Energy analysis of three energy crops in Greece

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Abstract: To assess the potential of energy crops to provide a stock material for biofuel production three crops (rapeseed, sunflower and sweet sorghum) were studied in field experiments in Thessaly, Central Greece in 2007 and 2008. The cropping activities were recorded. Energy analysis was carried out to assess benefits from the crops. Power requirements and energy consumption during field operations were measured directly using instrumented tractors. Literature data was used for the energy sequestered to the inputs of the system (indirect energy). Energy budgets were produced taking into account as output either the seed or including the stalks for the two oil seed crops. The results showed that in all cases positive energy balances were achieved. Analysis of the inputs showed that energy for fertilizer was the most important for the rain fed rapeseed but irrigation for sunflower and sweet sorghum. Pumping depth of the irrigation water had a high impact on the energy inputs of the irrigated crops. The overall results gave maximum energy efficiency coefficients of 4.62 for rapeseed without the stalks and 10.68 with stalks, of 2.89 for sunflower without the stalks and 6.16 with stalks and 8.92 for sweet sorghum. An analysis of data from the literature was carried out to assess the effect of new technological developments to the energy sequestered to different inputs. Several developments are expected to improve energy efficiency coefficient, such as variable rate application of inputs, as well as properly designed crop rotations and use of cover crops.

Keywords: rape seed, sunflower, sweet sorghum, energy analysis, net energy, energy efficiency coefficient

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1 Introduction

European Union was highly dependent on imported fossil fuels to cover the energy requirements of the member states. The transportation sector in particular, which accounts for more than 30% of the total energy consumption, is 98% dependent on imported fossil fuels (European Commission, 2006). In addition to energy consumption, substantial amounts of CO_2 were emitted from fossil fuel use. The Biofuels Advisory Council estimated that 90% of the increase of CO_2 emissions between 1990 and 2010 was caused by the transportation sector (European Commission, 2006). According to EU targets, biofuels should cover 25% of the fuels used for transportations by 2030 (European Commission, 2006; Biofuels Technology Platform, 2008). The new European Commission directive on biofuels set compulsory targets for each member state for renewables and biofuels. In Greece particularly, an 18% target of Renewable Energy Resources (RES) in total energy consumption is set for 2020 (EC, 2009). At the moment Greece is far behind achieving this target (Biofuels Barometer, 2007). A great effort was required from the stakeholders of the fuel supply chain to achieve these targets. New stock materials should be produced by innovative growing and handling methods to support the biofuels industry.

Existing knowledge and reports indicate that liquid fuels derived from biomass are the main alternatives we have at the moment for transportation fuels (Biofuels Technology Platform, 2008; CIGR, 1999). Two were

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the main sources of liquid fuels for transportation purposes under the EU targets: vegetable oils and alcohols. Vegetable oils were produced by oil seed producing crops after extraction by cold pressing or chemical treatment. The latter was more efficient and the major industrial method, while cold pressing was simple and could be used at the farm level. Alcohol is produced by sugars and starch fermentation (CIGR, 1999). Starchy material, such as cereal seeds, was used in many countries to produce alcohol. Sugars derived from sugarcane are the main raw material for the Brazilian alcohol industry. Second generation alcohol biofuels are expected to be produced by lignocellulosic raw material through gasification or fermentation (Mamma et al., 1995).

Greece is a country with very limited energy sources. Apart from lignite used for electricity production, oil production was limited to an oil field in the Northern Greece. Additionally, Greece had to conform to the international treaties as member of EU to reduce CO_2 emissions and the use of RES seemed to be the main tool to achieve this.

In the last years a discussion about the benefits of using biofuels to the environment had started. Several papers had questioned the benefits from the energy crops to the environment, to the CO_2 emissions and to the effects in the food supply. The basis of the evaluation of an energy crop was the energy balance which has to be positive. As a result, energy analysis of the cropping systems could offer the basis for assessing the benefits of an energy crop.

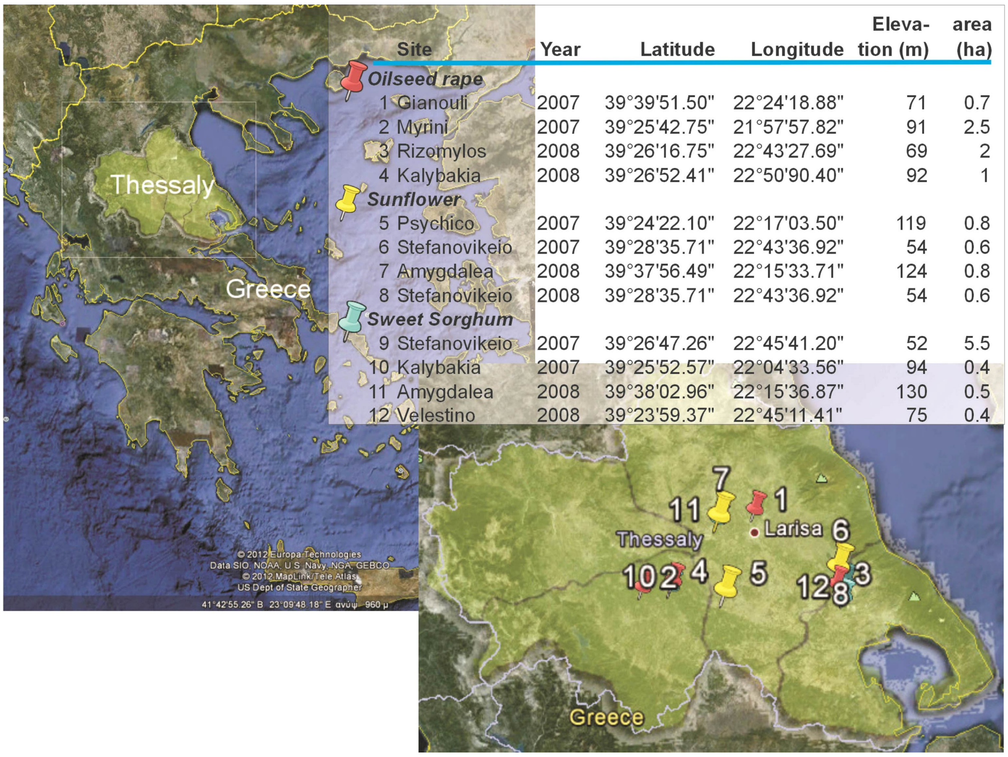
Several studies were published on the energy analysis of different crops. Kalivroussis et al. (2002) presented an energy analysis of rain fed sunflower in Northern Greece. The energy efficiency coefficient was 3.6 when only seed was taken as output and 4.5 when stalks were included. Davoodi and Houshyar (2009) performed energy analysis of rapeseed and sunflower in Iran. The energy efficiency coefficient was 2.9 for rapeseed and 2.17 for rain fed sunflower. Franzluebbers and Francis (1995) have analyzed the energy balance of maize and sorghum under different cropping systems. The energy efficiency coefficients ranged from 4.1 to 11.6.

