available road verge and crop density. Moreover, the management of roadside vegetation needs to be simple and effective, in order not to disturb the busy traffic (A. Reuver, personal communication, 7 October 2010).

The *Forest Act* provides forest conservation in the Netherlands. The logging of a tree which is thicker than 8 cm must be reported to the National Service of the Ministry of Agriculture and the tree has to be replanted where it is felled or, if not possible, as close as possible to compensate the original habitat. Rijkswaterstaat has an agreement with the Ministry of Agriculture on implementation of the *Forest Act* (Rijkswaterstaat and Dienst Weg- en Waterbouwkunde, 2006). Therefore, in order to cut down existing trees along roads, a logging permit is usually requested from local municipality, except for those emergencies such as car accident, storm and disease. Thinning of shrubs is not restricted by the law (Rijkswaterstaat and Dienst Weg- en Waterbouwkunde, 2006, Ministerie van LNV, 2000). However, the province of Overijssel is trying to improve safety in the road verge by cutting down trees at various locations (Provincie Overijssel, 2010), which indicates the forest on road verge can be available land resource under some condition.

As the *Code of Green Management Service* (Borst and Sprong, 2006) states, a certain amount of species along the Dutch roads are under protection, and there are three levels of conservation, generally protection, special protection and bird protection. It is forbidden to pick, collect, cut, stab, destroy, damage, uproot or remove those protected species from their habitat. Therefore, selective mowing strategy has to be applied. However, an alternative way of thinking is to discuss the trade-off of sparing other marginal land for natural conservation. Actually, there are at least two arguments objecting the idea of saving road verge for ecological protection. The soils of road verge are usually polluted by vehicle exhaust, containing heavy metals such as Cd, Cu, Pb and Zn (Warren and Birch, 1987), and the roadside environments are highly disturbed by traffic (Cuperus et al., 1996). An interesting study of Gommers et al. (2005) even suggests that it is particularly suitable to establish willow SRC on heavy-metal-contaminated land because of its soil-to-wood transfer of pollutant.

1.3. Energy crop

Preferable characteristics of energy crop, suggested by Ponton (2009), are fast growing, high yield, perennial, without the need of annual plough once planted, adapted to marginal land, and minimal fertilizer requirement. As the existence of large trees along the road is not safe for driving, feasible energy crops for road verge are restricted to small trees, shrubs and grasses (Faaij et al., 1998). Based on these resaons, energy crops suitable for road verge include,

- Short rotation woody crops, e.g., willow SRC, poplar (Fischer et al., 2010)
- Perennial grasses, e.g. *Miscanthus*, switchgrass (*Panicum virgatum*), reed canary grass (*Phalaris arundinacea*) (Huisman, 2003).

In this study, we choose willow SRC as the biomass feedstock for potentially available road verge because it is the most competitive energy crop under the Dutch conditions. First, willow SRC is well adjusted to the Dutch climate conditions (Gigler, 1999, Londo, 2002) and it has a long history of cultivation in the Netherlands (Schepers et al., 1992). Second, the biomass production of willow SRC is potentially high. It is found that under Dutch conditions the productivity of certain local clones is in a range of 5.62-15.62 t dry matter per ha per year (Bussel, 2006). Third, the characteristics of willow SRC, including uniform texture of woody biomass, high initial growth, a short life span, easy reproduction by vegetative means (stem cuttings) and the ability to re-sprout vigorously after each harvest, all promising its extraordinary suitability for energy production (Weih, 2004). Furthermore, willow SRC is friendly to environment due to its low inputs in cultivation, limited insect and pest problems, and considerably high occurring biodiversity (include several rare and threatened red list species) (Boosten, 2009). Another advantage is its wide range of genetic variability (Volk et al., 2009).

The research interest in bio-energy has been highlighted in the US for a few decades; while in Europe, Sweden, UK and Northern Ireland are the leading countries. Local clones of willow SRC have been well developed and observed in the Europe. However, in the Dutch context, few trials have been carried out to study the biomass production of local clones, among which the researches of Kuiper (2003) and Bussel

(2006) are of high importance. Their studies suggest that for the Netherlands, productive local clones of willow SRC include Zw. Driebast (*S. triandra*), Het Goor (*Salix alba*), Belders (*Salix alba*), Tora (*Salix viminalis x S. schwerinnii*), Bjorn (*Salix viminalis x S. schwerinnii*), Black Spaniard (*S. triandra*), Loden (*S. triandra*) and Jorr (*Salix viminalis*). Despite that certain clones produce more biomass than others, it is recommended to mix different willow species and varieties for pest and disease prevention (Ramstedt, 1999, Londo et al., 2004).

1.4. Conversion approach

Willow can be converted into energy by two main processes, thermo-chemical and bio-chemical/biological processes (McKendry, 2002b, Ni et al., 2006). Thermo-chemical approach provides three options, combustion, pyrolysis and gasification, while bio-chemical conversion includes digestion and fermentation (McKendry, 2002b). The advantages of thermo-chemical processes lie in a shorter reaction time (Bridgewater, 2001) and a better ability to destroy most of the organic material, and therefore a higher efficiency (Jenkins et al., 1998).

The main processes, intermediate and end products of thermo-chemical conversion are illustrated in Figure 5. The energy stored in biomass can be released as heat by direct combustion/co-firing, or transformed into solid (e.g., charcoal) or gaseous (e.g., synthetic gas) fuels via pyrolysis or gasification under different utilization purposes.

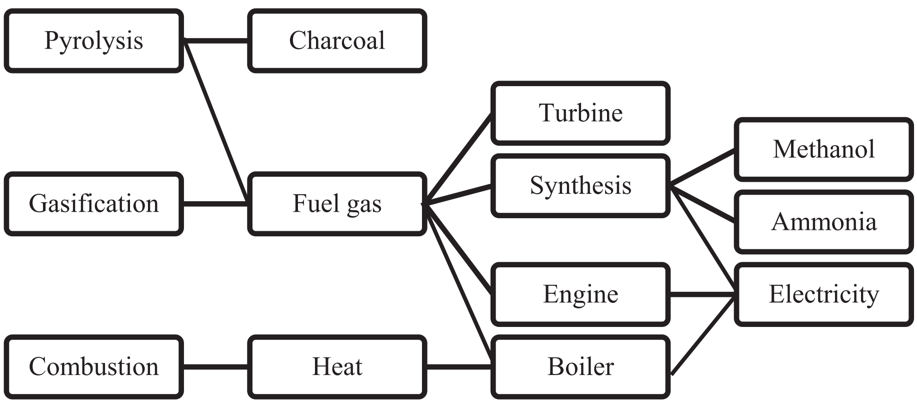

Figure 5 Main processes, intermediate and end products of thermo-chemical conversion of willow
Source: Bridgewater and Peacocke (2000)

Various research interests have been expressed on producing ethanol or biogas from specific energy crops in recent years (Demirbaş, 2007, Kim and Dale, 2005, Gray et al., 2006, Petersson et al., 2007, Börjesson and Mattiasson, 2008, Berglund and Börjesson, 2006), however, none of these conversion processes are of high efficiency. This is because using crops in the form of liquid or gas, which is different from their solid origin, greatly increases the processing energy demand (Ponton, 2009). Furthermore, current costs of these energy products (e.g., ethanol) are not competitive enough comparing with fossil fuel (McKendry, 2002b). On the other hand, low cost, high reliability, well understood process and commercial availability of combustion make it the most widely used conversion technology, which contributes to over 97% of bio-energy production all over the world (Ni et al., 2006). Table 2 tells the conversion efficiencies of some major thermo-chemical processes.

Table 2 Conversion efficiencies of some major thermo-chemical processes [a]

Process	***Output***	***Plant efficiency [b]***	***Heat to power ratio [c]***
Combustion	Electricity	25%	
Combustion	Electricity and heat	75%	4
Combustion	Heat only (industrial)	80%	
Combustion	Heat only (domestic)	89%	
Gasification	Electricity	35%	
Gasification	Electricity and heat	75%	1.5
Pyrolysis	Electricity	35%	
Pyrolysis	Electricity and heat	70%	1.5
Co-firing	Electricity (Existing plant)	35%	

[a)] Adapted from a Biomass Environmental Assessment Tool ($BEAT_2$), provided by the Department of Environment, Food and Rural Affairs of UK (Defra) and the Biomass Energy Centre and the Environment Agency of UK.
[b)] Plant efficiency is the percentage of the total energy content of a power plant's fuel which is converted into electricity.
[c)] Heat to power ratio refers to the quantity of heat recovered per unit of electricity generated.

Table 3 shows the recent situation of bio-energy production of the Netherlands (Central Bureau of Statistics, 2009b). The three main large-scale conversion approaches are co-firing of biomass in electricity power stations, municipal waste incineration plants and bio-fuels for road transport. The biggest contributions to heat production are from wood-burning stoves in households and municipal waste incineration plants. Apparently, combustion is the most applied technology in the Netherlands for bio-energy production, which is also the selected conversion approach of willow SRC in this study.

Table 3 Bio-energy production of the Netherlands, 2008

<table>
<tr><th>Biomass</th><th>Electricity production (GWh)</th><th>Heat production (TJ)</th></tr>
<tr><td>Municipal waste, renewable fraction</td><td>1 058</td><td>3 593</td></tr>
<tr><td>Biomass co-firing in large scale power plants</td><td>2 181</td><td>684</td></tr>
<tr><td>Wood stoves for heating in industry</td><td></td><td>2 257</td></tr>
<tr><td>Household wood stoves</td><td></td><td>5 191</td></tr>
<tr><td>Other biomass combustion</td><td>667</td><td>3 307</td></tr>
<tr><td>Landfill gas</td><td>104</td><td></td></tr>
<tr><td>Biogas from sewage purification plants</td><td>145</td><td rowspan="3">2 209</td></tr>
<tr><td>Biogas on farms</td><td>340</td></tr>
<tr><td>Other biogas</td><td>97</td></tr>
<tr><td>Bio-fuels for road transport</td><td></td><td></td></tr>
<tr><td>Total</td><td>4 592</td><td>17 241</td></tr>
<tr><td>Share within production from renewable energy (%)</td><td>51.1</td><td>75.9</td></tr>
</table>

Source: (Central Bureau of Statistics, 2009b)

1.5. Production chain

There are several major activities in the production chain of willow SRC (Figure 6).

Site preparation

As there is always some vegetation, especially grass, on the available road verge, it is necessary to execute mowing and removal before planting. An effective weed control starts from the very first application of herbicide and deep ploughing or sub-soiling allows willow roots to be fully developed (Caslin et al., 2010, Defra, 2004).

Establishment

(1) Planting density

Commercially, willow SRC is planted in twin rows 0.75 m apart, with 1.5 m between each set of twin rows. This is to allow machinery to pass through the crops after planting and at harvest. In this case, the planting density is 18000 plant$\cdot$ha^{-1}, and a final established crop density is around 15 000 ha^{-1} (Caslin et al., 2010).

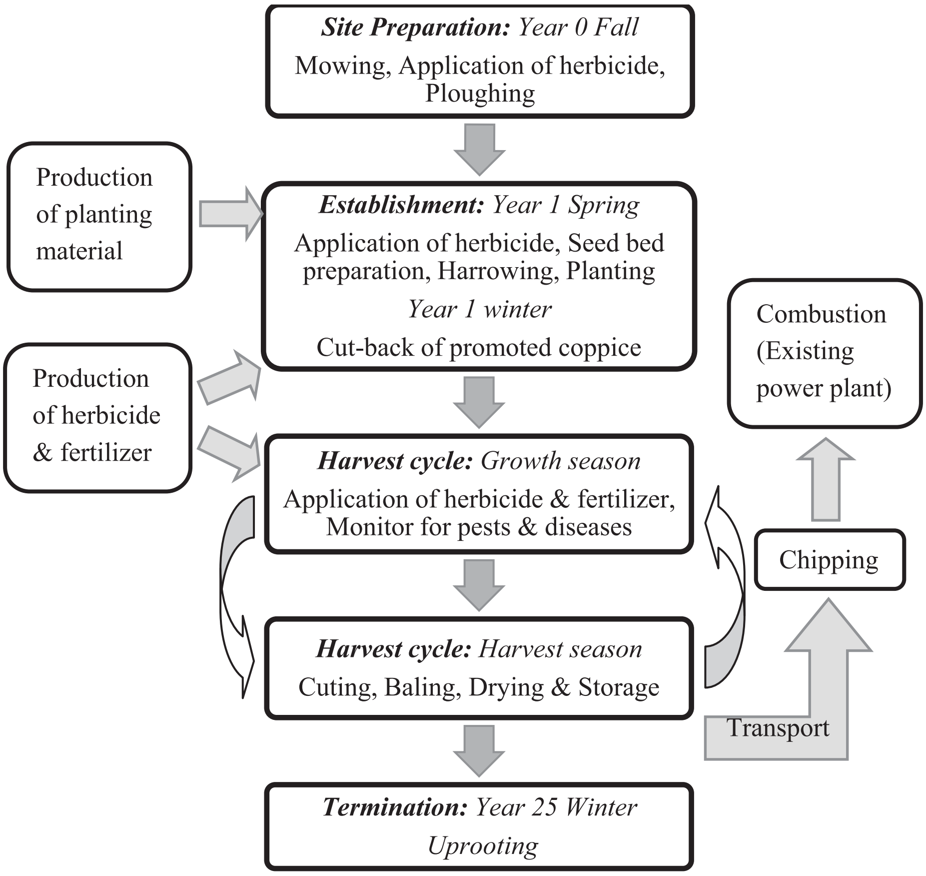

Figure 6 Major activities in the production chain of a willow short rotation plantation
Source: Defra (2004); Caslin et al. (2010)

(2) Planting
The site shall be power harrowed before planting. Willows are planted either as cuttings or rods, which are both taken from one-year-old material. The site should be rolled immediately after planting to consolidate the soil for effective herbicide application. From each cutting, 1-3 shoots will sprout and reach up to 4 m in height by the end of the first growing season, depending on soil conditions (Caslin et al., 2010, Defra, 2004).

