https://doi.org/10.1016/j.renene.2020.07.047

Title:

Application of photovoltaic system to modify energy use, environmental damages and cumulative exergy demand of two irrigation systems-A case study: barley production of Iran

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Abstract

Irrigation is one of energy-intensive operations in agriculture, which consumes great part of energy inputs and has harmful environmental effects. Thus, the goal of this study is to simulate application of photovoltaic (PV) system as an alternative clean energy supplier to achieve energy-environmental sustainability under two irrigation methods, namely, surface irrigation (SFI) and sprinkler irrigation (SPI) in barley cultivation. Data are collected during the growing season of 2018–2019 from a 100-hectare farm located in central region of Hamedan province, Iran. Moreover, applying PV system to SFI and SPI scenarios, which are simulated by using TRNSYS software, generate SFI-PV and SPI-PV scenarios, respectively. After that, environmental damages for all scenarios are evaluated by ReCiPe2016 method of life cycle assessment. Results indicate energy use efficiencies are 2.85 and 2.80 in SFI and SPI, respectively. On-Farm emissions in all scenarios, electricity in SFI and SPI and PV panels SFI-PV and SPI-PV are the hotspots of environmental damages. Cumulative exergy demand (CExD) findings show that shares of Non-renewable, fossil for barley production mainly result from electricity and diesel fuel. It is concluded that energy and environmental damage indices can be enhanced remarkably via using renewable energy technologies.

Keywords: Barley, Energy, Environmental damage, Exergy, Irrigation system, Photovoltaic.

1. Introduction

Barley (*Hordeum vulgare*) is one of the most adaptable and common cereals produced in arid and semi-arid climates. The global harvest of barley in 2017 was about 147 million ton (t) [1]. Barley, as important sources of energy, protein, dietary fiber, mineral elements and vitamins, is popular and important food for humans and livestock [2]. In Iran, due to its low water requirement, barley is ranked second in cultivated area after wheat and about 3 million t of barley are produced annually [3].

Today, energy sources consumption in production systems such as agriculture is very high and intensive, leading to environmental burdens such as resources depletion, global warming, and human health risks. One of the important challenges for energy use in agricultural sector is to reduce its environmental damages. Developing applications of renewable energy sources, like geothermal, wind, and solar types, will be one of fundamental and sustainable ways to meet this challenge [4][5][6].

Energy and water as essential inputs of irrigation system are key and vital elements for social and economic development [7]. Literature review shows that a main part of energy utilized for agricultural crops production is for irrigation systems including water extraction from wells and pumping stations [8][9][10][11]. Applications of modern methods of irrigation in agriculture can be considered from different aspects. Many studies on energy and water uses of irrigation systems indicated that although the use of sprinkler irrigation (SPI) increased water use efficiency, it also increased energy consumption [7][12][13]. Excessive energy use leads to environmental burdens, so effective and efficient usage of energy source is considered as fundamental requirements of sustainable agriculture. Life Cycle Assessment (LCA) is a structural and comprehensive approach to evaluate environmental impacts in various systems [14], which can also be applied to compare various options' environmental impacts and to select an optimum option [15].

Renewable energy sources (also known as green energy), such as sunlight, geothermal and wind power, are considered as clean and sustainable sources of energy, which are naturally renewable and have much lower environmental pollution than fossil energy sources [16][17][18]. Among different sources of renewable energy, solar energy is one of the most important and sustainable sources that can be harnessed via applying different technologies [19]. In agriculture, the application of photovoltaic cells for water pumping is considered as a modern and sustainable technology in most countries [20]. Solar photovoltaic (PV) irrigation technology can be investigated from various aspects, including economic feasibility, energy efficiency and environmental effects. Researchers have been studying on solar PV irrigation technology for a long time and they sometimes studied a single topic without regard to other aspects. On the other hand, environmental effects of solar systems were often ignored.

Cumulative exergy demand (CExD) approach is a remarkable analysis tool, which denotes anticipated energy use from production methods. In fact, CExD was considered as one of the best methods to reduce exergy [21].

As mentioned, several researches have been conducted on energy consumption, its environmental effects and applications of solar technologies for the production of different agricultural crops. Table 1 lists a summary of these works. It can be seen that, in some studies, solar PV cells application for irrigation systems were investigated from a single aspect.

Table 1

Although the mentioned studies in Table 1 were noteworthy, the use of solar technology in irrigating systems was denied. In several papers, solar systems were only surveyed partially from a single aspect, such as irrigations. Moreover, environmental emissions resulting from the application of solar systems were not considered at all. Thus, a comprehensive investigation of energy, environmental life cycle assessment (LCA) and cumulative exergy demand in two irrigation systems by using PV systems approach is considered as a main novelty in this study.

On the other hand, based on the solar radiation availability and climatic conditions in Hamedan province of Iran, and lack of research about energy-LCA of barley cultivation in this area, a comprehensive study about different aspects of photovoltaic irrigation systems can be considered as the first step of clean energy application in the agriculture sector.

With respect to the above background, the main goals of the current study are:

- Analysis of energy consumption of barley cultivation under the surface irrigation (SFI) and SPI systems.
- Simulation of PV systems as an alternative for supplying clean energy in barley production under the prescribed systems.
- Definition of the existing scenario for barley production to evaluate environmental impacts by ReCiPe2016 method of LCA and CExD.
- Comparative study of energy, LCA and CExD in barley cultivation under the prescribed scenarios.
- Discussion of results and introduction of optimum scenario in barley cultivation from energy and environmental points of view.

2. Methodology

2.1. Case study

This study is executed during the growing season of 2018–2019, in a 100-hectare (ha) farm located in the central region of Hamedan Province at 49° 0′ E, 35° 1′ N (Fig. 1). This region has an average annual temperature of 11 ^{o}C and an annual rainfall of 323 mm. The experimental site with semi-arid climate is 1618 meter (m) above sea level and barley, wheat and alfalfa are its main productions [3]. Two different irrigation systems, namely, SFI and SPI, are used in this farm. The utilized inputs for barley production, including total direct and indirect inputs, are recorded during the growing season. Some required inputs for barley cultivation consist of diesel fuel, fertilizers, human labor, agricultural machinery, seed, pesticides, and electricity. Its outputs are barley grain yield (BGY) and straw. Electricity consumption is for lifting water from well and diesel fuel is for agricultural machinery. Besides, in SPI, another pumping system is applied to pressurize water into the irrigation system, which is powered by diesel engine.

Fig. 1

2.2. Computation of input-output energy

Physical inputs applied in barley cultivation are determined and then energy equivalences are computed by using energy coefficients. Table 2 presents energy coefficients of inputs/outputs for a variety of barley production operations.