In 2007 and 2008 a research project was undertaken to assess the potential of cultivating energy crops in Thessaly, Central Greece, to cover part of the energy needs and provide the biofuel industry with local raw material. Three crops were tested in a wide range of experiments covering different environments, varieties and cultivation practices: Rape seed (Brasica napus) and sunflower (Hellianthus annuus) to produce vegetable oils and sweet sorghum (Sorgum bicolor) to produce alcohol. During the experiments data were collected and analyzed to provide energy balances and assess the real potential of these crops to produce primary energy for transportation. The aim of the paper is to present the energy analyses of the three crops under Greek conditions.

2 Material and methods

Before this current study, in 2006, plot experiments were carried out to evaluate differnet varieties of the three crops under Greek conditions (10 varieties of rape seed, 12 varieties of sunflower and 5 varieties of sweet sorghum). The best yielding varieties were chosen for the cultivation of the pilot fields used for the present analysis. The pilot fields were run for two years, in 2007 and 2008 in commercial farms to test the crops in real farming conditions.

All the experiments were carried out in Thessaly, Central Greece which was a representative area of arable crops in Greece (Figure 1). Thessaly can be divided in two climatic regions: the western part, with higher rainfalls (around 750 mm per year) and the Eastern part, with lower rainfall (around 500 mm per year). Each crop was tested in both regions such that, the data represented the mean Thessalian conditions. More specifically, four fields were cultivated for each crop every year, where the two were located in the Eastern part of Thessaly and the other two in the Western part. The fields were selected with medium texture soils which represented more than 70% of Greek soils. Field operations and cropping practices were based on the crop, weather and field conditions. For each experimental field a detailed record of all cropping activities was kept. Summaries of the records are shown in Table 1.



Site	Year	Latitude	Longitude	Eleva- tion (m)	area (ha)
Oilseed rape					
1 Gianouli	2007	39°39'51.50"	22°24'18.88"	71	0.7
2 Myrini	2007	39°25'42.75"	21°57'57.82"	91	2.5
3 Rizomylos	2008	39°26'16.75"	22°43'27.69"	69	2
4 Kalybakia	2008	39°26'52.41"	22°50'90.40"	92	1
Sunflower					
5 Psychico	2007	39°24'22.10"	22°17'03.50"	119	0.8
6 Stefanovikeio	2007	39°28'35.71"	22°43'36.92"	54	0.6
7 Amygdalea	2008	39°37'56.49"	22°15'33.71"	124	0.8
8 Stefanovikeio	2008	39°28'35.71"	22°43'36.92"	54	0.6
Sweet Sorghum					
9 Stefanovikeio	2007	39°26'47.26"	22°45'41.20"	52	5.5
10 Kalybakia	2007	39°25'52.57"	22°04'33.56"	94	0.4
11 Amygdalea	2008	39°38'02.96"	22°15'36.87"	130	0.5
12 Velestino	2008	39°23'59.37"	22°45'11.41"	75	0.4

Figure 1 Experimental field locations in the region of Thessaly, Central Greece

Table 1 Summary records of cultivation practices

	Oilseed rape		Sunflower		Sweet Sorghum	
Year	2007	2008	2007	2008	2007	2008
Soil Tillage						
Plough	1	1	1	1	1	
Heavy cultivator						1
Field cultivator			1	1	2	3
Disk harrow	2	2	2	3	2	2
Sowing						
Row spacing / cm	30	25.7	75	75	75	75
Population / seeds·ha^{-1}	617 000	926 000	78 500	93 827	80 150	77 970
Seed used / kg·ha^{-1}	3.33	4.91	7.46	8.14	1.65	1.61
Fertilisation (N-P-K)						
11-15-15 / kg·ha^{-1}	250	200	250	250	275	300
34.5-0-0 / kg·ha^{-1}					250	150
46-0-0 / kg·ha^{-1}			200	150		
Herbicides						
Trifluralin / kg·ha^{-1}	2.20		3.30	2.93		
Prometryne / kg·ha^{-1}				3.32		
Irrigation						
Pumping depth / m			10	48	45	70
Pump discharge / m^3·h^{-1}			50	40	35	40
Water applied by traveler irrigator / m^3·ha^{-1}			200		400	400
Water applied by drip irrigation / m^3·ha^{-1}			2 100	3 255	4 735	4 400

Based on these records the direct and indirect energy (Pimentel, 1992) consumption was estimated. Direct energy is consumed in the farm, in the form of energy products, such as fuel, lubricants and human labor. Indirect energy is consumed outside the farm boundaries to produce any input (machinery, chemicals) used in the farm. Any material brought into the farm was considered as “input” while any product sold to the market was added to “output”. Products used in the farm were considered “neutral”. Energy budgets then were estimated for each crop.

2.1 Energy inputs estimation

2.1.1 Machinery inputs

Two tractors were used for the field operations. A 82 kW 4WD, for the heavy field operations like tillage and transportation and a smaller 55 kW 2WD, to carry out the lighter operations like sowing, spraying and fertilization.

Indirect energy was estimated as the energy sequestered to the tractor and the machinery during manufacturing as well as the energy added to them during their estimated life for repairs and maintenance. The total sequestered energy was then divided by the estimated working life of the machinery and the field performance (estimated from the working width, the travel speed and the field efficiency) for each operation (Table 2). The manufacturing energy was estimated as the sum of the energy used in producing the raw materials and the energy for the machinery construction (Bowers, 1992). The energy estimated to be spent for transportation and handling of the machinery was also added at 8.8 MJ kg^{-1} (Bowers, 1992). The energy spent for repair and maintenance during the life of the machine was also added. It was estimated as a percentage of the energy spent to produce the machinery, using the Coefficients for Repair and Maintenance (CRM) (Bowers, 1992) (Table 2).