(3) Cutback
During the winter after planting, willow is usually cut back to within 10cm of ground level to promote the development of multi-stemmed coppice. After cutback, a contact herbicide shall be applied to control the weeds that have grown during the

establishment year. 5-20 shoots will emerge from each cutback stool depending on the variety. Within 3 months of cutback, canopy closure will have occurred providing natural weed control due to reduced light at ground level.

General management

(1) Fertilization

Generally, fertilizers aim to maintain nitrogen, potassium and phosphate content of soil, however, only N fertilizer is discussed in this research. Application of fertilizers is the most common way to maintain high production levels and soil fertility (Weih, 2004). Published N fertilizer figures for willow are in the range of 150 - 400kg ha^{-1} per three year rotation, however, no fertilizer should be applied during the establishment year (Caslin et al., 2010, Johnson, 1999). As the nitrogen concentration of road verge is actually higher than the background level due to vehicular activities (Haines-Young et al., 2000, Truscott et al., 2005), the recommended amount of N fertilizer can be reduced. An alternative option is to grow willow without any fertilizer, which may result in a lower biomass yield but would reduce pollution and energy input.

(2) Weed control

Application of mixed herbicides is necessary to keep the willow free of weed until it completes canopy closure. There are four distinct phases for weed control, pre-ploughing, post-planting, after cutback and the first growing season in the harvest cycle. According to Matthews (2001), a mixture of 2.25kg herbicide is estimated to be consumed per year per hectare.

Harvesting

(1) Biomass yield

If productive local clones of willow are planted in mixture, a sustainable annual biomass yield of 12-14 oven dry ton per ha can be expected under no constraints. Generally, an annual yield of 8-10 oven dry ton per ha can be achieved under average conditions (Ceulemans et al., 1996, Caslin et al., 2010, Boosten, 2009, Defra, 2004). Although yields that are higher than 30 oven dry ton per ha per year have been reported where intensive irrigation and fertilization is achieved artificially, it can only be considered as the theoretical maximum production but not a commercial reality (Ceulemans et al., 1996, Caslin et al., 2010).

Despite the fact that aging of the shoots decreases shoot density, the biomass production is compensated by thicker shoots (Bussel, 2006), which is why biomass production can be assumed to be the same at every harvest except the first one, as the stand closure is not complete until the middle of the second year (Defra, 2004, Caslin et al., 2010).

(2) Rotation length

According to the practice guidelines of planting willow SRC from UK and Northern Ireland, normally willow is harvested every 2 or 3 years and can remain viable for 25-30 years (Defra, 2004, Caslin et al., 2010). The shoots of willow can reach up to 6-8 m at the end of a three year harvesting cycle (Defra, 2004, Caslin et al., 2010). The maximal diameter that a harvest machine can handle is 60 to 70 mm (Nordh and Dimitriou, 2003), although this is not reached in Sweden for the 3 year cutting cycle, there are concerns that longer rotation length might cause harvest problem and that the Dutch circumstances may be more in favor of willow growth than Sweden (Bussel, 2006).

(3) Harvesting, drying and storage

Stick harvesting, cut and chip harvesting are the two most common approaches of willow harvesting, with a major difference in whether chipping at source or not. Generally, willow at harvest has a moisture content of 45-60%, which needs to be reduced below 30% for higher conversion efficiency (Tubby and Armstrong, 2002).

Stick harvesting: the whole stems of willow are cut and bound; the harvested sticks are typically stored on edge of field to dry naturally, and later transported to conversion plants where they are chipped. The bundles can be stacked and dry down to approximately 30% moisture content in 3-4 months (Defra, 2004).

Cut and chip harvesting: willow is cut and chipped fresh in a single pass, therefore, the quality of chips are much better than chipping dried bundles, and the power requirement for chipping operation is minimized. However, the harvested chips will self-heat quickly due to natural degradation and thus must be dried artificially immediately, which dramatically increases the energy input (Caslin et al., 2010).

Wood chip can also be manufactured into pellets and used to fuel specifically designed pellet stoves. However, this process requires further drying of the chips to below 15% moisture content, which is highly energy intensive (Caslin et al., 2010).

Based on a UK Biomass Environmental Assessment Tool ($BEAT_2$) (AEA Energy and Environment, 2008), the primary energy input and GHG emission of different combinations of harvesting methods, intermediate products, drying methods and end products are shown in Table 4, with the default parameters explained in Appendix 1.

Table 4 Primary energy input and GHG emission of different combinations of harvesting, intermediate products, drying methods and end products according to BETA$_2$ [a]

Harvesting	***Intermediate product (drying method)***	***End product(s)***	***Primary energy input (MWh/MWh$_{e/t}$)***	***GHG emission (kg eq CO$_2$/MWh$_{e/t}$)***
Cut and chip harvesting	Chips[b] (Continuous drying[c])	Electricity	0.96	243.9
		Combined heat and power	e: 0.77 [f] t: 0.39 [g]	e: 162.7 t: 81.4
		Heat (industrial)	0.31	74.5
	Pellets[d] (Bulk drying)	Heat (industrial)	0.65	135.84
		Heat (domestic)	0.63	130.74
Stick harvesting	Sticks, chips (Natural drying)	Electricity	0.37	99.6
		Combined heat and power	e: 0.45 t: 0.22	e: 85.95 t: 42.97
		Heat (industrial)	0.12	29.9
	Sticks, pellets (Bulk drying)	Heat (industrial)	0.65	136.39
		Heat (domestic)	0.63	131.22

a) Source: AEA Energy and Environment (2008)
b) Chips: moisture content = 25 % by weight, Net Calorific Value = 11.55 MJ/kg
c) There are four drying approaches defined by BETA$_2$, bulk drying, batch drying & cooling, continuous drying & cooling and natural drying & storage. Continuous drying & cooling requires the least energy input among the three ways of artificial drying.
d) Pellets: moisture content = 10 % by weight, Net Calorific Value = 16.64 MJ/kg
f) All the produced energy is calculated as electricity (power), using a heat to power ratio of 4.
g) All the produced energy is calculated as heat, using a heat to power ratio of 4.

It is clearly shown that stick harvesting with natural drying is more energy efficient than cut and chip harvesting with artificial drying. Furthermore, pellet production has a negative effect on the energy balance of willow SRC and largely cancels out its advantage over chips.

(4) Transport

The transport of willow biomass from field to conversion plant is obviously by road. As the bulk density of wood is low, the energy cost could be reduced if the fuel is used as close to its production site as possible. It is generally accepted in UK that the transport distance should not be more that 30km (Caslin et al., 2010). No similar conclusion is found in the Dutch context.

Termination

The final harvest can be taken about 25 years after planting, and the stools are still allowed to shoot after that. When they are about 15cm high, apply herbicide and cut the structural roots. The stools can be ploughed in prior to winter and an early re-seeding in the following spring can be expected (Defra, 2004) .

1.6. Study area

The selected study area is in eastern Overijssel province (Figure 7), which is located in the east of the Netherlands with the border of Germany to the east. It consists of six municipalities: Dinkelland (Denekamp), Enschede, Haaksbergen, Hengelo, Looser and Oldenzaal, with a total area of 608.44 km^2. This area is chosen because it is easy to access by the author and previous connection with Rijkswaterstaat East Netherlands has been built.

The road network of the study area is shown in Table 5 and Figure 8. There are two A-roads and eighteen N-roads in this area, which represent motorways and national highways respectively according to the Dutch road numbering system. The two-lane A-roads traverse cross the study area with a total length of 93.3 km and have the road verge managed by Rijkswaterstaat East Netherlands together with N18 and N35. N-roads have a narrower buffer zone compared to A-roads and the total length in the study area is 172.1 km. Most of the one-lane N-roads (except N18 and N35) are maintained by provincial greenery office of Overijssel (J.W. Slijkhuis, personal communication, 5 November 2010).

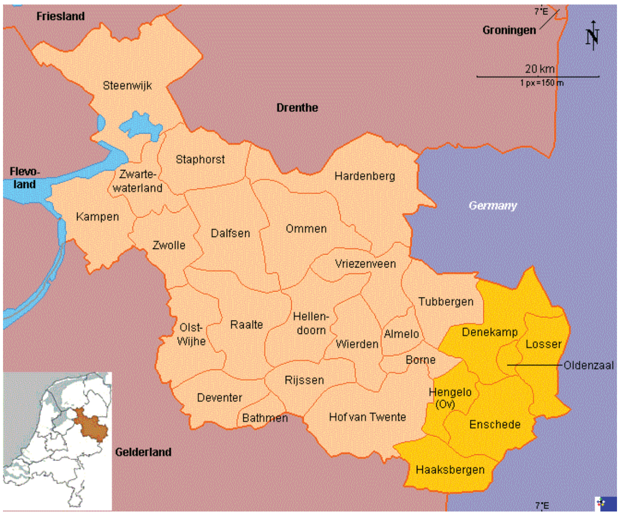

Figure 7 Location of the study area
(Source: http://www.crwflags.com/fotw/flags/nl(ov.html#map)

Table 5 Length of A & N roads in the study area

No.	A-Road	Length /km	N-Road	Length /km
1	A1	54.2	N18	18.4
2	A35	39.0	N315	1.0
3			N342	34.7
4			N343	9.2
5			N346	0.4
6			N347	8.0
7			N349	12.5
8			N35	5.6
9			N731	5.1
10			N732	6.2
11			N733	8.8
12			N734	11.8
13			N735	5.8
14			N736	10.1
15			N737	10.2
16			N738	8.2
17			N739	14.6
18			N743	1.5
Total	A-roads	93.3	N-roads	172.1

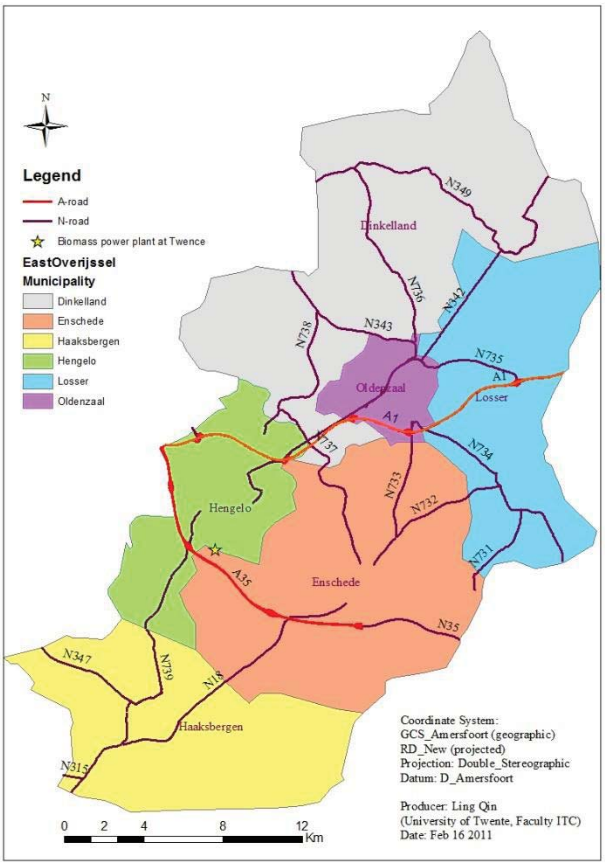

Figure 8 Road network in the study area

1.7. Energy performance

In order to assess the energy performance of willow SRC on road verge, a productivity index called Energy Return on Investment (EROI) is introduced. It is defined as the ratio of gross energy production to both direct and indirect energy cost occurred during the process (Cleveland et al., 1984). Here, energy investment includes energy consumption of different activities in the production chain while energy production is determined by crop yield and conversion efficiency. The conversion efficiency varies according to conversion approach and processing plant.

Within the study area, on the boundary of Hengelo and Enschede, there is a biomass power plant inside the Twence waste and energy plant, this biomass power plant is the first stand-alone facility in the Netherlands which converts large-scale of wood waste into electricity. With an 86% availability currently, it burns about 143 kton of biomass every year, generating a gross of 141.8 GWh electricity, 14.7 GWh of which is consumed internally (Twence, 2009). The processing procedure of willow chips in this study is assumed to take place in this biomass power plant at Twence, which indicates direct combustion of biomass to generate electricity.

1.8. Knowledge gap

Although various researches conducted in the Netherlands have confirmed the biophysical feasibility of growing willow SRC on marginal agricultural land (Londo, 2002, Bussel, 2006, Kuiper, 2003), little has been done to explore the feasibility of cultivation on marginal non-agricultural land such as road verge. A reference study is a master thesis conducted by Brandon Wysowski (Wysowski, 2010) at University of Twente, Faculty ITC, who mapped and estimated carbon stock of roadside woody vegetation in the same study area. But his research mainly considered the role of existing trees as a carbon storage reservoir without taking into account the energy potential of willow SRC. Therefore, a comprehensive assessment of the feasibility of willow SRC as an alternative bio-energy source along the Dutch roads is highly demanded to fill in the knowledge gap. Moreover, the energy production chain of willow from seed to end-product needs to be optimized.

Rijkswaterstaat used to sell the mown verge grass as fodder. But as the traditional markets disappear, verge grass becomes a burden to Rijkswaterstaat and municipal authorities, because the costs of mowing and dispose are high (Faaij et al., 1997). The cost budget is also the second major driving factor in defining mowing practices, following safety concerns (A. Reuver, personal communication, 7 October 2010). Therefore, potential energy generation of verge grass could be available at zero cost. Furthermore, if bio-energy production of willow along the roads is proved to be financially feasible and have high energy performance, it will actually become an additional profit to Rijkswaterstaat and municipal authorities. By promoting the production of renewable energy and thus reducing GHG emission, they would receive more public reliance.

Other potential users of this research may include engineering companies, consultancy companies, electricity producers, electricity distributions companies, industry (boiler and plant manufacturers), Ministry of Environment, Netherlands Organization for Energy and Environment (Novem) (Knoef and Stassen, 1995). By involvement of all possible interested parties in energy generation on the basis of roadside biomass, the efforts to introduce and commercialize bio-energy production on marginal non-agricultural land will have the greatest effect.