Table 2

The following equation expresses direct electricity energy utilization for extracting the required amount of water for the crop [58]:

$$DE = \frac{\delta \times g \times H \times Q}{\eta_1 \times \eta_0} \quad (1)$$

where H is total dynamic head of pumping system based on m, g is gravitational acceleration equal to 9.8 gram (gr) per second (s)$^{-2}$, δ is water density equal to 1000 kg m^{-3}, DE is direct energy based on joule (J), Q is overall rate of water based on cubic meter (m^3) ha^{-1}, η_0 is power device overall efficiency between 18% to 22% and η_1 is efficiency of the pump between 70% to 90%.

The energy equivalent of equipment (machinery, pumps, etc.) is measured in MJ kg^{-1}; so, the following formula is used to estimate the equipment energy, [59]:

$$TW = \frac{G \times W}{T} \quad (2)$$

where T is the economic lifetime of equipment (in h), W_h is the time that the equipment uses per hectare (in h ha^{-1}), G is the total weight of equipment (in kg) and TW is the depreciated equipment weight (in kg ha^{-1}).

In SPI systems, total diesel fuel used by diesel engine and total amortized weight of machinery (including diesel engine and wheel-move system) are considered as indirect energy consumption of the irrigation system.

According to inputs/outputs as well as their energy equivalents, energy indices including energy use efficiency (EUE), specific energy (SE), net energy gain (NEG) and energy productivity (EP) , are computed as below [9][51][60]:

$$EUE = \frac{TOE}{TIE} \tag{3}$$

$$EP = \frac{BGY}{TIE} \tag{4}$$

$$SE = \frac{TIE}{BGY} \tag{5}$$

$$NEG = TOE - TIE \tag{6}$$

where *NEG* is net energy gain based on MJ ha^{-1}, *SE* is specific energy based on MJ kg^{-1}, *EP* is energy productivity based on kg MJ^{-1}, BGY is based on kg ha^{-1} , *TIE* is total input energy based on MJ ha^{-1} , *TOE* is total output energy (TOE) based on MJ ha^{-1} and *EUE* denotes energy use efficiency that is dimensionless.

2.3. Design of PV system

In the studied region, electricity generation is supplied by fossil resource's combustion in a thermal power station. Owing to limited supply and high pollution of fossil fuels, replacing thermal power station with PV power station is one of the running projects in the studied region. Previous studies on energy use in agriculture have revealed that energy consumption in the irrigation sector accounted for a remarkable section of the input energy [9][10][11]. As such, one of the goals in the current study is to simulate PV system to supply renewable electricity for usage in irrigation systems of the studied farm. As mentioned, two different irrigation systems are used in the studied farm. In SFI system, diesel fuel (for machinery) and electricity consumption (for extraction of water from well) are convertible inputs into renewable electricity. In SPI system, electricity consumption and diesel fuel (used for machinery and pressurizing water into irrigation system) are considered as convertible inputs into renewable electricity. Diesel fuel energy, using coefficients showed in Table 2, is transformed to electricity (kWh). Finally, the total computed electricity is supported by PV technology.

The main factor affecting the photovoltaic output power is the absorbed solar radiation on the panel surface, which depends on incidence angle air mass and incident solar radiation. Incidence angle information and horizontal data can be used to estimate the absorbed solar radiation on the panel surface. For a PV system, ground-reflected components, diffuse and beam constitute the effective absorbed solar radiation [61].

Transient System Simulation (TRNSYS) is a software package tailored for dynamic transient analysis of solar energy systems and simulation of dynamic systems [62]. It is a versatile energy simulation tool, which can be applied to simulate transient system's manner [63]. TRNSYS comprises two parts, namely, (i) an engine (kernel) for designing system variables, determining convergence, solving the system, and reading and processing the input file; (ii) a vast library of components for simulating the performance of a sub-section of the system [15].

Solar panels are selected as type 94a in the software library for the simulated orbit of the investigated field. Based on the manufacturer’s catalog, the panel area, the panels closure, and the number of panels are specified via clicking on a parameter module. Furthermore, Meteonorm software is used to simulate climatic conditions of the studied area for a ten-year duration. By using this software, some determined meteorological data, such as direct and diffuse components of solar radiation, hours of sunshine, cloudy times and total energy transmitted from the sun, are computed for every hour.

Meteorological data of Hamedan province, including solar radiation on horizontal surface (diffuse and beam), sunshine distribution, air temperature, wind speed, latitude, etc., are taken from Meteonorm software and used for modelling in TRNSYS software. Fig. 2 shows sunshine distribution of Hamedan province in different months. Type 65d of the library is chosen for entering the network in the subsequent step. Finally, a printer choosing type 25c library is required in order to have this information available. The optimal energy supply circuit and the number of panels (PV power) are simulated by using TRNSYS software, after having considered all irrigation's and machineries' energy demands. Fig. 3 presents schematically PV circuit to supply clean energy in different irrigation systems. According to the solar panel manufacturer catalog, data regarding solar panels for TRNSYS software are determined and sharp Solar Panel Model ND AH325, 325 W is applied in PV systems.

Fig. 2

Fig. 3

2.4. LCA

LCA is expressed as analysis and evaluation of total outputs, inputs, and entire environmental impacts relevant to all steps of a product's life cycle [64]. In fact, it is an environmental management approach applying to assess environmental damages of production services or systems during its entire life cycle [15]. Generally LCA consists of four stages or phases, which are as follows [40][65]:

- Description of the scope and goal
- Analysis of the Life Cycle Inventory (LCI)
- Implementation of Life Cycle Impact Assessment (LCIA)
- Result interpretation

2.4.1. Scope and goal definition

Description of scope and goal is considered as the first step of LCA [66], in which system boundary and functional unit (FU) determination are main steps [40]. In the current study, two methods of barley production with different irrigation systems (SFI and SPI) are considered for LCA. These systems are investigated assuming potential applications of PV technology for supplying energy required in irrigation systems. In other words, 4 scenarios are investigated in this study from environmental impact point of view. Scenarios SFI and SPI are for barley production without applying PV technology in the studied region. Scenarios SFI-PV and SPI-PV include the first and second scenarios, yet with potential application of PV technology to provide renewable energy resources for extraction of water from well and use in tractors, respectively.

In this research work, FU is determined as 1 t of barley product and the system boundary covers total farm operations and applied inputs of barley cultivation in all scenarios [67]. Fig. 4 shows system boundaries for different scenarios.

