THE ENERGY BALANCE OF ENERGY CROP IRRIGATION

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Abstract

This paper examines the water requirements in energy crops production and the energy costs and benefits of irrigating energy crops. We find that energy inputs for irrigation system establishment is relatively small, while the energy inputs for pumping can reduce the net energy output substantially if the water application is large and the combined pumping requirement of water lift and pressurization is high. We also present an estimate of the net energy response to municipal wastewater and drainage water irrigation of willow plantations. The aim is to establish whether bioenergy systems based on willow would gain or lose in net energy terms when the willow plantations are used as vegetation filters. In the case of municipal wastewater irrigation, we find that the energy input for system establishment and pumping is higher than the combined energy savings gained from reduced fertilizer requirements and substitution of N and P removal in conventional wastewater treatment plants. In the case of irrigation using drainage water from intensively cultivated cropland, we find that the energy input for establishment and pumping is lower than what is gained from reduced N-fertilizer requirements. The major reason is lower pumping requirements due to assumed location of the drainage water storage pond and willow plantation at the same site. Both vegetation filter systems have a positive net energy gain thanks to expected yield increases.

1 INTRODUCTION

There are major expectations that biomass will supply large amounts of CO_2 neutral energy for the future. Modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development [1-3], and several authoritative organizations (e.g., International Energy Agency, World Energy Council, Shell, Greenpeace, UNDP and IPCC) emphasize bioenergy as an attractive option for climate change mitigation in the energy sector. Many scenarios of globally sustainable energy development suggest a huge growth in the use of biomass for energy, with dedicated bioenergy plantations being the major biomass supply source (see [4] for a review of 17 assessment of the global bioenergy potential).

A large-scale expansion of energy crop production could lead to a large increase in evapotranspiration appropriation for human uses, potentially as large as the present evapotranspiration from global cropland [5]. The implications for global and regional water resources and use depend on many factors, one of which is whether irrigation of energy crops will become frequent. The extent of energy crop irrigation will depend on the economics of such practices. One crucial question in this context will be whether energy crop irrigation pays off energetically.

The energy balance of bioenergy systems has been analyzed extensively. Besides clarifying whether specific bioenergy systems are sinks or sources of energy, assessments of the energy use in biomass production and conversion to fuels/electricity are employed in order to evaluate the overall environmental performance of bioenergy systems. In the context of competition for water, the net energy response to irrigation (and the value of biomass for energy vs. for food/feed/fiber purposes) will determine whether it is preferable to irrigate energy crops instead of food/feed/fiber crops. Few energy balance studies explicitly report energy requirements for irrigation. Usually rainfed cultivation is analyzed. In the case that bioenergy systems involving energy crop irrigation is analyzed, the energy inputs for irrigation are normally embedded in total farm electricity and fuel inputs.

This paper examines the water requirements in energy crops production and the energy costs and benefits of irrigating energy crops. The paper is structured as follows: the water requirements of energy crops are assessed in Section 2. Data on the efficiency in converting the harvested biomass into fuels and/or electricity is then used in order to estimate the water requirements of different bioenergy chains. Different irrigation systems, and their efficiency, are discussed in Section 3, where also the energy inputs for water pumping and irrigation system establishment are estimated. In Section 4, the net energy results of using willow for wastewater treatment are investigated. Finally, in Section 5, the overall conclusions are presented and discussed.

2 WATER REQUIREMENTS IN ENERGY CROP PRODUCTION

The water evapotranspiration (ET)[1] in energy crop production is given for different bioenergy systems in Table 1. The wide ranges in Table 1 can be explained by: (i) varying water use efficiency (WUE)[2] among energy crops, related to crop physiology, soil and climate, and agronomic practice (including WUE modification options such as changing sowing date and plant density, supplemental irrigation and microclimate manipulation); (ii) variations in the share of the aboveground biomass that is usable as feedstock in electricity/fuels production; and (iii) different conversion efficiencies of technology options available for biofuel production and electricity generation. These aspects are discussed in somewhat more detail in [5, 6].

Table 1. Energy crop ET per unit bioenergy feedstock and gross bioenergy production. Based on [5, 6].