2. Research Problem

Normally, concentrated fields of biomass plantation are preferred as the marginal cost can be reduced with respect to integrated cultivation and management, such as pesticide and fertilizer application, infrastructure improvements, special machinery (Defra, 2004), transportation to power plants, and thermodynamic conversion (Hellmann and Verburg, 2000). However, in the unique context of road verge, the optimal scale of energy production has to be achieved under the constraints of road safety, land use conflicts and ecological concerns. A fundamental question is that whether there is sufficient available road verge in the study area to support bio-energy production from willow SRC.

The willow biomass production chain contains several major activities: site preparation, establishment, general management, harvesting and termination. Different cultivation options can be developed in order to determine the highest biomass production with lowest energy investment, especially on variations of fertilizer and herbicide input, rotation length and harvesting cycle. Besides available land resource, biomass production and energy investment, other important aspects affecting the feasibility of generating energy (electricity) from roadside willow SRC include energy return, financial balance and environmental impact. All these uncertainties need to be determined before concluding the final answer of feasibility. Meanwhile, it is necessary to estimate the energy potential of current mown verge grass along A & N roads in the study area, which can be considered as a reference system.

The defined buffer zone of management is 10 m for motorway (A-road), 4.5 m for national highway (N-road) and 13 m for new road (A. Reuver, personal communication, 7 October 2010), however, the actual values of which vary locally according to different surrounding landscape features. Furthermore, due to road safety, ecological concerns and land use conflicts, not all buffer zone area of road is available for willow cultivation; therefore, an empirical model is necessary to estimate the amount of available road verge for willow development in the study area.

2.1. General Objective

To conduct a feasibility study in the study area of the Netherlands, of generating electricity from willow SRC along A & N roads, under constraints of road safety, ecological concerns and land use conflicts.

2.2. Specific objectives and questions

In order to achieve the main objective, the following specific objectives are defined, with several research questions addressed under each objective.

1. To spatially identify available road verge for willow SRC along A1, A35, N18, N35 in the study area
   - Where is the available road verge for willow SRC?
   - How much road verge land is available for willow SRC?

2. To estimate the amount of available road verge for willow SRC along all the A & N roads in the study area
   - What are the variables empirically determines the amount of available road verge?
   - What is the empirical relationship between amount of available road verge and determining variables?
   - How much land along other N-roads in the study area is available for willow SRC?

3. To estimate biomass production of different willow cultivation options on predicted available road verge along A & N roads in the study area
   - What are the common settings for different willow cultivation options on available road verge?
   - What are the different settings for different willow cultivation options on available road verge?
   - What are the estimated biomass productions of different willow cultivation options?

4. To estimate energy performance of verge grass (reference system) on predicted available road verge along A & N roads in the study area
   - What is the estimated amount of mown verge grass every year?
   - What is the energy investment on verge management every year?
   - What is the potential energy return from the verge grass every year?

5. To estimate energy performance of different willow cultivation options on predicted available road verge along A & N roads in the study area
    - What is the energy return of different willow cultivation options?
    - What is the energy investment of different willow cultivation options?
    - What is the best willow cultivation option, according to the index of EROI?

3. Materials and method

3.1. Data collection

The collected data describes information of road network, road verge, population and land uses in the study area (Table 6). The digital topographic map of the study area contains point layer of intersections on A & N roads, line and polygon layers of A & N roads. Rijkswaterstaat created several detailed road verge shapefiles in 2008, including polygon layers of verge management and roadside vegetation, point layers of recorded trees and protected species along A1, A35, N18 and N35 in the study area. Detailed information on shape area, covered vegetation type and current mowing practice is provided in the attribute table of road verge polygon. The 2009 district and neighborhood map of the Netherlands defines the boundary of regions in the study area. The code of region is expressed by ten digits: BU + municipality code (4) + district code (2) + region code (2). The BBG'06 land use map is reclassified into five classes, agricultural land, grassland, forest, build-up land and other.

Table 6 List of data collection

Data	***Year***	***Description***	***Source***
Top 10NL (1:10,000)	2009	Digital topographic map of the Netherlands: map sheet 28, 29, 34, 35	http://www.kadaster.nl/
Road verge shapefile	2008	Digital geometry maps of verge management and roadside vegetation along A1, A35, N18 and N35	Rijkswaterstaat
District and neighbor-hood map	2009	Administrative map with population information	Central Bureau of Statistics
Land use file-BBG'06	2006	Digital geometry map of land use in the Netherlands	Central Bureau of Statistics, Land Registry

3.2. Constraints on land availability

The road verge of A1, A35, N18 and N35 is under the management of Rijkswaterstaat East Netherlands and has been clearly identified by Rijkswaterstaat in the road verge shapefile, together with corresponding roadside vegetation and verge management plan. In order to spatially identify and quantify available land along these four roads, the constraints of land availability are developed.

3.2.1. Road safety concerns

According to road safety concerns, unavailable road verge for willow SRC is defined as follows and should be avoided,

- *Clear Sight Triangle of intersections on both A & N road*
  According to Table 1, the Intersection Sight Distance along major-road leg is 250m for A-road, 150m for N road and the Intersection Sight Distance along minor-road leg is 5m for all the roads.

- *Clear sight area of horizontal curves of A-road*
  Only horizontal curves on A-road are considered in this study as there are far more and larger horizontal curves on A-road than on N-road. With the design speed of 120 km/h on A-road, the stopping sight distance is 250m.

- *1.2 m buffer zone of road edge of both A & N road*
  The 1.20m buffer zone of road edge should be kept clean for road sign.

- *Intermediate zone of a two-way road*
  The intermediate zone of a two-way road is usually narrow and should be kept free of obstacle so that drivers are able to observe vehicle condition on the opposite direction.

However, these areas can still be considered available for verge grass as long as the length of grass does not exceed 0.50 m before mowing.

3.2.2. Land use conflicts

The use of land for other purposes, within and on borders of road verge, may prevent planting willow SRC and can be solved by preserving the original land use. Therefore, the road verge containing or bordering the following land uses should be avoided,

- *Land use conflict within road verge*
  Transportation (water area, side walk, cycle way, sandy path)
  Business (advertisement and electricity pole)

- *Land use conflict on border of road verge*
  Residence (building, garden)
  Agriculture
  Recreation (play ground, park)

3.2.3. Ecological concerns

It is forbidden to pick, collect, cut, stab, destroy, damage, uproot or remove those protected species along roads which are on the list of special protection recognized by Rijkswaterstaat (Borst and Sprong, 2006). Therefore, unavailable road verge for willow due to ecological concerns is defined as follows and should be avoided,

- *Locations of recorded protected species defined by Rijkswaterstaat*
- *Locations of recorded trees defined by Rijkswaterstaat*

However, under the condition of sparing other marginal land for natural conservation, the locations of recorded protected species and trees can be considered available for willow plantation.

With the major constraints clearly stated, two definitions of available road verge along A1, A35, N18 and N35 for willow development are determined (Table 7). For unconditional availability, all the unavailable land is excluded; while for conditional availability, other marginal land would be spared for protection of species and trees, thus ecological concerns are not addressed.

Table 7 Definitions of two road verge availability for willow development

Availability	***Constraints***
Unconditional availability	▪ Road safety concerns ▪ Land use conflicts ▪ Ecological concerns
Conditional availability	▪ Road safety concerns ▪ Land use conflicts

3.3. Empirical model

3.3.1. Model development

It is assumed that the amount of available road verge will be determined by length of road, number of junction, land use conditions and population density along the road. Using the calculated amount of available road verge along A1, A35, N18 and N35 from the previous step, an empirical model for land estimate can be developed, and extrapolated to the whole study area. Here, the road verge of conditional availability is selected for model development, as unconditional availability is more spatially varied and therefore not appropriate for extrapolation.

A method of multiple-linear regression is used for the empirical model development, the data of which comes from regions along A35 & N18 in the study area. Available road verge along A35 & N18 is split by region according to the district and neighborhood map.

Hypothesis: The amount of available road verge for willow of a specific region is a multiple linear equation of corresponding length of road, number of junction, population density of that region, and area of different land uses along the road.

$$S_R = b_0 + b_1 L_A + b_2 L_N + b_3 N_A + b_4 N_N + b_5 S_A + b_6 S_G + b_7 S_F + b_8 S_B + b_9 P$$

Where,

b_i = constants, model parameters

S_R = Available road verge of a specific region

L_A = Length of A-road of that region

L_N = Length of N-road of that region

N_A = Number of A-road junction of that region

N_N = Number of N-road junction of that region

S_A = Area of agricultural land along A&N roads of that region

S_G = Area of grassland along A&N roads of that region

S_F = Area of forest along A&N roads of that region

S_B = Area of build-up land along A&N roads of that region

P = Population density of that region

3.3.1. Significance test

The method of backward stepwise regression is adopted here where the significance of regression is tested by *F-test* and individual regression coefficients are tested by *t-test*. The significance level is set at .05 and the regression steps are as follows,

(1) Do the regression analysis in the presence of all variables; test the significance of both regression and individual regression coefficients.
(2) If one or more regression coefficients are not significant, remove the variable corresponding to the non-significant coefficient with the *t-value* closest to zero.
(3) Redo the regression analysis, with that variable omitted, and test again.
(4) Continue the process, until all variables are significant.
(5) Do not eliminate b_0 even if not significant, otherwise bias occurs.

3.3.2. Model validation

After coefficient calibration and significant test, the empirical model needs to be validated by data other than the one used for development. In this research, the model is validated by data from regions along A1 and N35 in the study area. By comparing predicted available road verge with existing data, allowing a 95% confidence interval, the quality of model can be assessed.

3.4. Willow cultivation options

Four different willow cultivation options are developed, of biomass production on predicted available road verge along all the A & N roads in the study area. The major differences between options are available area size, fertilizer and herbicide input, and rotation length. As mentioned above, the application of N fertilizer on road verge can be lower than literature recommendation as the background concentration of Nitrogen is higher, thus it is assumed as 60 kg $ha^{-1}yr^{-1}$ if applied. Conditionally available land is larger than unconditionally available land and more efforts are required to remove the current vegetation (usually trees), therefore, the use of conditionally available land needs more careful management. Besides, the soils of conditionally available land are loamy because of the previous presence of trees, rich in organic matter and nitrogen, and it is better for willow development (Mortensen et al., 1998). Therefore, the highest yield is achieved in option 4 under no obvious constraints. It is preferable to reduce the work demand of cultivation practice on the road verge, but lack of fertilizer and herbicide may result in decrease of biomass yield. The common settings for each scenario are demonstrated in Table 8 and the major differences are explained in Table 9.

Table 8 Common settings of four willow cultivation options

Options	***Assumptions***
Mixture of willow varieties	Zw. driebast, Het Goor, Belders, Tora, Bjorn, Black Spaniard, Loden and Jorr
Planting density	18 000 ha^{-1}
Final established density	15 000 ha^{-1}
Biomass yields	Remain the same from the 2nd harvest cycle to the last one, but the yields of the 1st cycle are calculated as 50% of the normal level
Lifetime of willow cultivation	25 yr
Harvesting	Stick harvesting
Drying	Natural drying in the field
Chipping location	at the plant
Moisture content by weight	at harvest = 50 % after drying = 25%
Conversion process	Take place in the biomass power plant at Twence, indicating firing alone of biomass to generate electricity

Table 9 Major differences of four willow cultivation options

Cultivation option	***1***	***2***	***3***	***4***
Available area size (ha)	Unconditional	Unconditional	Unconditional	Conditional
N Fertilizer input (kg $ha^{-1}yr^{-1}$)	0	0	60	60
Herbicide input (kg $ha^{-1}yr^{-1}$)	0	2.25	2.25	2.25
Rotation length (yr)	2	2	3	3
Harvesting cycle	12	12	8	8
Yield (moisture content = 50%) (t $ha^{-1}yr^{-1}$)	16	20	24	28

3.5. Energy performance

3.5.1. Reference system

The reference system in this study is defined as mowing and dumping (transporting) verge grass to the green composting plant at Twence, with a frequency of twice a year. The predicted unconditionally available land for willow in the study area is used to estimate the biomass amount of mown verge grass. It is assumed that the yield of verge grass is 10 t/yr with a 60% moisture content at harvest (H.Wolter Elbersen et al., 2002).

The generation of electricity from verge grass can be through gasification or prolysis (Hodgson et al., 2011, McKendry, 2002b). According to Table 2, the efficiencies of both conversion approaches are the same. However, according to $BETA_2$, the primary energy input and GHG emission of gasification is less than pyrolysis (AEA Energy and Environment, 2008). Therefore, the potential energy production of the reference system is set to generate electricity by gasification.

3.5.2. Energy return

The most common expression of bio-energy is based on oven dry material at 0% moisture content and different figures are reported in literature, within a range of 16-20 GJ per oven dry ton (Börjesson, 1996, Heller et al., 2003, Kuiper, 2003, Lettens et al., 2003). However, the process of natural drying can only reduce the moisture content to 25%, while further drying requires intensive energy input (AEA Energy and Environment, 2008). Therefore, it is necessary to calculate the Net Heating Value which takes into account moisture content and hydrogen content. According to the Milne equation (Energy Research Centre of The Netherlands, 1998) (Equation 1), if an average Higher Heating Value of dry willow is assumed to be 19.6 MJ/kg, the Net Heating Value as received material is calculated as 13.2 MJ/kg, the parameter assumptions and calculated LHV_{ar} of verge grass and willow are shown in table 10.

$$LHV_{ar} = HHV_{dry} \times (1-W) - Ew \times [M_{H2O} \times H \times (1-W)+W] \quad \text{[Equation 1]}$$

Where,

LHV_{ar}: Lower Heating Value (Net Heating Value) as received material

HHV_{dry}: Higher Heating Value of dry material

W: moisture content

H: hydrogen content (wt% of dry fuel)

Ew: energy required for evaporation of water (2.442 MJ/kg)

M_{H2O}: weight of water created per unit of hydrogen (8.936 kg/kg)

Table 10 Parameters on energy return of verge grass and willow

Parameter on energy return	***Verge grass***	***Willow***
HHV_{dry} (MJ/kg)	18.0[a]	19.6[b]
Moisture content at harvest (%)	60[a]	50[c]
Moisture content as received at the conversion plant (%)	25[c]	25[c]
Hydrogen content (% of dry fuel)	5.6[b]	5.7[b]
LHV_{ar} (MJ/kg)	12.0	13.2
Plant efficiency (%)	35	27[d]
Gross energy production/biomass as received (GJ/t)	4.2	3.6

[a] (Faaij et al., 1997)
[b] (Energy Research Centre of The Netherlands, 1998)
[c] (AEA Energy and Environment, 2008)
[d] (Twence, 2009)

3.5.3. Energy investment

The energy investment and GHG emission on major activities in the biomass production chain of willow coppice is shown in Table 11.

