

# Biogas production from energy crops in northern Greece: economics of electricity generation associated with heat recovery in a greenhouse

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**Abstract** Herein a techno-economic assessment was performed on an energy-crop-based biogas plant coupled with a greenhouse for utilizing thermal energy produced by cogeneration. Seven energy crops were evaluated: triticale, maize, alfalfa, sunflower, clover, barley and wheat. According to the evaluation, triticale was the most competitive energy crop under selected climate conditions for northern Greece. Although maize displays higher biomass yield and biogas potential than the drought-resistant crop triticale, it has high irrigation demand that contributes significantly to total production costs. For a triticale-based biogas production to become economically feasible, agricultural arable area larger than 500 ha, or biogas plant size larger than 1000 kW<sub>el</sub>, is required. However, with public funding, biogas production becomes feasible at smaller area (>250 ha) or biogas plant size (>500 kW<sub>el</sub>). The inclusion of a greenhouse into the design of the biogas plant contributes positively to the economic viability of the entire system. Under this scenario, greenhouse financial income accounts for about 17–18% of total income. Results of a sensitivity analysis suggest that the selection of an appropriate energy crop for biogas production should be based principally on both digestibility (specific methane

yield) and biomass yield per hectare, these factors being more critical than biomass production costs.

**Keywords** Biogas · Energy crops · Economics · Agriculture · Greenhouse

## List of symbols

$C$	Constant accounting for material properties of the pump
$C_{\text{CH}_4}$	Specific methane yield (m <sup>3</sup> CH <sub>4</sub> /t VS)
$C_{\text{DM}}$	Dry matter content of silage (%FM/100)
$C_G$	Specific investment costs (€/m <sup>2</sup> )
$C_R$	Carriage capacity of the tractor (m <sup>3</sup> )
$C_{\text{VS}}$	Volatile solids content of dry mass (%DM/100)
$D$	Inner diameter of the tube (mm)
$D_d$	Day duration (h)
$d_{\text{IT}}$	Depth of tillage (cm)
$D_n$	Night duration (h)
$D_S$	Depth of implement in the soil (cm)
$d_T$	Total distance travelled by the tractors (km)
$H_E$	Operational manometric pressure of equipment (m)
$H_L$	Pressure losses in the pipes (m)
$H_T$	Total manometric water pressure (m)
$H_W$	Depth of the water body from which water is pumped (m)
$k_{\text{AV}}$	Availability rate of biomass within the operational radius, here: 0.3
$k_{\text{FA}}$	Unplanted, fallow land coefficient
$k_{\text{LO}}$	Factor accounting for losses in harvesting and silaging
$k_P$	Specific power requirements of each implement (kW/(m <sub>IW</sub> × (km/h))
$k_{\text{PL}}$	Partial load operation factor (%)
$k_{\text{PM}}$	Coefficient for safety margin in tractor engine sizing

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$k_T$	Factor to include tractor turns on the fields	$t_W$	Time required to perform each individual field operation (h)
$k_{UN}$	Un-arable land area coefficient	$V$	Total volume of biomass to be transported ( $m^3$ )
$M_{BD}$	Dry mass of crops to be packed (t DM)	$\nu$	Value of cumulative cash flow at year showing last negative value of cumulative cash flow (€)
$M_{BF}$	Fresh mass of crop biomass transported (t)	$\nu_T$	Tractor velocity (km/h)
$M_{TT}$	Transportation capacity of the tractors (t)	$\nu_{TT}$	Average speed of the transport tractors (km/h)
$N$	Month of the year in the cultivation period (September–July)	$W_I$	Size of implements used for tillage and other field operations (m)
$N_H$	Hourly diesel fuel consumptions for each field work (L/h)	$W_{IT}$	Size of the ploughing implement attached to the tractor (m)
NPV	Net present value (€)	$Y_{BF}$	Fresh biomass yield before ensiling (t/ha)
$n_R$	Number of reactors in the biogas plant	$Y_{CH_4}$	Methane yields per hectare ( $m^3 CH_4$ /ha)
$n_{TT}$	Number of tractors required for biomass transportation	$Y_E$	Electrical efficiency of CHP unit (%)
$n_{TF}$	Number of tractors required for field works	$Y_N$	Years after initial investment showing the last negative value of cumulative cash flow (year)
$N_T$	Total fuel consumption of tractors (L)	$Y_{SD}$	Yield of dry ensiled biomass (t DM/ha)
$P$	Value of yearly cash flow at the year showing first positive value of cumulative cash flow	$Y_{TH}$	Thermal efficiency (%)
PBP	Payback period (year)	$\Delta T_{SUN}$	Indoor/outdoor temperature difference due to greenhouse effect ( $^{\circ}C$ )
$P_D$	Drawbar power (kW)	$\tau$	Tortuosity factor
$P_E$	Engine power per tractor (kW)		
$P_{EC}$	Cumulated engine power of all tractors (kW)		
$P_{EE}$	Electrical power of the engine (kW)		
$P_P$	Pump power required to drive water sprinklers (kW)		
$P_{TO}$	Power-take-off (kW)		
$P_{TT}$	Engine power of transport tractors (kW)		
$Q$	Water flow for irrigation ( $m^3/h$ )		
$R_A$	Ratio of direct availability of nutrients in digestates (%)		
$R_E$	Ratio of fertilizing efficiency (%)		
$r_e$	Pump efficiency coefficient		
$R_{FERT}$	Recycling rate of nutrients related to the spreading of digestate onto the fields (%)		
$R_L$	Nutrient losses during storage of the digestates		
$R_S$	Soil resistance ( $N/(m \times cm_{DS})$ )		
$r_{SIL}$	Packing rate (h/t DM)		
$r_U$	Engine power usage factor		
$S_C$	Operational cultivation area, after subtraction of un-arable land and fallow land (ha)		
$S_G$	Greenhouse surface (ha)		
$S_L$	Total cultivation area, including un-arable land and fallow land (ha)		
$T_A$	Duration available to perform ploughing operations (h)		
$T_d$	Target day temperature in the month ( $^{\circ}C$ )		
$T_D$	Total distance covered by tractors for biomass transportation (km)		
$T_{HD}$	Day heating degrees ( $^{\circ}C$ )		
$T_{HN}$	Night heating degrees ( $^{\circ}C$ )		
$T_{iav}$	Average day temperature in the month ( $^{\circ}C$ )		
$T_{imax}$	Maximum day temperature in the month ( $^{\circ}C$ )		
$T_n$	Target night temperature in the month ( $^{\circ}C$ )		
$t_{SIL}$	Operation time of packing tractors for silaging (h)		

## Introduction

European Union (EU) targets that 20% of energy consumption will derive from renewable sources by 2020 ([ec.europa.eu/energy/en/topics/renewable-energy](http://ec.europa.eu/energy/en/topics/renewable-energy); last accessed 15/9/2016). Biomass is expected to make a vital contribution to renewable energy supply; estimates suggest that two-thirds of renewable energy may be derived from biomass in the future (Panepinto et al. 2014). One of the most efficient biomass-to-energy conversion technologies, anaerobic digestion (AD), converts the biodegradable fraction of organic materials (i.e. urban, agricultural and agro-industrial waste, sewage sludge, energy crops) into biogas and digested residue (digestate). Biogas can be used for combined heat and electricity (CHP) production, vehicle fuel, or injected in the gas grid after upgrading, while the digestate can be recycled back to cultivated areas as a fertilizer (Pöschl et al. 2010). Within the EU, biogas production increased by about 600% from the 1990s to 2005, reaching around 11 Mt of oil equivalent in 2010 (Barbanti et al. 2014). Nevertheless, the level of diffusion of biogas technology varies widely between EU countries depending on national policy programs and sustainability targets (Faaij 2006).

Until now, biogas production in Greece has been limited, and mainly related to the collection of landfill gases or the digestion of municipal sewage sludge, accounting for 95% of biogas plants (EurObserve'ER 2014). The limited number of biogas plants operating in the agricultural sector was linked to low feed-in-tariffs for electricity production

that resulted in economically unfeasible investments. However, in 2010, a new legislation passed (No. 3851/2010) and updated in 2014 (No. 4254/2014), increasing the feed-in tariff from 75 €/MWh previously (legislation No. 3468/2006), to 190–230 €/MWh of electricity, depending on biogas plant size and whether or not the biogas plant also benefited from public funding. This increase in feed-in tariff generated strong interest for biogas production in the country, and several agricultural biogas plants, mainly based on the utilization of organic wastes and wastewater, are already installed or in the planning phase.

However, climatic conditions in Greece, and in particular in northern Greece, are favourable to energy crop production, allowing for high biomass yields. In central Europe, countries such as Germany extensively produce energy crops for biogas production and there is a vast research on this field. However, energy crop cultivation strategies and practices of southern countries differ from those prevailing in northern countries. Till now, due to lack of maturity of the agricultural biogas sector in Greece, although there is a great interest for investments, only still little information is available regarding the economics of energy crops as feedstock for AD in the country. While the use of agricultural residues in the biogas process may be more environment-friendly than dedicated energy crop production, the latter offers a way of process intensification, increasing the specific yields per unit volume of the reactors, and facilitating the co-digestion of agro-industrial residues and effluents. Cogeneration is currently the most simple and affordable technology for medium-scale biogas plants. However, the energy recovery achieved by cogeneration depends largely on heat use (Weiland 2010). Therefore, efficient pathways for heat recovery must be investigated, such as heating of residential buildings, farm buildings, agro-industries, while district heating is only feasible at larger scale (Konrad et al. 2011). Finally, in a sustainable development approach, economic parameters must be put in perspective with environmental indicators, such as energy and water consumption, as well as the efficiency of the energy conversion (Gabrielle et al. 2014). Economic feasibility assessments for energy-crop-based AD have been performed for various European countries such as Germany (Balussou et al. 2012), Austria (Walla and Schneeberger 2008), UK (Jones and Salter 2013) and Italy (Torquati et al. 2014), but there is still a lack of information for the Greek context.