Biofuel/Feedstock		WUE[a]	Energy crop ET[b]	
		(kg DM ha^{-1} mm^{-1} ET)	(Mg GJ^{-1} feedstock)	(Mg GJ^{-1} gross bioenergy)
Biodiesel	rapeseed	9-12	46-81	100-175
Ethanol	sugarcane	17-33	23-124	37-155
	sugar beet	9-24	57-151	71-188
	corn	7-21	37-190	73-346
	wheat	6-36	21-199	40-351
<u>Lignocellulosic crops</u>		10-95		
Ethanol			7-68	11-171
Methanol			7-68	10-137
Hydrogen			7-68	10-124
Electricity			7-68	13-195

[a] The WUE is given as kg aboveground DM mm^{-1} ET. The depth of water supply is often given in mm, where one mm corresponds to 10 Mg water ha^{-1}. 50 kg DM mm^{-1} is equivalent to a water loss as ET of 200 g per g DM produced. DM=dry matter.

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[1] Water is lost to the atmosphere in the process of transpiration. Water vapor diffuses from inside the leafs to the atmosphere through the stomata, as carbon dioxide diffuses in the opposite direction. Water is also lost to the atmosphere through evaporation from the soil and from the plant leaves. These losses are collectively designated evapotranspiration (ET) losses

[2] The concept water use efficiency (WUE) is a measure of the yield (photosynthetic, biological, or economic) per unit of water (transpiration, evapotranspiration, or applied water). It can be defined on various levels (leaf, plant, field, ecosystem) and for various purposes (agronomic, engineering, basin-level planning). In this paper, WUE is defined as the amount of dry aboveground biomass produced per unit of evapotranspired water.

[b] Lower range numbers refer to systems where: (i) harvest residues from non-lignocellulosic crops (50 percent of total) are used for power production (at 45 percent efficiency); or (ii) higher efficiencies in processing lignocellulosic crops are achieved. When ethanol is produced from sugarcane or lignocellulosic feedstocks, process by-products (bagasse and lignin, respectively) are used for internal heat and electricity. Here, lower range numbers refer to systems designs allowing for export of electricity in excess of internal requirements.

The lower bound data for energy crop evapotranspiration in Table 1 combine the highest WUE data with systems having a conversion efficiency in the upper range of what is found in literature, and where harvest residues and process by-products are used for energy purposes. The higher bound data in Table 1 combine the lowest WUE data with systems with lower conversion efficiency that do not use harvest residues or process by-products for energy. The numbers in Table 1 are not normalized to take into account the site-specific vapor pressure deficit conditions, and consequently no conclusions can be drawn regarding inter-crop differences in WUE. See, [6] for a more extensive discussion of T, ET and WUE and how factors influencing them can be modified. Note also that water use in the production of biofuels or in generation of electricity is not included in Table 1. However, this water use is low compared to evapotranspiration in energy crop production [5].

3 IRRIGATION SYSTEM CHARACTERISTICS

3.1 Efficiency and water supply in irrigated systems

Not all water in irrigated agriculture is supplied by means of irrigation. Part of the water is supplied by rainfall and to some extent by capillary rise from shallow water tables. On the average, irrigated agriculture takes around 40 percent of water from irrigation [7]. On the other hand, more water must be applied to the field than what is required for crop growth, since part of the water is lost to nonproductive evaporation, surface runoff and deep percolation. Worldwide, around 40 percent of the applied irrigation water is transpired by the crop [8]. Various definitions of irrigation efficiency exist, with emphasis ranging from field to basin scale level (see, e.g., [9-14]). The traditional evaluation of efficiency at the field level is computed on the basis of the ratio between water applied to the field and water consumed by the crops. Field-level efficiency measures have been criticized as potentially misleading for basin-level planning where aspects such as downstream re-use of runoff losses and basin-level competition must be considered. For the purpose of this paper, however, the field level efficiency is appropriate.

In addition to crop choice, climate, and soil factors, the irrigation efficiency depends on the irrigation system design and management. Traditional gravity-flow systems are characterized by comparatively high water loss [12], but require less pumping energy since the water distribution is accomplished by gravity. Systems for recovery of runoff water can increase the efficiency at the field level. In the United States, where gravity-flow systems account for slightly more than half of the irrigated area, efficiencies typically range from 40 to 65 percent [15]. In many surface irrigation systems in Asia, only 25-40 percent of the water channeled to fields is available for crop use [16], but efficiencies can be higher on a basin-wide scale thanks to re-use of water as it moves downstream. Sprinkler systems have efficiencies ranging from 60 to 85 percent under proper management [15, 17]. Low-flow irrigation systems, including drip and trickle irrigation, can reach very high efficiencies (90-95 percent), but are most commonly used for high-value plants, such as vegetables, and in vineyards.