Table 2 Indirect energy consumption for field operations

	Weight / kg	ME[1] / MJ·kg^{-1}	Working Width / m	Working Speed (u) / m·s^{-1}	fe[2]	Field Capa-city (fc) / ha·h^{-1}	Estimated Working Life (LE)/ hours	C_{RM}[3]	Indirect Energy Inputs		
									Imple-ment	Tractor	Total
										/ MJ·ha^{-1}	
Main Tractor 82 kW	4 200	86.8					16 000	0.49			
Secondary Tractor 55 kW	2 520	86.8					12 000	0.49			
Tillage implements											
Plough	500	52.8	1.2	1.15	0.85	0.42	2 000	0.97	66.6	85.6	152.2
Subsoiler	600	52.8	1.8	0.99	0.85	0.55	2 000	0.51	48.6	66.3	114.8
Heavy cultivator	370	52.8	2.0	1.18	0.85	0.72	2 000	0.51	22.7	50.2	72.9
Rotary Cultivator	320	52.8	2.0	1.56	0.85	0.95	2 000	0.51	14.9	38.1	52.9
Field cultivator	280	51.4	2.3	2.22	0.85	1.56	2 000	0.61	8.2	18.5	26.7
Power harrow	720	52.8	2.5	1.06	0.85	0.81	1 500	0.59	54.7	44.6	99.3
Disc harrow	1 050	50.0	3.0	2.17	0.80	1.88	2 000	0.61	25.0	15.5	40.4
Other implements											
Row crop seeder	400	56.9	3.0	1.97	0.65	1.38	1 500	0.43	17.4	20.9	38.3
Sprayer	130	56.9	12.0	3.01	0.65	8.45	1 500	0.37	0.9	3.4	4.3
Fertilizer distributor	150	52.8	12.0	2.08	0.70	6.30	1 200	0.49	1.7	4.6	6.3
Stalk chopper	150	52.8	1.2	2.96	0.80	1.02	1 500	0.33	7.7	7.7	15.4
Combine harvester	7 000	86.8	3.8	1.10	0.65	1.00	2 000	0.24	417.8		417.8
Processing						kg·h^{-1}	hours			MJ·kg^{-1}	
Wagon	900	52.8				20 000.00	3 000	0.80	0.0016	0.0011	0.003
Oil extraction screw press	45	86.8				16.77	10 000	0.55	0.0384		0.038

Note: (1) ME = Manufacturing energy (Bowers 1992, Batty and Keller 1980); (2) fe = field efficiency (ASABE D497.4); (3) C_{RM} = coefficient used to estimate the energy sequestered in repairs and maintenance (Bowers 1992).

For the direct energy, human labor (driver), fuel consumption and lubricants had to be added. Human labor energy consumption estimation was rather difficult. Different literature sources gave different values depending on the boundary of the system used. Fluck (1992) presented a literature analysis of the estimation of human labor from different sources, which ranged from 1 MJ d^{-1} (only for muscular energy consumption) to 1,450 MJ d^{-1} (for life style support). However, most researchers agree that human energy is a very small percentage in today’s mechanized agriculture (Hülsbergen et al., 2001) and therefore, it was not included in the calculation.

Fuel consumption was estimated from direct measurements in the field using an instrumented tractor (Papathanassiou et al., 2002) that included the following:

- A dynamometer for measuring forces in three dimensions, consisting of two metal Π shaped frames joined together with six loading cells. The frames were attached between the tractor and the implement and were able to measure the developed forces.
- A torque and rotating velocity measuring device was attached to the PTO and used to record the moment and the angular velocity for the PTO powered implements.
- A radar was used to record forward speed of the tractor.
- An analogue-to-digital converter and a counter card connected to a laptop were used to record the measured data.

The data were used to estimate the power required and the energy consumed for the operations. The estimation is shown in Table 3. The pulling force and the velocities measured were used to estimate the power required for the field operations. The pulling power was transformed to Equivalent PTO power (kW) using corresponding traction coefficients (Cavalaris, 2004). Specific fuel consumption (L kWh^{-1}) was estimated using the ASABE formula (ASABE, 2007) (Equation (1)):

$$SFC = 2.64X + 3.91 - 0.203\sqrt{738X + 173} \qquad (1)$$

where, X is the ratio of the equivalent PTO power required for an operation, to the maximum available from the PTO.

Table 3 Direct energy consumption for field operations

	Draft force (F_{TR}) / kN	PTO torque (t_{PTO}) / kN·m	Absorbed energy pull (Ea_{TR}) / MJ·ha^{-1}	Absorbed energy PTO (Ea_{PTO}) / MJ·ha^{-1}	Tractive efficiency (c_{TR})	PTO equivalent energy (Eeq_{PTO}) / MJ·ha^{-1}	X$^{(1)}$	Specific fuel consum-ption (SFC) / L·kWh^{-1}	Fuel consum-ption (FC) / L·ha^{-1}	Direct energy inputs (fuels and lubricants) (E_V) / MJ·ha^{-1}
Tillage implements										
Plough	22.7		222.3		0.53	419.5	0.73	0.42	49.2	2 445
Subsoiler	28.6		187.0		0.52	359.6	0.80	0.41	41.3	2 049
Heavy cultivator	19.6		115.0		0.53	217.1	0.64	0.44	26.7	1 327
Rotary Cultivator	11.2		65.9		0.53	124.4	0.48	0.51	17.8	882
Field cultivator	6.2		31.8		0.43	74.0	0.70	0.43	8.8	435
Power harrow	5.9	0.79	27.7	204.6	0.49	289.1	0.96	0.42	33.5	1 665
Disc harrow	5.9		24.5		0.41	59.9	0.68	0.43	7.2	356
Other implements										
Row crop seeder	1.6	0.04	8.2	5.9	0.24	40.6	0.34	0.63	7.1	350
Sprayer		0.03		0.8		0.9	0.05	1.11	1.2	60
Fertilizer applicator		0.08		2.6		2.9	0.11	0.96	2.5	124
Stalk chopper		0.09		18.0		20.4	0.13	0.93	5.6	278
Combine harvester									14.6	1 116
Processing								MJ·kg^{-1}		
Wagon								0.0018$^{(2)}$	0.33	23
Oil extraction screw press								1.0400		2 648

Note: $^{(1)}$ X = the ratio of equivalent PTO power to that maximum available to the PTO; $^{(2)}$ MJ·kg^{-1}·km^{-1}.