The overall goal of the present study was to apply a calculation methodology to evaluate the economic feasibility of producing energy crop as feedstock for AD in the context of northern Greece. To this end, a detailed

assessment of the economic feasibility of energy crop cultivation was performed on the following crops, which are well established in Greece: triticale, maize, alfalfa, sunflower, clover, barley and wheat. In addition, coupling of AD with a vegetable greenhouse was also investigated, aiming in partial recovery of thermal energy generated in the CHP unit (Fig. 1). According to Greek regulations, feed-in tariffs do not include bonuses for external heat use generated in the cogeneration process. The evaluation was performed based on the current electricity feed-in tariff for agricultural biogas plants, and economies of scale in energy crop cultivation were studied by varying the sizes of the agricultural surfaces available for biogas production. To the best knowledge of the authors, this is the first attempt for a detailed assessment of the economics of biogas production using energy crops cultivated in Greece, as well as giving an insight of the economics and heat recovery efficiency achieved by coupling a greenhouse to the CHP unit for vegetable production. The present study provided detailed economic simulations for the following processes: (1) cultivation of energy crops as feedstock for AD, (2) production of biogas and electricity through AD and (3) cultivation of a vegetable plant (tomato) in a greenhouse, using waste thermal energy from the CHP unit (Esen and Yuksel 2013).

## Materials and methods

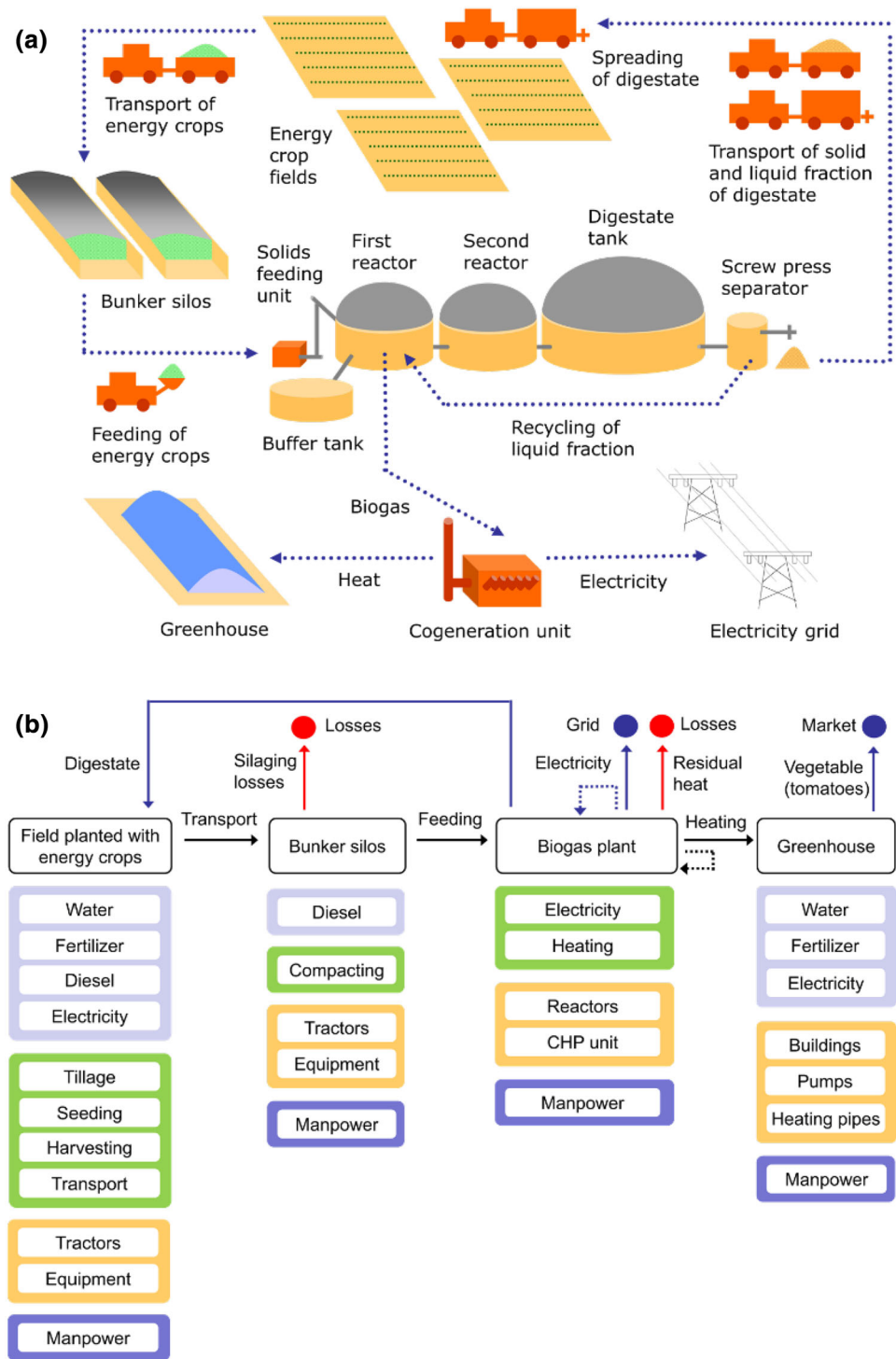
### System boundaries

The system considered in the performed economic analyses comprises a biogas plant, a cultivated area with energy crops available for AD, and a greenhouse. Electricity is sold to the grid, and residual heat from the CHP unit is valorized in the greenhouse for tomato cultivation. Digestates generated in AD are returned to the fields to serve further as fertilizer for energy crop cultivation, in order to optimize nutrient recovery and minimize fertilizing input requirements (Fig. 1).

### Cultivation costs for energy crops

The following energy crops were considered in the study: (1) maize, (2) barley, (3) triticale, (4) sunflower, (5) alfalfa and (6) clover. Cultivation operations taken into consideration for the calculation of energy crops production cost are detailed in Table 6 (“Appendix 2”). Purchasing prices for labour, equipment and consumables are given in Table 7. Costs for each cultivation step are calculated according to amounts of equipment, energy, and time

**Fig. 1 a** Design of the energy-crop-based biogas plant coupled to a greenhouse and **b** block diagram of the supply chain of the entire system



required for each of the cultivation steps, as explained in the following sections.

*Total land area*

The surface required for the cultivation of each energy crop is calculated under the assumption that 7% of the area

( $k_{UN}$ ) consists of un-arable land, including field limits and borders. Energy crops are evaluated in a monoculture system. Hence, in fields cultivated with maize, barley, triticale and sunflower, 25% of the land ( $k_{FA}$ ) is kept unplanted, to provide fallow surface (i.e. one year of fallow after three years of cultivation). Fallow surfaces are not allocated to alfalfa and clover cultivation since legumes

usually do not require fallow. The total land area was calculated using Eq. 1 (“Appendix 1”).

#### *Engine power, number of tractors and fuel consumption for cultivation*

The number of tractors and their power requirements to carry out field works on a specific cultivated area ( $S_C$ ) were evaluated based on the following steps:

In the first step, the power of tractors carrying out field operations was determined. Tractor sizing was based on power requirements for ploughing (one of the most energy-intensive cultivation steps). For this purpose, we estimated the tractor engine power required for pulling a medium-sized ploughing implement into a cultivated field. The number of available hours to perform tillage operations was set at 160 h (i.e. 20 days with 8 working hours per day). The required size of the ploughing implement ( $W_{IT}$ ) attached to the tractor was calculated according to Eq. 2. Subsequently, the drawbar power ( $P_D$ ; kW) corresponding to the selected implement size was calculated and converted into power-take-off ( $P_{TO}$ ; kW), and engine power for tillage ( $P_{EP}$ ; kW) applying Eq. 3 and conversion factors of Eqs. 4 and 5 (Mehta et al. 2011; NSW-Farmers 2013). By following the previous steps, values for tractor engine power were calculated for several field sizes. Processing these values provides a linear correlation between total engine power ( $P_{EP}$ ; kW) and the surface of cultivated area ( $S_C$ ; ha) in Eq. 6.

Based on the typical tractors sizes found on the market, engine power of individual tractors was set at minimum and maximum values of 75 and 275 kW, respectively. Therefore, for the case that total engine power necessary to perform tillage within the prescribed period of 20 days exceeds the maximal power per tractor (275 kW), then the number of tractors operating on the fields was set  $n_{TF} = \frac{\text{Total power(kW)}}{275(\text{kW})}$ , where  $n$  was rounded up to higher integer, with the power of each tractor being the total power divided by  $n$ .

Following the evaluation of the number and size of tractors, the duration and fuel consumption of field operations were calculated. In order to estimate field works duration, we first determined the respective sizes of individual implements fitted to the tractors, which correspond to each cultivation operation listed in Table 6. The width of implements ( $W_I$ ; m) fitted to the tractors for the different field operations was related to engine power ( $P_{ET}$ ; kW) and was calculated using Eqs. 2–5. Specific power requirements ( $k_P$ ; (kW/( $m_{IW} \times (\text{km/h})$ ))) of each implement were calculated with Eq. 7 with values for the factors  $R_s$  and  $D_I$  taken from Table 8. Using previously calculated implement widths, the required time ( $t_W$ ; h) to perform each

individual field operation was calculated using Eqs. 8 and 9. Hourly diesel fuel consumptions ( $N_H$ ; L/h) were estimated in Eq. 10, and total fuel consumption in Eq. 11.

#### *Irrigation and fertilizing of energy crops*

In Mediterranean countries like Greece, summer irrigation of crops is often required to reach satisfactory biomass yields and mitigate the inter-annual variability of rainfalls (Katerji et al. 2008). Among the crops investigated, maize has the highest irrigation requirements. In our study, irrigation was applied only to sunflower, maize, clover and alfalfa, while triticale, barley and wheat were considered as non-irrigated. However, it should be pointed out that biomass yields for these crops may be higher if irrigation would be applied.

Economic calculations are based on water delivery to energy crops via electric pumps connected to travelling sprinklers, of 500 m length, fitted with 125/110-mm tubes (outer/inner diameter). Sprinklers range was set at 65–100 m. The velocity of the travelling system was 12–16 m/h. Travelling speed was supposed to be optimized, so that the depth of water trickling into the soil remains within the range 12–15 mm to prevent water stagnation (Terzidis and Papazafeiriou 1997). Irrigation efficiency, accounting for water losses due to wind, evaporation and leakages, was set at 85%. Hence, water supply was considered as 1.18-fold (i.e. 100/85) of irrigation water requirements. Irrigation equipment was sized according to maximal monthly water requirements for each crop, assuming that water supply must be sufficient to meet the requirements and repeat irrigation of the whole area within less than 10 days. Pump power ( $P_P$ ; kW) required to drive the sprinklers was calculated from the total manometric water pressure ( $H_T$ , m), accounting for pressure losses in the pipes ( $H_L$ , m) according to Eqs. 12–14. Irrigation requirements for each energy crop are listed in Table 6.