Table 11 Energy investment and GHG emission in the production chain of willow SRC

Activity	***Primary energy investment (GJ ha^{-1} $activity^{-1}$)***	***GHG emission (t CO_2 eqv ha^{-1} $activity^{-1}$)***	***Notes***
Site preparation			
Mowing [a]	1.02	0.07	Reference system
Soil preparation [b]	0.54	0.04	Energy requirement for sub-soiling, ploughing, harrowing and spraying herbicides
Establishment			
Cutting production [c]	0.101 MJ/cutting	0.005 kg/cutting	Energy requirement for production of planting material
Planting [e]	1.11	0.09	
Cut-back [b]	0.65	0.04	
General management			

Herbicides [b]	0.88	0.03	Production and application of a mixture of herbicides
N fertilizer [d, e]	40.74 MJ kg^{-1}	0.007 t/kg	Production of N fertilizer
	0.84	0.07	Application of N fertilizer
Harvesting			
Harvesting [b]	0.41	0.03	Energy requirement for combined harvesting, baling and collection
Natural drying and storage [a]	28.57 MJ/t hfs [f]	1.87 kg/t hfs	Energy requirement for storage shed, loaders, front mounted, maintenance
Transport [c]	1.11 MJ $t^{-1}km^{-1}$ [g]	0.08 kg t^{-1} km^{-1}	
Chipping [b]	69.63 MJ/t dwc [h]	3.98 kg/t dwc	
Termination			
Termination [e]	6.65	0.45	

[a] (Kaltschmitt and Reinhardt, 1997)
[b] (Matthews, 2001, Matthews and Mortimer, 2000, Matthews et al., 1994)
[c] (Mortimer and Elsayed, 2001)
[d] (Defra, 2004)
[e] (Bussel, 2006)
[f] hfs: harvested feedstock.
[g] round trip; full outward and empty return.
[h] dwc: dried wood chips.

4. Results

4.1. Available road verge

Based on the defined land availability, the amount of unconditionally and conditionally available road verge for willow along A35 & N18, and A1 & N35 in the study area is calculated (Table 12). There is 0.71-2.39 km^2 of available road verge for willow development along A1, A35, N18 and N35 in the study area. Conditionally available road verge is 3.4 times of unconditionally available land. The spatially identified available road verge for willow SRC is shown in Figure 9, 10 & 11. However, Figure 9 & 10 are difficult to see because of the scale of road verge. Figure 11 shows the detailed difference between the two kinds of land availability. The reason why the upper-left zoom in map has more available road verge than the upper-right one (Figure 11) is because there are trees present on the roadside grassland.

Table 12 Available road verge along A35&N18 and A1&N35 for willow development in eastern Overijssel

Available road verge / km^2	***Along A35 & N18***	***Along A1 & N35***	***Total***
Unconditional availability	0.39	0.32	0.71
Conditional availability	0.98	1.41	2.39

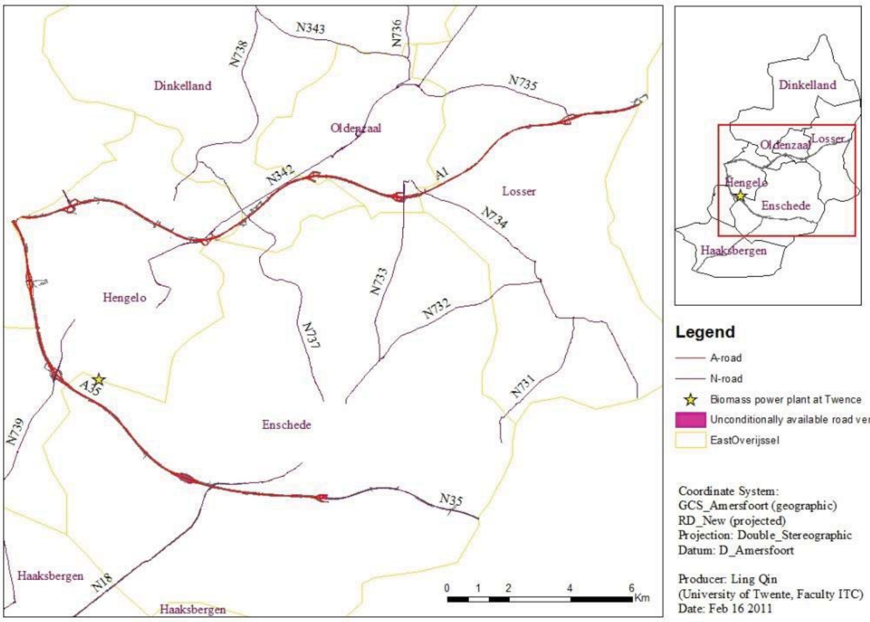

Figure 9 Unconditional available road verge along A1, A35, N18 and N35 for willow development in eastern Overijssel

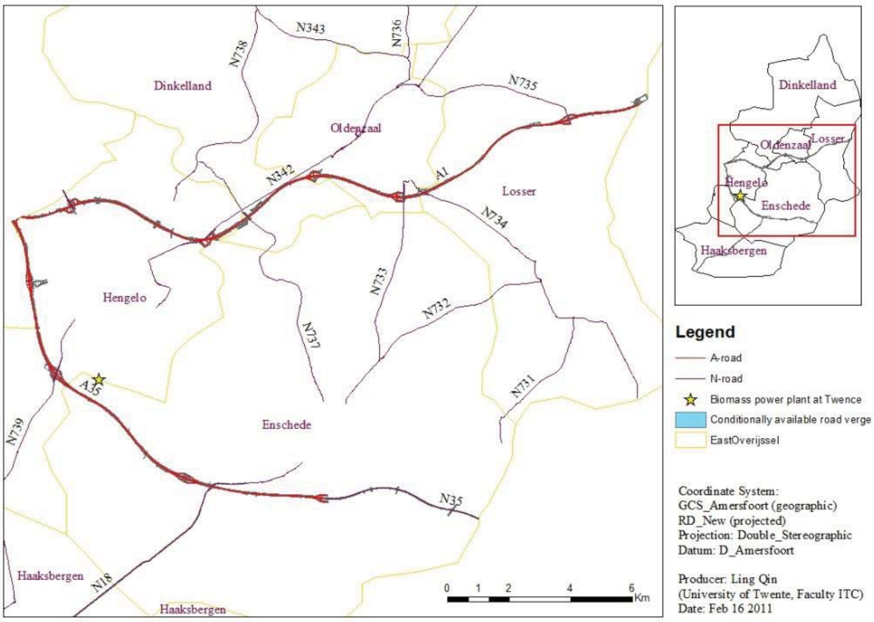

Figure 10 Conditional available road verge along A1, A35, N18 and N35 for willow development in eastern Overijssel

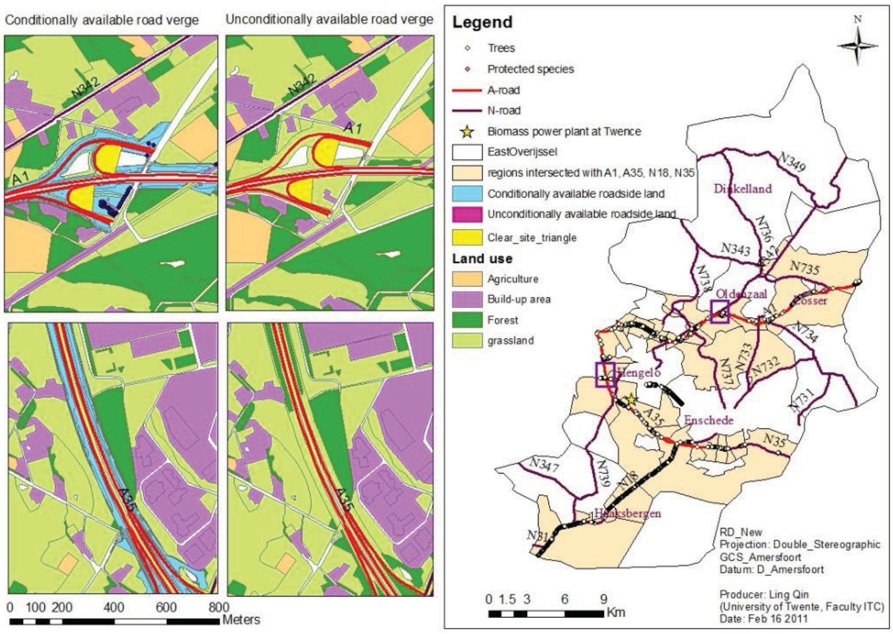

Figure 11 Available land along A1, A35, N18 and N35 for willow development in eastern Overijssel

4.2. Empirical model development and validation

The available road verge by region along A35 & N18 and corresponding values of length of road, number of junction, population density and area of different land uses along the road are shown in Appendix 2, which is the input data for model development. A seven-step backward regression (α=.05) results in an empirical model, which estimates conditionally available road verge through length of A-road, length of N-road and number of A-road junction. In other words, the coefficients of number of N-road junctions, area of different land uses and population density are not significant in this multiple-linear regression.

The final empirical linear model (by region) is as follows,

$$S_R = 18.3L_A + 11.7L_N + 10524.1N_A - 1711.7$$

[Equation 2]

The regression statistics of intermediate results and the final model are shown in Table 13 (process details in Appendix 3). The adjusted R^2 refers to the adjusted multiple coefficient of determination; here it is about 0.926, which means the multiple linear relationship is strong. The F-statistic tests whether the coefficients of length of A-road, length of N-road and number of A-road junction are all insignificant ($b_1=b_2=b_3=0$); Here Significance F is 1.26E-12, far less than .05, which means the difference is significant and at least one of the three coefficients is not equal to 0. The t-statistic tests respectively whether each coefficient is insignificant ($b_i=0$, i=0,1,2,3), all the P-values except the one for intercept are much less than .05, which means all coefficients for independent variables are significant.

Table 13 Regression statistics of intermediate results and the final model

Step	**1**	**2**	**3**	**4**	**5**	**6**	**7 (final)**
No. of variables	9	8	7	6	5	4	3
Adjusted R^2	.906	.912	.917	.921	.925	.926	.926
Sig. F	1.16 E-7	1.96 E-8	3.09 E-9	4.40 E-10	5.41 E-11	7.89 E-12	1.26 E-12
P-values:							
Intercept	.683	.389	.381	.309	.304	.442	.600
L_A	.000	.000	.000	.000	.000	.000	.000
L_N	.447	.387	.362	.051	.000	.000	.000
N_A	.021	.018	.015	.012	.008	.006	.002
S_G	.325	.281	.249	.250	.244	.290	
S_B	.748	.758	.751	.599	.426		
N_N	.738	.743	.747	.846			
S_A	.773	.784	.769				
S_F	.834	.793					
P	.887						

This empirical model is then validated with the data set along A1 & N35 and further applied to predict conditionally available land along all the A & N roads in the study area. Table 14 and Figure 12 show the results of validation. The empirical model well predicted the conditionally available land long A1 & N35, with a prediction R^2 of 0.9881. The code of region is expressed by ten digits: BU + municipality code (4) + district code (2) + region code (2).

Table 14 Validation of the empirical model for estimating available road verge along A1 & N35 in the study area

ID	**Region**	**Available land along A1&N35 /m^2**		**Relative error**	**Predicted available land along all A&N roads / m^2**
	Code	Observed	Predicted		
1	BU01530103	20186	24344	0.2060	24344

2	BU01530600	22976	23108	0.0057	23108
3	BU01530602	2691	2681	-0.0038	2681
4	BU01530902	14989	16724	0.1157	131994
5	BU01530904	82412	86708	0.0521	86708
6	BU01530905	67531	79665	0.1797	79665
7	BU01640103	6930	6211	-0.1038	6211
8	BU01640204	39208	41006	0.0458	58617
9	BU01640301	36895	39421	0.0685	39421
10	BU01640302	52532	55897	0.0640	64218
11	BU01640309	77496	64123	-0.1726	79690
12	BU01640700	36539	39284	0.0751	40865
13	BU01640705	63386	60602	-0.0439	65689
14	BU01640706	35741	30196	-0.1551	35456
15	BU01640800	30989	24636	-0.2050	28551
16	BU01640902	76128	57391	-0.2461	57391
17	BU01640903	22411	22209	-0.0090	22209
18	BU01640907	99563	106572	0.0704	108997
19	BU01680308	73302	62945	-0.1413	146309
20	BU01680309	264715	276384	0.0441	283286
21	BU01730018	266430	286085	0.0738	343385
22	BU17740908	67536	65840	-0.0251	122791
23	BU17740909	79697	65158	-0.1824	106667

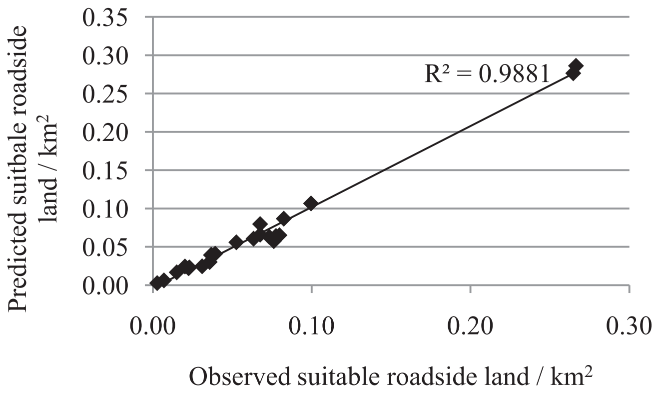

Figure 12 Validation of the empirical model for estimating conditionally available road verge along A1 & N35 in the study area

4.3. Estimated suitbale road verge

Based on the developed empirical model, available road verge along all the A & N roads in the study area is estimated around 3.88 km^2, with a deviation of 2.04 km^2 at 95% of confidence level. The unconditionally available land along all the A & N roads in the study area can be assumed as 3.88/3.4 = 1.15 km^2.

