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Effect of improvement actions on the life-cycle environmental and economic performance of synthetic biofuels from date palm waste in Tunisia

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The use of biowaste to produce synthetic fuels is often proposed to overcome sustainability issues associated with conventional fossil fuels. Several routes and processes from waste feedstock to final fuels have proven to be technically feasible, whereas economic and environmental aspects typically differ from one system to another depending on the specific conditions and context. In a previous study on the life-cycle sustainability performance of synthetic diesel and gasoline from Tunisian date palm waste, critical concerns on the use of grid electricity and conventional oxygen were reported. In order to further explore the potential environmental and economic suitability of this biofuel production pathway, this article revisits and extends the former case study by assessing the effect of implementing renewable electricity and alternative oxygen. In particular, the use of photovoltaics (PV) to provide electricity to the synthetic fuel plant, as well as its use in local oxygen production, is considered. System Advisor Model (SAM) software is used to simulate a PV plant, including the estimation of the levelised cost of energy. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are applied to estimate the environmental and economic life-cycle profile of the synthetic biofuels when the potential improvement actions are implemented. When compared to the original system, a slight decrease in total production costs is found, yet considering higher capital costs related to PV installation. Regarding the environmental dimension, findings on the suitability of the alternative system depend on the specific impact category and the reference target, with significant potential savings (*e.g.* climate change) but also greater potential impacts (*e.g.* use of minerals and metals) when benchmarked against both the original bioenergy system and conventional fossil fuels. This evinces complex decision-making when multiple sustainability aspects are taken into account, but suggesting the suitability of the proposed measures if the long-term benefits of climate change mitigation and the current national decarbonisation targets are prioritised.

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1. Introduction

The current context of the global energy crisis is having several implications for households, businesses and entire economies, such as high energy prices, pressure on markets, inflation, food and supply insecurity, vulnerability and poverty in society. This situation may worsen in the future, especially in the transport sector, where most of the energy consumption comes from oil (currently around 90%) and its demand is expected to grow, especially in aviation, shipping and long-distance road transportation.[1,2]

The transport sector is responsible for nearly 40% of the global greenhouse gas (GHG) emissions from end-use sectors,[1,3] evidencing the relevance of acting on this sector to achieve emission reduction targets. For instance, the European Commission estimates that a 90% reduction in transport emissions is needed to meet climate neutrality by 2050.[4] However, some of the effects of climate change are already irreversible.[5] These are likely to be more noticeable in North Africa, with expected annual temperature increases higher than the average of the planet.[6]

Despite the high contribution to GHG emissions from the transport sector, the demand for liquid fuels is expected to grow in the near future. This, along with the current energy crisis and supply security, calls for new policies boosting the structural transformation of the energy sector, aimed at climate change mitigation and energy security. Hence, alternatives to decarbonise the transport sector are required. In this sense, synthetic and bio-based liquid fuels could play an important role.

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Currently, liquid biofuels represent around 3.6% of the energy needs in the transport sector,[7] being expected to reach 5.4% by 2027.[8] While most of them are associated with first-generation biomass,[9] second- and third-generation biofuels coming from non-food feedstock may meet the medium-term need for biofuels, especially for jet fuel and diesel.[10,11] In particular, advanced biofuels coming from agricultural waste might represent 3–14% of the global energy supply in the coming years,[12] while other waste streams and dedicated short-rotation woody crops should also be used.[1]

In this regard, several pathways from biomass to final liquid fuels (biomass-to-liquid, BtL) have already been set up at different levels. Numerous studies have addressed assessments on the technical, economic and environmental performance of BtL systems, generally finding environmental improvements compared to conventional fossil-based fuels[13–17] and techno-economic viability.[18–26] In particular, previous studies from the authors evaluated the feasibility of synthetic biofuel production from date palm waste in Tunisia,[27,28] as an abundant and available local feedstock. Despite the nature of the feedstock and the technical feasibility of the system, the life-cycle sustainability assessment conducted by Ben Hnich *et al.*[27] found drawbacks associated with the system's demand for grid electricity and conventional oxygen. Tunisian electricity production was identified as the main hotspot, which is linked to the fact that approximately 97% of the country's electricity is generated from fossil fuels, mainly natural gas.[29,30] This fossil contribution to the power mix contrasts with the huge renewable potential of the country, especially wind and solar.[29] Tunisia holds a daily theoretical solar production potential of 5.3 kW h m^{-2} and 4.7 kW h per installed kW$_p$,[31] and the government has launched policies to encourage investment to achieve a renewable electricity capacity of around 3800 MW by 2030.[32,33]