Mineral nutrients contained in energy crops are partially conserved in the digestate. According to assumptions taken for nutrient conservation and availability (Herrmann 2013; Möller et al. 2012), the recycling rate of nutrients obtained when spreading digestate onto the fields ( $R_{FERT}$ ; %) amounts to 36% (Eq. 15). Total mineral fertilizer requirements of energy crops are specified in Table 9. Since 36% of these requirements can be met by spreading the digestate onto the fields, a remaining 64%—share of the total amounts should be supplied with mineral fertilizers. Prices for fertilizers are listed in Table 10.

#### *Transportation and silaging of energy crops and digestates*

Transport distance of harvested biomass to bunker silos was calculated by defining a captation radius according to

the method of Walla and Schneeberger (2008) (Eq. 16). Besides the tractors used to carry out cultivation works, additional tractors were considered to operate for biomass transportation from harvest site to silaging unit. The engine power of each tractor used for biomass transportation was set to 125 kW, working at 80% load. The total distance ( $T_D$ ; km) that the tractor(s) need to cover transportation was calculated by Eq. 17, while the total number of transportation tractors was calculated by Eq. 18. The working hours of transportation tractors were considered as the sum of the time needed for the tractors to follow up the harvesters, and the duration of transportation to the silaging unit. To the working time of transportation, an additional 20% idle time was considered.

The mass of digestate transported back to the field for fertilization is assumed to be 70% of the initial mass of substrate, considering the reduction in biomass by biodegradation during the biogas process, as well as mass reduction related to downstream solid/liquid separation of the digestate. This is based on the assumption that both the solid and liquid fractions have to be returned to the fields, as the liquid fraction still contains significant amounts of valuable nitrogen and phosphorus (Möller et al. 2012).

The silaging process consists mainly in pulling and packing of biomass to reach a dry matter density of 300 kg/m<sup>3</sup>. Compaction of fresh biomass is performed by rolling of packing tractor(s) on the silo. Engine power of packing tractors was set at 125 kW, at an engine working rate of 80%. The operation time of packing tractors for silaging ( $t_{SIL}$ ) was calculated using formulas of D'Amours and Savoie (2005) and Harrigan (2003) in Eq. 19.

### Methane yields of energy crops

Parameters for the calculation of biogas production are listed in Table 11. For simplification, the methane content in biogas was assumed to be 55% for all energy crops (Schievano et al. 2015). Furthermore, biases related to the presence of volatile organic compounds contained in silages, that affect the estimation of the specific methane yields and dry matter contents, were neglected (Brulé et al. 2013). Yields of dried ensiled biomass ( $Y_{SD}$ ; t DM/ha) and methane yields ( $Y_{CH_4}$ ; m<sup>3</sup> CH<sub>4</sub>/ha) were calculated according to Eqs. 20 and 21, respectively.

### Design of the greenhouse system

Greenhouse design was considered to be gable roof (A-frame) type, composed of a series of gables, each of them of 7 m width and 40 m length, covering an area of 280 m<sup>2</sup> and a volume of 840 m<sup>3</sup> (von Elsner et al. 2000). Tomato growing in hydroponics was modelled, with a vegetation

cycle ranging from September until July, and a harvesting period of 6.5 months and annual yield of 40 kg FM/m<sup>2</sup>.

Thermal requirements for greenhouse operation were evaluated with following input parameters: Indoor temperature, minimum 3.0 °C, target day 22.0 °C, target night 14.0 °C; heat transfer loss coefficients [W/(m<sup>2</sup> × °C)], top cover (double polyethylene) 4.2, side cover (fibreglass) 6.3, soil 1.3; average soil temperature 11.0 °C; air renewal ratio 0.8; volumetric heat capacity 0.3 W/(m<sup>2</sup> × °C). The pipe conveying thermal energy as warm water from the CHP of the biogas plant to the greenhouse was assumed to cover a rather short distance of 200 m. Calculations were performed in heating degree-hours according to the method of Mavrogiannopoulos (2005) with meteorological data from the Hellenic National Meteorological Service (Eqs. 22, 23). Costs of equipment, consumables and greenhouse operation, as well as fertilizers are specified in Tables 12, 13 and 14. Specific investment costs (€/m<sup>2</sup>) of the greenhouse in relation to the surface area are given by Eq. 24.

In an alternative scenario, the thermal energy demand of the greenhouse was met with an external source, such as biomass combustion, instead of CHP heat from the biogas plant. In the latter configuration, a heat price of 45 €/MWh<sub>th</sub> was considered. The marketing price for tomatoes produced in the greenhouse was assumed to be 1 € per kg (fresh weight).

### Design of the biogas plant

Anaerobic digestion of energy crops is generally performed as wet digestion process with a hydraulic retention time (HRT) of more than 100 days (Braun et al. 2008); therefore, the HRT in this study was set at 120 days. The maximal size for a biogas reactor was assumed to be 3000 m<sup>3</sup>. Hence, up to a useful volume of 3000 m<sup>3</sup>, the modelled biogas plant was designed with one single reactor. If the total useful reactor volume exceeded 3000 m<sup>3</sup>, the number of reactors was set as  $n_R = \frac{\text{Total volume (m}^3\text{)}}{3000 \text{ (m}^3\text{)}}$ , where  $n$  was rounded up to be an integer, with the volume of each reactor being the total useful volume divided by  $n$ .

Thermal needs of the digesters were calculated according to following parameters: heat transfer loss coefficients [W/(m<sup>3</sup> × °C)], roof 2.84, floor 0.68, soil 1.42; heat transfer capacity of biomass 2.90 MJ/(t × °C) according to Taricska et al. (2009). The modelled digester had 25% height buried under the earth surface. When headspace volume was included, the total volume of the digester was 25% higher than the useful volume. The operation temperature was set at 35 °C (mesophilic digestion). Since the study considered anaerobic digestion of energy crops as sole feedstock, i.e. without addition of animal manure,

addition of essential micro-nutrients into the digesters was necessary (Weiland 2010).

Electrical efficiency of the CHP unit ( $Y_E$ ; %) was calculated with the formula of Walla and Schneeberger (2008), and thermal efficiency ( $Y_{TH}$ ; %) was considered to be 20% higher than electrical efficiency (Eqs. 25 and 26, respectively). Table 15 shows the methodology for the estimation of investment and operation costs of the biogas plant. Investment costs were based on current market prices for various sizes of biogas plants. Power functions accounting for scale effects were designed as described by Amigun and von Blottnitz (2010).

In Greece, the feed-in tariff for electricity production from energy crops is currently 230 €/MWh<sub>el</sub> for biogas plants smaller than 3000 kW<sub>el</sub>, and 209 €/MWh<sub>el</sub> for biogas plants larger than 3000 kW<sub>el</sub> (legislation No. 4254/2014). However, if a share of public funding is already included into the investment, then regulations impose the guaranteed feed-in tariff to be about 9% lower. Contrary to other European countries, feed-in tariffs do not include bonuses for external heat use.

Hence, in our study, the biogas plant did not benefit from additional earnings from the supply of heat to the greenhouse. However, when the integrated system encompassing both the biogas plant and the greenhouse was considered, revenues from vegetable production in the greenhouse were added up to earnings from electricity sales to constitute the total earnings of the system.

### Methodology for economic evaluation

Economic feasibility analyses of the greenhouse and the biogas plant system (including energy crop cultivation) were performed according to Net Present Value (NPV) estimation detailed in Eq. 27 (Balussou et al. 2014). The evaluation of economic parameters took place according to the following steps: (1) sizing of the equipment, (2) evaluation of costs and benefits, (3) calculation of yearly cash flow, (4) calculation of NPV, and finally (5) calculation of the Payback Period (PBP; Eq. 28), i.e. the number of years required to reach positive NPV ( $NPV > 0$ ).

Depreciation of material and equipment was considered to be of the linear form. Depreciation parameters for machinery, greenhouse and the biogas plant are listed in Table 16. Input parameters for the evaluation are as follows: fuel (diesel) price 1.15 €/L, labour cost 10 €/h, other costs 10% of total operation costs (including insurance, i.e. 5% of total operation costs), amortization of investment 20 years, annual discount rate (depreciation of capital) 6%, taxes 26%, inflation 2%. Financial parameters for investment are as follows: financing capacity 30%, borrowing 70%, loan rate 8%. Payment for the loan was calculated using the PMT function of the software Microsoft Office Excel 2013.

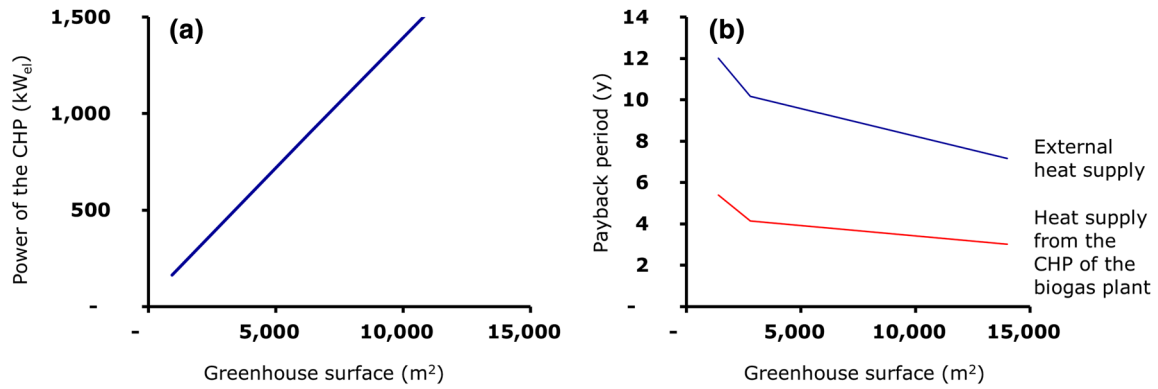
## Results

### Integration of the biogas plant with a greenhouse

Figure 2a shows the relationship between CHP power of the biogas plant and the size of greenhouse surface designed for a maximal heat use of the CHP; about 7500 m<sup>2</sup> of greenhouse surface could be installed for every 1000 kW<sub>el</sub> of CHP power from the biogas plant. The profitability of the greenhouse system for tomato cultivation is represented in Fig. 2b. As shown there, the payback period (PBP) decreases along with increasing greenhouse area, apparently due to scale effects. Figure 2b illustrates two different hypotheses: (1) thermal energy supply to the greenhouse from the CHP to fully cover heat requirements of the greenhouse, and (2) thermal energy supply from a conventional source (combustion of biomass; see Sect. 2.4). In the first hypothesis (lower curve), the biogas plant would provide heating energy free of charge (except for the heat network connecting the greenhouse with the nearby biogas plant and electricity driving pumps of the heating system). It is evident that recovery of thermal energy from CHP has a profound positive effect on the economics of the greenhouse system. Applying the threshold of a payback period (PBP) of 10 years, greenhouses for tomato cultivation in Greece are economically feasible at surfaces larger than 5000 m<sup>2</sup> (Fig. 2). In contrast, when thermal energy requirements are met with residual heat from the CHP unit of the biogas plant, smaller installations of 1000 m<sup>2</sup> would be feasible. This indicates that thermal energy supply represents a determinant factor in the operational costs of the greenhouse (Mavrogianopoulos 2005). However, the scenario of using thermal energy from CHP was based on the assumption that both biogas plant and greenhouse belong to the same owner. It is probable that if thermal energy from CHP would be sold by the biogas plant owner to the greenhouse, it will be for the latter a source of additional operational costs.