Table 15 Estimated conditionally available land for willow along all the A & N roads in the study area

No.	*Length of A-Road (km)*	*Length of N-Road (km)*	*No. of A-road junction*	*No. of intersected region*	*Estimated available land (km^2)*
	93.3[a]	172.1	35	120	3.88 ± 2.04

[a] Source: Dijkman and Benders (2010)

4.4. Biomass production

The key assumptions for calculating biomass production of different cultivation options are as follows,

- Conditionally available road verge = 388 ha
- Unconditionally available road verge = 115 ha
- Annual yield of reference system occurs on unconditionally available land
- Moisture content of biomass in calculation = 0%

The results of biomass production of reference system (verge grass) and four willow cultivation options are shown in Table 16, the estimated verge grass production is about half of the willow cultivation option 1.

Table 16 Biomass production of reference system and four cultivation options for willow SRC

Options	*Unit*	*Reference system*	*1*	*2*	*3*	*4*
Annual yield	10^3 odt/yr [a]	0.46	0.92	1.15	1.38	5.43
Total yield	10^4 odt	1.15	2.21	2.76	3.31	13.04

[a] odt: oven dry ton

4.5. Energy Return on Investment

The energy return is calculated by the values of biomass yield (Table 16) and gross energy production per unit of received biomass (Table 10). By multiplying energy inputs and GHG emissions of major activities (Table 11) with number of times executed in a lifetime of 25 years, EROI of four willow cultivation options and reference system can be estimated (Table 17). The round trip distance of collecting and transporting biomass is assumed to be 30 km for both verge grass and willow.

Reference system

Mowing of verge grass is assumed to occur twice a year and the potential energy production performance refers to gasification of grass to produce electricity. Because currently the mown verge grass in the study area does not have any energy output, the EROI is actually 0. By taking values from Table 10 & 11, including the activities of mowing, transport, natural drying & storage, and chipping, the potential EROI of the reference system can be estimated as,

$$EROI_{Reference\ potential}$$
$$= \frac{\text{Gross energy production by received verge grass}}{\text{Energy investment on mowing, transport, natural drying \& } chipping}$$
$$= \frac{0.46/0.75 \times 10^3 \times 4.2}{1.02 \times 115 \times 2 + 1.11 \times 0.46/0.4 \times 30 + 28.57 \times 0.46/0.4 + 69.93 \times 0.46/0.75}$$
$$= \frac{2576}{425.2} = 7.4$$

Different willow cultivation options

The energy inputs of different activities in the four willow cultivation options are estimated in Table 17, and true EROIs (without comparing to reference system) and relative EROIs (compared to reference system) are both calculated. The energy inputs of reference system are negative because if any of the willow cultivation option is adopted, the energy costs on mowing and transporting verge grass would be saved, which can be considered as an energy gain.

Table 17 Energy input and GHG emission of the four willow cultivation options in 25 years

Cultivation option			***1***		***2***		***3***		***4***	
Available area (ha)			Unconditional		Unconditional		Unconditional		Conditional	
N Fertilizer input (kg $ha^{-1}yr^{-1}$)			0		0		60		60	
Herbicide input (kg $ha^{-1}yr^{-1}$)			0		2.25		2.25		2.25	
Rotation length (yr)			2		2		3		3	
Harvesting cycle			12		12		8		8	
Yield (moisture content = 50%) (t $ha^{-1}yr^{-1}$)			16		20		24		28	
Activity	No. of times in 25 years (Rotation)		Energy input	GHG emission	Energy input	GHG emission	Energy input	GHG emission	Energy input	GHG emission
	2yr	3yr	GJ	t	GJ	t	GJ	t	GJ	t
Mowing	1	1	117.3	8.1	117.3	8.1	117.3	8.1	395.8	27.2
Soil preparation	1	1	62.1	4.6	62.1	4.6	62.1	4.6	209.5	15.5
Cutting production	1	1	209.1	10.4	209.1	10.4	209.1	10.4	705.4	34.9
Planting	1	1	127.7	10.4	127.7	10.4	127.7	10.4	430.7	34.9
Cut-back	1	1	74.8	4.6	74.8	4.6	74.8	4.6	252.2	15.5
Herbicides	0 or 26	26	0.0	0.0	2631.2	89.7	2631.2	89.7	8877.4	302.6
N fertilizer Production	0	24	0.0	0.0	0.0	0.0	6746.5	1159.2	22762.3	3911.0

N fertilizer Application	0	24	0.0	0.0	0	0	2318.4	193.2	7822.1	651.8
Harvesting	12	8	565.8	39.7	565.8	41.4	377.2	27.6	1272.6	93.1
Natural drying & storage	12	8	1209.1	79.1	1511.4	98.9	1774.2	116.1	6983.7	457.1
Transport	12	8	939.5	67.7	1174.4	84.6	1378.6	198.7	5426.6	782.2
Chipping	12	8	1964.5	112.3	2455.6	140.4	2882.7	164.8	11346.9	648.6
Termination	1	1	764.8	51.8	764.8	51.8	764.8	51.8	2580.2	174.6
Total energy input			6034.5	388.5	9694.0	544.7	19464.5	2039.0	69065.3	7149.2
Reference system (mowing)	25	25	-5865.0	-402.5	-5865.0	-402.5	-5865.0	-402.5	-5865.0	-402.5
Reference system (transport)	25	25	-957.4	-69.0	-957.4	-69.0	-957.4	-69.0	-957.4	-69.0
Relative total energy input			-787.9	-83.0	2871.6	73.2	12642.1	1567.5	62242.9	6677.7
Total Energy Return/GJ			101568		126960		149040		586656	
True EROI			16.8		13.1		7.7		8.5	
Relative EROI			-123.3		44.2		11.8		9.4	

The summary results of energy balances in reference, reference potential and different willow cultivation options are shown in Table 18. The energy investment of reference potential option is higher than willow cultivation option 1, which can be explained by the intensive energy inputs on mowing and transporting verge grass. The mowing of grass twice a year requires more energy than harvesting willow sticks every two years, and transporting freshly cut grass directly to conversion plant costs more energy than collecting natural dried willow sticks from road verge. Willow cultivation option 1 (unconditionally available road verge, no fertilizer or herbicide input, short rotation length) has the least energy investment but highest EROI, which indicates that the increased willow production due to application of herbicide is actually offset by the additional energy investment. Willow cultivation option 2 (conditionally available road verge, with herbicide but no fertilizer input, short rotation length) has higher EROI than option 3 (unconditionally available road verge, with fertilizer and herbicide input, long rotation length), meaning that the increased willow production due to application of fertilizer is actually offset by the additional energy investment. Willow cultivation option 4 (conditionally available road verge, with fertilizer and herbicide input, long rotation length) has the highest energy return, energy investment and GHG emission, but the EROI of which is slightly higher than option 3, which is attributed to the higher biomass yield on better soil conditions, as the available road verge area for willow does not affect the value of EROI.

Therefore, the best cultivation option according to EROI is to plant willow without any application of fertilizer or herbicide. Under this condition, the rotation length can be either 2 or 3 years as long as a sustainable yield in the lifetime of 25 years can be achieved.

Table 18 Energy balances of reference, reference potential and four willow cultivation options in 25 years

Options	***Reference***	***Reference potential***	***Willow cultivation***			
			1	***2***	***3***	***4***
Energy return (10^5 GJ)	0	0.64	1.02	1.27	1.49	5.87
Energy investment (10^4 GJ)	0.68	0.87	0.60	0.97	1.95	6.91
EROI	0	7.4	16.8	13.1	7.7	8.5
GHG emission (10^3 t CO_2 eq.)	0.47	0.59	0.39	0.54	2.04	7.15

5. Discussion

The feasibility of generating energy (electricity) from roadside biomass (verge grass and willow SRC) can be discussed from three aspects, resource feasibility, financial feasibility and environmental feasibility.

5.1. Resource feasibility

Land

The large difference between road verge area of conditional (2.39 km^2) and unconditional availability (0.71km^2) along A1, A35, N18 and N35 indicates that there are great opportunity in utilizing the conditionally available road verge for bio-energy production. As a matter of fact, from the land use map of the study area, it is measured that the area of forest in eastern Overijssel equals to 102.47 km^2, of which the roadside forest only accounts for about 1.6%. Although the roadside trees thicker than 8 cm are under protection by the Dutch *Forest Act* (Rijkswaterstaat, 2008), it is suggested that other large area of forest which is not so close to road actually has a better position in protecting valuable or vulnerable species. Therefore, estimating available road verge by conditional availability is feasible.

The large predicted range (2.04 km^2) of available road verge along all the A & N roads in the study area might be attributed to multiple variables used in the empirical model. It is first observed from the map (Figure 13) that there tends to be more grassland along A & N roads than other land cover types. However, the development of the empirical model does not confirm that road verge associating with grassland has wider buffer zone. The reason could be attributed to lack of input data when developing the model. Actually, it is the size of the study area that restricts the model accuracy and further application. In order to achieve more accurate estimate of available road verge in future research, it is suggested to develop an advanced differential algorithm, which can connect the width of road verge per length unit of road with surrounding land covers.

The result of estimated available road verge in eastern Overijssel looks quite exciting, as 10 ha is considered the minimum operational scale for willow SRC (Lawrence P. Abrahamson et al., 2002). It can be concluded that the available road verge in the study area is feasible to support the production of willow biomass.

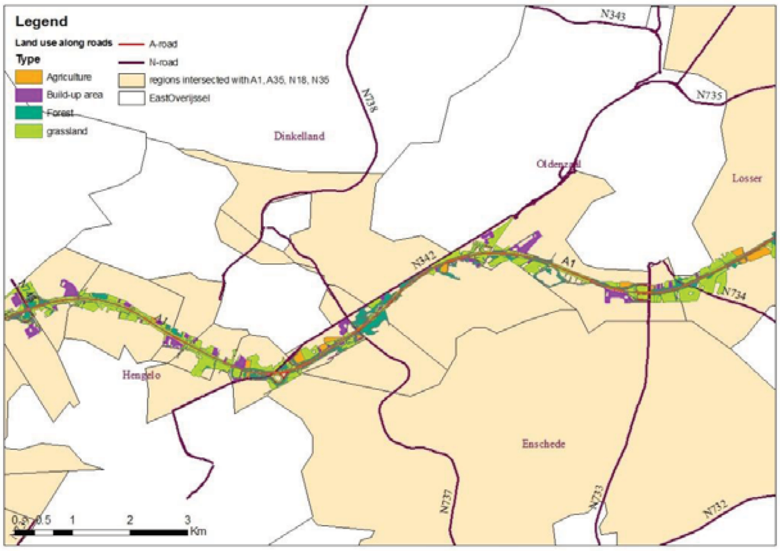

Figure 13 Land uses along A-1

Biomass

In the Netherlands, the total biomass production in natural fields is around 3 million tons dry matter every year, 1.7 million of which is contributed by forests and approximately 1 million from grassland. Due to conservation of biodiversity, about 1.9 to 2.3 million tons of the total amount of biomass can be harvested annually (Spijker et al., 2007). Although the estimated biomass production on available road verge in the study area (0.46-5.43 ktons dry matter per year) is relatively small comparing to the national level, about 0.27% of the total in maximum, it is compatible to the capacity of the biomass power plant at Twence, which can convert about 140 ktons of biomass every year. The slight increase of biomass input for Twence would not become a burden but to increase the green electricity production at the meantime. Therefore, from the perspective of biomass supply, it is feasible to make use of our roads for energy generation. More importantly, the unused road verge can be turned into a feedstock for biomass and even some financial gain can be expected.

Energy

According to Europe's Energy Portal (2010a), the average electricity consumption for a Dutch household is 3500 kWh/yr (30% during nighttime) in 2010. According to Table 18, the least energy return is gained from verge grass of the reference potential option, which is sufficient to meet the electricity needs of 5 079 households in the study area every year. For willow cultivation option 1, the number equals to 8095 households. If the entire conditionally available road verge is used to support energy production from willow, about 46 587 households can be satisfied. As there are about 153 550 private households in the study area (Central Bureau of Statistics, 2009a), 3-30% of the household consumption of electricity can be solved by making use of available road verge in the study area.

In order to optimize the chain of willow cultivation and increase energy efficiency of the system, it is necessary to discuss the energy inputs of willow cultivation option 1, which has the highest EROI among different options. According to Table 17, chipping, natural drying & storage are the largest shares of its energy investment. It is generally accepted that the transport distance should not be more than 30km, under which circumstances the EROI can be expected higher than 30 (Caslin et al., 2010), but this is not the case in this study, which indicates that road verge is not as efficient or competitive as commercial cultivation of willow. However, if we take into account the energy input of reference system; it is actually even higher than the energy investment of willow cultivation option 1. Therefore, it would be an energy saving for Rijkswaterstaat and municipal authorities if the willow cultivation option 1 is applied.

The energy potentials of verge grass and willow are overestimated in this study, as the operation costs at the assumed conversion plant are not considered, which would reduce the value of EROI. There are at least two reasons behind this. First, as we target Rijkswaterstaat as a potential user of this research, a conversion plant is not within the system boundary of Rijkswaterstaat, and therefore the energy invested on the plant are supposed to be additional energy costs for other participants of this process. Second, no gasification plant is found in the study area, which is beyond the author's knowledge. If it is true, then there is a risk of planning a new gasification plant for processing the verge grass, which would definitely increase the energy investment (e.g., construction costs) and it is likely that because of small scale of electricity output (711MWh/yr), the whole bio-energy production chain would not be profitable.

