Sustainability in willow cultivation
A case study with scenario simulation in CoupModel

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Foreword

This report is a Bachelor thesis made by two students at the Royal Institute of Technology spring 2014. We would like to send our deepest gratitude to our supervisor Magnus Svensson for support and assistance during the complete process! We would also like to thank Anders Jonsson, farmer at Skrehalla, and Anna Hedenrud, PhD student at the site, for letting us visit the site and providing useful information about the cultivation. All of your efforts has really made it a great experience writing this thesis with the reality in Skrehalla on one hand and CoupModel in the other.
Abstract

One of Sweden’s visions set to be real before 2050 is to replace fossil fuels with renewable energy sources; this could be done partly by using biomass as a substitute. One kind of common energy crop is short-rotation willow coppice (SRWC) which is a fast growing energy crop cultivated by farmers in the agricultural landscape. In this report a SRWC cultivation in Västergörland, Sweden was studied and modelled with CoupModel to evaluate the sustainability in the cultivation, especially focusing on the green house gas balance in the system and eutrophication enhancing substances. One reference case and two different scenarios where modelled and evaluated (with enhanced fertilizing and a different climate) and a brief economic calculation was made for the farmer and the thermal station that buys the SWRC to judge the economic sustainability in the system. The study showed that there are several advantages with SRWC cultivation. In the studied case it was an economically sustainable substitute to fossil fuels, and an economically profitable crop for the farmer. It contributes to a renewable fuel mix and therefore to a reduced climate impact, and it appears to contribute less to eutrophication than traditional agricultural crops. In an area where the SRWC does not restrain food production it might be a sustainable energy source.
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1. Introduction

1.1 Background

Our time is one of many urgent challenges regarding how humanity affects the planet. Several changes must be brought about if we are to give future generations a healthy planet. In Sweden the parliament has adopted 16 environmental quality objectives that will make it possible to hand over a country to the next generation where the most urgent environmental issues are solved. The first objective concerns climate change. The main reason for the global warming is the combustion of fossil fuels (IPCC, 2013). Sweden has an ambitious zero net emission vision to be made real before 2050 which means, despite that the energy consumption should decrease, that fossil fuels must be replaced by renewable energy sources (Naturvårdsverket, 2012).

One option is to use biomass instead of fossil fuels and this is seen as a vital part of renewable energy supply in Sweden. Since 1970 Sweden has increased the energy production from biomass fuels from 40 TWh to 130 TWh in 2012 (Andersson, 2013). But using biomass fuels might also affect other environmental quality objectives. There could be impacts on the objects “a varied agricultural landscape” and “a rich diversity of plant and animal life” as energy crop cultivations compete with other types of land-use and might affect preservation of biodiversity and cultural heritage.

Analogically the change in land-use could affect the objective to maintain “a rich diversity of plant and animal life” (Naturvårdsverket, 2012). In Sweden more than 40 % of the nitrogen and phosphorus that eutrophic the sea due to human activities originate from agriculture, which means that the objective “zero eutrophication” could be affected by energy crop cultivations (Jordbruksverket, 2013). Forestry can cause problems related to the objective “natural acidification only”. Even though the use of biomass fuels might be seen as a better alternative than fossil fuels when it comes to climate change, there are other sustainability aspects to take into consideration.

There are different types of biomass fuels. Two big groups are biomass fuels from forestry and from agriculture (Egnell, 2008). In 2007 the Swedish government released a report (Regeringskansliet, 2007) concerning the agricultural production of bioenergy, now and in the future. In 2007 the agricultural bioenergy production only made up about 0.2 % of the Swedish energy production, but the report points out a potential to increase its contribution.

One common kind of energy crop in Sweden is short-rotation willow coppice (SRWC), which contains different willow species that are fast-growing and can be cultivated efficiently. It is used in both heat and power production. Every 3-5 years the crop is harvested mechanically. After harvest there is no need for replanting, the same plant can be used for 20-25 years (Dimitriou, 2005).

The Swedish Board of Agriculture (Hjulfors, 2014) describes several advantages of energy crop cultivation. Biomass plays an important role in substituting fossil fuels with renewables. Energy crop cultivations are usually part of a symbiotic relationship where the biomass fuels local heat and power plants, which distributes the heat or power locally. This gives rise to an efficient system with short transportation distances. Compared to annual crops, perennial crops such as SRWC take up more nutrients which leads to a reduced leakage of nitrogen. SRWC also requires less chemical pesticides and herbicides than traditional agricultural crops. The fields can be used for wastewater and sewage sludge purification, and for reducing the cadmium content in the soil. Often the energy crop fields cleans the sewage sludge more efficiently than a sewage treatment plant could do when it comes to fosfor and nitrogen. They also clean the water from heavy metals. Another use for willow field is as noise barriers alongside roads, or as protection from wind erosion in flat areas. Also, they
attract pollinators whose services benefit all cultivations nearby. Soils containing cadmium and other pollutants can be cleaned by willow cultivations.