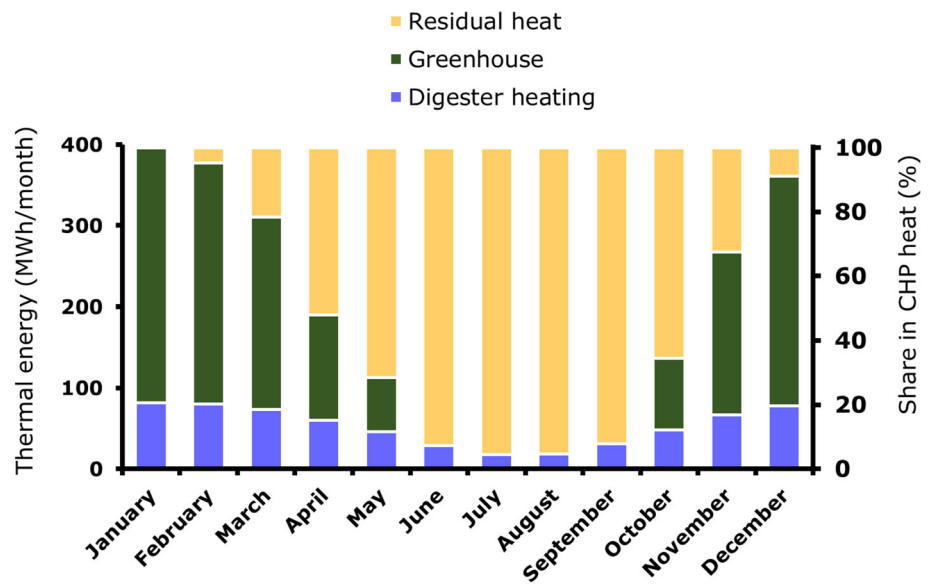
### Recovery of CHP heat for greenhouse heating

Figure 3 presents the share of thermal energy recovered from the CHP of a biogas plant of 500 kW<sub>el</sub> coupled with a greenhouse of 3567 m<sup>2</sup> (sized for maximal heat recovery). The modelled CHP delivers a constant thermal energy production of 396 MWh<sub>th</sub>/month over the whole year. As shown in the figure, most of the heat energy is recovered for greenhouse heating during winter months. Under Greek climate conditions, January is the month with the highest heat demand from the greenhouse and finally defines also the size the greenhouse. With cooler ambient temperatures of the winter season, amounts of available heat from the



**Fig. 2** Greenhouse design: **a** relation between CHP power and greenhouse surface for maximal heat use, and **b** Payback period (PBP) of the greenhouse in relation to its surface, with heat supplied either from a conventional source or from the CHP of the biogas plant

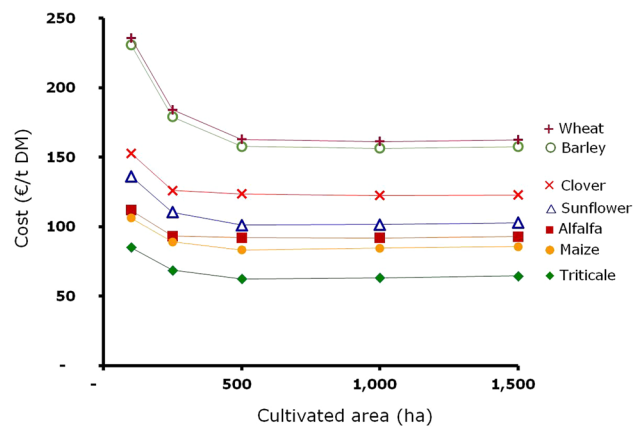
**Fig. 3** Recovery rate of thermal energy from the CHP of the biogas plant. Case scenario: biogas plant of 500 kW coupled with greenhouse of 3567 m<sup>2</sup>



CHP are also at lower levels, due to higher demand for digester heating. In contrast, in the summer, heat supply to the greenhouse is not necessary, leaving large amounts of thermal energy unused.

**Biomass production costs of energy crops**

Production costs of energy crop silages delivered to the biogas plant are given in Fig. 4. Biomass production costs follow a decreasing trend up to around 500 ha land size, a fact which can be attributed to scale effects yielding savings in investment, as well as more efficient utilization of machinery. For land areas larger than 500 ha, production costs increase slightly along with increasing cultivated surface. This is due to increasing costs for biomass and digestates transport between the fields and the biogas plant. Therefore, as property size increases, increased transportation costs mitigate and eventually surpass savings achieved through scale effects on investment in machinery



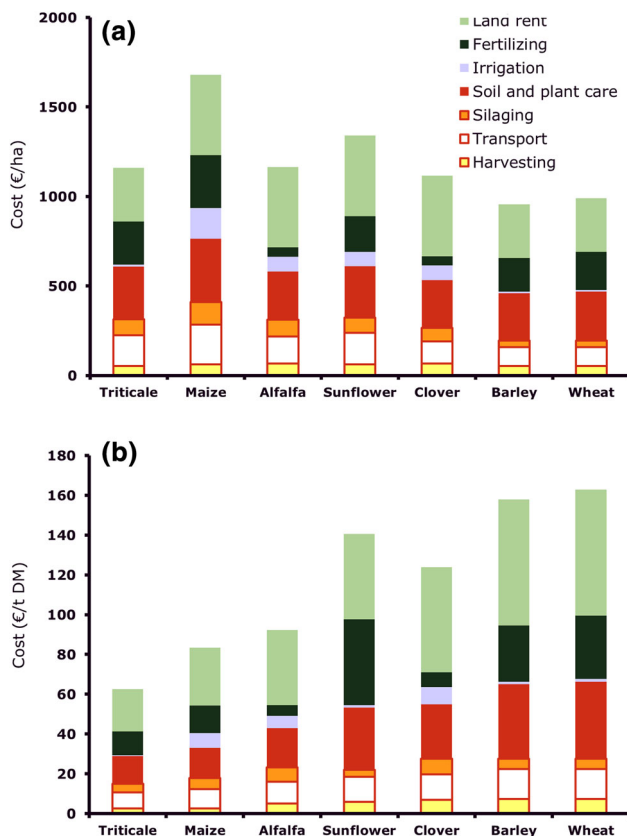
**Fig. 4** Production costs of ensiled energy crops in relation to the operational cultivation surface

equipment. The latter effect becomes even more evident if depreciation costs of capital investments are neglected in the total production costs (data not shown). Triticale



displays the lowest production costs, while sunflower, maize and alfalfa have almost similar production costs on a dry matter basis.

The relative contribution of individual cultivation steps in biomass production costs is presented in Fig. 5. Silaging, transport and harvesting account for a significant share of biomass production costs. Expressing the costs per unit of dry mass provides a measure of the efficiency of crop cultivation. Maize is a high-input crop, resulting in high cultivation cost per ha (Fig. 5b). However, due to high biomass productivity, maize is still among the most profitable crop within the energy crops investigated, ranking second after triticale (Fig. 5b). Alternately, low-input crops, clover, barley and wheat, are expensive to produce due to low biomass yields per hectare (cf. Table 11). In the case of non-irrigated crops (triticale, barley and wheat), the major cost factor in plant production is fertilizing. In this study, it was assumed that digestates produced from feeding energy crops into the biogas plants were returned to cultivated areas, reducing mineral fertilizer requirements by 36%. Under this assumption, fertilizing operations still contributed up to 25% of biomass production costs.



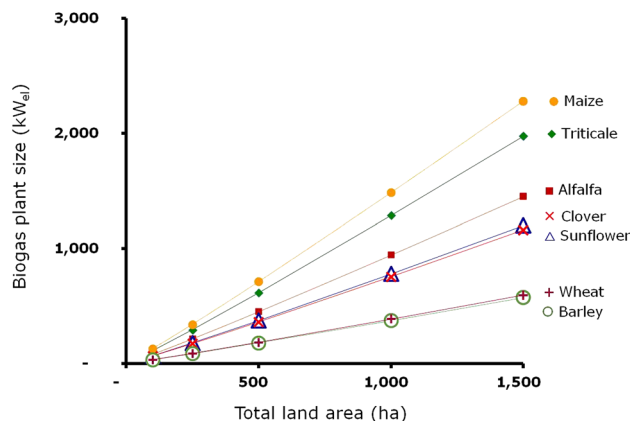
**Fig. 5** Silage production costs for a land area of 500 ha, as **a** cost per hectare, and **b** cost per t of dry mass. Values are given based on the operational cultivation surface

**Land area requirements for biogas production**

Maize has the highest biomass yield per hectare (t DM/ha), as well as high digestibility, reflected in high methane yield (cf. Table 11). Hence, biogas plants fed on maize can be powered with smaller arable surfaces (Fig. 6). Triticale also displays relatively high biomass yields per hectare. On the opposite, traditional food cereals, wheat and barley, have low productivities per hectare, and would require very large cultivated areas for powering a biogas plant, which means that under Greek conditions, in which the availability of land is limited, they do not constitute a feasible option for biogas production.