5.2. Financial feasibility

Twence charges fee for treating green waste, the prices of which are shown in Table 19 (Twence, 2007). As the treatment of verge grass (reference system) is decided as green composting in this study, which is the most expensive one according to Table 19, any other way of treating verge grass shall be financially feasible for

Rijkswaterstaat. For example, the dispose of verge grass as berm clipping for waste incineration could save Rijkswaterstaat $€\,0.46 \times 10^3 \times 30 \div (1 - 60\%) =$ $€\,34\,500$ every year, only regarding the study area.

Table 19 Fees of green waste charged by Twence BV in 2007

Green waste	***Fees (€ / wet ton)***
Green waste , shredded	25
Green waste , not shredded	35
Grass	40
Green composting	60
Berm clipping	30

Source: (Twence, 2007)

Different from verge grass, which is treated as green waste, willow chips can be sold on the energy market as fuels. The annual costs of different activities for willow cultivation option 1 are shown in Table 20. It is estimated that the newest price of willow chips (30% moisture content) at the power plant gate or on the heat market is about € 130/t (Caslin et al., 2010). Therefore, the annual estimated financial gain for Rijkswaterstaat in developing willow on available road verge in the study area would be $€\,0.92 \times 10^3 \div (1 - 30\%) \times 130 - 46755 = €\,124\,102$.

Table 20 Annual costs of different activities for willow cultivation option 1 [a]

Activity	***€ / ha. activity***	***Annual costs for willow cultivation option 1 € / year***
Establishment [b]	83	383
Harvest	198	22742
Drying + Storage	16	1869
Transport /t	12	14866
Chipping	27	2139
Removal [b]	582	4756
Total		46755

[a] Source: Venturi et al (1999), the prices have been adjusted to 2010 level using a discount rate of 3%.

[b] The establishment and removal costs are evenly distributed through 25 years. The removal costs are calculated twice, one for the removal of vegetation before willow planting, another for removal of willow plantation.

Therefore, with the energy potential of verge grass and willow cultivation exploited, it is financially feasible for Rijkswaterstaat and municipal authorities to change the current management of verge vegetation.

5.3. Environmental feasibility

GHG emission of equivalent electricity production by three kinds of fossil fuels is shown in Table 21. To illustrate, by willow cultivation option 1, a reduction of 3.91kton CO_2 eq. (5.78-1.87=3.91) can be achieved by saving the use of natural gas. To compare, the Province of Overijssel aims to reduce the emission of CO_2 by 2 200 000 tons in 2017 (Twence, 2009), of which the reduction can contribute 0.2%. Although the reduced amount is not significant, it is proved that the introduction of utilizing verge grass or cultivating willow on available road verge do decrease the GHG emission. By taking actions and publicity, Rijkswaterstaat and municipal authorities could increase the public awareness of leading a low-GHG-emission life.

Table 21 GHG emission of equivalent electricity production by fossil fuels

GHG emission *10^3 t CO_2 eq.*	***Reference potential***	***Willow cultivation option 1***
Cultivation	0.59	0.39
Biomass to electricity [a]	0.93	1.48
Total emission	1.52	1.87
Coal to electricity [b]	-6.92 [f]	-11.04
Oil to electricity production [c]	-3.96	-6.31
Natural gas to electricity [d]	-3.63	-5.78

[a] GHG emission of biomass combustion for electricity production: 52.3 kg CO_2 eq./MWhe (Heller et al., 2004)

[b, c, d] CO_2 emission of coal and coal products for electricity production: 108.2 kg/GJ; CO_2 emission of oil products for electricity production: 61.9 kg/GJ; CO_2 emission of natural gas for electricity production: 56.7 kg/GJ (Central Bureau of Statistics, 2009b).

[f] Negative value represents the reduction of CO_2 by producing electricity from non-fossil fuels.

6. Conclusion and recommendations

In the study area of eastern Overijssel, due to the constraints on land availability, including land use conflicts, road safety and ecological concerns, the amount of available land for willow development along A1, A35, N18 and N35 is estimated in the range of 0.71-2.39 km^2. If other marginal land is spared for natural conservation purpose instead of road verge, higher value in the range can be achieved.

In order to estimate available road verge along all the A & N roads in the study area, an empirical model is developed, linking the amount of available road verge with length of A & N roads, and number of A-road junctions. It is estimated that about 3.88 km^2 road verge is available for willow development in the study area, 1.15 km^2 of which can be used without any ecological concern. However, the empirical model does not confirm the observation that road verge associating with grassland has more available area. A potential future research could be devoted to developing an advanced differential algorithm, trying to connect the width of road verge per length unit of road with surrounding landscape features. In this way, with a larger study area and more data input for model development, a more complete and accurate estimate of available road verge in the whole Netherlands can be expected.

Six different management options of bio-energy production on estimated available road verge are developed. Reference option refers to composting of verge grass, reference potential option means gasification of verge grass, and four willow cultivation options are defined with different available area sizes, fertilizer and herbicide inputs, and rotation lengths. The comparison of EROI shows that willow cultivation on conditionally available (three constraints on land availability considered) road verge without any application of fertilizer or herbicide has the best energy performance, which is also the recommended management option in this research; but it is still not as efficient or competitive as common commercial cultivation of willow. However, if the energy input of reference system (mowing and transporting verge grass twice a year) is considered as a baseline, it would actually become a saving of energy and costs for Rijkswaterstaat and municipal authorities, who currently take charge of verge vegetation management in the Netherlands.

The reference potential option of making use of verge grass is expected to deliver an annual biomass production of 0.46×10^3 oven dry ton. By producing 0.64×10^5 GJ electricity through gasification, the mown verge grass is sufficient to meet the electricity needs of 5 079 households every year in the study area. Furthermore, the treatment change of verge grass from composting to energy production would save about € 34 500 for Rijkswaterstaat and municipal authorities annually.

It is estimated that the best willow cultivation option can produce 0.92×10^3 oven dry ton of biomass every year, generating 1.02×10^5 GJ electricity, which can provide the electricity consumption of 8095 households in the study area. Moreover, a financial gain of € 124,102 can be potentially expected by Rijkswaterstaat and municipal authorities, for selling the willow chips as fuels.

Although the available road verge, biomass production, electricity generation, and reduction of GHG emission from the best willow cultivation option are not significant comparing to the national or even provincial level in the Netherlands, the idea of making use out of the Dutch roads is definitely feasible from the perspectives of resource, finance and environment, as the presently unused road verge is turned into a feedstock for biomass and some extra energy, financial gain and reduction of GHG emission can be expected.

7. References

AEA ENERGY AND ENVIRONMENT 2008. Biomass Environmental Assessment Tool Version 2 User Guide. Defra, Biomass Energy Centre, Environment Agency, UK.

BASU, P. 2010. Definition of Biomass. *Biomass Gasification Design Handbook.* Boston: Academic Press.

BERGLUND, M. & BÖRJESSON, P. 2006. Assessment of energy performance in the life-cycle of biogas production. *Biomass and Bioenergy,* 30**,** 254-266.

BOOSTEN, M. 2009. Poster: 'Short Rotation Coppice (SRC) in the Netherlands'. *International Energy Farming Congress.* Papenburg, Germany.

BÖRJESSON, P. & MATTIASSON, B. 2008. Biogas as a resource-efficient vehicle fuel. *Trends in Biotechnology,* 26**,** 7-13.

BÖRJESSON, P. I. I. 1996. Energy analysis of biomass production and transportation. *Biomass and Bioenergy* 11**,** 305-318.

BORST, R. H. J. & SPRONG, R. 2006. GEDRAGSCODE: Bestendig beheer groenvoorzieningen (Code of Green Management Service). Ede, the Netherlands: Vereniging Stadswerk Nederland, Vakgroep Groen, Natuur en Landschap Vereniging van Hoveniers en Groenvoorzieners (VHG).

BRIDGEWATER, A. V. 2001. Thermal conversion of biomass and waste: the status. *Bio-Energy Research Group.* Birmingham (UK): Aston University.

BRIDGEWATER, A. V. & PEACOCKE, G. V. C. 2000. Fast pyrolysis processes for biomass. *Renew Sustain Energy Rev* 4**,** 1-73.

BUSSEL, L. V. 2006. *The potential contribution of a shortrotation willow plantation to mitigate climate change.* Msc thesis, Wageningen University, the Netherlands.

CASLIN, B., FINNAN, J. & MCCRACKEN, A. (eds.) 2010. *Short Rotation Coppice Willow Best Practice Guidelines*: Teagasc, Crops Research Centre, Oak Park, Carlow; AFBI, Agri-Food and Bioscience Institute, Newforge Lane, Belfast

CENTRAL BUREAU OF STATISTICS. 2009a. *Gebruik gegeneraliseerde geometrie Wijk- en buurtkaart 2009 (Generalized geometry and neighborhood district map 2009)*. Den Haag.

CENTRAL BUREAU OF STATISTICS 2009b. Renewable energy in the Netherlands 2008. The Hague.

CENTRAL BUREAU OF STATISTICS. 2011. *Traffic and transport* [Online]. Available: http://www.cbs.nl/en-GB/menu/themas/verkeer-vervoer/nieuws/default.htm [Accessed 1 January 2011].

CEULEMANS, R., MCDONALD, A. J. S. & PEREIRA, J. S. 1996. A comparison among eucalypt, poplar and willow characteristics with particular reference to a coppice, growth-modelling approach. *Biomass and Bioenergy,* 11**,** 215-231.

CLEVELAND, C. J., COSTANZA, R., HALL, C. A. S. & KAUFMANN, R. 1984. Energy and the U.S. Economy: A Biophysical Perspective. *Science,* 225**,** 890-897.

CUPERUS, R., CANTERS, K. J. & PIEPERS, A. A. G. 1996. Ecological compensation of the impacts of a road. Preliminary method for the A50 road link (Eindhoven-Oss, The Netherlands). *Ecological Engineering,* 7**,** 327-349.

DEFRA 2004. Growing short rotation coppice. Best practice guidelines for applicants to Defra's energy crops scheme. UK: Department for Environment, Food and Rural Affairs.

DEMIRBAŞ, A. 2005. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Progress in Energy and Combustion Science,* 31**,** 171-192.

DEMIRBAŞ, A. 2007. Progress and recent trends in biofuels. *Progress in Energy and Combustion Science,* 33**,** 1-18.

DIJKMAN, T. J. & BENDERS, R. M. J. 2010. Comparison of renewable fuels based on their land use using energy densities. *Renewable and Sustainable Energy Reviews,* In Press, Corrected Proof.

DYSON, T. 1996. Population and Food, Global Trends and Future Prospects. *Global Environmental Change Series.*

ECK, R. W. & MCGEE, H. W. 2008. Vegetation Control for Safety, A Guide for Local Highway and Street Maintenance Personnel. Vienna, VA: Vanasse Hangen Brustlin Inc.

ENCYCLOPEDIA OF THE NATIONS 2007. Road density (km of road per sq. km of land area) - Transportation - Infrastructure - World Development Indicators. *Encyclopedia of the Nations.* Advameg, Inc.

ENERGY RESEARCH CENTRE OF THE NETHERLANDS 1998. Phyllis Database on the composition of biomass and waste. Energy research Centre of the Netherlands.

EUROPE'S ENERGY PORTAL. 2010a. *Domestic Gas & Electricity* [Online]. Available: http://www.energy.eu/#Domestic [Accessed 1 Feburary 2011].

EUROPE'S ENERGY PORTAL. 2010b. *Statistics of Renewables: 2006-2010.* [Online]. Available: http://www.energy.eu/#renewable [Accessed 12 August 2010].

EUROPEAN COMMISSION 2007. MEMO/07/8: Aiming towards a low CO2 fossil fuel future. Brussels: European Communities.

EUROPEAN PARLIAMENT & EUROPEAN COUNCIL 2009. Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Brussels: European Commission.

FAAIJ, A., MEULEMAN, B., TURKENBURG, W., VAN WIJK, A., AUSILIO, B., ROSILLO-CALLE, F. & HALL, D. 1998. Externalities of biomass based electricity production compared with power generation from coal in the Netherlands. *Biomass and Bioenergy,* 14**,** 125-147.

FAAIJ, A., VAN DOORN, J., CURVERS, T., WALDHEIM, L., OLSSON, E., VAN WIJK, A. & DAEY-OUWENS, C. 1997. Characteristics and availability of biomass waste and residues in The Netherlands for gasification. *Biomass and Bioenergy,* 12**,** 225-240.

FAOSTAT 2010. ResourceSTAT: Fertilizers, Pesticides Consumption & Land. 9 September 2010 ed.: Food and Agriculture Organizaiton of the United Nations.

FISCHER, G., PRIELER, S., VAN VELTHUIZEN, H., LENSINK, S. M., LONDO, M. & DE WIT, M. 2010. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. *Biomass and Bioenergy,* 34**,** 159-172.

GIGLER, J. K., MEEUSEN-VAN ONNA, M.J.G., ANNEVELINK, E. (ed.) 1999. *Kansen voor energie uit biomassa! Resultaten van een 4-jarig DLO-onderzoekprogramma*: Dienst Landbouwkundig Onderzoek, Wageningen.

GOMMERS, A., GÄFVERT, T., SMOLDERS, E., MERCKX, R. & VANDENHOVE, H. 2005. Radiocaesium soil-to-wood transfer in commercial willow short rotation coppice on contaminated farm land. *Journal of Environmental Radioactivity,* 78**,** 267-287.

GRAY, K. A., ZHAO, L. & EMPTAGE, M. 2006. Bioethanol. *Current Opinion in Chemical Biology,* 10**,** 141-146.

H.WOLTER ELBERSEN, EDWIN R.P. KEIJSERS & DOORN, J. V. 2002. Biorefinery of Verge Grass to Produce Bio-Fuel. *12th European Conference on Biomass for Energy, Industry and Climate Protection.* Amsterdam, The Netherlands.