In Sweden several farmers converted from grain production to energy crop production in the 90’s. This was a result of a government initiative in 1990 called “Omställning 90” offering economic compensation to farmers helping decrease the overproduction of grains in the country by a change of land use (Harding Olson, 1995).

1.2 Aims and objectives
The aim of this report was to evaluate the sustainability of a SRWC cultivation in Västergötland, central Sweden. The main focus was on effects on the greenhouse gas (GHG) balance, but other ecological as well as social and economic aspects of sustainability was considered and discussed.

This was done with the help of a case study of a willow cultivation in the area for which the following aspects were studied:

- What is the GHG balance of the studied system (specifically focusing on carbon dioxide and nitrous oxide)?
- How are the eutrophication enhancing substances affected?
- How are the answers to the questions above affected by a different climate scenario, and by a different dose of fertilizers?
- How is the economic budget for the cultivation formulated, and is it economically profitable for the farmer?
- What does the thermal station pay for the willow, and what would the cost be if the same amount of heat was to be produced from coal or oil?

1.3 Limitations
In this report methane and water vapor was not taken into account in the GHG-balance, this was partly because of big uncertainties in the model and partly because they are volatile and hard to relate to one specific action. There were not any expectations that there would be any large quantities of these gases in the specific system or that they would have a big effect on the GHG balance.
2. Methods and material

The ecological aspect of the sustainability was investigated by the use of CoupModel, a research tool that is described closer in the following section. Data and information for the modelling was provided by an ongoing research project at the site – “Holistiska mätningar av växthusgasemissioner från Salixodling under konventionella betingelser” – performed by the University of Gothenburg and funded by the Swedish Energy Agency. The economic sustainability of the willow cultivation was described based on a review of literature and discussion with researchers involved in the project, focusing on the economic aspects of the system.

2.1 Site description

The cultivation site described in the study is located at Skrehalla farm in Västergötland in central Sweden. SRWC has been cultivated at the farm since 1991 as a result of the Swedish government initiative Omställning 90. 3 ha were planted yearly between 1991 and 1994 resulting in a cultivation covering an area of 12 ha. The SRWC is harvested every four years and fertilizers consisting of 100 kg nitrogen per ha are added in the second and third year of every cycle. In the fourth year sewage sludge from the local sewage treatment plant is added as an extra fertilizer after the harvest. There are no herbicides or pesticides in use, except as preparation before replanting which must be done every 25 years, and no irrigation.

During harvest approximately 200 m³ of wooden chips are extracted per hectare. The chips are stored on the farm for a short period and time, before transported to the local thermal plant. 5-10 cm high stumps of the plants are left and the growth cycle starts over (Jonsson, 2014).

2.2 CoupModel

CoupModel is a process-based ecosystem model based upon two differential equations describing heat and water flows, which are solved using explicit numerical methods. The basic assumption behind the differential equations relies on the conservation of mass and energy, Darcy’s and Fourier’s law, that states that flows occur from gradients in water potential or temperature. The name CoupModel derives from different submodels that has been coupled to model both soil, heat and water processes, representing the whole ecosystem. One of the difficulties with using this model is that the knowledge it builds on is true for small field samples, but when it is used for different field scales it still has to be validated with real values because this difference is not yet well understood (Jansson, 2011).

2.3 Modelling approach

The simulation performed was based on a previous simulation of a forest ecosystem performed by Svensson (2008), but with some adjustments made to imitate the situation on the site described. To get realistic soil properties a well-known clay soil from Ultuna, Uppsala was used in the simulation. Climate data for a location 50 km northeast of the site was obtained from SMHI (Swedish Meteorological and Hydrological Institute), and duplicated to cover the simulation period. Information from the farmer and the researchers on the site regarding the management of the cultivation was applied in the simulation. Harvest takes place every 4 years and results in a removal of what is approximated to be 90% of the plant. Fertilizers consisting of 100 kg nitrogen per ha is added once in the second and once in the third year of the harvest cycle. After harvest sewage sludge, presumed to contain 25 kg nitrogen per ha, is added. The plant in the simulation, that is meant to act as SRWC, was given a maximum height of 5 m and a rooting depth of 0.4 m corresponding to available site information. In contrast to in a coniferous forest, in this simulation the plant could not take in organic nitrogen, but only mineral nitrogen. No field layer was included in the model.
In addition to the simulation described above, referred to as the reference scenario, two alternative scenarios were simulated. One identical to the reference in every way except for a fertilizer dose of 200 kg nitrogen per ha. The other one was performed with a climate change scenario applied. The climate model used was HadAM3H from Hadley Centre, United Kingdom used together with IPCC’s emission scenario A2, a scenario in which the development of renewable energy is slow and the energy efficiency improvements are poor (IPCC, n. d.).

All simulations were run from April 1992 to April 2016 covering 6 full harvest cycles.

2.4 Definitions

**Sustainable development** – development which meets the needs of current generations without compromising the ability of future generations to meet their own needs (Brundtland Kommissionen, 1987).

2.5 Economic sustainability measurements

To be able to say something about the economic sustainability of the willow cultivation a simple budget was done, comparing the cultivation’s annual revenues with its annual costs.