Fig. 4

2.4.2. Inventory analysis

Inventory analysis, being the second stage of LCA, computes amounts of all inputs and outputs [68][69]. Inputs comprise actual farm practice and resource usage recorded during the growing season and outputs are barley grain and straw yield. On-Farm emissions are categorized into five parts, comprising emissions attributed to biocides, diesel fuel, human labor, chemical fertilizers, and residue [70]. Emissions due to biocides, human labor, chemical fertilizers and residue are related to different scenarios. However, emissions due to diesel fuel are solely associated with SFI and SPI since, in SFI-PV and SPI-PV, renewable energy is applied rather than diesel fuel. Table 3 shows direct emissions to air related to combustion of 1 MJ of diesel fuel.

Table 3

Direct emission coefficients to air, water and soil related to inputs (including emissions from fertilizers, human labor and residual) in barley production are illustrated in Table 4.

Table 4

Chemical fertilizers and FYM can also cause environmental pollution because of the presence of heavy metals. In this study, coefficients illustrated in Table 5 are used to compute direct emissions of heavy metals.

Table 5

2.4.3. Impact assessment

This is the third step of LCA, whose goal is to gauge different environmental effects on various protection areas (human health, ecosystems, resources, etc.) [40]. LCIA can be further categorized into 4 steps: (i) the selection of impact classification; (ii) normalization; (iii) their pertinent taxonomy and (iv) weighting [15]. Various methods of environmental impact assessment have been used in previous studies [36][38][68][69][75]. This research work is conducted based on ReCiPe2016 method. The mentioned impact categories has an effect on ecosystems, human health, resources, etc. [38]. The midpoints content of each endpoint in ReCiPe2016 method are shown in Fig. 5.

Fig. 5

2.4.4. Energy form analysis by CExD

CExD denotes the summation of total resources energy required for the estimation of a product's extra energy demand. It demonstrates sensitivity of natural resources to all pertinent networks throughout the process [68]. Exergy is used to all real production activities, both for energy carriers and non-energy materials, which is proportional to the entropy created. Exergy analysis, as a main component of the LCA approach, employs resource utilization method in LCIA. Energy form categories of CExD are demonstrated in Fig. 6.

Fig. 6

In this study, barley outputs and inputs data are analyzed by using Excel 2019 software. In addition, TRNSYS V.16 is used in the solar system design. At last, LCA evaluation is performed by applying SimaPro V9.0.0 software.

3. Results and discussion

3.1. Input-output energy analysis in two irrigation systems

Table 6 shows the total energy inputs employed in barley production as well as output energy for the present conditions of two irrigation systems computed by using energy coefficients of inputs and outputs. As it can be seen, average human labor consumed by SFI and SPI in barley production are 85.8 and 41.1 respectively. In SFI, human labor is mainly for irrigation operations. Average water consumed by SFI and SPI for barley cultivation are 3629 m^3 ha^{-1} and 2333 m^3 ha^{-1}, respectively; indicating that SPI system consumes 35.7% less water than SFI system. Total energy consumed for barley production in SFI and SPI are 35490.73 MJ ha^{-1} and 39331.82 MJ ha^{-1}, respectively. Results demonstrate that although the application of SPI system decreases water consumption, it increases energy consumption. This is in agreement with results reported by some previous studies [7][12][13]. TOE in SFI and SPI are calculated as 101060 MJ ha^{-1} and 110100 MJ ha^{-1}, respectively. Average BGY are 5300 and 5600 kg ha^{-1} in SFI and SPI, respectively.

A comparison between the two systems indicates that SPI produces about 6% grain yield more than SFI. This can be due to adequate and sufficient water supply in this method. Nasseri [39] studied energy consumption pattern for wheat production in northwest of Iran under different tillage and irrigation systems. Results indicated that conservation tillage with SPI system could increase wheat grain yield compared to conventional tillage with SFI system. According to Table 6, pesticides and human labor are the minimum demanding energy input of barley cultivation in the two investigated systems.

Table 6

Fig. 7 presents the share of each input for barley production under the two studied systems. In SFI system, electricity used for extraction of water consumes 49.8% of the entire energy inputs, which is followed by diesel fuel (16.1%). In this system, diesel fuel is remarkably consumed by tractors as a result of different operations. In SPI system, 40.4% of the entire energy inputs are consumed by diesel fuel, which is followed by electricity (28.9%). According to results, it can be concluded that barley cultivation in the investigated field is highly dependent on non-renewable energy sources. A substantial part of diesel fuel in SPI system is used by diesel engine to pressurize water into the irrigation system. Karimi et al. [10] pointed out that around 2 billion l of diesel fuel and 20.5 billion kWh of electricity were used yearly in Iran as a result of groundwater pumping in irrigation system. In order to decrease electricity and diesel fuel consumption, the use of renewable energy source with less environment pollution, such as PV systems, was recommended.

Fig. 7

Energy indices of barley cultivation are computed by using Eqs. (3)-(6) and results are illustrated in Table 7. These indices are useful tools to compare EUE in different systems. EUE in SFI system is computed as 2.85, while the corresponding value in SPI system is 2.80. Regarding other agricultural crops, EUE were reported as 3.02 for canola [76], 2.86 for barley [54], 6.5 for wheat [77] and 1.28 for paddy [35]. NEGs of barley production in SFI and SPI are about 65569 and 70768 MJ ha^{-1}, respectively. Thus, energy is gained in barley production.

Table 7

Results show that although the yield of SPI is greater than that of SFI, energy indices (EUE and EP) of SPI are lower than those of SFI. This is due to the high consumption of diesel fuel in SPI to pressurize water into irrigation system. In order to improve energy indices in SPI, it is necessary to reduce input consumption, especially diesel fuel. The capacity of engine used in SPI system is greater than power required to pressurize water. As such, in order to reduce diesel fuel consumption, the use of a smaller but high performing diesel engine is suggested. This leads to decrease in both energy and water consumptions in barley cultivation. Nitrogen fertilizer is another input that has high energy consumption in barley cultivation. The use of

SPI system allows proper timing and uniform distribution of fertilizers in barley cultivation. This leads to substantial savings in N fertilizer and energy usage.

3.2. Simulated PV system for two irrigation systems

According to Table 6, the total use of diesel fuel in SFI and SPI are in 5698.57 and 15890.68 MJ ha^{-1}, respectively. Thus, by dividing the total diesel fuel's energy use to electricity's energy equivalent, renewable energy for diesel fuel replacement is determined. These amounts are computed as about 478 and 1332 kWh for SFI and SPI, respectively. The total electricity needed, which should be provided by the PV system, is computed by adding these amounts to electricity uses in irrigation systems. These amounts are computed as about 1959 and 2285 kWh for SFI and SPI, respectively. According to the barley cultivation period in the surveyed area, these estimated amounts should be divided by 4 months. The average numbers of solar panels (PV power) in SFI-PV and SPI-PV scenarios are then computed.