Within this context, this study revisits the above-mentioned work by Ben Hnich *et al.*[27] to explore the effect of improvement actions on the identified hotspots under environmental and economic life-cycle aspects. In particular, the production of the required electricity in a dedicated photovoltaic (PV) plant is proposed and assessed, given the solar potential in Tunisia. Moreover, oxygen production with renewable electricity is also proposed. The ultimate goal is to elucidate how contextual conditions (in this case, electricity production) may affect the economic and environmental performance of a specific energy system, thus supporting holistic decision-making processes in the path towards the delivery of sustainable fuels.

2. Materials and methods

2.1. Case study

2.1.1. Bioenergy plant. The studied bioenergy plant corresponds to that previously reported by Ben Hnich *et al.*,[27,28] which is based on the valorisation of biomass waste generated during date palm cultivation and oasis management through a BtL strategy implemented in Gabès (Tunisia). Additionally, in contrast to the original study, a PV plant (further described in Section 2.1.2) was considered to satisfy the net power needs of the bioenergy plant. Both plants are hypothetical,[27] using modelling and simulation to obtain data for their economic and environmental evaluation according to the current performance levels of the involved (mature and commercially available) technologies.

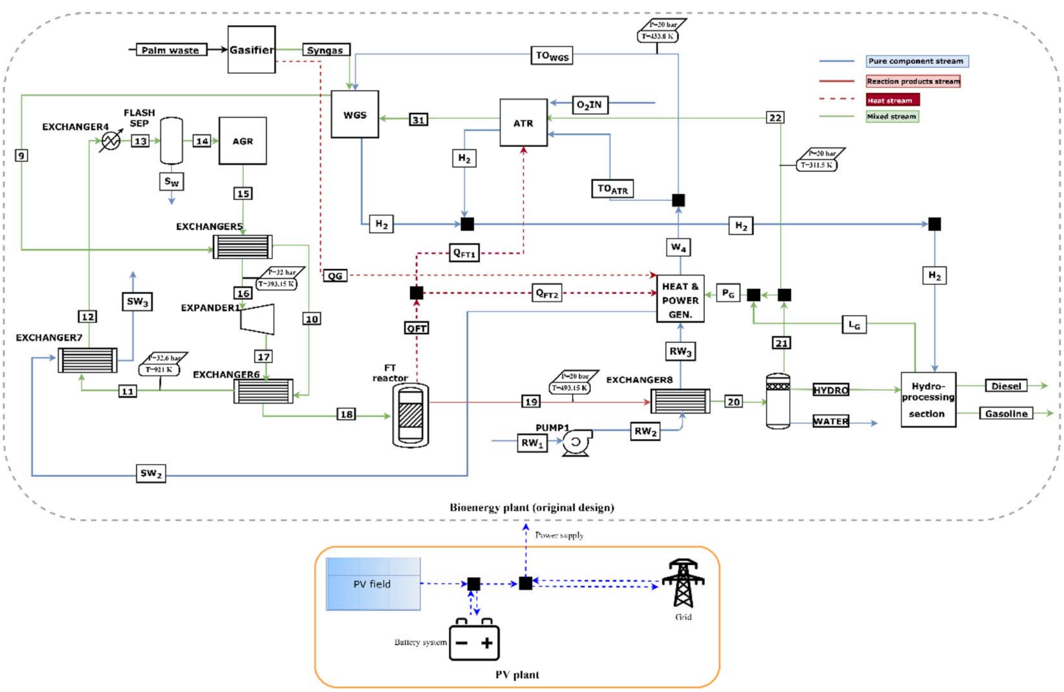

Fig. 1 Process diagram of the synthetic biofuel production plant (grey dashed box) with PV plant integration (orange box).