For the implements, using PTO power (i.e. rotary cultivator), the energy consumption by the PTO was calculated using an electric PTO dynamometer (Froment XT 200) to measure the real maximum PTO power for the two tractors. Fuel consumption (L h^{-1}) was estimated as the product of Specific Fuel Consumption and equivalent PTO power. Dividing the fuel consumption by Field Performance, the Fuel Consumption per unit of area (L ha^{-1}) was calculated. Fuel consumption was then converted to energy by using the energy content of the fuel (38.66 MJ L^{-1}) and the production and handling energy (9.12 MJ L^{-1}), giving total energy content of 47.78 MJ L^{-1} (Leach, 1976). This was equal to 57.57 MJ kg^{-1}, if 0.83 t m^{-3} density was taken into account. Leach (1976) gave a value of the energy content of Diesel fuel of 45.6 MJ kg^{-1} which was multiplied by 1.134 for the energy sequestered for extraction, manufacturing and handling giving a total of 51.7 MJ kg^{-1}. In the present study the Pimentel value was used. The consumed energy by lubricants was taken at 4% of the fuel energy (Fluck, 1992). The sum of fuel and lubricant energy was the total direct energy inputs (Table 3).

2.1.2 Consumable goods input

Consumable goods were used in several stages of crop growth. For most of them energy sequestered values was found in the literature. The values and the sources are shown in Table 4. Helsel (1992) estimated the total energy of the N fertilizer at 69.5 GJ t^{-1} for production, 2.6 GJ t^{-1} for packaging, 4.5 GJ t^{-1} for transportation and 1.6 GJ t^{-1} for the application. Energy values for pesticides were also taken from the literature.

Table 4 Consumable goods sequestered energy

Consumable goods	Energy content / MJ kg^{-1}	Source
Fertilizers		
N	78.1	Helsel (1992)
P_2O_5	17.0	Helsel (1992)
K_2O	13.7	Helsel (1992)
Seeds		
Oilseed rape	103.1$^{(1)}$	Heichel (1980)
Sunflower	26.3	Kalivrousis et al. (2002)
Sweet Sorghum	103.1$^{(1)}$	Heichel (1980)
Herbicides		
Trifluralin	150.0	Helsel (1992)
Prometryne	460.0$^{(2)}$	estimation

Note: (1) As no data are available, the mean value of the crops seed energy from Heichel are taken into account; (2) Value from prometryne was not found and it was assumed that the price of the herbicide was directly connected to the energy content.

2.1.3 Energy consumed for transportation

A platform weighing 900 kg was used to transport the final products to the storage facilities. The payload was 5,000 kg. The energy sequestered for manufacturing was taken at 52.78 MJ kg^{-1} plus 8.8 MJ kg^{-1} for transportation and handling (Fluck, 1992) giving an initial energy for the platform of 55,422 MJ. For repair and maintenance a coefficient 0.8 of the manufacturing energy was used or 38,001 MJ. Total indirect energy for the platform was then 93,423.6 MJ and for the 82 kW tractor, which towed this platform, was 347,980 MJ. Working life of the platform was 3,000 h and of the tractor 16,000 hours (Tsatsarelis, 2000). As such, the energy per hour was 31.14 MJ h^{-1} for the platform and 21.75 MJ h^{-1} for the tractor. With an average transportation speed at 20 km h^{-1} and travelling distance 10 km (5+5 km) and delivery efficiency of 0.6 the travelling time was 0.83 h, the work rate 6 t h^{-1} and the fixed energy was 0.0052 MJ kg^{-1} for the platform, 0.0036 MJ kg^{-1} for the tractor and the total 0.0088 MJ kg^{-1} of transported material (Table 2). The direct energy consumption was estimated by considering the value given for trucks by Fluck (1992), 0.0018 MJ kg km^{-1}.

2.1.4 Energy for irrigation

Irrigation water in Greece can be from underground reservoirs, pumped from different depths but also from surface waters of rivers or irrigation channels. The pumping depth varied from a maximum of six meters for the surface waters and could be much deeper for the underground reservoirs. In our experiments the water was pumped from underground reservoirs, it was distributed by aluminium pipes and applied to the crops by traveller irrigators with gun sprinklers or by drip irrigation. Drip irrigation could not be used for crop emergence irrigation and the farmer was obliged to have both.

The pumping plant consisted of the pump and the power unit which was either an electrical motor or a diesel engine. The pump was made by ferrous material with energy content of 84 MJ kg^{-1} (Fluck, 1992) and total weight of 150 kg giving an embodied energy for manufacturing of 12,600 MJ. Transportation and handling energy at 8.8 MJ kg^{-1} was added. For repair and maintenance energy estimation, a coefficient of 0.55 was used (Tsatsarelis, 2000) to give total indirect energy of 20,850 MJ. For 12 years of working life and irrigation of 16 ha per year (the pump discharge was 40 m^3 h^{-1} and a ten days cycle was taken into account) the indirect energy was 108.6 MJ ha^{-1}. Similar steps were followed to estimate the indirect energy for the electrical motor or the diesel engine and the rest of the irrigation equipment (Table 5). Aluminium pipes were used to distribute the water in the field at 73.3 m per ha weighing 0.89 kg m^{-1} (Batty and Keller, 1980). The traveller irrigator was composed of ferrous material (700 kg) and polyethylene for the pipe (339 kg). For drip irrigation, with between crop row spacing 0.75 m and pipes placed every second row, the total length of the pipes with emitters was calculated to 6,667 m ha^{-1}. The sequestered energy for the plastic pipes was estimated at 160 MJ kg^{-1} (Batty and Keller, 1980).

Table 5 Indirect energy inputs for irrigation

	Pump	Electrical motor	Diesel motor	Main water network pipes	Drip irrigation pipes	Traveler Irrigator	
Material	Steel	steel - copper	Steel	Aluminum	Polyet-hylene	Steel	Pol/ne
Indirect Energy Inputs							
Pipes length / m·ha^{-1}				73.33	6 666.67		
Weight / kg / kg·ha^{-1*}	100.00	50.00	840.00	65.26*	972.00*	700.00	339.00
Material and manufacturing energy / MJ·kg^{-1}	84.00	122.00	86.77	280.00	160.00	56.90	160.00
Transportation energy / MJ·kg^{-1}	8.80	8.80	8.80	8.80	8.80	8.80	
R&M coefficient / cRM	0.55	0.29	0.49	0.22	0.90	0.61	
Total sequestered energy / MJ	13 900	8 309.00	115 993	22 869	304 092.00	67 913.00	
Estimated life / years	12.00	12.00	15.00	20.00	10.00	20.00	
tal indirect energy inputs / MJ·ha^{-1}	72.40	43.30	454.90	67.30	1900.26	190.70	

The pumping plant was powered by electrical motors or diesel engines. Electrical motors have efficiency of 90%, while diesel engines thermal efficiency is about 25% (Sloggett, 1992). However, the energy sequestered for producing and delivering electricity was much higher than that required for shipping, refining and delivering diesel oil. The overall efficiency coefficient for electrical motors was 0.18 and for the diesel engine 0.213 (Sloggett, 1992). The required pressure was 810 kPa for the traveller irrigator with gun sprinkler and 253 kPa for the drip irrigation. Using a pump efficiency of 0.76 and water distribution efficiency of 0.75 for the traveler irrigator and 0.91 for the drip irrigation (Sloggett, 1992), the consumed direct energy estimation is shown in Table 6.