**Profitability analysis of the biogas plant**

Table 1 shows the payback period (PBP) of biogas production from each energy crop in Greece depending on cultivation land area. Without public investment funding, agricultural surfaces larger than 500 ha are required for energy-crop-based AD to be economically feasible. With public funding granted at a level of 50% in the initial investment, biogas production becomes feasible only with a surface usage higher than 250 ha. Considering biogas plant size (Table 2), without public investment funding, biogas plants larger than 1000 kW<sub>el</sub> are required for energy-crop-based AD to be economically feasible. With public funding granted at a level of 50% in the initial investment, biogas production becomes feasible at biogas plant sizes larger than 500 kW<sub>el</sub>. The relationship between payback period (PBP) and rate of public investment funding in a scenario of a biogas plant of 1000 kW<sub>el</sub> with triticale as feedstock is presented in Fig. 7. At funding rates below 25%, profitability decreases because Greek



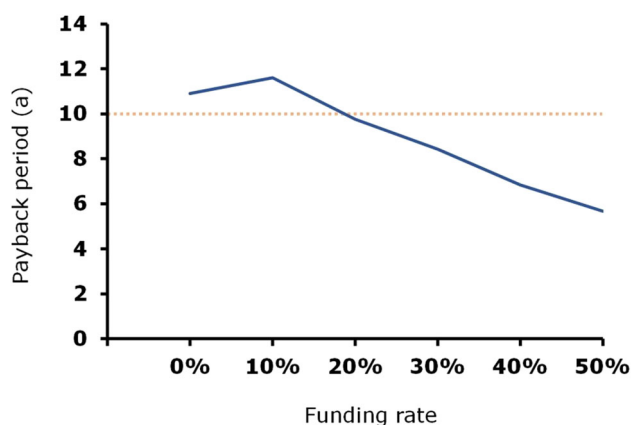
**Fig. 6** Biogas plant size in relation to total required land area including fallow (25% of surface except for legumes), and un-arable, marginal land (7% of surface)

**Table 1** Profitability of a biogas plant dedicated to various land areas and coupled with a greenhouse depending on energy crop variety and funding rate (0% and 50%)

Scenario	Surface (ha)	Payback period of the biogas plant (a)						
		Sunflower	Maize	Clover	Triticale	Barley	Wheat	Alfalfa
Without funding	100	>20	>20	>20	>20	>20	>20	>20
	250	>20	>20	>20	>20	>20	>20	>20
	500	>20	14.9	>20	11.9	>20	>20	>20
	1000	>20	11.5	>20	8.8	>20	>20	>20
With 50% funding	100	>20	>20	>20	>20	>20	>20	>20
	250	>20	11.7	>20	9.7	>20	>20	>20
	500	>20	7.4	>20	6.0	>20	>20	15.7
	1000	14.6	5.8	15.7	4.7	>20	>20	9.8

**Table 2** Profitability (payback period; y) of a biogas plant of different sizes coupled with a greenhouse depending on energy crop variety and funding rate (0% and 50%)

Scenario	Size (kW <sub>el</sub> )	Payback period of the biogas plant (a)						
		Sunflower	Maize	Clover	Triticale	Barley	Wheat	Alfalfa
Without funding	250	>20	>20	>20	>20	>20	>20	>20
	500	>20	>20	>20	18.7	>20	>20	>20
	1000	>20	14.9	>20	10.9	>20	>20	>20
	2000	>20	10.9	>20	8.6	>20	>20	18.0
With 50% funding	250	>20	>20	>20	19.7	>20	>20	>20
	500	>20	10.9	>20	8.4	>20	>20	15.9
	1000	14.7	7.4	15	5.7	>20	>20	10.9
	2000	10.5	5.7	10.8	4.6	>20	>20	8.5

**Fig. 7** Relationship between PBP and rate of public investment funding for a 1000 kW<sub>el</sub> biogas plant coupled with a greenhouse powered with triticale as energy crop

regulations impose a fixed reduction in electricity feed-in tariff when biogas projects are awarded public funding. This reveals that although the decreased feed-in-tariff prices imposed due to public investment funding is about 9%, the overall economic effect is multiplied. Hence, only public investment funding higher than 25% can have a positive effect on the economics of the biogas plant. Our overall results show that only triticale and maize are

suitable feedstocks for biogas production, whereas all other energy crops considered in our study are far less profitable.

### Costs of the integrated system

Within the integrated system, comprising of energy crop cultivation and supply for biogas production, a biogas plant for heat and electricity delivery, and a greenhouse for tomato production, the biogas plant makes up by far the heaviest share of the investment (Table 3). Including a vegetable greenhouse into the design of a biogas project will require total investment to be only 10% higher, while providing as much as 17–18% of additional yearly income, making this strategy economically viable, especially in places where no other opportunity for utilization of thermal energy is achievable.

### Sensitivity analysis of major cost factors

Figure 8 illustrates a sensitivity analysis on a selection of cost factors for a biogas plant powered with 500 ha of triticale. The impacts of the cost factors on the PBP were assessed by varying their values at –20 and +20% levels. Sensitivity analysis was performed in order to investigate the effect of the variation of the values on the economics of the biogas plant, addressing at the same time the effect of

**Table 3** Overview of total calculated costs and earnings related to triticale and maize silage production (land area: 500 ha) as well as biogas plant and greenhouse operation (figures were rounded)

		Size	Investment costs (euro)	Depreciations (euro/y)	Operational costs (euro/y)	Incomes (euro/y)
Triticale	Silage (feedstock)	4726 t DM	728,000	50,000	394,000	–
	AD	871 kWe	3765,000	502,000	153,000	1397,000
	Greenhouse	6573 m <sup>2</sup>	437,000	26,000	68,000	263,000
	Other		–	–	30,000	–
	Total		4930,000	578,000	645,000	1660,000
Maize	Silage (feedstock)	5152 t DM	1325,000	90,000	555,000	–
	AD	990 kWe	4118,000	549,000	158,000	1,586,000
	Greenhouse	7235 m <sup>2</sup>	474,000	28,000	75,000	289,000
	Other		–	–	39,000	–
	Total		5,917,000	667,000	827,000	1,875,000

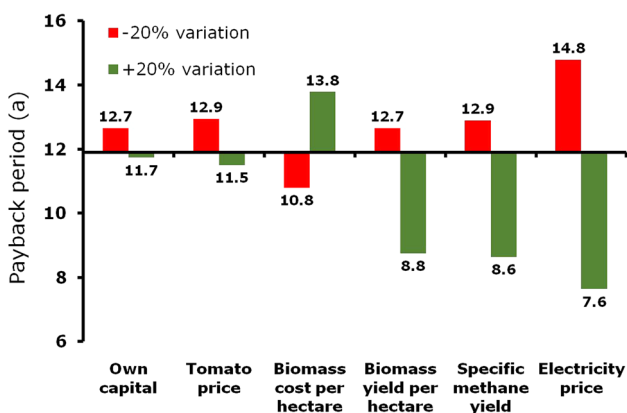
the uncertainties of technical or market information included in the economic analysis. The level of own capital (financing capacity), i.e. borrowing requirements, is a factor with the least impact on the project’s economic viability. The marketing price of the greenhouse product (tomato) has a slightly higher impact, at an almost similar level as biomass (silage) production costs. This indicates that coupling greenhouse with biogas plant has a significant impact on the overall system. Biomass yield has a higher impact than biomass cost. Hence, in the selection of energy crops for the biogas process, achieving higher biomass yields on the fields is more crucial than reducing the inputs (cultivation costs). However, higher biomass productivities are not necessarily linked to cheaper prices per ton of biomass and reduced transportation costs. In the selection of energy crops, high digestibility (specific methane yield) is even more critical than high biomass yield per hectare. The most influencing parameter, however, is the electricity price, which determines at a very high level the feasibility of the biogas plant.

### Discussion

#### Economic efficiency of the system

Crop selection greatly affects economic performance of AD because of their diversity on terms of inputs, biomass yields and biogas potential. Our results reveal that triticale is the most economical energy crop for biogas production in northern Greece, followed by maize. The sensitivity analysis (Fig. 8) shows that the most impacting factor is the electricity price, followed by biogas potential, biomass yield and cultivation costs. Maize, although it has higher biomass yield and biogas potential than triticale, has higher production costs, mainly due to elevated irrigation requirements, resulting in lower economic and environmental benefits than triticale. For a 500 kW<sub>e1</sub> biogas plant, the dry biomass yield per m<sup>3</sup> of irrigation water amounts to 3.4 kg DM/m<sup>3</sup> water (overall data not shown in “Results”). Considering the overall energy balance of energy-crop-based biogas production, maize displayed a slightly lower energy yield (input/output, MWh/MWh including direct and indirect energy consumption; Table 17) of 3.77, than triticale, which displayed a yield of 3.98 MWh/MWh (overall data not shown in “Results”). Production costs are closely related to cultivation requirements of the crops. From these observations, we conclude that energy crop selection for biogas production should be based on a favourable combination of high biomass yield, high biogas potential and low production costs.

Besides the selection of the most appropriate energy crop, the inclusion of a greenhouse into the design of the biogas plant contributes favourably in the economic viability of the system (17–18%). In addition to thermal energy utilization for greenhouse heating, researchers suggested feeding CO<sub>2</sub>-rich flue gas from the CHP unit into the greenhouse to further increase vegetable productivity via enhanced photosynthesis



**Fig. 8** Sensitivity analysis of a biogas plant receiving no funding based on triticale (land area: 500 ha) coupled with a greenhouse of 6573 m<sup>2</sup>

(Jaffrin et al. 2003; Menardo et al. 2013). However, such an approach may raise practical concerns such as worker health and safety issues, along with the difficulty of cleaning and cooling the flue gas (Dion et al. 2011).

### Economic efficiency of energy crops for AD

Economic analyses of energy crop production for AD in several European countries are gathered in Table 4. In line with our study, the economic efficiency of energy crops for AD considered in literature is linked primarily to the following factors: (1) biomass yield per hectare, (2) biomass production cost and (3) digestibility in the biogas process (specific methane yield) (Konrad et al. 2011). Nevertheless, the suitability of particular energy crops for bioenergy production depends on climate conditions, as crop yields per hectare may differ according to climate zones (Tuck et al. 2006). In Germany and most of Central Europe, high-yielding maize is the most competitive energy crop for AD (Balussou et al. 2014). However, in our study, under climate conditions of northern Greece, triticale as a feedstock for AD outcompetes maize in terms of energy production costs (ct/kWh<sub>el</sub>), confirming previous findings by Schievano et al. (2015), who investigated both crops in Northern Italy. The significant advantage of triticale is its drought resistance combined with fairly elevated biomass yield. These characteristics are of paramount importance for dry climates, since cultivation can be performed with few or no irrigation. The different costs of the various energy-crops given in Table 4 reflect different biomass yield and cultivation requirements for each country.