HAINES-YOUNG, R. H., BARR, C. J., BLACK, H. I. J., BRIGGS, D. J., BUNCE, R. G. H., CLARKE, R. T., COOPER, A., DAWSON, F. H., FIRBANK, L. G., FULLER, R. M., FURSE, M. T., GILLESPIE, M. K., HILL, R., HORNUNG, M., HOWARD, D. C., MCCANN, T., MORECROFT, M. D., PETIT, S., SIER, A. R. J., SMART, S. M., SMITH, G. M., STOTT, A. P., STUART, R. C. & WATKINS, J. W. 2000. Accounting for nature: assessing habitats in the UK countryside. London: Department of the Environment, Transport and the Regions.

HARWOOD, D., MASON, J., BRYDIA, R., JOUBERT, H., LAMM, R. & PSARIANOS, B. Year. International Sight Distance Design Practices. *In:* Proceedings of the International Symposium on Highway Geometric Design Practices, 1995 Boston, MA, USA.

HELLER, M. C., KEOLEIAN, G. A. & VOLK, T. A. 2003. Life cycle assessment of a willow bioenergy cropping system. *Biomass and Bioenergy* 25**,** 147-165.

HELLMANN, F. & VERBURG, P. H. 2000. Spatially explicit modelling of biofuel crops in Europe. *Biomass and Bioenergy,* In Press, Corrected Proof**,** 1-14.

HODGSON, E. M., NOWAKOWSKI, D. J., SHIELD, I., RICHE, A., BRIDGWATER, A. V., CLIFTON-BROWN, J. C. & DONNISON, I. S. 2011. Variation in Miscanthus chemical composition and implications for conversion by pyrolysis and thermo-chemical bio-refining for fuels and chemicals. *Bioresource Technology,* 102**,** 3411-3418.

HUANG, B. K. 1987. Dynamic Simulation of a Vehicle Interaction with Biological and Physical Systems. *American Control Conference, 1987.* Minneapolis, MN, USA

HUISMAN, W. 2003. Optimising Harvesting and Storage Systems for Energy Crops in The Netherlands. *International Conference on Crop Harvesting and Processing.* Louisville, Kentucky, USA.

JENKINS, B. M., BAXTER, L. L. & MILES, T. R. 1998. Combustion properties of biomass. *Fuel Processing Technology,* 54**,** 17-46.

JOHNSON, P. 1999. Fertiliser requirements for short rotation coppice. *ETSU report B/W2/00579/REP/1.*

KALTSCHMITT, M. & REINHARDT, G. (eds.) 1997. *Nachwachsende Energietrager - Grundlagen, Verfaben, Okologische Bilanzierung (Renewable Energy Sources, Basis, Processes and Ecological Balances),* Vieweg, Braunschweig/Weissbaden, Germany.

KIM, S. & DALE, B. E. 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. *Biomass and Bioenergy,* 29**,** 426-439.

KNOEF, H. A. M. & STASSEN, H. E. M. 1995. Energy generation from biomass and waste in the Netherlands: A brief overview and perspective. *Renewable Energy,* 6**,** 329-334.

KUIPER, L. 2003. *Samenvatting van de resultaten van zes jaar onderzoek naar energieteelt Centrum voor Biomassa Innovatie.* Wageningen.

LAWRENCE P. ABRAHAMSON, TIMOTHY A. VOLK, RICHARD F. KOPP, EDWIN H. WHITE & BALLARD, J. L. 2002. *Willow Biomass Producer's Handbook,* Syracuse, NY, State University of New York, College of Environmental Science and Forestry.

LETTENS, S., MUYS, B., CEULEMANS, R., MOONS, E., GARCIA, J. & COPPIN, P. 2003. Energy budget and greenhouse gas balance evaluation of sustainable coppice systems for energy production. *Biomass and Bioenergy,* 24**,** 179-197.

LONDO, H. M. 2002. *Energy farming in multiple land use: An opportunity for energy crop introduction in the Netherlands.* Ph.D. thesis, Utrecht University.

LONDO, M., ROOSE, M., DEKKER, J. & DE GRAAF, H. 2004. Willow short-rotation coppice in multiple land-use systems: evaluation of four combination options in the Dutch context. *Biomass and Bioenergy,* 27**,** 205-221.

LUQUE, R., HERRERO-DAVILA, L., CAMPELO, J. M., CLARK, J. H., HIDALGO, J. M., LUNA, D., MARINAS, J. M. & ROMERO, A. A. 2008. Biofuels: a technological perspective. *Energy & Environmental Science,* 1**,** 542-564.

MATTHEWS, R. 2001. Modelling of Energy and Carbon Budgets of Wood Fuel Coppice Systems. *Biomass and Bioenergy,* 21**,** 1-19.

MATTHEWS, R. & MORTIMER, N. D. 2000. Estimation of Carbon Dioxide and Energy Balances of Wood-fired Electricity Generation. *ETSU Report*

B/U1/00601/05/REP. Harwell, United Kingdom: Energy Technology Support Unit.

MATTHEWS, R., ROBINSON, R., ABBOTT, S. & FEARIS, N. 1994. Modelling of Carbon and Energy Budgets of Wood Fuel Coppice Systems. *ETSU Report B/W5/00337/REP*. Harwell, United Kingdom: Energy Technology Support Unit.

MCKENDRY, P. 2002a. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology,* 83**,** 37-64.

MCKENDRY, P. 2002b. Energy production from biomass (part 2): conversion technologies. *Bioresource Technology,* 83**,** 47-54.

MINISTERIE VAN LNV 2000. Uitvoering Boswet Rijkswaterstaat. Den Haag: Ministerie van LNV.

MINISTRY OF HOUSING, SPATIAL PLANNING AND THE ENVIRONMENT & DIRECTORATE-GENERAL FOR THE ENVIRONMENT 2004. Environmental Management Act. *Strategy and Policy Affairs Directorate/code 660* THE HAGUE.

MORTENSEN, J., HAUGE NIELSEN, K. & JØRGENSEN, U. 1998. Nitrate leaching during establishment of willow (Salix viminalis) on two soil types and at two fertilization levels. *Biomass and Bioenergy,* 15**,** 457-466.

MORTIMER, N. D. & ELSAYED, M. A. 2001. Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates. *ETSU Report B/U1/00644/00/00REP*. Harwell, United Kingdom.

NI, M., LEUNG, D. Y. C., LEUNG, M. K. H. & SUMATHY, K. 2006. An overview of hydrogen production from biomass. *Fuel Processing Technology,* 87**,** 461-472.

NORDH, N.-E. & DIMITRIOU, I. 2003. Harvest techniques in Europe. *Short Rotation Crops for Bioenergy.* New Zealand.

ÖLZ, S., SIMS, R. & KIRCHNER, N. 2007. Contribution of Renewables to Energy Security. *Renewable Energy Working Party*. International Energy Agency.

PERTTU, K. L. 1999. Environmental and hygienic aspects of willow coppice in Sweden. *Biomass and Bioenergy,* 16**,** 291-297.

PETERSSON, A., THOMSEN, M. H., HAUGGAARD-NIELSEN, H. & THOMSEN, A.-B. 2007. Potential bioethanol and biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba bean. *Biomass and Bioenergy,* 31**,** 812-819.

PONTON, J. W. 2009. Biofuels: Thermodynamic sense and nonsense. *Journal of Cleaner Production,* 17**,** 896-899.

PROVINCIE OVERIJSSEL. 2010. *Vlotte en veilige kruispunten (Safe intersections)* [Online]. Available: http://www.overijssel.nl/thema's/bereikbaar/overijssel-doet/vlotte-veilige/ [Accessed 6 December 2010].

RAMSTEDT, M. 1999. Rust disease on willows - virulence variation and resistance breeding strategies. *Forest Ecology and Management,* 121**,** 101-111.

RIJKSWATERSTAAT 2008. Overzicht van de vegetatie langs Rijkswegen (Overview of the vegetation along National Road). Amsterdam: Ministerie van Verkeer en Waterstaat.

RIJKSWATERSTAAT & DIENST WEG- EN WATERBOUWKUNDE 2006. Leidraad beheer groenvoorzieningen (Green management guidance). Amsterdam: Ministerie van Verkeer en Waterstaat.

SCHEPERS, J. A. M., HAPEREN, A. A. M. & VAN DER JAGT, J. L. E. 1992. *Grienden: hakken of laten groeien: inventarisatie van het hakgriendenareaal en mogelijkheden voor ontwikkeling (Traditional willow coppice: coppicing or letting grow; an inventory of the arsenal of traditional willow coppice and*

potentials for development), Utrecht, IKC-NBLF.

SPIJKER, J. H., ELBERSEN, H. W., JONG, J. J. D., BERG, C. A. V. D. & NIEMEIJER, C. M. 2007. Biomassa voor energie uit de Nederlandse natuur : een inventarisatie van hoeveelheden, potenties en knelpunten (Biomass energy from the Dutch nature: an inventory of amounts, and potential bottlenecks). Wageningen: Biobased Products, Centrum Landschap.

STAATSUITGEVERIJ 1986. Richtlijnen Voor Het Ontwerpen Van Niet-Autoschnellwegen Buiten de Bebouwde Kom. *In:* KRESIPUNTEN (ed.). Hague: Staatsuitgeverij.

TRUSCOTT, A. M., PALMER, S. C. F., MCGOWAN, G. M., CAPE, J. N. & SMART, S. 2005. Vegetation composition of roadside verges in Scotland: the effects of nitrogen deposition, disturbance and management. *Environmental Pollution,* 136**,** 109-118.

TUBBY, L. & ARMSTRONG, A. 2002. Establishment and Management of Short Rotation Coppice. *In:* FOREST COMMISSION (ed.). Edinburgh, UK.

TWENCE. 2007. *ALGEMENE TARIEVENLIJST TWENCE B.V. 2007 (GENERAL FEES Twence BV 2007)* [Online]. Hengelo. Available: http://www.twence.nl/en/shared%20resources/downloads/TABELPR1%20 Twence%202007.pdf [Accessed 8 Feburary 2011].

TWENCE 2009. Sustainability Report. Hengelo.

VAN DER HEIJDEN, L. A. M. & MARTENS, M. J. M. 1982. Traffic noise reduction by means of surface wave exclusion above parallel grooves in the roadside. *Applied Acoustics,* 15**,** 329-339.

VENTURI, P., GIGLER, J. K. & HUISMAN, W. 1999. Economical and technical comparison between herbaceous (Miscanthus x giganteus) and woody energy crops (Salix viminalis). *Renewable Energy,* 16**,** 1023-1026.

VISSER, H. 2010. *Total length Dutch roads stretches halfway to the moon* [Online]. Statisitcs Netherlands. Available: http://www.cbs.nl/en-GB/menu/themas/dossiers/nederland-regionaal/publicaties/artikelen/archief/2010/2010-3247-wm.htm?RefererType=RSSItem&RSSFeedTitle=Bevolking [Accessed 24 November 2010].

VOLK, T. A., BUCHHOLZ, T., CASTELLANO, P., ABRAHAMSON, L. & SMART, L. Year. Woody Biomass from Forests and Fields. *In:* Heating the Northeast, April 29 -30 2009 2009 Nashua, NH. SUNY-ESF, Syracuse, NY.

VOLK, T. A., VERWIJST, T., THARAKAN, P. J., ABRAHAMSON, L. P. & WHITE, E. H. 2004. Growing fuel: a sustainability assessment of willow biomass crops. *Frontiers in Ecology and the Environment,* 2**,** 411-418.

VOLLEBERGH, H. 1997. Environmental externalities and social optimality in biomass markets: waste-to-energy in The Netherlands and biofuels in France. *Energy Policy,* 25**,** 605-621.

WARREN, R. S. & BIRCH, P. 1987. Heavy metal levels in atmospheric particulates, roadside dust and soil along a major urban highway. *Science of the Total Environment,* 59**,** 253-256.

WEIH, M. 2004. Intensive short rotation forestry in boreal climates: present and futurn perspectives. *Canadian Journal of Forest Research 34***,** 1369-1378.

WYSOWSKI, B. 2010. *Mapping and estimation of Carbon Stock of Roadside Woody Vegetation along Roadways in Eastern Overijssel, the Netherlands.* Msc, University of Twente.