Results of simulation solar systems via TRNSYS in SFI-PV and SPI-PV scenarios are presented in Table 8. According to this table, the mean PV power for SFI-PV and SPI-PV systems are estimated as 3.90 and 4.22 kW, respectively. This means that on average 529.24 and 633.89 kWh electricity is required for each month in barley production period in SFI-PV and SPI-PV scenarios, respectively. Nevertheless, they cannot furnish the needed electricity for all barley cultivation periods in the surveyed area. For solving this problem and providing sustainable electricity production, the maximum panel's power in each scenario has to be considered. According to Table 8, the maximum electricity needed, which should be provided by the PV system is 529.24 and 633.89 kWh in SFI-PV and SPI-PV scenarios, respectively. In other words, the maximum PV power required to supply electricity are 4.55 and 5.20 kW in SFI-PV and SPI-PV scenarios, respectively. Hosseini-Fashami et al. [15] applied TRNSYS Software for modelling solar technologies for replacing diesel and electricity with renewable energy, which were needed in strawberry greenhouse in Alborz province, Iran. Results showed that numbers of required solar panels to supply sustainable energy were 150 and 147 in photovoltaic and photovoltaic/thermal systems respectively.

Table 8

3.3. Exergoenvironmental analysis of two irrigation systems

As mentioned previously, 4 defined scenarios are investigated from environmental impact point of view. Scenarios SFI and SPI are for barley production without applying PV technology. Scenarios SFI-PV and SPI-PV include the first and second scenarios, yet with potential application of PV technology, respectively.

Table 9 shows LCI of various scenarios for 1 ha of barley cultivation in the studied farm. Results show that amounts of CO_2 emission owing to diesel fuel usage in barley production are 424.54 and 1183.86 kg ha^{-1} in SFI and SPI, respectively. Results indicate that SPI system increases barley yield and improves water use efficiency. It also improves irrigation systems management and working conditions of farmers, but increases energy consumption, which leads to increased environmental impacts and GHG emission. This is because of high consumption of diesel fuel by pumping stations in the studied farm.

Table 9

Tarjuelo et al. [7] reported that energy consumption by pumping stations generated significant GHG emissions, which then contributed to climate change. Ghasemi-Mobtaker et al. [79] reported that CO_2 emission's amount from diesel fuel's consumption in wheat production was around 427 kg ha^{-1}.

CO_2 emissions by human labor to air are estimated as 60.06 and 28.77 kg ha^{-1} in SFI and SPI, respectively, indicating that the use of SFI can reduce this index by 52%. Besides, nitrate and phosphate emissions to water in both systems are computed as 13.90 and 1.32 kg ha^{-1}, respectively. Mousavi-Avval et al. [67] reported that annual CO_2 emission from urea fertilizer's usage in oilseed production was about 155 kg ha^{-1}.

3.3.1. Exergoenvironmental analysis without PV system

Endpoints results by using LCA method in SFI and SPI scenarios for production of 1 t of BGY are presented in Table 10. In SFI and SPI, human health damage categories generated are 1.67E-03 and 1.87E-03 Disability Adjusted Life Years (DALY)per 1 t of BGY , respectively. This indicates that SPI increase human health damage by 11.98%. Furthermore, resources damage categories are 24.38 and 25.23 USD2013 in SFI and SPI, respectively, indicating that SPI increase this index by 3.49%.

Table 10

The share of different inputs to endpoints of barley production in SFI and SPI scenarios are presented in Fig. 8. According to Fig. 8a, in SFI scenario, On-Farm emissions constitute the greatest effects in human health damage categories. On the other hand, electricity has the highest impact in ecosystems and resources. This indicates that in SFI, electricity use for barley production causes high damage on environment and its consumption should be reduced. Managing water consumption can lead to reduced electricity consumption. Nitrogen fertilizer is another input which has high impact on all damage categories. As mentioned, proper timing and uniform distribution of fertilizers can reduce N fertilizer consumption in barley cultivation. In a similar study, Ghasemi-Mobtaker et al. [79] investigated environmental performance of wheat farm in Hamedan province and reported that electricity was a main hotspot in FE, ADF, PO, OLD and GWP impact categories.

Fig. 8

According to Fig. 8b, in SPI scenario, the greatest effects in human health and ecosystems damage categories are from On-Farm emissions. Furthermore, in resources damage categories, the greatest effects are from diesel fuel and electricity. As mentioned previously, a large part of diesel fuel in this scenario is related to the pumping station, which results in high GHG emissions compared to other scenarios. The use of a proper engine in the pumping station can reduce fuel consumption in this scenario.

Table 11 shows energy analysis's results based on CExD in SFI and SPI scenarios of barley production. It can be observed that the largest energy consuming form of two scenarios is Non-renewable, fossil fuel. Their values are 6135.21 and 6248.52 MJ per 1 t of BGY in SFI and SPI, respectively. Results demonstrate that amounts of Non-renewable, fossil; Non-renewable, metal;s Renewable, solar and Renewable, kinetic in SPI are greater than those of SFI. As mentioned, in SPI system, fossil fuel consumption is high, which leads to high amount of Non-renewable, fossil in this system. Kaab et al. [40] reported that in planted and ratoon farms of sugarcane, Non-renewable, fossil rates amounted to 85.96 and 48.44 GJ ha^{-1}, respectively.

Table 11

Shares of inputs in energies for SFI and SPI scenarios in CExD analysis are presented in Fig. 9. Results show that, in SFI, electricity shares the largest portion in Non-renewable, fossil (about 65%) and Renewable, potential (about 70%) form. Moreover, in many forms such as Non-renewable, meals; Renewable, solar, Non-renewable, primary and Renewable, kinetic nitrogen has high energy consumption among inputs. This indicates that a proper use of nitrogen fertilizer can result in a large reduction in energies for barley cultivation.

According to Fig. 9b, in SPI scenario, electricity and diesel fuel have the largest shares in Non-renewable, fossil. Besides, in Non-renewable, primary, Renewable, solar and Non-renewable, meals, nitrogen has high energy consumption among inputs. According to Table 11, a great portion of CExD is occupied by Non-renewable, fossil. Moreover, according to Fig. 9, electricity and diesel fuel are major components of Non-renewable, fossil. Thus, a proper management of diesel fuel and electricity can be an efficient way to lower CExD.