While conducting a field study in Northern Italy, Schievano et al. (2015) gave higher biomass yields per hectare compared with our study. However, these authors acknowledged that high biomass yields were related to very fertile cultivation conditions, since Po Valley is one of the most fertile region in Europe. However, while particular assumptions as well as local conditions vary widely between scientific reports, our results are in line with general trends observed by the literature. They indicate high profitability for triticale and maize, and in general higher costs for AD from the remaining C3 grasses. Unfortunately, we did not find economic data in the literature regarding legumes. In our study, the costs for alfalfa and clover as AD feedstocks were lower than for C3 grasses, indicating that crop rotations including legumes might still be interesting for AD, especially if they can reduce the use of fallow. Further studies are required to confirm this hypothesis.

In our study, we assumed that digestates produced from feeding energy crops into the biogas plants are returned to cultivated areas, reducing mineral fertilizer requirements by 36%. Under these conditions, fertilizing still contributed

significantly in production cost for most crops, at a share of up to 35%. However, from an economic point of view, fertilization rates of energy crops must be brought in perspective with the levels of biomass yields that can be achieved. In this regard, the C3 grasses investigated, barley and wheat, are inefficient under Greek climate conditions, as biomass yields remain low under high fertilization rates. On the opposite, nitrogen-fixing legumes, clover and alfalfa, require lower fertilization.

Transportation of harvested biomass to silaging site and of digestates back to the fields for fertilization contributes in 10–15% of total costs for biomass production, and increases with larger biogas plant sizes that require larger cultivated area. As surface increases, so do transportation costs, mitigating positive impacts of scale effects. The negative impact of transportation is higher as biomass availability decreases (cf. Eq. 16). In our study, energy crop availability rate was set at 30% which corresponds to an area with moderate intense production of energy crops, in order to take into account possible scattered land pieces in the region. In areas with limited biomass availability, only small-sized biogas plants may be economically viable. Walla and Schneeberger (2008) studied the impact of biomass transportation costs on the economy of an agricultural biogas plant operated with maize silage only in monofermentation. The authors found that the optimal size was 575 kW<sub>el</sub> if 5% of the land was available for maize silage production, 825 kW<sub>el</sub> if 10% was available, and 1150 kW<sub>el</sub> if 20% was available.

Our results suggest that an agricultural surface larger than 500 ha or a biogas plant size larger than 1000 kW<sub>el</sub> is required for energy-crop-based biogas production coupled to vegetable production in a greenhouse to be economically feasible. However, with public funding, biogas production becomes feasible with a smaller land surface or biogas plant size. Nevertheless, public investment funding should be higher than 25% in order to be economically beneficial (Fig. 7). For public funding at a level of 50% in the initial investment, biogas production becomes feasible with land sizes of >250 ha, or >500 kW<sub>el</sub> (in case of triticale). Investment costs of medium-sized agricultural biogas plants reported in literature are compared in Table 5. The evaluations of the specific investment costs by the selected works presented in this table lie in the range 3800–5600 €/kW<sub>el</sub> depending on biogas plant size and the country considered. In this regard, we must note that specific investment costs of biogas plants are highly impacted by scale effects.

### Heat recovery from the CHP

In our study, greenhouse size is adjusted in such a way that heating requirements can be fully covered with thermal energy from the CHP of the biogas plant. In this scenario,

**Table 4** Biomass yields and costs of energy crops for biogas production in Europe from selected published works

Country and authors	Crop silage	Biomass production cost (€/t DM)	Dry mass yield (t DM/ha)	Specific methane yield	Energy production cost with biogas technology
Austria (Stürmer et al. 2011)	Maize	–	14	340 m <sup>3</sup> /kg VS	6 ct/kWh <sub>el</sub> <sup>a</sup>
	Millet	–	12	317	7
	Sugar beet	–	14	377	7.5
	Wheat	–	10	292	10
	Sunflower	–	10	275	10.5
	Rye	–	7	332	11
Sweden (Gissén et al. 2014)	Triticale	170	9	380 m <sup>3</sup> /t DM	14 €/GJ CH <sub>4</sub>
	Sugar beet top	150	–	300	15
	Maize	190	10	350	17
	Ley	170	10	300	19
	Hemp	180	10	250	22
Italy (Schievano et al. 2015)	Triticale	76	17	372	6.8 ct/kWh <sub>el</sub>
	Maize	98	22	382	8.6
	Grass	91	11	317	9.6
	Sorghum	86	19	233	12.3
	Rye	137	9	306	15.0
Greece our study (for 500 ha) without greenhouse	Triticale	62	14	320 m <sup>3</sup> /t DM	7.4 ct/kWh <sub>el</sub>
	Maize	83	16	330	8.1
	Alfalfa	92	9	280	10.0
	Sunflower	101	11	290	11.2
	Clover	124	7	320	11.3
	Barley	158	5	300	14.8
	Wheat	163	5	310	14.7

These values assume full use of the vegetation period, which can be obtained in monoculture or in association with catch crops

<sup>a</sup> Excluding transportation; with 10 km of transportation, the cost for each feedstock increases by about 20 €/MW<sub>el</sub>

on yearly average, only 40% of the heating energy generated by the CHP is utilized. Heat recovery in the greenhouse occurs mostly in autumn and winter, from December till March. January is the month with the highest heating energy demand that determines greenhouse sizing in relation to the biogas plant. In the summer period, heat use is unnecessary, at the time when heat generation from the biogas plant is at the highest level. The recovery rate of thermal energy can be increased by using the CHP in complement to other sources of heating energy, such as natural gas or wood combustion in order to enhance greenhouse size in relation to the CHP. However, in summer, alternative heat use options may be considered, such as turning thermal energy into cold generation (de Castro Villela and Silveira 2005) for the cooling of greenhouse facilities. This would increase thermal energy utilization rates.

Further options must be investigated to enhance heat recovery from the CHP. For example, thermal energy may be used for drying of vegetables derived from the greenhouse. Since dried vegetables and fruits can reach higher market

prices, it may be of interest to spend thermal energy for such processes. However, heat use would be affected by the seasonality and frequency of vegetable harvest. For large-scale biogas plants, heat networks (district heating) can be designed to connect the CHP with thermal energy users from industries and the residential sector, in hybridization with other energy sources (Vallios et al. 2009). An innovative approach for medium-sized biogas plants consists in off-site satellite-CHP units connected to the biogas plant via a biogas grid and providing heat closest to remote users (Kusch 2012).

### Future developments in energy crops cultivation

In this article, conventional crop cultivation practices were considered. Some authors (Šarauskiš et al. 2014) suggest that conventional practices, including ploughing, are expensive, energetically inefficient, and that reduced-tillage and no-tillage technologies should be investigated. Moreover, in this study, energy crop monoculture was considered for providing feedstock for biogas production, and fallow was assumed to be performed one year in every

**Table 5** Biomass yields and costs of energy crops for biogas production in Europe

Country and authors	Power of the biogas plant	Costs	Specific investment costs	Economic parameters
UK (Jones and Salter 2013)	500 kW <sub>el</sub>	Running costs 124,500 £/y (180 k€/y)	4000 £/kW <sub>el</sub> (5600 €/kW <sub>el</sub> )	–
Austria (Walla and Schneeberger 2008)	500 kW <sub>el</sub>	Investment 1.9 M€/20a Capital cost 220 k€/y Biomass supply 180 k€/y	3800 €/kW <sub>el</sub>	–
Germany (Balussou et al. 2012)	500 kW <sub>el</sub>	Investment 2.0 M€/20a	4000 €/kW <sub>el</sub>	Electricity production cost 18.77 ct/kWh <sub>el</sub>
Germany (Balussou et al. 2014)	500 kW <sub>el</sub>	Total Investment 6.2 M€/20a Biomass production 7.8 M€/20a Transportation 3.2 M€/20a	4000 €/kW <sub>el</sub>	Electricity production cost 18.9 ct/kWh <sub>el</sub> PBP 6.9 a
Italy (Torquati et al. 2014)	620 kW <sub>el</sub>	Total investment 3.0 M€/20a	4800 €/kW <sub>el</sub>	
Greece Our study <sup>a</sup>	870 kW <sub>e</sub>	Biomass supply 390 k€/y Investment for AD 4.9 M€/20a	5660 €/kW <sub>e</sub> <sup>b</sup>	Electricity production cost <sup>c</sup> 17.5 ct/kWh <sub>el</sub>

<sup>a</sup> With triticale as energy crop; 500 ha

<sup>b</sup> Including the greenhouse

<sup>c</sup> Including the effect of capital costs (borrowing costs) of the investment; including the contribution of the greenhouse; without public investment funding

four year for soil regeneration. The economy of the system may be improved by resorting to a legume-based crop rotation to regenerate the nitrogen content of the soil, hence reducing or eliminating the need for fallow land (Zegada-Lizarazu and Monti 2011). Recently, environmentally sustainable approaches such as double-cropping, crop rotations (Konrad et al. 2011), as well as the exploitation of marginal land (Wünsch et al. 2012), are investigated to provide energy crops for AD, but economic costs for these options are still elevated. Since legumes and some cereals are high added-value products, which may be too noble to be targeted for energy production alone, hybrid energy/food/feed crop cultivation schemes may have positive economic and environmental impacts (Jones and Salter 2013). Further options include the use of grasses (Seppälä et al. 2009) and perennial crops (Mast et al. 2014; Wünsch et al. 2012), alone or in inter-cropping with other crops. In Germany, farmers are now operating agricultural biogas plants with feedstocks produced in conformity with organic farming practices (Grieb and Gerlach 2013), but research in this area is still scarce. Optimal crop rotation schemes specifically designed for organic farming, as well as their economic and environmental suitability, must yet be thoroughly investigated.

The development, selection and improvement of energy crops for AD must meet specific requirements: fibrous fractions, including cellulose and hemicellulose, can be digested only if lignin contents in crops are low (Brulé 2014). High biomass-yielding annual crops such as sweet sorghum and sudan grass are currently investigated for AD, but breeding practices are still in their infancy (Herrmann 2013). High biomass-yielding perennial crops such as giant reed, cardoon, switchgrass, miscanthus and willow are unsuitable for AD due to high lignin contents (Wilson et al. 2014), and better suited to combustion and gasification (Venturi and Venturi 2003). On the opposite, frequently harvested perennial crops such as lucerne, energy dock, szarvasi, amaranth, jerusalem artichoke and cup plant have lower lignin contents and may be suitable for biogas production (Mast et al. 2014; Sitkey et al. 2013).