3.2 Energy input for irrigation system establishment and for water pumping

The energy input for water pumping is calculated based on a modification of the equation suggested by Sloggett [18] (Equation 1). The first factor in this equation accounts for the primary energy required to lift 10 Mg water 1 meter (J mm^{-1} (m lift)$^{-1}$, where 1 mm corresponds to 10 Mg water per ha). The second factor accounts for the amount of water to be lifted and/or pressurized (mm). The third factor is total dynamic head (TDH), representing required meters of lift plus pressurization requirements.

$$E = (10000g\ n_{prim}^{-1}\ n_{lift}^{-1})(WUE\ Y\ F_{irr}\ n_{appl}^{-1}\ n_{conv}^{-1}\ 10^{-1})(TDH) \qquad \text{(Eq. 1)}$$

E = primary energy inputs for irrigation
g = acceleration of gravity at sea level, 9.81 m s^{-2}
n_{prim} = efficiency of the power unit
n_{lift} = efficiency of the pump
WUE = crop-specific water use efficiency (g water per g DM produced)
Y = yield level (Mg DM ha^{-1})
F_{irr} = fraction of crop water requirements supplied by means of irrigation
n_{appl} = efficiency of the field application system
n_{conv} = efficiency of the conveyance facility
TDH = total dynamic head. The pressure required to overcome friction in water distribution lines and to operate field distribution systems is converted to meters (pressure in kPa is multiplied by 0.10) and added to required meters of lift to obtain the total dynamic head.

For the calculations of irrigation energy input below, it is assumed that 0.5 MJ is required to lift 10 Mg water 1 meter. This corresponds to a combined efficiency of the power unit and pump at about 20 percent. The efficiencies of power units are highly variable. Small engines (1-2 kW) have efficiencies ranging from around 10 percent (petrol) to 15-35 percent (diesel), while larger diesel engines have efficiencies around 30-40 percent. Electric motors have higher efficiencies, 75-90 percent [19, 20], but the overall efficiency depends on the efficiency of the electricity generation. At 30-40 percent efficiency in electricity generation, the efficiency of the electric motor alternative is around 20-35 percent. The efficiency of pumps varies with pump type and size. At optimum head and speed, pump efficiencies range from 40 to 80 percent, while performance outside optimum is lower [19]. A 40-80 percent pump efficiency range and a 10-40 percent power unit efficiency range, results in an overall efficiency of power unit and pumping unit of 4-32 percent.

Energy inputs associated with establishment of the irrigation systems are given in Table 2. The primary energy input is calculated based on a 40-year irrigation system life. See[6] for a more detailed description of the specific energy inputs for manufacture of the included products (e.g., pumps and pipes), expected product life, and excavation requirements.

Table 2. Annual primary energy inputs (MJ ha^{-1} yr^{-1}) associated with establishment of different irrigation systems designed for a 65 ha field[a].

	Total	Pumping unit (el. motor)	Pipes		Other equipment	Excavation	
			PVC	Al		Grading	Ditching
Surface systems							
Surface without IRRS[b]	360	43	53	0	0	254	11
Surface with IRRS	787	43	91	387	0	254	11
Sprinkle systems							
Solid set sprinkler	3380	53	241	2919	162	0	5
Permanent sprinkler	1467	53	1024	0	180	0	210
Hand-moved sprinkler	527	53	241	211	12	0	11
Side-roll sprinkler	715	53	241	363	47	0	11
Center-pivot sprinkler	616	58	178	0	377	0	3
Traveler sprinkler	561	68	339	0	146	0	8

[a] Calculated based on a 40-year irrigation system life. See [6] for calculation procedures.

b IRRS = Irrigation runoff recovery system.