8. Appendices

Appenndix 1:

Default parameters for different harvesting methods, intermediate products, drying methods and end products according to $BETA_2$

Feedstock Or Tech Name	***Life Stage Name***	***Parameter***	***Default Value***	***Data Type Units***	***Range***
SRC (cut and chip/stick harvesting) (chips/pellets)	Cultivation and harvesting	Average annual yield	14	ar t/ha per year	12-28
SRC (cut and chip/stick harvesting) (chips/pellets)	Cultivation and harvesting	Fertilizer applied at establishment	8	kg N/ha	0-10
SRC (cut and chip/stick harvesting) (chips/pellets)	Cultivation and harvesting	Moisture content when harvested	50	%	45-55
SRC (cut and chip/stick harvesting) (chips)	Cultivation and harvesting	Ash content	1.3	% by weight (oven dry ton)	0.5-2
SRC (cut and chip/stick harvesting) (pellets)	Cultivation and harvesting	Ash content	0.5	% by weight (oven dry ton)	0.5-2
Electricity (Powerplant)	Site access	Description of Site Access	Average		
Electricity (Powerplant)	Site access	Description of Site Location	Rural / Isolated		
Combined Heat and Power (CHP)	Site access	Description of Site Location	Rural / Isolated		
Combined Heat and Power (CHP)	Site access	Description of Site Access	Average		
Heat Only	Site access	Description of Site Location	Rural / Isolated		
Heat Only	Site access	Description of Site Access	Average		
SRC (cut and chip/stick harvesting) (chips/pellets)	Reference system	Include reference land use (maintained set aside)	yes	yes/no	
SRC (cut and chip) (chips)	Drying	Type of drying	continuous	bulk/batch/ continuous/natural	
SRC (stick harvesting) (chips)	Drying	Type of drying	natural	bulk/batch/ continuous/natural	

SRC (cut and chip/stick harvesting) (pellets)	Drying	Type of drying	bulk	bulk/batch/ continuous/natural	
SRC (cut and chip/stick harvesting) (chips/pellets)	Drying	Days in storage	40		0-730
SRC (cut and chip/stick harvesting) (chips)	Drying	Moisture content of chips after drying	25	% by weight	20-50
SRC (cut and chip/stick harvesting) (pellets)	Drying	Moisture content of chips before pelleting	10	% by weight	8-10
SRC (cut and chip/stick harvesting) (chips/pellets)	Losses in processing	Losses during harvesting and chipping	0	%	0-5
SRC (cut and chip/stick harvesting) (chips)	Losses in processing	Losses during drying and storage	0	%	0-5
SRC (cut and chip/stick harvesting) (pellets)	Losses in processing	Losses during milling	3	%	0-5
SRC (cut and chip/stick harvesting) (pellets)	Losses in processing	Losses during pelletization	3	%	0-5
SRC (cut and chip/stick harvesting) (chips)	Transport	Transport mode – From plantation to storage/drying	road	road/rail/ barge/ship	
SRC (cut and chip/stick harvesting) (chips)	Transport	Average round trip distance - From plantation to storage/drying	65	km	0-200
SRC (cut and chip/stick harvesting) (pellets)	Transport	Average round trip distance - From plantation to storage and pelleting plant	90	km	0-200
SRC (cut and chip/stick harvesting) (chips/pellets)	Transport	Losses - From plantation to storage/drying	3	%	0-5
SRC (cut and chip/stick harvesting) (chips)	Transport	Transport mode - From storage facility to CHP plant	road	road/rail/ barge/ship	
SRC (cut and chip) (chips/stick harvesting)	Transport	Average round trip distance - From storage facility to power/CHP plant	0	km	0-200
SRC (cut and chip/stick harvesting)	Transport	Average round trip distance – From storage/drying/pelleti	90	km	0-200

(pellets)		ng plant to boiler site			
SRC (cut and chip/stick harvesting) (chips)	Transport	Losses - From storage facility to power/CHP plant	0	%	0-5
SRC (cut and chip/stick harvesting) (pellets)	Transport	Losses - From storage/drying to power plant	3	%	0-100
Electricity (Powerplant)	Electricity plant	Size of plant (thermal input rating)	40	MWth	3-85
Electricity (Powerplant)	Electricity plant	Net generating efficiency	25	%	20-30
Electricity (Powerplant)	Electricity plant	Include high temperature drying?	no	yes/no	
Electricity (Powerplant)	Electricity plant	Annual load factor	85	%	50-90
Electricity (Powerplant)	Electricity plant	Lifetime of plant	25	years	20-30
Electricity (Powerplant)	Electricity plant	No of start up operations per year	6	per year	4-12
Electricity (Powerplant)	Electricity plant	Average energy consumption per start-up	57.6	GJ/start up	40-75
Electricity (Powerplant)	Ash disposal	Round trip distance for ash disposal	100	km	0-200
Electricity (Powerplant)	Ash disposal	Allow for ash displacing application of lime to land	yes	yes/no	
Combined Heat and Power (CHP)	CHP plant	Overall thermal efficiency of CHP unit	75	%	30-85
Combined Heat and Power (CHP)	CHP plant	Size of plant (thermal input rating)	10	MWth	2-20
Combined Heat and Power (CHP)	CHP plant	Include high temperature drying?	no	yes/no	
Combined Heat and Power (CHP)	CHP plant	Heat to power ratio	4		1-8
Combined Heat and Power (CHP)	CHP plant	Annual load factor	55	%	50-90
Combined Heat and Power (CHP)	CHP plant	Lifetime of plant	25	years	20-30
Combined Heat and Power (CHP)	CHP plant	No of start up operations per year	6	per year	4-12
Combined Heat and Power (CHP)	CHP plant	Average energy consumption per start-up	14.4	GJ/start up	10-19
Combined Heat and Power (CHP)	CHP plant	Weighting given to electrical energy compared to heat (for allocation of emissions)	2		1-5

Combined Heat and Power (CHP)	Ash disposal	Round trip distance for ash disposal	100	km	0-200
Combined Heat and Power (CHP)	Ash disposal	Allow for ash displacing application of lime to land	yes	yes/no	
Heat Only	Ash disposal	Round trip distance for ash disposal	100	km	0-200
Heat Only	Ash disposal	Allow for ash displacing application of lime to land	yes	yes/no	
Heat Only (Industrial)	Boiler	Size of plant (thermal input rating)	0.8	MWth	0.1-1.5
Heat Only (domestic)	Boiler	Size of plant (thermal input rating)	30	kWth	5-100
Heat Only (Industrial)	Boiler	Net thermal efficiency of boiler	80	%	75-92
Heat Only (domestic)	Boiler	Net thermal efficiency of boiler	89	%	75-92
Heat Only (Industrial)	Boiler	Include high temperature drying?	no	yes/no	
Heat Only (Industrial)	Boiler	Annual load factor	65	%	65-90
Heat Only (domestic)	Boiler	Annual load factor	25	%	30-60
Heat Only	Boiler	Lifetime of plant/boiler	25	years	20-30
Heat Only (Industrial)	Boiler	% energy used for start up and feed	1.1	%	0.5-2
Heat Only (domestic)	Boiler	% energy used for start up and feed	1.6	%	1-2

Appenndix 2:

Data for model development (regions along A35 & N18 in the study area)

Region	***Available land***	***Length of road***		***No. of junction***		***Pop. density***	***Grass-land***	***Forest***	***Build -up***	***Agriculture***
	ha	m				p/km^2			ha	
BU Code		A	N	A	N					
01530200	3.23	1670	0	2	0	3236	8.59	0	2.15	0
01530201	0.91	438	0	0	6	6770	0	0	12.9	0
01530208	1.23	974	0	0	4	3332	5.01	0	2.86	0
01530603	3.28	1765	0	2	0	4387	7.88	0	0	0
01530606	3.03	1410	0	0	0	4926	8.59	0	2.86	0
01530607	1.00	432	0	0	0	4164	2.15	0	0	0
01530701	5.39	2189	0	1	0	47	7.16	0	0	0
01530905	6.75	1187	3823	0	8	53	13.6	1.43	3.58	22.2
01530906	15.36	5381	1599	3	10	65	6.44	1.43	0	0
01530907	9.09	5015	911	0	3	67	8.59	7.88	0	3.58
01530908	5.07	4925	0	0	0	33	0	0	0.72	0
01580002	0.10	0	166	0	2	3690	0.72	0	0	0
01580003	0.57	0	515	0	2	4829	0.72	0	0.72	0
01580004	0.54	0	638	0	4	3658	2.15	0	4.30	0
01580010	0.98	0	1178	0	5	1825	5.73	0	4.30	0
01580020	0.64	0	668	0	3	395	12.9	7.88	1.43	7.88
01580170	3.54	0	3327	0	10	47	25.8	0	0	2.15
01580180	1.78	0	1989	0	4	44	12.2	0	0	0
01580490	1.74	0	1458	0	7	44	6.44	0	0.72	0
01640600	2.16	1036	0	1	0	29	2.15	2.15	0	0
01640604	3.95	1310	0	0	0	3524	3.58	2.86	0.72	0
01640605	0.24	84	0	0	0	1635	18.6	7.16	2.86	0
01640606	3.62	2039	0	0	0	0	31.5	3.58	0	2.15
01640906	10.00	3208	0	2	0	30	20.0	2.15	3.58	4.30
01640907	9.96	4371	0	1	0	25	0.72	0.72	0	0

Appenndix 3:

Regression statistics of intermediate results and the final model

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.970[a]	.941	.906	11711.258
2	.970[b]	.941	.912	11347.222
3	.970[c]	.941	.917	11032.998
4	.970[d]	.941	.921	10750.232
5	.970[e]	.941	.925	10474.717
6	.969[f]	.939	.926	10385.606
7	.967[g]	.935	.926	10430.433

a. Predictors: (Constant), Agriculture, A_Junct, Build_up, Forest, Grassland, N_Junct, A35, P_km2, N18
b. Predictors: (Constant), Agriculture, A_Junct, Build_up, Forest, Grassland, N_Junct, A35, N18
c. Predictors: (Constant), Agriculture, A_Junct, Build_up, Grassland, N_Junct, A35, N18
d. Predictors: (Constant), A_Junct, Build_up, Grassland, N_Junct, A35, N18
e. Predictors: (Constant), A_Junct, Build_up, Grassland, A35, N18
f. Predictors: (Constant), A_Junct, Grassland, A35, N18
g. Predictors: (Constant), A_Junct, A35, N18

ANOVA[h]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.308E10	9	3.676E9	26.802	.000[a]
	Residual	2.057E9	15	1.372E8		
	Total	3.514E10	24			
2	Regression	3.308E10	8	4.135E9	32.115	.000[b]
	Residual	2.060E9	16	1.288E8		
	Total	3.514E10	24			
3	Regression	3.307E10	7	4.724E9	38.812	.000[c]
	Residual	2.069E9	17	1.217E8		
	Total	3.514E10	24			
4	Regression	3.306E10	6	5.510E9	47.679	.000[d]
	Residual	2.080E9	18	1.156E8		
	Total	3.514E10	24			
5	Regression	3.306E10	5	6.611E9	60.256	.000[e]
	Residual	2.085E9	19	1.097E8		
	Total	3.514E10	24			
6	Regression	3.298E10	4	8.246E9	76.450	.000[f]
	Residual	2.157E9	20	1.079E8		
	Total	3.514E10	24			
7	Regression	3.286E10	3	1.095E10	100.668	.000[g]
	Residual	2.285E9	21	1.088E8		
	Total	3.514E10	24			

a. Predictors: (Constant), Agriculture, A_Junct, Build_up, Forest, Grassland, N_Junct, A35, P_km2, N18
b. Predictors: (Constant), Agriculture, A_Junct, Build_up, Forest, Grassland, N_Junct, A35, N18

c. Predictors: (Constant), Agriculture, A_Junct, Build_up, Grassland, N_Junct, A35, N18
d. Predictors: (Constant), A_Junct, Build_up, Grassland, N_Junct, A35, N18
e. Predictors: (Constant), A_Junct, Build_up, Grassland, A35, N18
f. Predictors: (Constant), A_Junct, Grassland, A35, N18
g. Predictors: (Constant), A_Junct, A35, N18
h. Dependent Variable: Area

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-2943.509	7066.599		-.417	.683	-18005.608	12118.591
	A35	17.156	2.276	.757	7.538	.000	12.305	22.007
	N18	6.954	8.903	.193	.781	.447	-12.021	25.930
	A_Junct	9211.984	3588.479	.210	2.567	.021	1563.322	16860.646
	N_Junct	659.244	1933.712	.057	.341	.738	-3462.366	4780.855
	P_km2	-.249	1.731	-.014	-.144	.887	-3.938	3.440
	Grassland	.044	.043	.094	1.018	.325	-.048	.135
	Forest	.024	.115	.016	.213	.834	-.220	.269
	Build_up	.041	.125	.030	.327	.748	-.225	.306
	Agriculture	.033	.111	.040	.293	.773	-.205	.270
2	(Constant)	-3744.391	4227.999		-.886	.389	-12707.347	5218.566
	A35	17.256	2.100	.761	8.218	.000	12.804	21.707
	N18	7.333	8.242	.204	.890	.387	-10.139	24.805
	A_Junct	9175.634	3468.330	.209	2.646	.018	1823.102	16528.166
	N_Junct	620.107	1855.028	.054	.334	.743	-3312.376	4552.590
	Grassland	.045	.040	.097	1.115	.281	-.041	.130
	Forest	.029	.107	.019	.267	.793	-.199	.256
	Build_up	.037	.118	.027	.314	.758	-.213	.288
	Agriculture	.030	.106	.036	.279	.784	-.195	.254
3	(Constant)	-3690.026	4106.164		-.899	.381	-12353.274	4973.223
	A35	17.447	1.919	.770	9.090	.000	13.398	21.497
	N18	7.485	7.994	.208	.936	.362	-9.382	24.352
	A_Junct	9037.964	3334.935	.206	2.710	.015	2001.867	16074.061
	N_Junct	590.549	1800.455	.051	.328	.747	-3208.078	4389.176
	Grassland	.046	.039	.100	1.194	.249	-.036	.128
	Build_up	.037	.115	.027	.323	.751	-.205	.279
	Agriculture	.031	.103	.037	.299	.769	-.186	.247
4	(Constant)	-4028.804	3845.193		-1.048	.309	-12107.254	4049.646
	A35	17.682	1.706	.780	10.365	.000	14.098	21.266
	N18	9.430	4.518	.262	2.087	.051	-.063	18.922
	A_Junct	9070.291	3247.751	.207	2.793	.012	2247.020	15893.562
	N_Junct	282.384	1437.550	.024	.196	.846	-2737.797	3302.564
	Grassland	.044	.037	.094	1.188	.250	-.034	.122

	Build_up	.053	.099	.039	.535	.599	-.155	.261
5	(Constant	-3920.193	3707.708		-1.057	.304	-11680.516	3840.130
	A35	17.712	1.656	.781	10.696	.000	14.246	21.177
	N18	10.178	2.368	.283	4.299	.000	5.222	15.134
	A_Junct	9173.937	3122.473	.209	2.938	.008	2638.527	15709.348
	Grassland	.043	.035	.092	1.202	.244	-.032	.117
	Build_up	.064	.079	.047	.813	.426	-.101	.229
6	(Constant)	-2588.678	3298.191		-.785	.442	-9468.585	4291.229
	A35	17.628	1.639	.778	10.758	.000	14.210	21.046
	N18	10.431	2.327	.290	4.482	.000	5.577	15.285
	A_Junct	9525.883	3066.020	.217	3.107	.006	3130.277	15921.489
	Grassland	.038	.035	.081	1.087	.290	-.035	.110
7	(Constant)	-1711.678	3211.801		-.533	.600	-8390.983	4967.627
	A35	18.315	1.518	.808	12.061	.000	15.157	21.472
	N18	11.687	2.029	.325	5.761	.000	7.468	15.906
	A_Junct	10524.053	2937.916	.240	3.582	.002	4414.323	16633.783

a. Dependent Variable: Area