### Future developments in anaerobic digestion

Due to unsustainable irrigation requirements for energy crop cultivation, in Southern Greece and other parts of Southern Europe, biogas plants should be designed for agricultural and agro-industrial wastes feedstocks, with

only minor shares of energy crops (Fierro et al. 2014). However, since biowaste processing plants are more expensive (Balussou et al. 2014; Hublin et al. 2014), and the availability of agro-industrial wastes highly variable (Jones and Salter 2013), research and optimization works must be performed to mitigate treatment costs and capture the full potential from organic waste feedstocks at a regional scale.

Digestate processing, such as solid–liquid separation and subsequent drying of the solid fraction, may result in volume reduction of digestates and lower transportation costs (Pöschl et al. 2010). However, much of the nutrients, especially nitrogen, are still caught into the liquid phase, which must be transported back to the fields as well to avoid important losses (Möller et al. 2012). Alternately, Balussou et al. (2012) reported the use of a thermal vacuum evaporator to recover concentrated nutrients from the liquid phase. A further alternative option may be the purification of the liquid phase by means of ultrafiltration allowing the injection into pipelines connected to irrigation systems on the fields.

## Conclusions

Seven energy crops were evaluated for their economic profitability as feedstock for biogas production under the climate conditions and economic context of northern Greece. Furthermore, the coupling of the biogas plant with heat recovery in a greenhouse for vegetable production was studied. Main findings are summarized as follows:

- Among the seven energy-crops evaluated, triticale was found to be the cheapest in terms of energy production costs (7.4 ct/kWh<sub>el</sub>), followed by maize (8.1 ct/kWh<sub>el</sub>). In the Greek context, triticale as a drought-resistant crop displays favourable characteristics compared to maize in terms of water use; however, the energy yields (inputs/outputs) were almost similar for both crops.
- Selection of an appropriate energy crop should be based on a favourable combination of high biomass yield, high biogas potential and low production costs.
- The inclusion of a greenhouse into the design of the biogas plant contributes favourably in the economic viability of the system, increasing the total financial incomes by 17–18%.
- The costs for alfalfa and clover as AD feedstocks were lower than for C3 grasses, indicating that crop rotations including legumes might still be interesting for AD, especially if they can reduce the use of fallow.

- C3 grasses (barley and wheat) are inefficient under Greek climate conditions, as biomass yields per hectare remain low under high fertilization rates.
- Agricultural surface larger than 500 ha or a biogas plant size larger than 1000 kW<sub>el</sub> is required for energy-crop-based biogas production coupled to vegetable production in a greenhouse to be economically feasible.
- With public funding, biogas production becomes feasible with smaller land surfaces or biogas plant sizes. Public investment funding should be higher than 25% in order to be economically beneficial. For public funding at a level of 50% in the initial investment, biogas production becomes feasible with land sizes of >250 ha, or >500 kW<sub>el</sub> (in case of triticale).
- In this scenario, the thermal energy recovery rate is about 40% (yearly average). Thus, further options must be investigated to enhance heat recovery from the CHP.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that there is no conflict of interest.

## Appendix 1

### Equation for section “Total land area”

Total land area ( $S_L$ ) is given from the operational cultivation area ( $S_C$ ) by the following equation:

$$S_L = S_C \times \frac{1}{1 - k_{UN} - k_{FA}}; \quad (1)$$

$$S_L = 1.08 \times S_C \text{ for legumes; } S_L = 1.47 \times S_C \text{ for other crops}$$

### Equations for section “Engine power, number of tractors and fuel consumption for cultivation”

The required size of the ploughing implement ( $W_{IT}$ ) attached to the tractor was calculated according to the following equation:

$$W_{IT} = \frac{10S_C}{T_A \times v_T} \quad (2)$$

$S_C$  operational cultivation area (ha),  $T_A$  duration available to perform ploughing operations, here: 160 h,  $v_T$  tractor velocity (km/h), here 6 km/h for ploughing operation.

Drawbar power ( $P_D$ ; kW) corresponding to the selected implement size is calculated and converted into power-take-off ( $P_{TO}$ ; kW), and engine power for tillage ( $P_{EP}$ ; kW) applying the following equation and conversion factors (Mehta et al. 2011; NSW-Farmers 2013):

$$P_D = \frac{R_S \times d_{IT} \times W_{IT} \times v_T}{3600} \quad (3)$$

$$P_{TO} = P_D \times 1.8 \quad (4)$$

$$P_{EP} = P_{TO} \times 1.18 \times (1 + k_{PM}) \quad (5)$$

$R_S$  soil resistance, here: 890 N/(mIW  $\times$  cmDS),  $d_{IT}$  depth of tillage (plough), here: 20 cm,  $W_{IT}$  width of implement used for tillage (plough),  $v_T$  tractor velocity, here: 6 km/h,  $k_{PM}$  additional factor providing a safety margin in tractor sizing, here: 10%

Linear correlation between total engine power ( $P_{EP}$ ; kW) and the surface of cultivated area ( $S_C$ ; ha) is described by the following eq.:

$$P_{EP} = 0.656 \times S_C + 0.294 \quad (6)$$

Specific power requirements [ $k_P$ ; (kW/(mIW  $\times$  (km/h)))] of each implement were calculated with the following equation, with values for the factors  $R_s$  and  $D_I$  taken from Table 8.

$$k_P = R_s \times D_I \times 1.18 \times 1.8 \quad (7)$$

Time ( $t_W$ ; h) required to perform each individual field operation is given by the following equations, according to the total distance travelled by the tractors ( $d_T$ ; km):

$$t_W = \frac{S_C}{d_T \times v_T} \quad (8)$$

$$d_T = \frac{S_C \times (1 + k_T) \times 10}{W_I \times v_T} \quad (9)$$

$k_T$  factor to include tractor turns on the fields, here: 1%,  $W_I$  width (m) of each implement,  $r_U$  engine power usage, set at 0.8 (80%) to prevent engine overloading (Mehta et al. 2011).

Hourly diesel fuel consumptions ( $N_H$ ; L/h) for each field work were estimated using the empirical equation given by Jílek et al. (2008). Subsequently, the total fuel consumption ( $N_T$ ; L) of tractors was calculated for the work durations ( $t_W$ ; h) estimated previously for each field work:

$$N_H = 0.036 \times P_E^{0.938} \times r_U^{0.781} \quad (10)$$

where  $P_E$  is for the engine power (kW).

$$N_T = N_H \times t_W \quad (11)$$

### Equations for section “Irrigation and fertilizing of energy crops”

Pump power ( $P_P$ ; kW) required to drive the sprinklers was calculated from the total manometric water pressure ( $H_T$ , m), accounting for pressure losses in the pipes ( $H_L$ , m) (Terzidis and Papazafeiriou 1997):

$$P_P = \frac{H_T \times Q \times 9.81}{3600 \times r_e} \quad (12)$$

$$H_T = H_L + H_E + H_W \quad (13)$$

$$H_L = 1.13 \times 10^{11} \times \left(\frac{Q}{C}\right)^{1.852} \times D^{-4.87} \quad (14)$$

$H_E$  operational manometric pressure of equipment, here: 80 m,  $H_W$  depth of the water body from which water is pumped, here: 10 m,  $Q$  water flow (m<sup>3</sup>/h), depends on irrigation requirements,  $r_e$  pump efficiency, set at 70% (Buckmaster 2009),  $C$  constant depending on material properties, here: 150 (Terzidis and Papazafeiriou 1997),  $D$  inner diameter of the tube (mm).

Total fertilization requirements:

$$R_{FERT} = 100 \times R_E \times (1 - R_L) \times R_A; R_{FERT} = 36\% \quad (15)$$

$R_E$  fertilizing efficiency (here: 80%),  $R_L$  nutrient losses during storage of the digestates, here: 35%,  $R_A$  direct availability of nutrients in digestates, here: 70%.

### Equations for section “Transportation and silaging of energy crops and digestates”

Transport distance of harvested biomass to bunker silos was calculated by:

$$d_T = \frac{2}{3} \times \tau \times \sqrt{\frac{M_{BF}}{k_{AV} \times 100 \times Y_{BF} \times \pi}} \quad (16)$$

$d_T$  haul distance (km),  $\tau$  tortuosity factor, here: 1.8,  $M_{BF}$  fresh mass of crop biomass ( $t$ ) to be transported,  $k_{AV}$  availability of biomass, here: 0.3,  $Y_{BF}$  fresh biomass yield before ensiling (t/ha).

The total distance ( $T_D$ ; km) that the tractor(s) need to cover transportations was calculated as follows:

$$T_D = 2 \times \frac{V}{C_R} \times d_T \quad (17)$$



$V$  total volume of biomass to be transported ( $m^3$ ),  $C_R$  Carriage capacity of the tractor ( $m^3$ ): here  $18 m^3$ .

The number of tractors required for biomass transportation ( $n_T$ ) was calculated according to:

$$n_{TT} = 0.44 + 0.0746 \times \left[ \frac{1.6 \times P_{TT} \times d_T}{M_{TT} \times v_{TT}} \right] + 1.06 \quad (18)$$

$n_T$  number of tractors required,  $P_{TT}$  engine power of transport tractors (kW),  $M_{TT}$  transportation capacity of the tractors, here: 20 t of dry matter,  $v_{TT}$  average speed of the transport tractors, here: 20 km/h.

The operation time of packing tractors for silaging ( $t_{SIL}$ ) was calculated as

$$t_{SIL} = r_{SIL} \times M_{BD} \quad (19)$$

$r_{SIL}$  packing rate, here: 0.017 h/t DM,  $M_{BD}$  dry mass of crops to be packed (t DM).

### Equations for section “Methane yields of energy crops”

Yields of dry ensiled biomass ( $Y_{SD}$ ; t DM/ha) are calculated for each crop:

$$Y_{SD} = Y_{BF} \times (1 - k_{LO}) \times C_{DM} \quad (20)$$

$Y_{BF}$  yield of fresh biomass (t FM/ha),  $k_{LO}$  factor accounting for losses in harvesting and silaging, here: 13% (Davies 2004),  $C_{DM}$  dry matter content of silage (%FM/100).