Figure 1 reports total irrigation energy input (establishment plus pumping) and also illustrates how the significance of establishment energy varies with irrigation water supply and pumping depth. The total irrigation energy, and the ratio of establishment energy to total irrigation energy, are plotted against the irrigation water transpiration —i.e., the amount of transpired water that comes from irrigation. The actual amount of irrigation water supply depends on the irrigation efficiency[3] of the respective system (e.g., if the irrigation efficiency is 50 percent, then the actual amount of irrigation water supply is twice the irrigation water transpiration). Two different groundwater depths (10 and 100 meters) are considered. Two surface systems (with and without IRRS) and two sprinkler systems (traveler and solid set sprinkler) are included in Figure 1. The traveler sprinkler system has the lowest, and the solid set sprinkler system the highest ratio of establishment energy to total energy of the six sprinkler systems included in Table 2. The four sprinkler systems included in Table 2, but not in Figure 1, have total irrigation energy inputs similar to the solid set sprinkler system. The irrigation efficiency and the required pressure for the different systems are given in the Caption to Figure 1. For comparison, given bioenergy system characteristics (e.g., WUE and conversion efficiency) corresponding to 100 Mg ET GJ^{-1} gross bioenergy (see Table 1), and assuming that half of water losses to ET is irrigation water, 500 mm of irrigation water ET would correspond to the production of 100 GJ gross bioenergy.

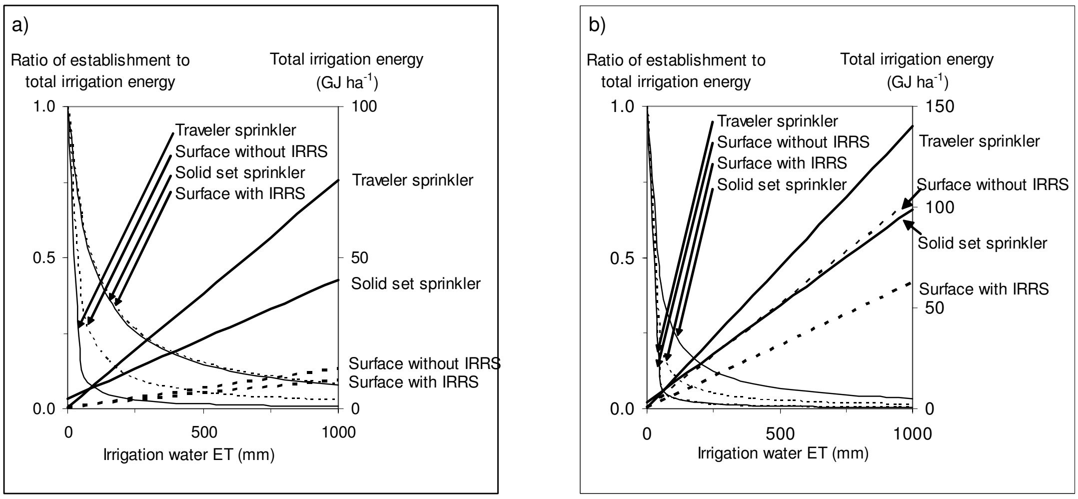

Figure 1. Total irrigation energy input and ratio of establishment energy to total energy at 10 meter (fig. a) and 100 meter (fig. b) pumping depth. Dashed lines refer to surface systems, and solid lines refer to sprinkler systems. Bold lines refer to total irrigation energy input (right axis), and plain lines refer to the ratio of establishment energy to total energy (left axis). Irrigation water transpiration varies from 0 to 1000 mm. Irrigation efficiencies are 85 and 50 percent for surface systems with, and without IRRS; 80 percent for solid set; and 70 percent for traveler sprinkler systems [21]. The required pressure corresponds to 5 and 3 meter lift for surface systems with, and without IRRS; 53 meter for solid set, and 95 meter for traveler sprinkler systems.