Fig. 9

3.3.2. Exergoenvironmental analysis with PV system

Endpoints results by using LCA method in SFI-PV and SPI-PV scenarios for production of 1 t of BGY are presented in Table 12. Results demonstrate that applying PV technology reduce all impact categories in both SFI-PV and SPI-PV systems. In other words, compared to SPI, the SPI-PV scenario reduces human health damage and resources by 14.44% and 36.82%, respectively. Human health damage categories produced per 1 t of BGY are 1.54E-03 and 1.60E-03 Disability Adjusted Life Years (DALY) in SFI-PV and SPI-PV, respectively. Furthermore, resources damage categories are 14.27 and 15.94 USD2013 in SFI-PV and SPI-PV, respectively. Hosseini-Fashami et al. [15] studied energy-environmental indices of greenhouse strawberry cultivation by applying solar technologies scenario and reported that applying PV system for supplying energy resources could decrease all impact categories in strawberry production processes.

Table 12

Shares of different inputs to endpoints of barley production in SFI-PV and SPI-PV scenarios are presented in Fig. 10. As can be seen from Fig. 10a, in SFI-PV scenario, the greatest effects in human health damage categories are from PV panels and On-Farm emissions. Moreover, PV panels impose the greatest impact in ecosystems and resources. Results show that PV panels have high impact on all damage categories. In other words, electricity generation, whether through thermal power station or through renewable sources, has a significant detrimental effect on the environment and, in order to reduce these damages, its use in barley production should be managed.

Fig. 10

In SPI-PV scenario, the main portion of resource damage, ecosystems and human health, categories are from the application of PV panels. Besides, On-Farm emissions are another factor, which has a high impact in human health damage categories. Comparison of results of scenarios SPI and SPI-PV show that the application of PV panels systems is able to mitigate On-Farm emissions in barley cultivation.

Table 13 shows energy analysis results based on CExD in SFI-PV and SPI-PV scenarios of barley production. In SFI-PV scenario, it is assumed that fossil fuel and electricity are replaced by PV system. Findings show that the application of PV panels, instead of diesel fuel and electricity, leads to changes in energy forms in SFI-PV. In other words, compared with SFI, SFI-PV scenario increases all energy form except Non-renewable, fossil and Renewable, solar. As can be seen from Tables 11 and 13, SFI-PV reduces Non-renewable, fossil form by 43.68%. This is due to a high share of fossil fuel and electricity in SFI, which has been replaced by PV panels in SFI-PV. Results also indicate that SFI-PV increases Renewable, potential form by 172.08 MJ. Results also demonstrate that, compared with SPI, SPI-PV scenario increases all energy form except Non-renewable, fossil. The Non-renewable, fossil reduction value is about 40%. Similarly, Hosseini-Fashami et al. [15] reported that the application of PV system for supplying energy resources in greenhouse strawberry cultivation was able to reduce Non-renewable, fossil form by 52.04%.

Table 13

Shares of inputs in energy forms of CExD analysis for SFI-PV and SPI-PV scenarios are presented in Fig. 11. As can be seen from Fig. 11a in SFI-PV scenario, the largest shares of Non-renewable, metals; Renewable, kinetic; Non-renewable, fossil and Renewable, potential energy forms depend on PV panels. Furthermore, in Non-renewable, primary and Renewable, solar, nitrogen has high energy consumption among inputs. Production process of phosphate constitutes the greatest energy-consumption share in Non-renewable minerals. Findings also show that the application of PV panels, rather than diesel fuel and electricity , leads to energy form changes in SPI-PV. In SPI-PV scenario, the largest shares of Non-renewable, metals; Renewable, kinetic; Non-renewable, fossil and Renewable, potential energy forms are dependent on PV panels. Besides, in Renewable, solar and Non-renewable, primary nitrogen has high energy consumption among inputs. Production process of phosphate constitutes the largest energy consumption portion in Non-renewable minerals.

Fig. 11

3.4. Selection of energy-environmental friendly scenario

In the last part of the study, damage categories amongst various scenarios are compared. Results of comparisons for different scenarios of barley production based on weighted endpoints are presented in Fig. 12. Results indicate that, in all damage categories, amounts of emissions are reduced by applying PV panels for both SFI and SPI scenarios. In other words, SFI-PV and SPI-PV scenarios can decrease the total damage by about 17% and 20%, respectively.

Results indicate that, compared with SFI and SPI scenarios, SFI-PV and SPI-PV scenarios can decrease human health index by about 7% and 14%, respectively. In human health damage categories, emissions rate is the least for SFI-PV. In this scenario, diesel fuel and electricity consumptions, which are basically generated by non-renewable fossils resources, are replaced with PV panels. This leads to the reduction of On-Farm emission. Hence, in SFI scenario, human health becomes better through PV panels. SPI-PV scenario enhances this damage category in comparison with SFI-PV scenario. The use of some additional equipment in pumping stations increases On-Farm emission and carcinogens in SPI-PV and thus renders human health's worse situation.

In the case of ecosystems, approximately stable trends are observed in the four investigated scenarios. The main cause of this is the low dependence of ecosystems to diesel fuel and electricity consumptions. In resources damage category, non-renewable fossil energy and mineral extraction are two main midpoints. Since diesel fuel and electricity are basically generated by non-renewable fossils resources, it can be concluded that resources damage category mainly depends on diesel fuel and electricity. Therefore, SFI-PV and SPI-PV scenarios can decrease resources damage category by about 42% and 37%, respectively.

Fig. 12

A comparison of different scenarios of barley production based on total CExD is shown in Fig. 13. According to Fig. 13, about 37% and 33% of CExD can be saved by SFI-PV and SPI-PV, respectively. According to results of this study, diesel fuel and electricity consume a large share of input energy. Due to low efficiency of thermal power stations, the generation of electricity is very energy consuming; thus, the use of PV panels to produce clean energy can reduce environmental damage and sustain natural resources.

According to results of this study, SFI-PV is the best system from environmental point of view. It is because damage categories and CExD in this scenario are lower than other scenarios. The utilization of PV panels decreases many energy environmental damages of barley production, but the share of PV panels is considerable in many indices. Therefore, despite the advantages of SPI-PV (namely, less water and human labor use), this scenario is not selected as an environmental-friendliness scenario.

Fig. 13

Water scarcity is one of the main issues in the studied region. As such, results of this study can also be considered from a water consumption perspective. From this point of view, SPI-PV, despite the high environmental impact, has the lowest water consumption among different scenarios. The reason for high environmental indices in SPI-PV relative to the SFI-PV is due to the inefficient use of diesel fuel in the irrigation system. In the investigated farm, Perkins A4.318 engine (4-cylinder) is used to pressurize water into irrigation system, which can be replaced by a smaller engine with less fuel consumption. Nitrogen fertilizer is another input with high energy consumption and high environmental damage in barley cultivation. The application of SPI-PV system allows proper timing and uniform distribution of fertilizers in barley cultivation. This can reduce diesel fuel and nitrogen consumption in SPI-PV, which can be developed as an environmentally friendly system.