To say something about the profitability in a longer period of time the payback method and present value method was used. The payback method simply states in what time the initial costs of the project is paid back with help of the annual profits.

\[ PBV = \frac{\text{Initial cost}}{\text{Annual profit}} \]

The present value method summarises the future profits from the project and uses a discount rate to calculate their present value. When this NPV is compared to the initial cost of the project the project is considered profitable if the NPV is the same or higher than the initial cost.

\[ NPV = \frac{a_1}{(1+k)^1} + \frac{a_2}{(1+k)^2} + \cdots + \frac{a_n}{(1+k)^n} + \frac{R}{(1+k)^n} \]

Where:

- \( a_x \) = profit year \( X \)
- \( k \) = discount rate
- \( R \) = scrap value
- \( n \) = economic life of the project

(Olsson, 2010)
3. Results

3.1 Carbon balance

Figure 1 shows the carbon content in the plant over time and illustrates what happened during the simulation period. The growth of the plant can be seen during each of the 6 harvest cycles, reaching its peak before instantly approaching zero when the plant is harvested. The growth levels were higher than in the reference case in both scenarios. Which one that had the largest growth differs between the different harvest cycles.

Figure 2 – accumulated carbon balance for the system, showing ingoing and outgoing carbon during the simulation periods. The colours green, brown and red are used in the figure for the reference case, the scenario with increased fertilization and the climate change scenario respectively. All are measured in g C/m².

The input of carbon by photosynthesis varied greatly between the different simulations: 21 349 (reference case), 30 257 (fertilization scenario) and 33 773 (climate scenario) g C/m². 13 881 (reference case), 18 028 (fertilization scenario) and 21 127 (climate scenario) g C/m² left the system.
as respiration and 8,134 (reference case), 11,871 (fertilization scenario) and 13,904 (climate scenario) g C/m² left with the harvest. The variable Difference in soil shows the difference between initial and final carbon content. In the fertilization scenario the carbon content in the soil increased with 315 g C/m², in the other cases it decreased with 707 g C/m² (the reference case) and 303 g C/m² (the climate change scenario). The water leakage was similar in all three cases: 41, 43 and 46 g C/m².

3.2 Nitrogen balance

Figure 3 - accumulated nitrogen balance for the system, showing ingoing and outgoing nitrogen during the simulation period. The colours green, brown and red are used in the figure for the reference case, the scenario with increased fertilization and the climate change scenario respectively. All are measured in g N/m².
In all three simulations 19 g N/m² was deposited from the atmosphere. In the reference case and in the climate change scenario 133 g N/m² was added as fertilization, and 253 g N/m² in the scenario with increased fertilization. The N₂O emissions were 9 g N/m² in the reference and fertilization scenarios, and 8 g N/m² in the climate scenario. Furthermore 43 (reference case), 62 (fertilization scenario) and 12 (climate scenario) g N/m² left the system as N₂ emissions, and 92 (reference case), 99 (fertilization scenario) and 82 (climate scenario) g N/m² as NO emissions. The harvest contained 35 (reference case), 56 (fertilization scenario) and 48 (climate scenario) g N/m². Leakage water transported 48 (reference case), 60 (fertilization scenario) and 84 (climate scenario) g N/m² from the system. In all cases the nitrogen content in the soil decreased: 77 (reference case), 17 (fertilization scenario) and 83 (climate scenario) g N/m².

<table>
<thead>
<tr>
<th>Nitrogen loss allocation</th>
<th>Reference case</th>
<th>Fertilization scenario</th>
<th>Climate scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O</td>
<td>4 %</td>
<td>3 %</td>
<td>3 %</td>
</tr>
<tr>
<td>N₂</td>
<td>19 %</td>
<td>21 %</td>
<td>5 %</td>
</tr>
<tr>
<td>NO</td>
<td>40 %</td>
<td>34 %</td>
<td>35 %</td>
</tr>
<tr>
<td>Harvest</td>
<td>15 %</td>
<td>19 %</td>
<td>20 %</td>
</tr>
<tr>
<td>Water leakage</td>
<td>21 %</td>
<td>21 %</td>
<td>36 %</td>
</tr>
</tbody>
</table>

Figure 4 The allocation of all the nitrogen losses divided into the reference case and the two scenarios. All shown as percentage of total loss for the different case and scenarios.

Figure 4 shows how the input of nitrogen is distributed percentually between the different losses. In the reference case most of the nitrogen leaves the system as NO (40%), 21 % leaks with the water 19% leaves as N₂ gas, 15 % goes in to the harvest and 4% leaves as N₂O. When more fertilizer is added to the system most nitrogen still leaves as NO (34%), but just as much nitrogen leaves as N₂ gas and leaks with the water (21 %), 19% leaves as harvest and 3% leaves as N₂O gas. In the scenario with a more extreme climate most of the nitrogen leaks away with the water (36%), almost as much leaves as NO gas (35%), 20% leaves in the harvest, 5% as N₂ gas and 3% leaves the system as N₂O.

