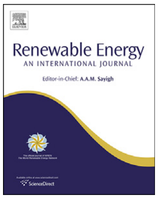
Renewable Energy 69 (2014) 233–241

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Energy and economic assessments of bio-energy systems based on annual and perennial crops for temperate and tropical areas

Simone Fazio, Lorenzo Barbanti*

Department of Agricultural Sciences (DipSA), University of Bologna, Viale Fanìn 44, 40127 Bologna, Italy

ARTICLE INFO

Article history:
Received 14 August 2013
Accepted 24 March 2014
Available online

Keywords:
Energy crops
Cumulative energy demand
Net energy balance
Energy efficiency
Annual equivalent net profit
Energy opportunity cost

ABSTRACT

Bio-energy systems based on dedicated crops depend on efficient and economic feedstock production as a pre-requisite for sustainable development. In this study, 15 annual and perennial species suited for temperate or tropical areas were assessed in terms of energy and financial balance: oil and coconut palm, jatropha, castor bean, sunflower and rapeseed (biodiesel); sugar cane, maize and wheat (1st generation ethanol); poplar, cardoon, giant reed, miscanthus, switchgrass and fibre sorghum (heat and power, or 2nd generation ethanol). Net energy and energy efficiency as respective difference and ratio between produced and consumed energy, and net profit (revenues minus costs) were appraised under temperate or tropical conditions, depending on crop species. In addition, a sensitivity analysis was run to rate the use of oil and grain crop residues as additional energy sources. Net energy, energy efficiency and net profit exhibited a wide range ranged between 22 and 340 GJ ha^{-1}, 2.2 and 21.1 GJ GJ^{-1}, 38 and 415 € ha^{-1}, respectively. Energy sector (biodiesel $<$ 1st generation ethanol $<$ biomass crops) and plant habit (annual $<$ perennial species) were the two main drivers of these large differences. The complementary use of crop residues enhanced net energy (+202%) and energy efficiency (+71%), whereas net profit decreased, as average (−24%), because of higher costs (residue recovery and additional fertilizer doses) than financial returns. It is concluded that accurate evaluation of energy and economic trade-off should be the driver of crop choice and management in energy initiatives involving dedicated crop cultivation.

1. Introduction

The most important reason supporting biofuels is their environmental benefits, compared to fossil fuels: several studies point out that replacing fossil fuels with biofuels would significantly reduce greenhouse gas (GHG) emissions and other environmental pollutants [1–4]. However, other key issues as energy efficiency and economic aspects need to be investigated, in order to outline the best scenario under multiple viewpoints. All the EU countries have adopted innovative policies to increase the share of renewable energy in the current mix of production. However, still in 2008 the European Environment Agency stated that if European countries simply stuck to current measures, energy consumption would continue to rise up to 26% by 2030, fossil fuels remaining the main source of supply [5]. To promote a shift in the use of renewable vs. non-renewable energy sources, it is proposed that the former sources be coupled with the pursuit of high energy efficiency, so as to achieve relevant goals in terms of net energy production and EROEI (energy return on energy invested).

Beside environmental and energy issues, the economic sustainability of any bio-energy initiative is deemed a key factor in the future development of this sector. In fact, as recently as in 2010 the Roundtable for Sustainable Biofuels defined a series of multi-faceted principles for sustainable biofuel production [6], stating that biofuels should also contribute to the social and economic development of local, rural and indigenous peoples and communities.

From a methodological point of view, the life cycle assessment (LCA) is a powerful tool for environmental impact analysis, and is also used to estimate the energy flows related to products, services and technologies [7]. Within LCA procedures, the calculation of the cumulative energy demand is one of the most common methods in energy flow evaluations [8].

Abbreviations: AEC, annual equivalent cost; AER, annual equivalent revenue; AENP, annual equivalent net profit; BEE, biochain economic evaluation; CED, cumulative energy demand; EAC, energy actual cost; EE, energy efficiency; EOC, energy opportunity cost; EROEI, energy return on energy invested; GE, gross energy; GHG, greenhouse gas; LCA, life cycle assessment; LHV, lower heating value; NE, net energy; PV, present value.

* Corresponding author. Tel.: +39 051 2096643; fax: +39 051 2096241.
E-mail address: lorenzo.barbanti@unibo.it (L. Barbanti).

http://dx.doi.org/10.1016/j.renene.2014.03.045
0960-1481/© 2014 Published by Elsevier Ltd.

Likewise, several models have been developed for economic evaluations of bio-energy chains [9–13]. Among them, the biochain economic evaluation model [14] is more focused on the agricultural steps, therefore concentrates on a farmer's viewpoint providing a better appraisal of crop profitability as a sound basis to build a project on.

Often crop management is only secondarily addressed in the above mentioned tools, because these methodologies were originally conceived to evaluate the implications of industrial steps, instead of processes involving biological and environmental factors. To compensate for this scarcity of information, in this study energy and financial balances were calculated in order to provide a deeper insight into the agricultural phase of a bio-energy chain; this in turn will foster the adoption of suitable strategies and specific decisions in view of enhancing crop profitability.