The ratio of establishment energy to total energy differs significantly among the systems at low water lifts and/or low irrigation water transpiration. Aluminum use in the IRRS-equipped surface system leads to establishment energy inputs more than twice as high as for the surface system without IRRS. As pumping energy requirements increase, the relative importance of the establishment energy decreases, and the energy savings from higher irrigation efficiency dominate over the energy cost of installing IRRS equipment. Aluminum use is also a dominating factor behind the higher ratio for solid set sprinkler systems. The higher required pressure for traveler sprinkler systems further contributes to the difference in ratio between solid

[3] Refering to Equation 1, n_{appl} and n_{conv} are here merged into one irrigation efficiency factor (see Figure 1 Caption).

set and traveler sprinkler systems. The traveler sprinkler system has significantly higher total energy inputs than the other systems due to high operating pressure and relatively low irrigation efficiency. The solid set sprinkler system has higher energy inputs than both surface systems at 10 meters pumping depth due to higher operating pressure, but has lower total energy inputs than the surface system without IRRS at 100 m pumping depth due to higher efficiency. The IRRS-equipped surface system has the lowest total energy inputs due to low operating pressure and relatively high irrigation efficiency.

The intention here is not to differentiate between various irrigation systems regarding suitability for energy crop irrigation, but rather to investigate whether energy inputs for establishment of irrigation systems are large enough to influence the energy balance of irrigated bioenergy systems. It can be concluded that the establishment energy can account for a significant part of total irrigation energy inputs at low TDH and/or sparse irrigation (such as in supplemental irrigation). But it is small (always less than 5 GJ ha^{-1} yr^{-1}) compared to the expected gross yield of biomass, and therefore not crucial from an energy balance point of view.

4 WASTEWATER IRRIGATION OF WILLOW

Research and demonstration projects, in Sweden and elsewhere, show that perennial energy crop plantations can provide additional functions (e.g., buffer strips reducing nutrient leaching and erosion, and vegetation filters for the treatment of municipal wastewater, landfill leachate, sewage sludge and wood ash). In this way *multifunctional bioenergy systems* can provide desirable services, such as pollution reduction and improved resource use efficiency [22]. Below, the net energy results of using willow as vegetation filters for wastewater management are evaluated based on two specific examples of such activities in Sweden.

4.1 Willow vegetation filter characteristics: treatment efficiency

The purification efficiency of willow vegetation filters has been demonstrated in several countries, e.g. Sweden, Poland, Denmark, and Estonia [23]. Currently, there are about five municipalities in Sweden which are utilising willow vegetation filters as a complement to conventional wastewater treatment methods. When wastewater percolates through the soil the well-developed root system takes up 75-95% of nitrogen (N) and phosphorus (P) in the wastewater [24]. The nutrient content in municipal wastewater corresponds fairly well to nutrient requirements in willow cultivation. An annual municipal wastewater load of 600 mm, containing about 100 kg N, 20 kg P, and 65 kg K, will supply, not only the demand for water, but also the demand of nitrogen and other macro-nutrients [23]. The willow filter systems should be regarded as a complementary treatment step in existing conventional treatment plants, primarily for nutrient removal. The wastewater is pumped to the willow vegetation filter after secondary treatment, before ordinary chemical P precipitation so that the nutrient is applied to the willow plantation. This approach reduces the risk of spreading pathogens [23].

The concept of using willow vegetation filters for the treatment of N-rich drainage water has been tested in a large-scale field trial in southern Sweden since 1993 [25]. Here, a storage pond received drainage water from surrounding intensively cultivated land, which was subsequently used for irrigation of a willow plantation, using a furrow system for water distribution. Results from the field trial show that the nitrate concentration in the drainage water was significantly reduced when passing the vegetation filter [25]. A suitable drainage water load was 900 mm, containing about 100 kg N.

4.2 Willow vegetation filter characteristics: biomass yield response

A previous study by Lindroth and Båth [26] shows that water deficiency is often a growth-limiting factor in willow cultivation, even in countries like Sweden with significant rainfall all year around. The regional variation in biomass yields could be significant due to differences in water supply during the vegetation period. For example, the willow yield in conventional rainfed plantations in south-east Sweden is normally around 50 to 60 percent of those in south-west Sweden, due to a lower rainfall in the summer season. Thus, the biomass yield response to wastewater irrigation will be more significant in regions with relatively low precipitation during the vegetation period. Wastewater irrigation is here estimated to increase the yields by 4 to 8 Mg DM ha^{-1} yr^{-1}, or 30 to 100 percent compared to rainfed willow plantations (Table 3). Biomass yields in conventional rainfed plantations refer to well managed plantations on good soils, excluding the first harvest after plantation establishment where the harvest is around 40% lower than for subsequent rotations.