4. Conclusions

The aim of this research work is to evaluate energy consumption pattern as well as environmental analysis of two irrigation systems (SFI and SPI) in barley cultivation with an integration of PV technology for supplying energy consumed in irrigation systems of Hamedan province, Iran. TRNSYS software is applied in order to simulate solar technologies as renewable energy to replace diesel and electricity. Then LCA and CExD analysis are used to assess environmental damages of different scenarios. According to findings of this research work, the following conclusions are drawn:

1. Total energy consumptions of SFI and SPI are computed as 35490.73 and 39331.82 MJ ha^{-1}, respectively. In SFI, electricity (49.81%) has the highest share of energy inputs. In SPI, diesel (40.40%) has the highest portion within total energy inputs.
2. EUE of SFI is found to be higher than that of SPI, indicating that although SPI consumes 35.7% less water than the SFI, its energy indices is not better than SFI.
3. Results of simulation solar systems by TRNSYS show that the maximum PV power needed, which should be provided by the PV system are 4.55 and 5.20 kW in SFI-PV and SPI-PV scenarios, respectively.
4. On-Farm emissions results demonstrate that the amount of CO_2 emissions from diesel fuel in barley production are 424.54 and 1183.86 kg ha^{-1} in SFI and SPI, respectively. High consumption of diesel fuel by pumping stations is the reason of high CO_2 emission in SPI system.
5. Under SFI and SPI systems, shares of diesel fuel, electricity, nitrogen and On-Farms emissions are main factors in all categories. In SFI-PV and SPI-PV systems, shares of PV panels, nitrogen and On-Farms emissions are main factors in all categories.

6. Results of CExD analysis indicate that the application of PV panels cause changes in energy forms in SFI-PV and SPI-PV and reduce environmental impacts of these systems. In SFI and SPI systems, electricity and diesel fuel have a great share in Non-renewable, fossil form, while in SFI-PV and SPI-PV systems, PV panels have a significant portion in Non-renewable, fossil form.
7. SFI-PV scenario is the best system from environmental point of view because damage categories and CExD in this scenario are lower than those of other scenarios.
8. This study provides valuable information, which can be used for the design and evaluation of photovoltaic irrigation in other regions and for other crops.
9. Finally, it is suggested that input consumptions are investigated in the studied farm to provide solutions for reduction of their consumptions. This will reduce environmental impacts of barley cultivation.

Highlights

- Energy-Life cycle-Exergy of different irrigation systems are examined for barley.
- Photolytic systems are simulated to supply energy in SFI and SPI scenarios.
- Energy use efficiencies are 2.85 and 2.80 in SFI and SPI, respectively.
- Non-renewable, fossils are 6135 and 6249 MJ/1t of BGY in SFI and SPI, respectively.
- SFI-PV is the best scenario in energy-environmental friendly perspective.

Fig. 1. Hamedan province location in the west of Iran [3].

Fig. 2. Sunshine distributions of Hamedan province of Iran in different months [3].

Fig. 3. Designed PV circuit to supply clean energy in SFI and SPI systems of barley production [15].

Fig. 4. System boundaries of barley production based on different irrigation systems.

Fig. 5. Midpoint content of each endpoint in ReCiPe2016 method of LCA.

Fig. 6. Schematic diagram of energy forms based on CExD.

Fig. 7. Contribution of each inputs for barley production under SFI and SPI systems.

Fig. 8. Distribution of each endpoint based on inputs in SFI and SPI scenarios.

Fig. 9. Share of each input in energy forms of CExD analysis for SFI and SPI scenarios.

Fig. 10. Distribution of each endpoint based on inputs in SFI-PV and SPI-PV scenarios.

Fig. 11. Share of each input in energy forms of CExD analysis for SFI-PV and SPI-PV scenarios.

Fig. 12. Comparison of different scenarios of barley production based on weighted endpoints.

Fig. 13. Comparison of different scenarios of barley production based on total CExD.

Table 1
Summary of samples research with energy, LCA, PV systems and CExD approaches in agricultural production process.

Investigated researches	Case study location	Crop	Energy analysis	LCA	LCA method	PV systems	CExD
Zangeneh et al. [22]	Iran	Potato	Complete coverage	-	-	-	-
Knudsen et al. [23]	Denmark	Orange	Input-Output	Greenhouse gas (GHG)	CML2 Baseline 2000	Applying for pump	-
Boulard et al. [24]	France	Tomato	Energy indices	Partial coverage	IMPACT 2002+	Applying for whole system	Yes
Mobtaker et al.[25]	Iran	Alfalfa	Input-Output	-	-	-	-
Page et al. [26]	Australia	Tomato	Complete coverage	Complete coverage	CML1	Applying for pump	-
Senol [27]	Turkey	Apple	-	-	-	Applying for pump	-
Vázquez -Rowe et al. [28]	Spain	Grape	Input-Output	Partial coverage	-	-	-
Alhajj Ali [29]	Italy	Wheat	Complete coverage	-	-	-	-
Mohammadi et al. [30]	Iran	Rice paddy	Input-Output	Partial coverage	-	-	-
Houshyar and Grundmann [31]	Iran	Wheat	Complete coverage	Complete coverage	CML 2 baseline 2000	-	-
Raheli et al. [32]	Iran	Tomato	Complete coverage	-	-	-	-
Rubio-Aliaga et al. [33]	Spain	-	Energy deficiency	-	-	Applying for irrigation	-
Yu et al. [34]	China	Cassava	-	-	-	Applying for irrigation	-
Nabavi-Pelesaraei et al. [35]	Iran	Paddy	Complete coverage	Complete coverage	CML	-	Yes
Fathollahi et al. [36]	Iran	Forage	Complete coverage	Complete coverage	CML-IA baseline	-	-
Yildizhan and Taki [37]	Turkey	Tomato	Input-Output	-	-	-	Yes
Taki et al. [38]	Iran	Wheat	Input-Output	Complete coverage	CML-IA baseline	-	-
Nasseri [39]	Iran	Wheat	Complete coverage	-	-	-	-
Kaab et al. [40]	Iran	Sugarcane	Complete coverage	Complete coverage	CML 2 baseline 2000	-	Yes
Mérida García [41]	Spain	-	-	Complete coverage	CML	Applying for irrigation	-
Parvaresh-Rizi et al. [42]	Iran	Citrus and vineyard	-	-	-	Applying for irrigation	-
Rubio-Aliaga et al. [43]	Spain	-	-	-	-	Applying for irrigation	-
Rubio-Aliaga et al. [44]	Spain	-	Complete coverage	GHG	-	Applying for irrigation	-
Todde et al. [45]	Mediterranean region	Olive	Complete coverage	GHG	Carbon payback times	Applying for irrigation	-
Pardo et al. [46]	Spain	-	Storage in battery	Environmental cost	-	Applying for irrigation	-
Meerida García et al. [47]	Spain	-	Energy efficiency	Complete coverage	CML-IA baseline	Applying for irrigation	-
Nikzad et al. [48]	Iran	Rice	-	GHG	-	Applying for irrigation	-
Carrêlo et al. [49]	Mediterranean region	-	-	-	-	Applying for irrigation	-
Present study	**Iran (Hamedan)**	**Barley**	**Complete coverage**	**Complete coverage**	**ReCiPe2016**	**Applying for whole system**	**Yes**