Table 6 Direct energy inputs for irrigation for four senarios

	Electrical motor 70 m pumping depth	Electrical motor 1 m pumping depth	Diesel motor 70 m pumping depth	Diesel motor 1 m pumping depth
Traveller irrigator				
Total dynamic head (TDH) / kPa	1 497.00	820.00	1 497.00	820.00
Motor power / kW	23.00	12.60	23.00	12.60
Actual pumping energy / MJ·m^{-3}	2.07	1.14	2.07	1.14
Direct energy inputs / MJ·m^{-3}	11.50	6.30	10.10	5.50
Drip				
Total dynamic head (TDH) / kPa	939.80	263.10	939.80	263.10
Motor power / kW	15.10	4.20	15.10	4.20
Actual pumping energy / MJ·m^{-3}	1.36	0.38	1.36	0.38
Direct energy inputs / MJ·m^{-3}	7.52	2.11	6.63	1.86

2.1.5 Harvesting energy

Rape seed and sunflower were harvested by a combine harvester. A silage harvester was used to harvest sweet sorghum. Indirect energy inputs derived from the use of the harvesting machinery were estimated as described earlier (Table 2). Direct energy was estimated by literature data (Leach, 1976). For collecting sunflower and rapeseed stalks, a round baler was used. Direct energy consumption was taken from Leach (1976).

2.1.6 Farm oil extraction

Oil extraction of the two oilseed crops (rapeseed and sunflower) can be carried out in the farm by cold pressing. A screw type of small size press was used with an electrical motor of 1.1 kW (1.5 hp) and a capacity of 6-7 L of oil per hour. An electrical power meter connected in series to the press was used to measure power consumption. The average power was 0.87 kW. At the same time the processed seed and the produced oil were measured to estimate the energy per kg of seed processed. For the sunflower the energy use was 0.180 MJ kg^{-1} of seed and for oilseed rape 0.187 MJ kg^{-1}. Increasing these values by a coefficient of 0.18 for production and delivery of electricity (Sloggett, 1992) the total direct energy use was 1.00 MJ kg^{-1} for sunflower and 1.04 MJ kg^{-1} for rapeseed. The indirect energy for manufacturing, repairing and maintaining the press was added (Table 2).

2.2 Energy output estimation

Rape seed outputs were the seed and the stalks. Field measurements gave average dry stalk/seed ratio of 1.9, while the cold pressing gave in average 32% oil and 68% cake. The energy content of oil was 37.6 MJ kg^{-1} and for cake 15 MJ kg^{-1} (Riva and Sissot, 1999). The plant stalks could be left in the field as manure or harvested as dry biomass. The energy content of the stalks was estimated at 18 MJ kg^{-1} (Karaosmanoglou et al., 1998). In this case the energy consumed for stalk baling with a round baler and for transportation was added to this analysis.

Sunflower outputs were also the seed and the stalks. Field measurements gave dry stalk/seed ratio of 1.23, while the cold pressing of seed gave in average 33.5% oil and 66.5% cake. The energy content for oil was 36.8 MJ kg^{-1}, for cake 15 MJ kg^{-1} (Riva and Sissot, 1999) and for the stalks 17.3 MJ kg^{-1} (Gemtos, 1992).

For sweet sorghum the dry matter of the plant stems were considered as the energy output. The energy content was 15.4 MJ kg^{-1} (Badger, 1999) of dry material.

2.3 Energy efficiency estimation

Three indices were used for the energy efficiency estimation. The net energy which was the energy output minus the energy input measured in MJ. The energy efficiency coefficient was obtained by dividing the energy output by the energy input, which was a dimensionless number. Finally, the energy productivity was the energy spent per kg of output measured in kg MJ^{-1}.

3 Result and discussion

3.1 Rape seed

The average dry seed yield was 583 kg ha^{-1} for 2007 and 1,618 kg ha^{-1} for 2008. The low yield in 2007 was due to very low precipitation during spring. The energy budgets are shown in Table 7. Without the stalks, the net energy was positive and up to 28,596 MJ ha^{-1}, which was a rather satisfactory result. When the stalks were taken into account the net energy was over doubled and reached 81,114 MJ ha^{-1}. Maximum energy efficiencies were 4.62 without the stalks and 10.68 with the stalks.

Table 7 Energy budgets for the oilseed rape crop experiments

	without the stalks			with the stalks		
	2007	2008	AVERAGE	2007	2008	AVERAGE
Energy Inputs/MJ·ha^{-1}						
Tillage	3 390	3 390	3 390	3 390	3 390	3 390
Sowing	780	841	810	780	841	810
Fertilization	3 317	2 680	2 998	3 317	2 680	2 998
Pesticide application	809	0	405	809	0	405
Harvest	948	948	948	1 381	1 381	1 381
Transportation	12	32	22	34	86	60
Total	9 257	7 892	8 574	9 711	8 377	9 044
Yield, dry weight/kg·ha^{-1}						
Seed	583	1 618	1 101	583	1 618	1 101
Oil	181	540	354	181	540	354
Cake	402	1 078	746	402	1 078	746
Stalks				1 246	2 945	2 095

	without the stalks			with the stalks		
	2007	2008	AVERAGE	2007	2008	AVERAGE
Energy Outputs/MJ·ha^{-1}						
Oil	6 794	20 322	13.325	6 794	20 322	13 325
Cake	6 033	16.166	11 193	6 033	16 166	11 193
Stalks				22 424	53 003	37 714
Total	12 827	36.488	24 517	35 251	89 491	62 231
Energy budget						
Net Energy/MJ·ha^{-1}	3 571	28 596	15 943	25 540	81 114	53 186
Energy Efficiency	1.39	4.62	2.86	3.63	10.68	6.88
Energy Productivity/kg·MJ^{-1}	0.06	0.21	0.13	0.19	0.54	0.35

The crop achieved a positive budget even in year 2007 with the very low yield. It was clear that with better adaptation of the varieties to the Greek conditions and better knowledge of the crop, rapeseed could offer a crop with positive energy balance. Figure 2 shows the average (for the two years) input energy consumption. Soil tillage and fertilization were the most important inputs accounting for 64.5% of the energy consumption while harvesting and transportation accounted for 15.8%.