Table 3. Estimated biomass yield in conventional rain-fed and wastewater irrigated willow plantations, respectively, in different Swedish regions[a].

Region	Biomass yield		Yield increase	
	Conventional rainfed plantations	Wastewater irrigated plantations		
	Mg DM ha^{-1} yr^{-1}	Mg DM ha^{-1} yr^{-1}	Mg DM ha^{-1} yr^{-1}	%
South-west Sweden	14	18	+ 4	+ 30
South-east Sweden	8	16	+ 8	+ 100
Central Sweden	10	16	+ 6	+ 60

[a] Estimations based on data from [26].

4.3 Energy costs and savings of using municipal wastewater and drainage water for willow irrigation

Establishment of wastewater irrigation systems and water pumping requires additional energy inputs. On the other hand, recycling of nutrients in wastewater reduces the need for commercial fertilizers and hence the energy inputs in fertilizer production. Additional energy savings are obtained from substitution of conventional N and P removal with the willow filter system. The replacement of P precipitation leads to lowered production of sewage sludge, and consequently to reduced handling and transportation requirements. This indirect energy saving is not included in the net energy analysis employed here.

The energy input for the establishment of a 10-50 ha controlled-flooding willow filter system suitable for municipalities with around 50,000 inhabitants is estimated to be 500 MJ ha^{-1} yr^{-1}, based on data in Table 2 (surface irrigation with additional energy input for 5 km PVC load pipe [27]). The pumping energy input is estimated to be 12 GJ ha^{-1} yr^{-1}, given 600 mm application depth and 40 m TDH (50 kPa end-use pressure plus distribution losses [28, 29]). This corresponds to 0.5 MJ mm^{-1} m $lift^{-1}$. The energy input for N removal in a conventional treatment plant varies, for example with N concentrations and the C/N ratio. On average, 6 MJ is required to remove one kg N, corresponding to 25 percent of total net energy inputs at the plant. Additional indirect energy inputs for N removal (pumps, pipes and concrete) are estimated to be 0.5 MJ per kg N. Direct and indirect energy inputs for chemical P precipitation correspond to around 5 percent of total energy inputs at the plant [30]. The energy input for N-fertilizer production is taken to be equivalent to 45 MJ per kg N, referring to the performance of modern fertilizer plants [31]. Energy inputs in older plants can be significantly higher, while the theoretical minimum energy input is around 25% lower. The energy inputs for production of commercial P- and K-fertilizers are taken to be 7.9 and 4.8 MJ kg^{-1}, respectively [31].

Given an annual municipal wastewater load of 600 mm (containing 100 kg N, 20 kg P, and 65 kg K), the combined energy savings from using willow filter systems instead of conventional systems is around 5.8 GJ ha^{-1} yr^{-1}. The largest saving (5 GJ ha^{-1} yr^{-1}) comes from reduced fertilizer requirements, where the major part (4.5 GJ ha^{-1} yr^{-1}) is due to reduced N-fertilizer requirements. Replacement of conventional N and P removal saves 0.65 and 0.15 GJ ha^{-1} yr^{-1}, respectively. The combined energy savings are slightly less than half of the energy input for the willow filter system establishment and wastewater pumping.

The energy input for establishment of a controlled-flooding willow filter system suitable for drainage water is estimated at 360 MJ ha^{-1} yr^{-1} (Table 2). The pumping energy input is estimated at 2.3 GJ ha^{-1} yr^{-1}, given 900 mm application depth, 5 m TDH (pressurization and losses), and 0.5 MJ mm^{-1} m $lift^{-1}$. The pond is assumed to be located in direct connection to the willow plantation, which means that load-pipes are not required. The energy saving from reducing N fertilizer requirements by 100 kg is around 4.5 GJ, or 1.8 GJ ha^{-1} yr^{-1} higher than the combined energy inputs for willow filter system establishment and pumping.

4.4 Net energy results of irrigating willow plantations with municipal wastewater and drainage water

Table 4 summarizes the energy balances of irrigating willow plantations with municipal wastewater and drainage water. The energy input for willow filter system establishment and pumping is estimated to be higher than the combined energy savings gained from reduced fertilizer requirements and substitution of N and P removal in conventional wastewater treatment plants. Willow filter cleaning of drainage water from intensively cultivated cropland requires less establishment and pumping energy inputs than the energy gained from reduced N-fertilizer requirements. The major reason is lower TDH due to location of the drainage water storage pond and willow plantation at the same site.