Table 2
Energy coefficients of inputs/output in different operations of barley production.

Item	Input									Output	
				Chemical fertilizers							
	Human labor	Agricultural machinery	Diesel fuel	Nitrogen	Phosphate	Farmyard manure (FYM)	Pesticides	Electricity	Seed	Barley	Straw
Unit	Hour (h)	Kilogram (kg)	Liter (l)	kg	kg	kg	kg	Kilowatt hour (kWh)	kg	kg	kg
Energy equivalent*	1.96	142.7	56.31	66.14	12.44	0.3	199	11.93	14.7	14.7	9.26
References	[50][51]	[52]	[53][54]	[52][55]	[52]	[54]	[56]	[9][22]	[57]	[57]	[50]

* This amount is based on Megajoule (MJ) per unit.

Table 3
EcoInvent database coefficient of direct emissions to air related to burning 1 MJ of diesel fuel [35].

Emission	Amount (gr MJ^{-1} diesel)
Carbon dioxide (CO_2)	74.5
Sulfur dioxide (SO_2)	2.41E-02
Methane (CH_4)	3.08E-03
Benzene	1.74E-04
Cadmium (Cd)	2.39E-07
Chromium (Cr)	1.19E-06
Copper (Cu)	4.06E-05
Dinitrogen monoxide (N_2O)	2.86E-03
Nickel (Ni)	1.67E-06
Zinc (Zn)	2.39E-05
Benzo (a) pyrene	7.16E-07
Ammonia (NH_3)	4.77E-04
Selenium (Se)	2.39E-07
Polycyclic hydrocarbons (PAH)	7.85E-05
Hydro carbons (HC), as Non-methane volatile organic compound (NMVOC)	6.80E-02
Nitrogen oxides (NO_x)	1.06
Carbon monoxide (CO)	1.50E-01
Particulates (b2.5 micrometer (μm))	1.07E-01

Table 4
On-Farm emissions related to use of chemical fertilizers, FYM, human labors, pesticides and residue management in barley production.

Emission	Unit	Cause	Coefficient (Reference)
A. Emissions to air			
1. N_2O	kg N_2O equivalent (eq.)	Nitrogen content of chemical fertilizers and FYM	0.01 [71]
2. NH_3	kg NH_3 eq.	Nitrogen content of FYM	0.2 [71]
3. NH_3	kg NH_3 eq.	Nitrogen content of chemical fertilizers	0.1 [71]
4. N_2O	kg N_2O eq.	Atmospheric deposition of nitrogen in chemical fertilizers	0.001 [71]
5. N_2O	kg N_2O eq.	Atmospheric deposition of nitrogen in FYM	0.003 [71]
6. NOx	kg NOx eq.	N_2O content of fertilizers and soil	0.21 [71]
7. CO_2	kg CO_2 eq.	CO_2 derived from human activity per h	0.7 [72]
8. Effective material of pesticides	kg effective material eq.	Pure content of effective material in pesticides	0.1 [73]
B. Emissions to water			
1. Nitrate (NO_3^-)	kg NO_3^- eq.	Nitrogen content of chemical fertilizers and FYM	0.1 [71]
2. Phosphate	kg phosphate eq.	Phosphate content of chemical fertilizers and FYM	0.02 [71]
C. Emissions to soil			
1. Effective material of pesticides	kg effective material eq.	Pure content of effective material in pesticides	0.85 [73]
2. Residue incorporating	kg N_2O eq.	Mixing of residue to soil	0.01 [72]

Table 5

Emissions to soil coefficients of heavy metals related to using chemical fertilizers and FYM in barley farms [74].

Heavy metal	Miligram (mg) per kg of applied nitrogen fertilizer	mg per kg of applied phophate fertilizer	mg per kg of applied FYM dry matter	
			Cattle	Poultry
1. Cd	6	39.5	0.64	1.52
2. Cu	26	90.5	452.25	99
3. Zn	203	839	1018	469
4. Lead (Pb)	5409	67	13.55	16.2
5. Ni	20.9	88.3	17.43	19.05
6. Cr	77.9	543	13.23	8.7
7. Mercury (Hg)	0.1	0.3	0.08	0.09

Table 6
Content of energy use and output energy in two present conditions of irrigation systems in barley production of Hamedan province, Iran.

Item	Scenario	Input (unit)										Output (unit)		
		Human labor (h)	Agricultural machinery (kg)	Diesel fuel (l)	Chemical fertilizers (kg)		FYM (kg)	Pesticides (kg)	Electricity (kWh)	Seed (kg)	Total energy use (MJ)	Barley (kg)	Straw (kg)	Total energy output (MJ)
					Nitrogen	Phosphate								
Unit per ha	SFI	85.8	11.56	101.20	69	45.5	5000	0.7	1481.76	240	-	5300	2500	-
	SPI	41.1	11.91	282.20	69	45.5	5000	0.7	952.56	240	-	5600	3000	-
Energy content*	SFI	168.17	1649.61	5698.57	4563.66	566.02	1500	139.30	17677.40	3528	35490.73	77910	23150	101060
	SPI	80.56	1699.56	15890.68	4563.66	566.02	1500	139.30	11364.04	3528	39331.82	82320	27780	110100

* The amount is MJ per ha

Table 7
Energy indices of barley production in Hamedan province, Iran.

Scenario	EUE (-)	EP (kg MJ^{-1})	SE (MJ kg^{-1})	NEG (MJ ha^{-1})
SFI	2.85	0.15	6.70	65569.27
SPI	2.80	0.14	7.02	70768.18

Table 8
Results of simulation PV systems by TRNSYS in different irrigation methods of barley production.