Figure 5 – accumulated nitrogen in leakage water, organic nitrogen (dark bar) and mineral nitrogen (light bar). All measured in g N/m²^2
Figure 5 illustrates the difference in accumulated nitrogen in leakage water between the different scenarios. The dark and light coloured part symbolizes organic and mineral nitrogen respectively. 2.6 (reference case and fertilization scenario) and 3.4 (climate scenario) g N/m² was organic nitrogen and 45.7 (reference case), 57.4 (fertilization scenario) and 80.4 (climate scenario) g N/m² was mineral nitrogen.
3.3 Economy

The economic budget was constructed by information about the revenues from the farmer (Jonsson, 2014) and set to 26 000 SEK per hectare, this is equal to an annual revenue of 78 000 SEK when the farmer sells three hectare per year. The annual costs added up to 19 116 SEK consisting of fertilizer (6 hectare à 686 SEK, 4 116 SEK), supervision (12 hectare à 200 SEK, 2 400 SEK), harvest and transportation costs (3 hectare à 2 200 SEK, 6 600 SEK) and common business expenses (12 hectare à 500 SEK, 6 000 SEK)(Rosenqvist, n.d.). This means that the farmer has an annual profit of 58 884 SEK. There is not any salary for the work of the farmer included in this budget nor any taxes.

When the cultivation was established in 1991 to 1995 the farmer received a planting subsidy of 10 000 SEK per hectare, the planting costs on the other hand was about 11 000 SEK per hectare. With three hectare planted every year during four years and other costs as given above the yearly investment during the first four years where 5 100 SEK, 9 258 SEK, 13 416 SEK and 15 516 SEK respectively.

With an interest rate at 4 percent the initial investment was calculated to 1991’s level at 40 199 SEK. The annual revenues is 58 884 SEK and this gives an NVP at 756 482 SEK. Compared to the initial investment this makes a total profit of 716 283 SEK. In the total lifespan of the project this makes a profit of 28 651 SEK per year. The NVP-quota divides the NVP-value by the initial cost and shows that the investment pays of 1880 %, that means that the project pays for itself almost 19 times during its lifespan.

The PBV shows that the project has paid for itself in about 8 months, which is approximately 3% of the lifespan of the project. If you include the four years of investment prior to the 8 months it has paid for itself in 56 months or 18,7 % of the lifespan.

(See calculations in Appendix I)

<table>
<thead>
<tr>
<th>Fuel data from thermal plant</th>
<th>Willow wood chips</th>
<th>Coniferous wood chips</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part of fuel mix</td>
<td>15 %</td>
<td>84 %</td>
<td>1 %</td>
</tr>
<tr>
<td>Price [SEK / MWh]</td>
<td>200</td>
<td>205</td>
<td>970</td>
</tr>
<tr>
<td>Energy content [MWh / m³]</td>
<td>0.67</td>
<td>0.83</td>
<td>9.96</td>
</tr>
</tbody>
</table>

Figure 6 – Fuel data for willow wooden chips, coniferous wood chips and oil. The data shown is how big part of the fuel mix it stands for in the thermal plant, (in percent) the price the thermal plant pays (in SEK/MWh) and its energy content (in MWh/m³).

Figure 6 shows data from the thermal plant in Grästorp. The price paid per MWh for willow wood chips, coniferous wood chips and oil, how much they use of each fuel in their fuel mix and the energy contents per volume unit (Klahr, 2014).
4. Discussion

4.1 Carbon balance

Figure 2, illustrating the carbon balance for the system, contains some interesting results of the simulations. As might be expected an increased fertilization gave rise to an increased intake of CO$_2$ from the atmosphere by photosynthesis. Fertilizers cause an increased growth as long as growth is not restricted by other substances necessary to the plant, which leads to an intensified photosynthesis. The carbon uptake was even larger in the climate change scenario, which is in accord with the results of Cline (2007). Cline concludes that Scandinavia is one of relatively few regions in the world where agricultural production will benefit from global warming.

As harvest is increasing proportionally to the growth, and therefore to the CO$_2$ uptake, the corresponding increase in harvest was observed. When it comes to ecological sustainability the harvest is a variable of interest as the crop substitutes fossil fuels. 1 m$^3$ willow chips has about the same energy content as 0.07 m$^3$ or 70 L oil. This is equivalent to 1008 m$^3$ oil that can be substituted by willow during the 24 years of the reference simulation. Of course the substitution effect was even better in the two scenarios where the harvest was bigger: 1472 (fertilization scenario) and 1724 (climate scenario) m$^3$ (see calculations in Appendix II).

The increased respiration observed in the two scenarios, compared to the reference, is a logical consequence of increased plant growth as a large share is respired from the plant. However, one could expect that, unlike in the simulation, the relative size of the respiration from the organisms in the soil would increase in the climate change scenario, with high temperatures supporting degradation. This would be interesting to analyse further, as this possible deviation from the real situation might cause errors in other variables in the model.

4.2 Nitrogen balance

In figure 3 it is shown that there were differences in the allocation of nitrogen losses when comparing the three simulations, with two major differences. The first one was that the N$_2$ emissions in the climate change scenario was significantly lower than in the other two simulations and the second one is that the nitrogen level in leakage water was significantly higher in the climate scenario.