Both vegetation filter systems have a positive net energy gain thanks to the expected yield increase, which is here set to 5 Mg DM ha^{-1} yr^{-1} (see Table 3). Note that the energy balance in Table 4 is limited to the vegetation filter function of the willow plantations. Willow production requires additional inputs, such as motor fuels, for harvesting and other operations. The overall net energy yield in conventional willow production in Sweden is around 170 GJ ha^{-1} yr^{-1} [31]. The overall net energy yield of willow vegetation filter cultivation will be substantially higher —provided that the expected yield increases are realized.

Table 4. The energy balance of using willow filter systems for treatment of municipal wastewater and drainage water from intensively cultivated croplands[a].

	Energy cost (-) /saving (+) (GJ ha^{-1} yr^{-1})	Yield increase[b] (GJ ha^{-1} yr^{-1})	Net energy balance (GJ/ha^{-1} yr^{-1})
Municipal wastewater treatment			
Irrigation[c]	-12.5		
Substitution of conventional treatment[d]	+0.8		
Reduced N fertilizer requirement	+4.5		
Reduced P & K fertilizer requirement	+0.5		
Sum	**-6.7**	**+100**	**+93**
Drainage water treatment			
Irrigation[c]	-2.7		
Reduced N fertilizer requirement	+4.5		
Sum	**+1.8**	**+100**	**+102**

[a] The energy balance is estimated based on a reference case where willow is cultivated without irrigation using commercial fertilizers. Conventional methods for treatment of municipal wastewater are used, and there is no treatment of drainage water.

[b] 5 Mg DM ha^{-1} yr^{-1}, 20 GJ Mg^{-1} DM.

[c] Including direct energy use for pumping and indirect energy input for irrigation system establishment.

[d] Energy savings (direct and indirect) from replacement of conventional N and P removal in wastewater treatment plants.

5 CONCLUSION AND DISCUSSION

The water requirements in energy crop production vary substantially, due to possible variations of a range of factors, such as WUE among energy crops, soil and climate and agronomic practice. There are also large variations in how large shares of the energy crops that are useful as bioenergy feedstock and in the conversion efficiency in electricity and biofuel production. This further widens the range in water requirements per usefuel energy carrier (electricity/biofuel) delivered.

The possible range of critical parameters (such as irrigation efficiency and TDH) prevents general conclusions regarding the net energy benefits of irrigating the energy crops. However, it is clear that energy inputs for irrigation system establishment is relatively small, while the energy inputs for pumping can reduce the net energy output substantially if the water application is large and the combined pumping requirement of water lift and pressurization is high.

Nutrient recirculation in wastewater irrigation of willow plantations reduces the requirements of commercial fertilizers, and reduces water pollution and eutrophication known to cause loss of biodiversity in water streams and toxic algal bloom. Willow vegetation filters are also less expensive than conventional treatment methods [29]. This paper suggests one additional benefit: improved energy balance. The projected yield increase from municipal wastewater irrigation corresponds to around 15 times the net energy cost of irrigation. Similar net energy results are obtained when polluted drainage water from agricultural land is used. In addition to providing nutrients, wastewater irrigation also has the advantage of being a surface source, which means that high energy inputs for pumping can be avoided when groundwater levels are deep. Willow filter cleaning of wastewater must be employed so that soils are not contaminated. Practices that lead to soil degradation and preclude subsequent conversion to food production are of course not acceptable. This applies also to conventional irrigation and land use in general.

The extent to which energy crops will be irrigated depends on where they will be established, and on the economics of irrigating the crops. The economics of energy crop irrigation depends on the relative cost of irrigation and other inputs compared to the biofuel output. Domestic politics and national energy security considerations may also influence the importance of the total energy balance for the perceived feasibility of bioenergy systems. Climatic change also introduces substantial uncertainties regarding future crop production. There is ample evidence that the climatic change that is now unavoidable will include non-trivial changes in temperature and precipitation regimes. As for present agriculture and silviculture, such changes could have profound implications for the future prerequisites for energy crop production, and for irrigation water demand in a prospective bioenergy sector.

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