Item	Optimal slop (Degree) [78]	PV power (kW)		Electricity power (kWh)	
		SFI-PV	SPI-PV	SFI-PV	SPI-PV
A. Production period					
1. 23 September - 22 October	41.4	3.25	3.57	522.95	581.06
2. 23 October - 21 November	53.4	4.55	5.20	529.24	610.66
3. 21 March – 20 April	24.1	3.90	4.23	527.99	575.99
4. 21 April – 21 May	6.3	2.93	3.57	507.11	633.89
B. Statistics indices					
1. Average	31.3	3.90	4.23	521.82	600.40
2. Standard deviation	20.55	0.72	0.77	10.18	27.06
3. Minimum	6.3	2.93	3.57	507.11	575.99
4. Maximum	53.4	4.55	5.20	529.24	633.89

Table 9
LCI of different scenarios for 1 ha of barley production in Hamedan province of Iran.

Item (unit)	Scenarios			
	SFI	SFI-PV	SPI	SPI-PV
A. Off-Farm				
1. Agricultural machinery (kg)	11.56	11.56	11.91	11.91
2. Chemical fertilizers (kg)				
(a). Nitrogen	69	69	69	69
(b). Phosphate	45.5	45.5	45.5	45.5
3. FYM (kg)	5000	5000	5000	5000
4. Pesticides (kg)	0.7	0.7	0.7	0.7
5. Diesel (kg)	87.03	-	242.69	-
6. Electricity (kWh)	1481.76	-	952.56	-
7. PV panels (m^2)	-	24.78	-	28.32
B. On-Farm				
1. Emissions by diesel fuel to air (kg)				
(a). CO_2	424.54	-	1183.86	-
(b). SO_2	0.14	-	0.38	-
(c). CH_4	0.02	-	0.05	-
(d). Benzene	9.92E-04	-	2.76E-03	-
(e). Cd	1.36E-06	-	3.80E-06	-
(f). Cr	6.78E-06	-	1.89E-05	-
(g).Cu	2.31E-04	-	6.45E-04	-
(h). N_2O	0.02	-	0.05	-
(i). Ni	9.52E-06	-	2.65E-05	-
(j). Zn	1.36E-04	-	3.80E-04	-
(k). Benzo (a) pyrene	4.08E-06	-	1.14E-05	-
(l). NH_3	2.72E-03	-	7.58E-03	-
(m). Se	1.36E-06	-	3.80E-06	-
(n). PAH	4.47E-04	-	1.25E-03	-
(o). HC, as NMVOC	0.39	-	1.08	-
(p). NOx	6.04	-	16.84	-
(q). CO	0.85	-	2.38	-

(r). Particulates (b2.5 μm)	0.61	-	1.70	-
2. Emissions by fertilizers to air (kg)				
(a). N_2O	1.64	1.64	1.64	1.64
(b). NH_3 by FYM	8.66	8.66	8.66	8.66
(c). NH_3 by chemical fertilizers	8.38	8.38	8.38	8.38
3. Emission by atmospheric deposition of fertilizers to air (kg)				
(a). N_2O by chemical fertilizers	0.11	0.11	0.11	0.11
(b). N_2O by FYM	0.11	0.11	0.11	0.11
4. Emissions by fertilizers to water (kg)				
(a). Nitrate	13.90	13.90	13.90	13.90
(b). Phosphate	1.32	1.32	1.32	1.32
5. Emission by N_2O of fertilizers and soil to air (kg)				
(a). NOx	0.39	0.39	0.39	0.39
6. Emission by human labor to air (kg)				
(a). CO_2	60.06	60.06	28.77	28.77
7. Emission by heavy metals of fertilizers to soil (mg)				
(a). Cd	3947.03	3947.03	3947.03	3947.03
(b). Cu	448896.25	448896.25	448896.25	448896.25
(c). Zn	1247134.70	1247134.70	1247134.70	1247134.70
(d). Pb	400176.60	400176.60	400176.60	400176.60
(e). Ni	34771.06	34771.06	34771.06	34771.06
(f). Cr	47700.53	47700.53	47700.53	47700.53
(f). Hg	151.14	151.14	151.14	151.14
8. Emissions by pesticides to air (kg)				
(a). Deltamethrin	0.07	0.07	0.07	0.07
9. Emissions by biocides to soil (kg)				
(a). Deltamethrin	0.60	0.60	0.60	0.60
10. Emissions by residue incorporating to soil (kg)				
(a). N_2O	0.18	0.18	0.54	0.54
C. Yield				
1. Barley (kg)	5300	5300	5600	5600

Table 10
Endpoint results of ReCiPe2016 method in SFI and SPI scenarios for 1 t production of barley.

Endpoint	Unit	Scenarios	
		SFI	SPI
Human health	DALY [a]	1.67E-03	1.87E-03
Ecosystems	species.yr [b]	5.71E-06	6.23E-06
Resources	USD2013 [c]	24.38	25.23

[a] Damage of 1 is tantamount to: lack of 1 life year of 1 individual, or 1 person travails 4 years from a disability with a weight of 0.25.
[b] The unit for ecosystems is the local species loss integrated over time.
[c] The United States dollars rate for 2013.

Table 11
Energy forms of CExD analysis in SFI and SPI scenarios for 1t production of barley.

Energy form	Unit	Scenarios	
		SFI	SPI
Non-renewable, fossil	MJ	6135.21	6248.52
Renewable, kinetic	MJ	7.40	7.59
Renewable, solar	MJ	0.04	0.04
Renewable, potential	MJ	112.52	91.42
Non-renewable, primary	MJ	1.22	1.20
Non-renewable, metals	MJ	89.62	107.28
Non-renewable, minerals	MJ	84	79.94

Table 12
Endpoint results of ReCiPe2016 method in SFI-PV and SPI-PV scenarios for 1 t production of barley.

Endpoint	Unit	Scenarios	
		SFI-PV	SPI-PV
Human health	DALY	1.54E-03	1.60E-03
Ecosystems	species.yr	4.86E-06	5.15E-06
Resources	USD2013	14.27	15.94

Table 13
Energy forms of CExD analysis of SFI-PV and SPI-PV scenarios for 1t production of barley.

Energy form	Unit	Scenarios	
		SFI-PV	SPI-PV
Non-renewable, fossil	MJ	3455.57	3753.85
Renewable, kinetic	MJ	9.55	10.70
Renewable, solar	MJ	0.03	0.04
Renewable, potential	MJ	306.14	335.47
Non-renewable, primary	MJ	1.26	1.24
Non-renewable, metals	MJ	170.49	198.47
Non-renewable, minerals	MJ	84.65	80.66