There are three likely reasons that the water leakage is higher in the climate scenario, disregarding that the model might be wrong. It could be an effect caused by a higher temperature that causes the nitrogen to dissolve more easily or an effect of higher water flows due to increased precipitation that leaks the nitrogen from the system. There might also be an effect of when the fertilizers were added to the soil in the model. If it is done in times of high water flows most if it could leak away. In reality fertilizers might be added at other times than in the simulation.

The results in the reference simulation stated that 48 g N/m$^2$ or, if split between the 24 years of simulation, 20 kg N/ha left the system yearly with leakage water. According to a study by the Swedish Environmental Protection Agency (Johnsson, 2002) the mean nitrogen leakage in the area for different soil types and different crops was slightly lower than 30 kg N/ha in 1999. Their study is for different annual crops. The Swedish Board of agriculture states that cultivations with perennial crops such as SRWC leaches less nitrogen leakage than annual crops. Hence 20 kg N/ha yearly might be a realistic value. In the fertilization and climate scenarios the leakage was 25 and 35 kg N/ha*year respectively.
The \( \text{N}_2\text{O} \) emissions are about 5 times higher in this model than the field data from the site. This could be an effect of the sensitivity in the system and uncertainties when trying to describe what happens in a fertilized SRWC cultivation. In the nitrogen budget of this system most of the nitrogen leaves the system as \( \text{N}_2 \) or \( \text{NO} \) that doesn’t have any effect on either eutrophication or global warming. If this is a miscalculation in the simulation of the system, and in reality more \( \text{N} \) leaches, the eutrophication effects of using SRWC as energy source might have been underestimated. To confirm if these things are actual errors in the model it would be interesting to sample more field data of leaching \( \text{N} \) and \( \text{N}_2\text{O} \) emissions.

In the three different simulations the \( \text{N}_2\text{O} \) emissions were the same regardless if more \( \text{N} \) was added, it was actually lower percentually with more fertilizer and a warmer climate than in the reference scenario. This might indicate a miscalculation in the simulation. In the case of the fertility of the soil it has been affected in all three scenarios, the nitrogen in the soil leached but slightly less in the scenario where more fertilizer was added.

### 4.3 Economy

Both the NVP and the PBV showed that the cultivation of SRWC is profitable in the long run. With a payback period of 19% of the whole project time and a project that pays for itself 18 times in its lifespan it has quite a big margin until it’s not profitable. The annual profit calculated (58 884 SEK per year) is also consistent with the annual profit Rosenqvist (n.d.) has calculated which is about 52 000 SEK per year for a cultivation of 12 hectare, which would indicate that the magnitude of the calculation is in order.

If the farmer would use the area for grain cultivation such as wheat or barley his profit would be about half, or as low as one tenth of the profit he makes from cultivating SWRC (Rosenqvist, n.d.). This indicates that SRWC is a profitable crop to cultivate in this land area and the farmer also holds a full time work on the side of the cultivation, which means that he is not financially dependent on the cultivation.

The SRWC produced in the reference case, equivalent to about 9600 MWh, serve to reduce the costs of the local thermal plant with 325 000 SEK per year compared to if they would have used oil instead. As Skrehalla is only one of many suppliers of willow chips to the thermal plant, it is clear that energy from SRWC is an economically sustainable alternative to fossil fuels in heat production.

### 4.4 Sustainability

So, is a SRWC cultivation like the one in Skrehalla able to play a part in a sustainable development? To begin with the substituted 1008 m\(^3\) oil in the reference simulation can be roughly estimated to be equivalent to 3150 t CO\(_2\) (Appendix II) that would have been emitted to the atmosphere and added to the carbon cycle if it was not for the SRWC produced in the reference case. This was calculated using the assumption that the CO\(_2\) emissions from combustion of oil is 314 kg CO\(_2\)/MWh (centre, n.d.). That is a very positive effect that is however to some extent counteracted by the N\(_2\)O emissions from the cultivation. As mentioned earlier the values regarding those emissions generated by the simulations were several times higher than field data, and therefore questionable. If the emissions during the simulation period really were correct at 9 g/m\(^2\) that would be equivalent to about 1.6 t N\(_2\)O (Appendix II), or 0.3 t if the field data are correct. N\(_2\)O contributes about 290 times more than CO\(_2\) to global warming (Norman et al, 2008) which means that these emissions are equivalent to 460 (simulations) or 90 (field data) t CO\(_2\). The net reduction of CO\(_2\) emission compared to the same amount of energy being produced from oil is hence at least around 3 700 t for the complete simulation period of 24 years.
This indicates that SRWC is an energy source that contributes to the environmental objective “reduced climate impact” as one of many renewable sources substituting fossil fuels. In the fertilization and climate scenarios the substituted oil was equivalent to even larger CO₂ emissions, 4 600 and 5400 t CO₂ respectively. The N₂O emissions were similar to or slightly lower than in the reference case. This means that in terms of a reduced climate impact the results from this study suggests that the SRWC production of Skrehalla would be even more effective with increased fertilization and with an escalating, “worst case scenario” global warming.