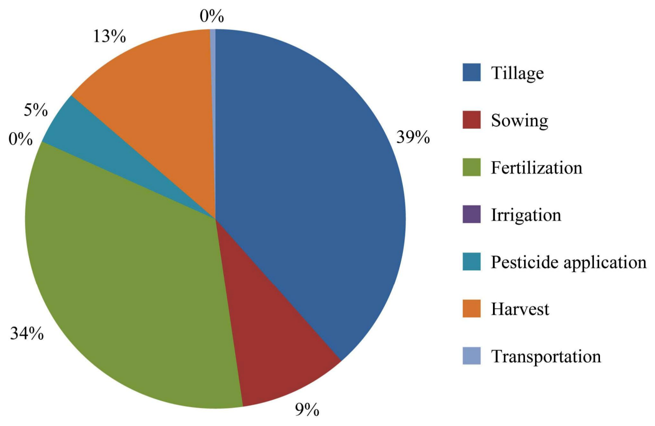


Figure 2 Energy input distribution for rape seed in Greece

3.2 Sunflower

The average yield for the two years was 3,707 kg ha^{-1}. The energy budgets for each experiment are shown in Table 8. Net energy averaged from 51,002 MJ ha^{-1} without the stalks and reached 147,123 MJ ha^{-1} with the stalks. Energy efficiencies were 2.89 and 6.16 respectively. The stalks offered considerable energy and it was important to find potential applications to improve the energy balance. However, using the stalks large amounts of nutrients will be removed from the soil and should be replaced by additional fertilizers, while the bare soil will be sensible for erosion. In this case, when the stalks will be removed from the field, alternative cultivation systems should be developed using winter cover crops most probably mixtures of cereals and legumes to protect the soil and add organic matter and nutrients to replace the removed stalks. Figure 3 shows the average energy inputs distribution. The energy input for irrigation was the main input accounting for 54.1% of the total inputs when considering a mean water application of 2,900 m^{3} ha^{-1} and an average pumping depth of 56.2 m. The second main input was fertilization with a 25.9% of the total.

Table 8 Energy budgets for the sunflower crop experiments

	Without the stalks			With the stalks		
	2007	2008	AVERAGE	2007	2008	AVERAGE
Energy Inputs / MJ·ha^{-1}						
Tillage	4 326	4 255	4 290	4 326	4 255	4 290
Sowing	585	603	594	585	603	594
Fertilization	10 364	7 552	8 958	10 364	7 552	8 958
Pesticide application	459	1 179	819	459	1 179	819
Irrigation	8 635	21 618	15 127	8 635	21 618	15 127
Harvest	1 117	1 117	1 117	1 585	1 585	1 585
Transportation	68	81	74	160	191	175
Total	25 553	36 404	30 979	26 114	36 983	31 548

	Without the stalks			With the stalks		
	2007	2008	AVERAGE	2007	2008	AVERAGE
Yield, dry weight / kg·ha^{-1}						
Seed	3 376	4 038	3 707	3 376	4 038	3 707
Oil	1 067	1 353	1 210	1 067	1 353	1 210
Cake	2 310	2 685	2 497	2 310	2 685	2 497
Stalks				5 090	6 088	5 589
Energy Outputs / MJ·ha^{-1}						
Oil	39 264	49 781	44 523	39 264	49 781	44 523
Cake	34 643	40 274	37 458	34 643	40 274	37 458
Stalks				88 065	105 315	96 690
Total	73 907	90 055	81 981	161 971	195 371	178 671
Energy budget						
Net Energy / MJ·ha^{-1}	48 353	53 651	51 002	135 857	158 388	147 123
Energy Efficiency	2.89	2.88	2.89	6.20	6.12	6.16
Energy Productivity / kg·MJ^{-1}	0.13	0.13	0.13	0.32	0.31	0.32

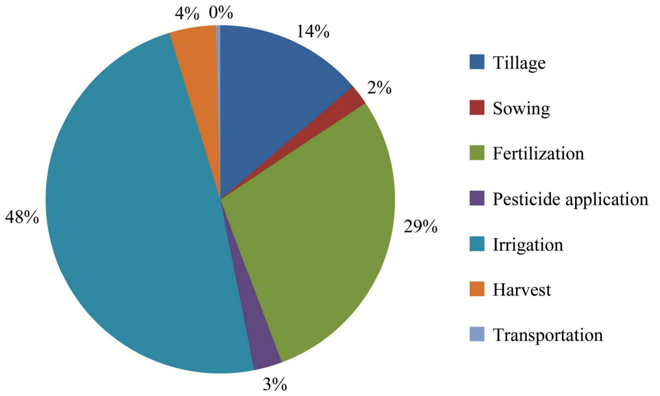


Figure 3 Energy input distribution for sunflower in Greece

3.3 Sweet sorghum

Sweet sorghum energy analysis is presented in Table 9. Yield was generally high around 31.37 t ha^{-1} of dry matter which led to high net energy of 427,767 MJ ha^{-1}. Energy efficiency was also high, around 8.92. High sweet sorghum yield were experienced in other Greek experiments, as well (CRES, 2006). It is important that the plant can produce good quality of raw material for second generation bio-ethanol production (Christakopoulos et al., 1993). Figure 4 illustrates the analysis of the energy spent for the production. About 67% of the energy was devoted to irrigation by pumping water from average depth of 53 m and average application of 5,200 m^3 ha^{-1}. Sweet sorghum required high water depth for high yield and pumping from deep reservoirs increased significantly energy inputs. Fertilization was the second important energy input accounting for 17% of the total.