Yields of dry ensiled biomass are converted into methane yields per hectare ( $Y_{CH_4}$ ;  $m^3 CH_4$ /ha):

$$Y_{CH_4} = Y_{SD} \times C_{VS} \times C_{CH_4} \quad (21)$$

$C_{VS}$  volatile solids content of dry mass (%DM/100),  $C_{CH_4}$  specific methane yield ( $m^3 CH_4$ /t VS).

### Equations for section “Design of the greenhouse system”

Day heating degrees ( $T_{HD}$ ; °C) and night heating degrees ( $T_{HN}$ ; °C) are calculated as follows:

$$T_{HD} = \sum_{i=1}^N \left( (T_d - \Delta T_{SUN}) - \frac{T_{imax} + T_{iav}}{2} \right) \times D_d \quad (22)$$

$$T_{HN} = \sum_{i=1}^N \left( T_n - \frac{T_{imin} + T_{iav}}{2} \right) \times D_n \quad (23)$$

$T_{imax}$  maximum day temperature in the month (°C),  $T_{iav}$  average day temperature in the month (°C),  $T_d$  target day

temperature in the month, here: 22 °C,  $\Delta T_{SUN}$  indoor/outdoor temperature difference due to greenhouse effect, here: 6 °C,  $T_n$  target night temperature in the month, here: 14 °C,  $D_d$  day duration (h),  $D_n$  night duration (h),  $N$  month of the year in the cultivation period (September–July).

Specific investment costs ( $\text{€}/m^2$ ) of the greenhouse in relation to the surface area were calculated with the following equation (input parameters for economic evaluation cf. “Appendix 2” section):

$$C_G = 260 \times S_G^{-0.155} \quad (24)$$

$S_G$  greenhouse surface (ha).

Electrical ( $Y_E$ ; %) and thermal efficiency ( $Y_{TH}$ ; %) of the CHP unit was calculated with:

$$Y_E = (5.572 \times \log_{10}(P_{EE}) + 22.43) \times k_{PL} \quad (25)$$

$$Y_{TH} = Y_E \times 1.2 \quad (26)$$

$P_{EE}$  electrical power of the engine,  $k_{PL}$  partial load operation factor, here: 97%.

### Equations for section “Methodology for economic evaluation”

For this purpose, annual cash flow calculations were made using the following equation:

$$NPV = \sum_{i=1}^t \frac{C_i}{(1+r)^i} - C_0 \quad (27)$$

$C_i$  net cash inflow during the period  $t$ ,  $C_0$  total initial investment costs,  $r$  discount rate; here 6%,  $T$  number of time periods (years).

The PBP was calculated as follows:

$$PBP = 1 + Y_N - \frac{v}{p} \quad (28)$$

$Y_N$  number of years after the initial investment at which the last negative value of cumulative cash flow occurs,  $v$  value of cumulative cash flow at the year with the last negative value of cumulative cash flow,  $p$  value of yearly cash flow at the year with the first positive value of cumulative cash flow.

### Appendix 2

See Tables 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, and 17.

**Table 6** Energy crops: cultivation requirements

	Number of operations per year				Irrigation requirement (mm water/year) <sup>a</sup>	Grain per ha for sowing (kg/ha)	price of grains (€/kg)
	Cultivator	Disc harrowing	Plant protection	Harvesting			
Triticale	1	1	2	1	0	200	0.35
Maize	2	1	2	1	500	30	0.75
Alfalfa	1	1	1	3	200	40	1.5
Sunflower	1	1	2	1	200	5	0.45
Clover	1	1	1	3	200	40	1.5
Barley	1	1	2	1	0	180	0.25
Wheat	1	1	2	1	0	180	0.3

Data are based on current cultivation practices (data taken from Hellenic Ministry of Rural Development and Food) and market prices in Greece

<sup>a</sup> Conversion: 1 mm/year = 10<sup>6</sup>m<sup>3</sup>/(ha × year)

**Table 7** Energy crops: cost of equipment (data taken from Greek market)

Application	Machinery and materials	Base price factor (C <sub>B</sub> )	Scale effect
Crop cultivation	Tractors	65,000 €	$C_{\text{EQU}} = C_{\text{B}} \times 0.0035 \times P_{\text{ET}}^{0.89}$
	Silage harvesting equipment	20,000 €	
	Silage packer	60,000 €	
	Cultivator	7000 €	
	Disc harrower	20,000 €	
	Sprayer(plant protection)	11,000 €	
	Sower	15,000 €	
	Fertilizer	20,000 €	
	Other equipment	25,000 €	
	Land rental	300 €/ha	
Transportation	Digestate box dispenser	30,000 €	As additional cost per tractor
	Transport tractor + boxes	75,000 €	For non-irrigated land
Irrigation	Irrigation system	17,000 €	For irrigated land
	Ensilage		
Ensilage	Silage cover	0.5 (€/m <sup>2</sup> )	Per unit
	Tires for cover	1 (€/m <sup>2</sup> )	Per unit
	Silage pit bunker	10 (€/m <sup>2</sup> )	Per unit

**Table 8** Calculation of engine power and specific power requirement with medium-sized equipment for maize cultivation (NSW-Farmers 2013; Summer and Williams 2014)

	$R_S$ (N/m/cm <sub>DS</sub> )	$D_I$ (cm)	$v_T$ (km/h)	$k_P$ (kW/(m × (km/h)))
Plough	890	20	6	10.5
Disc harrow	592	10	9	3.5
Sower + herbicide + coulter	1892	5	8	5.6
Cultivator	1200	5	8	3.5
Harvesting	–	–	6	14.0
Digestate spreading	–	–	10	6.8
Spraying	–	–	10	3.0

$R_S$  soil resistance (Newton per m of implement per cm of soil depth,  $D_I$  soil depth,  $k_P$  specific power requirement)

**Table 9** Total mineral fertilizer requirements of the energy crops considered in this study

	N (kg/ha)	P (kg/ha)	K (kg/ha)	Mg (kg/ha)	Other nutrients (kg/ha)
Triticale	160	80	80	5	3
Maize	200	100	100	5	3
Alfalfa	10	20	15	5	3
Sunflower	100	80	80	5	3
Clover	10	20	15	5	3
Barley	120	60	60	5	3
Wheat	120	80	80	5	3

Data are taken from Hellenic Ministry of Rural Development and Food and reflect current cultivation practices in Greece

**Table 10** Energy crops and greenhouse: price of fertilizing nutrients (data taken from Greek market)

Nutrient	Price (euro/kg)
N	1.1
P	1.35
K	1.45
Mg	4.75
Other nutrients	5

**Table 12** Greenhouse: cost of equipment (data taken from Greek market)

Parameter	Cost
Structural and framing materials	20 €/m <sup>2</sup>
Cover material	4 €/m <sup>2</sup>
Groundwork	10 €/m <sup>2</sup>
Plant stringing	2 €/m <sup>2</sup>
Shading mesh	2 €/m <sup>2</sup>
Flooring	0.7 €/m <sup>2</sup>
Automation and monitoring apparatus	10,000–25,000 €
Ventilation (cooling)	2500 €/gable
Ventilation (air circulation)	500 €/piece
Irrigation system	0.5 €/m <sup>2</sup>
Gutters	0.5 €/m <sup>2</sup>
Pumps/containers	2.5 €/m <sup>2</sup>
Desalination system	12,000–30,000 €
Cooling system	2.4–2.8 €/m <sup>2</sup>
Thermal pipes	8 €/m
Packaging system	2.3–2.7 €/m <sup>2</sup>
Pipeworks (from biogas plant to greenhouse)	40,000 €

**Table 13** Greenhouse: fertilizer requirements

Fertilizer	Amount (kg/t FM of tomato fruit)
N	6.0
P	2.0
K	1.2
Mg	2.0
Other nutrients	2.0

**Table 11** Productivity and methane yields of the energy crops used for biogas production

Energy crop	$Y_{BF}^a$ (t FM/ha)	$Y_{SF}^a$ (t FM/ha)	$C_{DM}$ (%)	$Y_{SD}^a$ (t DM/ha)	$C_{VS}$ (%VS)	$C_{CH_4}^b$ (m <sup>3</sup> /t VS)	$Y_{CH_4}^a$ (m <sup>3</sup> /ha)
Triticale	45	39	37	14	95	320	3500
Maize	55	48	33	16	96	330	5300
Alfalfa	35	31	30	9	92	280	3000
Sunflower	35	31	35	11	87	290	2600
Clover	25	22	30	7	92	320	2100
Barley	15	13	37	5	95	300	1400
Wheat	15	13	37	5	95	310	1400

$Y_{BF}$  yield of fresh biomass,  $Y_{SF}$  yield of fresh silage,  $C_{DM}$  dry matter content of fresh mass,  $Y_{SD}$  yield of dry silage,  $C_{VS}$  volatile solids content of dry mass,  $C_{CH_4}$  specific methane yield;  $Y_{CH_4}$  methane yield per hectare

<sup>a</sup> Data per ha of operational cultivation surface. Data were taken from the Greek Ministry of Rural Development and Food

<sup>b</sup> Medium values of methane yields reported by FNR (2013), Herrmann et al. (2012), KTBL (2009), Raposo et al. (2012)

**Table 14** Greenhouse: cost of operation

Parameter	Cost (€/m <sup>2</sup> )
Growth medium	0.75
Labour cost	5
Plant protection	1
Packaging	10
Electrical energy	23.1
Miscellaneous	2.5

**Table 15** Investment and operation costs of the biogas plant

Cost type	Specific cost calculation accounting for scale effect
Investment	Biogas plant <sup>a</sup>
Operation	Desulfurization (€/kW)
	Micro-nutrient supply
	Personnel
	Miscellaneous

$P_{EE}$  electrical power of biogas plant (kW<sub>el</sub>)

<sup>a</sup> Data were taken by current market prices in Greece

**Table 16** Biogas plant: depreciation parameters

Parameter	Machinery for energy crops	Greenhouse	CHP unit	Digester and equipment
Residual value (%)	25	10	20	15
Lifetime (years)	11	15	12	20

**Table 17** Indirect input of energy based on primary energy consumption for the production of agro-chemicals *Source:* [www.biograce.net](http://www.biograce.net)

	MJ/kg
Synthetic fertilizers	
Nitrogen	48,99
Phosphorus	15,23
Potassium	9,68
Other, e.g. calcium	1,97
Plant protection	
Herbicides/pesticides	268,4

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