A very important aspect of sustainability in Sweden is avoiding eutrophication caused by nutrients in leakage water from agriculture. As the name of the objective “zero eutrophication” indicates, Sweden has a zero vision for this problem. As mentioned in chapter 4.2 the nitrogen leakage in the reference case is, even though not zero, lower than the mean leakage in the area. In the two scenarios the leakage was even larger, which of course is a threat. Still the leakage from other crops, annual crops in particular, would probably be even larger in a scenario with a dramatic climate change. The Swedish Board of Agriculture (Hjulfors, 2014) writes that land used for perennial energy crops such as SRWC has been shown to leach less nitrogen than grain cultiva- tions. In summary both this study and the information from the Swedish Board of Agriculture states that the leakage of nutrients from this kind of agriculture is lower than from traditional grain cultivation, which is a step towards leakage levels low enough to stop the eutrophication caused by agriculture. Even though not scientifically reliable or validated this study showed very high leakage levels in the climate change scenario. These results would be interesting to validate with other studies.

It is hard to say how SRWC cultivation affects the objective “a varied agricultural landscape”. An advantage is that the land used for the willow can be re-transformed to what it was before, or be used in another way. With other words there is no lock-in effect when growing SRWC, which benefits future variety. The Swedish Board of Agriculture (2014) states that energy crops have a positive effect on the variation as agriculture has become very intensive with large areals with one particular crop. In these kinds of areas a willow cultivation might provide a welcome landscape variation that benefits the diversity of species thriving in the area, which is also in accord with the environmental objective “a rich diversity of plant and animal life”. The board actually states that there are several studies confirming that fields with energy crops host a higher biological diversity than traditional cultivations.

Keoleian and Volk (2005) states that SRWC is a crop with potential for sustainable energy production. It is a fast-growing crop with a long life-cycle, and also has a high energy content. To further increase the sustainability they suggest that the petroleum used by farm equipment is substituted with bio diesel, as this makes up a significant part of the fossil input in the production. Another great source of fossil input is synthetic fertilizers, which can be substituted with organic fertilizers. According to their study the GHG emissions from the complete willow life cycle is 40-50 g CO₂ equivalents per kWh electricity. They also suggests a significant reduction of emissions of nitrogen oxides and sulphur dioxide compared to use of fossil energy. When it comes to economical sustainability they draw the conclusion that willow would be competitive on the market if the positive externalities of the willow along with the negative externalities of fossil fuels where taken into consideration. This is somehow in conflict with the economic analysis of this study, which suggests a significant cost difference between the SRWC chips and oil which is much more expensive per energy unit.

Another advantage of SRWC and other types of biomass, mentioned by Keoleian and Volk (2005), is that in contrast to other renewables, it can be stored. This means that it should be possibly to use in
power plants to handle peaks in power demand, the same way that oil is used when non-storable energy sources as wind power cannot satisfy the momentary demand. Also it means that it is an energy source that can be used all year and not only during the months it can be produced, which is not the case with many other renewables.

It is impossible to discuss biomass production without mentioning the conflict between biofuel production and food production. In many parts of the world food is a scarce commodity and biomass production competes with food production at the expense of the food supply to the local people. In Sweden that is not an urgent problem. Even if it would become a problem, the advantage of SRWC is that it is possible to go back to for example grain cultivation if needed. Also, as the SRWC can be grown on land not suitable for food cultivation, for example on soils containing cadmium, it does not necessarily have to compete with food production.

4.5 Criticism of method and sources

There are significant uncertainties in the results of this study. The modelling program CoupModel had at the time not before been used to model a similar system. In order to be reliable at all, it needs to be calibrated with the help of field data, which was not done in these simulations. Some of the results were similar to field data, but some were not which might indicate that other parameters are incorrect as well. This was taken into consideration in the discussion.

Many of the sources that were used for this report are authorities, as IPCC, the Swedish Board of Agriculture (Jordbruksverket) and the Swedish Environmental Protection Agency (Naturvårdsverket). This should give material from these sources verity, but content might be colored by interests from the authorities. Also, many sources used were scientific articles and reports that should be reviewed and therefore reliable.

In the economic budget a lot of secondary sources were used because there was no access to primary information. Even though the report from JTI and SP is seen as a reliable source from Swedish authorities it is constructed to encourage farmers to plant SWRC and to show that it is profitable. This might imply that the profits are overrated or that the costs are underestimated in the report, but even if this was the case the profits shown in the calculations are so great that if they lowered it would still imply that the farmer made a profit from the cultivation. There are costs that’s not covered in the budget such as salary for the farmer and taxes, but there are also subsidies for the farm that’s not included. These would of course have had effected the results but the magnitude of the profits are still quite close to the truth. Also the interest rate is set to 4% and could have been both higher and lower, but as the results are greatly positive a higher rate would just had lowered the profits a bit, not made the project unprofitable.
5. Conclusions
The study showed that 8 134 (reference case), 11 871 (fertilization scenario) and 13 904 (climate scenario) g C/m² left with the harvest during the simulation period of 24 years. This is for the 12 ha during the 24 years equivalent to 3150, 4600 and 5400 t CO₂ emissions respectively if the same energy had been produced from oil.