Table 9 Energy budgets for the sweet sorghum crop experiments

	2007	2008	AVERAGE
Energy Inputs / MJ·ha^{-1}			
Tillage	5 054	5 292	5 173
Sowing	1 317	1 296	1 306
Fertilization	10 249	7 925	9 087
Irrigation	33 008	39 889	36 448
Harvest	406	406	406
Transportation	3 306	2 615	2 961
Total	53 341	57 423	55 382
Yield, dry weight / kg·ha^{-1}			
Stalks	30 436	32 310	31 373
Energy Outputs / MJ·ha^{-1}			
Stalks	468 719	497 580	483 149
Energy Budget			
Net Energy / MJ·ha^{-1}	415 378	440 157	427 767
Energy Efficiency	9.18	8.67	8.92
Energy Productivity / kg·MJ^{-1}	0.59	0.56	0.58

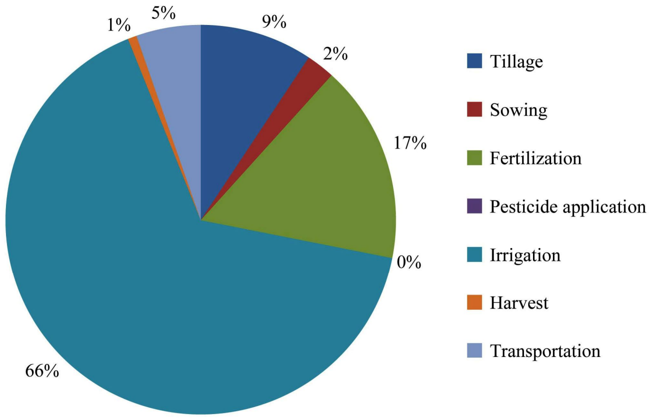


Figure 4 Energy input distribution for sweet sorghum in Greece

4 Discussion

The above results are based on field measurements and literature data. However, literature data present a range of values that can lead to different results. A brief discussion is presented below.

4.1 Manufacturing energy

Summary data about manufacturing energy for various agricultural equipment have been presented by Bowers (1992). Since then however it was well known that the technological progress affected the energy sequestered to tractor and machinery. Mikkola and Ahokas (2010) agreed that in about 20 years after Bowers (1992) calculations, considerable changes were observed in farm machinery construction. While energy spent for metal materials was reduced at the same time a lot of new materials like plastics and aluminium with high energy content were added to modern tractors to achieve lower weight per power output. Mikkola and Ahokas (2010) referred to literature sources claimed that despite the energy savings in metal production the energy spent for car manufacturing was not changed due to the new materials added. It was therefore reasonable to accept Bowers (1992) values for the present study. However a possible change in the manufacturing energy would affect the energy balance. A 50% reduction to the values of Bowers (1992) would improve energy efficiency at 0.12, 0.24 and 0.39 for sunflower, rapeseed and sweet sorghum respectively. These energy savings would represent 3%-4.3% of the total energy inputs to the crops.

4.2 Repairs and maintenance energy

In the present study the estimation of the repairs and maintenance (R&M) energy was based on Bowers (1992) values and were given as percentage of the energy of the implement production. Different sources however were quoting different percentages. In many cases a monetary approach was accepted correlating the energy inputs to the economic cost for Repair & Maintenance (R&M). ASABE (2007) suggested for the estimation of the cumulative repair and maintenance economic cost a formula based on the initial value of the machine, the estimated life and two given coefficients. The deviation of the value of the ASABE Standard formula and the real calculation was within 25% (ASABE, 2007). Fluck and Baird (1980) presented two models to estimate the energy consumption for R&M. An Industry Cost Model estimated a mean percentage of 55% of the energy needed for machinery manufacturing, while a Lifetime Machine Repair Cost Model was about 138%. They admitted that the second model was overestimating the real R&M energy use. Bowers (1992) tried to combine the two models by giving a table of R&M energy used for 14 different machineries with an average of 55%. Mikkola and Ahokas (2010) referred also to the luck of sufficient data for estimating the actual R&M energy consumed. It should be stressed that the R&M cost was directly connected to the machine use. It is a fact that during the working life of a machine there is an initial period of the first year of relatively high R&M costs (covering any damages from transportation and handling), a period of five to six yr of low costs and then the cost is increasing with the use (Mygdakos and Gemtos, 1996). The tractor working life of 12,000 or 16,000 h was also a very optimistic assumption. Most probably values even less than 10,000 h should be taken into account. Using the ASABE formula for 10,000 h, the cumulative R&M cost becomes 70% of the initial. It is quite clear that we are far away from the average R&M coefficient of 0.55 that was assumed by Bowers (1992) and taken to the present analysis. In the case presented by Fluck and Baird (1980) with 138% coefficient, the R&M energy would increase energy inputs by 235 MJ ha^{-1} for rapeseed (the crop with the least demands) to 2,834 MJ ha^{-1} for sorghum (the higher energy demanding crop). In that case R&M would represent 3.2% to 5.1% of the total inputs and the energy efficiency would be decreased by 0.21 to 0.42 units. On the other hand, use of smaller R&M coefficients (27.5% of the manufacturing energy) would benefit 90-938 MJ ha^{-1}, for rapeseed and sweet sorghum respectively, a reduction equal to 1.0%-1.7% of the total energy inputs and would improve efficiency 0.07 - 0.15 units.

4.3 Machinery estimated life

The estimated life of the machinery was another major problem in the estimation of energy budgets.

ASABE (2007) and other authors following (Tsatsarelis, 2000) quoted a working life of 12,000 for 2WD, 16,000 h for 4WD tractors. A 1990 study of tractors was used in Greece (Gemtos et al., 1998) gave 355.8 h yr^{-1} use for tractors not used for irrigation but around 924.3 h yr^{-1} for tractors used for irrigation. Naydenof and Geddy (1993) gave for tractors yearly use 580-1,130 h yr^{-1} for Bulgaria, 100-600 h y^{-1} for the former Western Germany regions and 1,000-1,500 for the former Eastern Germany regions, 400-500 h yr^{-1} for France, Holland, Denmark, Austria and Belgium. More recent data on tractor use were lacking in the literature to the best of our understanding. It was obvious that machinery use vary widely among the countries according to the farm sizes, mechanization intensity, crops, etc. Reducing working life to 50% would increase energy inputs by 415-3418 MJ ha^{-1} (for rapeseed and sorghum), an increase of 4.4%-5.7% in the total energy inputs and would decrease efficiency 0.30-0.50 units.

4.4 Consumable goods

Consumable goods energy estimation were also based on literature data which however were limited and also may have changed through the years. As an example considerable efforts have been made to reduce the energy sequestered to the Nitrogen fertilizer production. The International Fertilizer Association (IFA, 2010) estimates that a modern factory producing NH_3 consumes 28.3 GJ t^{-1} of NH_3 (equivalent to 36.38 GJ t^{-1} of N) with the thermodynamic limit at 20 GJ t^{-1}. Several agricultural practices aimed at increasing N efficiency by improving application technology (i.e. variable rate applicators) which could have a positive impact. Reduction of the energy consumed in the industry at 50% resulted to 1,098, 3,980 and 4,515 MJ ha^{-1} savings (in rapeseed, sorghum and sunflower respectively) and a reduction of 12.2%, 7.1% and 11.1% to the total energy inputs. Energy efficiency was improved by 0.95, 0.67 and 0.50 for the three crops.