In the scientific literature, agricultural practices are shown to strongly influence the environmental impact of bio-energy chains, including the energy flows normally associated with GHG emissions [15–18]: the operations associated with cropping account for a relevant share (10%–80%) of the total primary energy input in most bio-energy production processes [1].

Several scenarios may be envisaged by matching crop plants featuring different characteristics with bio-energy sectors involving different specifications. Since the environmental and economic impact needs to be carefully evaluated within each sector, our research focused the analysis of annual and perennial crop plants suited for temperate or tropical areas in the frame of three main energy uses (biodiesel, bioethanol, heat and power or 2nd generation biofuels), in order to rate each crop's energy and economic performance. Both criteria are key points in the viability of any bio-energy initiative, exerting a strong influence on energy crop diffusion in a given area. In all the investigated scenarios, standard cropping techniques under specific climatic conditions were assumed.

2. Material and methods

2.1. Energy assessments

The cumulative energy demand (CED) method answers the question of the amount of energy spent in exchange for energy gained. CED calculates the total amount of primary energy used through a life cycle based analysis [19], focussing the analysis "from cradle to farm gate", i.e. from the production of raw materials, equipment and consumables needed for cropping (e.g., seed), to the end of the agricultural phase. Briefly, the method accounts the

Table 1

Inputs and outputs of arboreal/shrubby perennial cropping systems referred to temperate or tropical areas.

Inputs	Units	Castor bean (tropical)	Oil palm (tropical)	Coconut palm (tropical)	Jatropha (tropical)	Poplar (temperate)
Establishment						
Ploughing[a] depth	m	0.3	0.5	0.6	0.4	0.5
Harrowing	No.	3	2	2	2	3
Fertilization	kg ha^{-1}					
- N		–	15	70	10	–
- P		80	20	20	10	50
- K		80	40	30	10	120
Irrigation	m^3 ha^{-1}	–	200	500	200	100
Weeding	kg ha^{-1}					
- Glyphosate		3	3	3	3	3
- Other herbicides		2	3	3	2	2
Pesticides	kg ha^{-1}	2	2	2	–	–
Hoeing	*n*	1	3	3	1	2
Fuel (diesel)	L ha^{-1}	125	145	150	120	155
Seed	kg ha^{-1}	10	–	–	–	–
Seedlings[b]	No. ha^{-1}	–	170	160	1100	10,000
Eradication[c]	No. ha^{-1}	1	1	1	1	1
Productive years						
Fertilization[d]	kg ha^{-1}					
- N		60 (25)	72 (150)	30 (120)	40 (25)	70
- P		12 (8)	21 (12)	10 (9)	10 (5)	–
- K		12 (40)	110 (60)	100 (60)	30 (30)	–
Hoeing	No.	–	2	2	2	1
Pesticides	kg ha^{-1}	2	2	2	–	
Harvesting	Type	Combine	Manual	Manual	Shaking	Chopper
Fuel (diesel)	L ha^{-1}	50	20	20	30	60
Outputs						
- Biomass (d.w.)[e]	Mg ha^{-1}	(4.2)	(12.5)	(9)	(4.5)	12
- Grain/fruit	Mg ha^{-1}	2.3	20	5	4,5	–
- Gross energy[f,g]	GJ ha^{-1}	45 (74)	225 (370)	61 (170)	60 (78)	252

[a] For oil and coconut palm and jatropha, single row ploughing was accounted, given the wide inter-row spacing: 9 m in oil and coconut palm; 3 m in jatropha.

[b] The inputs used for plant production at the nursery were accounted as a single input per plant alike raw material production.

[c] Plant eradication at the end of crop life was considered among establishment operations, because the annual equivalent impact on energy and costs is calculated similarly.

[d] Within brackets, the additional doses of nutrients if leaves and pruning residues are removed for energy uses. Nutrient removals with press cakes, husks/shells and empty fruit bunches were already considered in normal fertilization.

[e] Within brackets, residual dry biomass yields corresponding to: in coconut palm, 1, 6 and 2 Mg ha^{-1} for press cake, leaves and shells/husks, respectively; in oil palm, 1.5, 6 and 5 Mg ha^{-1} of press cake, leaves and empty fruit bunches, respectively; in castor bean, 3 and 1.2 Mg ha^{-1} of straw/wood and press cake, respectively; in jatropha, 3.5 and 1 Mg ha^{-1} of pruning wood and press cake, respectively.

[f] In poplar, the lower heating value (LHV) of biomass (21 MJ kg^{-1}) was multiplied by yield; in castor bean and jatropha, the oil content of seeds (50% and 35%, respectively) was multiplied by grain yield and then by oil LHV (39.5 and 37.5 MJ kg^{-1}, respectively); in oil and coconut palm, the oil content of fruits (around 30% for both crops) was multiplied by oil LHV (37.6 and 40.5 MJ kg^{-1}, respectively).

[g] Within brackets, additional energy output using residues as biomass for energy. It was obtained by multiplying residue yields by their respective LHV's (15.5 MJ kg^{-1} for jatropha wood; 17 MJ kg^{-1} for leaves, pruning wood, straw and empty fruit bunches; 18.5 MJ kg^{-1} for palm oil, jatropha and castor bean press cakes; 19 MJ kg^{-1} for coconut press cake and shell/husks).