In the simulations about 1.6 t N₂O was emitted during the 24 years in the reference case and the fertilization scenario, or 460 CO₂ equivalents, and slightly less in the climate scenario. According to field data the emissions might be up to 5 times lower.

There was, according to the model, a leakage of nitrogen of 20 (reference case), 25 (fertilization scenario) and 35kg (climate scenario) N/(ha*year).

The economic analysis suggests that the SRWC project in Skrehalla did pay for itself in 8 months after the end of the 4 years of investments, which is approximately 19 % of the lifespan of the project. The net present value in 1991 was about 700 000 SEK.

If the local thermal station was to replace the willow chips from Skrehalla with oil it would cost them 325 000 SEK per year.

In summary, there are several advantages with SRWC cultivation. In the studied case it was an economically sustainable substitute to fossil fuels, and an economically profitable crop for the farmer. It contributes to a renewable fuel mix and therefore to a reduced climate impact, and it appears to contribute less to eutrophication than traditional agricultural crops. In an area where the SRWC does not restrain food production it might be a sustainable energy source.
6. References


Coupled heat and mass transfer model for soil-plant-atmosphere systems.


KLÄHR, T. 28 march 2014 2014. RE: E-mail conversation with Lantmännen Type to FALK, H.


Appendix I – Economy

Economic budget for the cultivation

<table>
<thead>
<tr>
<th>Revenues</th>
<th>Per ha</th>
<th>Annually</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest</td>
<td>26 000 SEK</td>
<td>78 000 SEK</td>
</tr>
</tbody>
</table>

**Costs**

| Fertilization   | 686 SEK | 4 116 SEK |
| Supervision     | 200 SEK | 2 400 SEK |
| Harvest         | 1 250 SEK | 3 750 SEK |
| Transport       | 950 SEK | 2 850 SEK |
| Common business expenses | 500 SEK | 6 000 SEK |

**Results**

| Results         | 22 414 SEK | 58 884 SEK |

Calculation of the initial investment

Calculated with an interest rate of 4%.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting subsidy</td>
<td>10 000 SEK</td>
<td>30 000 SEK</td>
<td>30 000 SEK</td>
<td>30 000 SEK</td>
<td>30 000 SEK</td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planting costs</td>
<td>11 000 SEK</td>
<td>33 000 SEK</td>
<td>33 000 SEK</td>
<td>33 000 SEK</td>
<td>33 000 SEK</td>
</tr>
<tr>
<td>Fertilization</td>
<td>686 SEK</td>
<td>0 SEK</td>
<td>2 058 SEK</td>
<td>4 116 SEK</td>
<td>4 116 SEK</td>
</tr>
<tr>
<td>Supervision</td>
<td>200 SEK</td>
<td>600 SEK</td>
<td>1 200 SEK</td>
<td>1 800 SEK</td>
<td>2 400 SEK</td>
</tr>
<tr>
<td>Common business expenses</td>
<td>500 SEK</td>
<td>1 500 SEK</td>
<td>3 000 SEK</td>
<td>4 500 SEK</td>
<td>6 000 SEK</td>
</tr>
<tr>
<td>Results</td>
<td>---</td>
<td>5 100 SEK</td>
<td>9 258 SEK</td>
<td>13 416 SEK</td>
<td>15 516 SEK</td>
</tr>
<tr>
<td>Results in 1991’s level</td>
<td>---</td>
<td>5 100 SEK</td>
<td>8 902 SEK</td>
<td>12 404 SEK</td>
<td>13 794 SEK</td>
</tr>
</tbody>
</table>

**Total investment**

40 199 SEK

Calculation of the net present value, NVP

With the scrap value of the cultivation set to 0 and an interest rate of 4%:

\[
NPV = \frac{58 884 \text{ SEK}}{(1 + 0.04)^4} + \frac{58 884 \text{ SEK}}{(1 + 0.04)^5} + \cdots + \frac{58 884 \text{ SEK}}{(1 + 0.04)^{25}} = 756 482 \text{ kr}
\]

NPV compared to the initial cost = 756 482 SEK - 40 199 SEK = 716 283 SEK

With a lifespan of 25 years this is an annual profit for the project of \(\frac{716 283 \text{ kr}}{25} = 28 651 \text{ kr}\)

The NVP-quota between the NVP-value and the initial cost \(\frac{756 482 \text{ kr}}{40 199 \text{ kr}} = 18.8\)

Calculations with the payback method

\[
PBV = \frac{40 199 \text{ kr}}{58 884 \text{ kr}} = 0.68
\]

This is equal to 0.68 · 12 ≈ 8 months, including the four years of investment this is 56 months.