Savings in the production of pesticides was less important as the embodied energy comes mainly from the active ingredients but the industries always tended to improve their efficiencies. Moreover, seeds for sowing also accounted for a small part of the energy budgets.

4.5 Irrigation

For sunflower and sweet sorghum, irrigation was the main energy input accounting for 32.7% and 72.4% of the total inputs. The variation was caused by the different water application rates and the pumping depth. Reducing the water application could cause significant energy savings but such treatment would require experiments to investigate the effect to yields. Different pumping depths which would affect the energy consumption but not the productivity of the crops were analyzed. Using surface water instead of pumping from a depth of 100 m, the total energy consumption would be reduced by 44.2% in the sunflower and 53.8% in the sweet sorghum leading to an increase in energy efficiency of 2.57 units in sunflower and 7.57 units in sorghum.

4.6 Use of produced oils on the farm

Two of the tested crops, rapeseed and sunflower produce oil containing seeds with significant content in oil which can be easily extracted in the farm by cold pressing. The raw oil after some filtering and sedimentation processes could be used as fuel in diesel engines (Hossain and Davies, 2010; Ozsezena et al., 2009). This option could lead to energy self-sufficient farms.

Tables 10 and 11 show the energy budgets when part of the seed produced by the two oilseed crops was used to produce oil by cold pressing and then to power farm machinery. The energy consumed for oil extraction was added to the inputs. For irrigation a diesel engine had to be used. Five different levels of Diesel fuel substitution were examined. The 0% meant only diesel fuel was used and all the produced seed was sold to the market. Blends of 10%, 30% and 50% oil and diesel fuel were considered. The 100% scenario assumed that all the fuel needs of the farm were covered by oil.

For rapeseed, energy efficiency was improved as the diesel oil was gradually substituted by oil. The use of diesel (case 0%) gives energy efficiency (without stalks) of 6.88 while use of self-produced oil (case 100%) doubles the efficiency to 12.84 (shown in Table 10). Similar results were found for sunflower. As diesel oil is substituted by self-produced oil, energy efficiency is increased (from 4.19 in the zero case, to 8.32 in the 100% case) (shown in Table 11).

Table 10 Effect of on the farm use of rapeseed oil in different mixtures with diesel to power farm machinery

Biofuel percent	0%	10%	30%	50%	100%
Energy Inputs / MJ·ha^{-1}					
Tillage	3 390	3 087	2 480	1 872	354
Sowing	810	752	635	518	227
Fertilization	2 998	2 986	2 963	2 939	2 879
Pesticide application	405	402	396	390	375
Harvest	1 381	1 279	1 075	871	361
Transportation	60	57	51	45	30
Oil extraction	0	35	104	174	347
Total	9 044	8 597	7 703	6 809	4 574
Yield / kg·ha^{-1}					
Oil (in biofuel production)		9	28	47	93
Seeds (in biofuel production)		29	87	145	290
(% total)		*3%*	*8%*	*13%*	*26%*
Seeds (in commercial production)	1 101	1 072	1 013	955	810
Stalks	37 714	37 714	37 714	37 714	37 714
Energy Outputs / MJ·ha^{-1}					
Oil (in commercial production)	13 325	12 973	12 270	11 567	9 809
Cake	11 193	11 193	11 193	11 193	11 193
Stalks	37 714	37 714	37 714	37 714	37 714
Total	62 231	61 879	61 176	60 473	58 715
Energy budget					
Net Energy / MJ·ha^{-1}	53 186	53 282	53 473	53 664	54 142
Energy Efficiency	6.88	7.20	7.94	8.88	12.84
Energy Productivity / kg·MJ^{-1}	0.35	0.37	0.41	0.46	0.68

Table 11 Scenarios for using sunflower oil produced in the farm at different mixtures with diesel oil to power the farm equipment

Biofuel percent	0%	10%	30%	50%	100%
Energy Inputs / MJ·ha^{-1}					
Tillage	4 722	4 300	3 454	2 609	495
Sowing	596	561	491	421	246
Fertilization	10 573	10 561	10 537	10 513	10 453
Pesticide application	1 115	1 109	1 097	1 086	1 056
Irrigation	20 467	18 730	15 255	11 780	3 093
Harvest	1 585	1 484	1 280	1 077	569
Transportation	161	153	137	121	81
Oil extraction	0	165	494	823	1 645
Total	39 219	37 061	32 745	28 430	17 640
Yield / kg·ha^{-1}					
Oil (in biofuel production)		48	144	239	479
Seeds (in biofuel production)		143	429	714	1.429
(% total)		4%	13%	21%	42%
Seeds (in commercial production)	3 398	3 255	2 969	2 683	1 969
Stalks	5 123	5 123	5 123	5 123	51.123
Energy Outputs / MJ·ha^{-1}					
Oil (in commercial production)	41 885	40 124	36 602	33 079	24 273
Cake	33 891	33 891	33 891	33 891	33 891
Stalks	88 621	88 621	88 621	88 621	88 621
Total	164 397	162 635	159 113	155 590	146 784
Energy budget					
Net Energy / MJ·ha^{-1}	53 186	53 282	53 473	53 664	54 142
Energy Efficiency	6.88	7.20	7.94	8.88	12.84
Energy Productivity / kg·MJ^{-1}	0.35	0.37	0.41	0.46	0.68

5 Conclusions

From the presented results the following conclusions can be drawn:

1) All three crops presented a positive energy balance and they were candidates to cover the transportation fuels of the Greek market.

2) Rape seed as rain fed crop had a great advantage with low energy inputs but adaptation of the studied varieties and the cropping practices to the Greek conditions were poor.

3) Sunflower and sweet sorghum showed good adaptation to Greek conditions and can offer raw material for biofuels production.

4) Use of the crop residues improved energy balances.

5) Irrigation was a major energy input for sunflower and sweet sorghum. Especially when water was pumped from deep aquifers. Significant savings can be achieved by using surface water.

6) Fertilization was the major energy input in the rape seed and the second more important in sunflower and sweet sorghum crops. Improving industry efficiency promoting practices and reducing the energy consumed for Nitrogen will significantly improve energy efficiency of the crops.

7) On farm use of the oil produced by rape seed and sunflower can improve energy efficiency.

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