Compared to the lifespan of the project it has paid for itself in \(\frac{56}{12} \approx 18.7\) % of the time.
Appendix II – GHG calculations
Effect of substituting oil with willow

**Harvest volume during the simulation period**

\[ \text{harvest volume}_{\text{reference}} = 200 \frac{m^3}{ha \times 4 \text{ years}} \]  
(\text{Jonsson, 2014}) = 200 \times 12 \times 6 \ m^3  
= 14400 \ m^3 \text{ during the simulation period} 

Assuming that the harvest volume is proportional to the carbon content in the harvest, \( C_{\text{harvest}} \), the harvest volume in the two scenarios was calculated by multiplying the harvest volume in the reference case with the quotient of the harvest carbon content in the scenario divided by the harvest carbon content in the reference case:

\[ \frac{C_{\text{harvest, fert.scenario}}}{C_{\text{harvest, reference}}} = 1.46 \]

\[ \text{harvest volume}_{\text{fert.scenario}} = 1.46 \times 14400 = 2024 \ m^3 \text{ during the simulation period} \]

\[ \frac{C_{\text{harvest, climate scenario}}}{C_{\text{harvest, reference}}} = 1.71 \]

\[ \text{harvest volume}_{\text{climate scenario}} = 1.71 \times 14400 = 24624 \ m^3 \text{ during the simulation period} \]

**Substituted oil**

Energy content in the willow used in the local power plant = 0.67 \( MWh/m^3 \). Energy content in the willow used in the local power plant = 9.96 \( MWh/m^3 \) (Klahr, 2014).

\[ \text{The quotient of the energy contents} = \frac{0.67}{9.96} = 0.07 \]

*When it comes to energy content 1 m\(^3\) willow equals 0.07 m\(^3\) oil*

14 400 \( m^3 \) willow equals \( 14400 \times 0.07 = 1008 \ m^3 \) oil substituted by willow in the reference case.

21 024 \( m^3 \) willow equals \( 0.07 \times 21024 = 1472 \ m^3 \) oil substituted by willow in the fertilization scenario.

24 624 \( m^3 \) willow equals \( 0.07 \times 24624 = 1724 \ m^3 \) oil substituted by willow in the climate scenario.
The N₂O emissions

Emission of N₂O during the simulation period = 9 \( \frac{g \text{N}}{m^2} \) in the reference case and the fertilization scenario (and slightly smaller in the climate scenario).

Molar mass of N = \( M_N = 14 \frac{g}{mol} \)

Amount of substance \( n_N = \frac{9g}{14g/mol} = 0.643 \text{ mol} \)

0.643 mol N equals \( \frac{0.643}{2} = 0.321 \text{ mol N}_2O \)

Molar mass of N₂O \( M_{N2O} = 44 \frac{g}{mol} \)

Mass of N₂O \( m_{N2O} = n_{N2O} \times M_{N2O} = 0.321 \times 44 = 14 \text{ g} \)

\[ 14 \frac{g \text{N}_2O}{m^2} \times 12 \times 10000 \text{ m}^2 = 1680 \text{ kg N}_2O \text{ emitted during the simulation period.} \]

CO₂ emissions from oil combustion

The CO₂ emissions from combustion of oil was assumed to be 314 kg CO₂/MWh (Biomass Energy Center, 2014). This was used to calculate the CO₂ emissions avoided by willow combustion in the three scenarios.

Reference case

\[ 1 \text{008 m}^3 \text{ substituted oil} \times 9.96 \frac{MWh}{m^3} = 10 \text{040 MWh} \]

\[ 314 \text{ kg CO}_2 \text{ MWh} \times 10 \text{040 MWh} \approx 3150 \text{ t CO}_2 \]

Fertilization scenario

\[ 1 \text{472 m}^3 \text{ substituted oil} \times 9.96 \frac{MWh}{m^3} = 14 \text{610 MWh} \]

\[ 314 \text{ kg CO}_2 \text{ MWh} \times 14 \text{610 MWh} \approx 4600 \text{ t CO}_2 \]

Climate scenario

\[ 1 \text{724 m}^3 \text{ substituted oil} \times 9.96 \frac{MWh}{m^3} = 10 \text{040 MWh} \]

\[ 314 \text{ kg CO}_2 \text{ MWh} \times 10 \text{040 MWh} \approx 5400 \text{ t CO}_2 \]

Economical benefit from substitution
The local thermal plant pays 200 SEK per MWh for the willow, and 970 SEK per MWh for the oil (KLahr, 2014).

The cost for buying all the willow produced in the reference case would be $14\,400 \text{ m}^3 \text{ willow} \times 0.67 \frac{\text{MWh}}{\text{m}^3} \times 200 \frac{\text{SEK}}{\text{MWh}} = 1\,929\,600 \text{ SEK}$

The cost for using oil to produce the same amount of heat would be $1\,008 \text{ m}^3 \text{ oil} \times 9.96 \frac{\text{MWh}}{\text{m}^3} \times 970 \frac{\text{SEK}}{\text{MWh}} = 9\,738\,490 \text{ SEK}$

This results in the following savings for the thermal plant

$9\,738\,490 - 1\,929\,600 \approx 7\,800\,000 \text{ SEK}$

$\frac{7\,800\,000 \text{ SEK}}{24 \text{ years}} = 325\,000 \text{ SEK/year}$