Table 1 Main specifications implemented in SAM for the PV plant

Section	Specifications
PV module	Type: monocrystalline silicon modules SunPower SPR-E19-310-COM; 310 W_{dc} max, 19.01% nominal efficiency, 96 cells, 1.63 m^2
PV system and layout	1 subarray; DC-to-AC ratio: 1.2; module 2-axis tracking; ground coverage ratio: 0.3; module aspect ratio: 1.7. Losses: 5% soiling losses, 2% module mismatch, 0.5% diodes and connections, 2% DC wiring, 1% AC wiring; 0.5% annual DC degradation
Inverter	Type: SMA America SC750CP-US; 770 kW_{ac} max; 792 kW_{dc} max; 97.59% CEC weighted efficiency
Battery cell and system	Type: Li-ion:Ni–Mn–Co oxides (NMC/graphite); 500 V_{dc} bank voltage, 3.6 V_{dc} cell voltage, 3.2 Ah cell capacity. Dispatch: 15%/98% minimum/maximum state of charge; manual dispatch with 100% allowance
Costs	Module: 0.41 $ per W_{dc}. Inverter: 0.05 $ per W_{dc}. Battery: 293.84 $ per kW h + 263.12 $ per kW. Balance of system: 0.2 $ per W_{dc}. Installation: 0.11 $ per W_{dc}. Installation margin and overheads: 0.06 $ per W_{dc}. Contingencies: 3% direct costs. Indirect capital costs, total installed costs and operation & maintenance costs set with default SAM parameters. Financial parameters: *cf.* Section 2.2

The synthetic fuel production process (Fig. 1) consists of syngas production, syngas conditioning, Fischer–Tropsch (FT) synthesis, heat & power generation, and product upgrading. Firstly, date palm waste is pretreated and prepared to meet the specifications of the considered dual fluidised bed gasification technology. The bioenergy plant annually processes a date palm waste of *ca.* 90 kt. The gasification section was based on previous studies.[34–36] The generated syngas is a mixture of predominantly H_2 and CO, along with CO_2, light hydrocarbons and impurities.[37] In order to adapt its composition to FT requirements, the H_2/CO molar ratio is shifted to around 2.15 in a water gas shift reactor. Then, as FT Co-based catalysts are sensitive to sulphur poisoning, syngas undergoes cleaning before being injected into the FT reactor. The gas mixture is fed to the acid gas removal (AGR) section, where acid gas species (such as H_2S and CO_2) are removed. The resultant clean and adjusted syngas is sent to the FT reactor, where it is converted into linear hydrocarbons of a wide range of molecular weight. This hydrocarbon stream is cooled and taken to a separation step to retrieve water, recover unreacted syngas and purify the hydrocarbons, which are fed to the hydroprocessing section to obtain diesel and gasoline, as main products, and a tail gas stream. This tail gas is mixed with part of the recovered unreacted gases to be fed to a heat & power generation section to produce steam and electricity, while the rest (around 90%) of the unreacted gases undergo autothermal reforming (ATR) to produce additional syngas to be processed. Further details on process simulation and assumptions can be found in previous studies.[27,28]

2.1.2. Photovoltaic plant integration. According to original data,[27,28] the biofuel production plant self-produces part of the consumed electricity in the heat & power generation section. The required net power is 3585 kW, which means an annual consumption of around 25 GW h. Considering this, a dedicated PV plant was designed and simulated using the NREL's System Advisor Model (SAM, v2020.11.29). Given the important electricity requirement of the bioenergy plant, different strategies of PV production for the plant were considered regarding partial or full supply, for which three scenarios were studied:

- Scenario A: PV plant capable of producing around 50% of the electricity consumption, assuming net balance with the grid.

- Scenario B: PV plant that supplies around 50% of the required electricity (net balance with the grid), with power storage in batteries to ensure 40% off-grid operation.

- Scenario C: PV plant fulfilling all the electricity consumption of the plant, considering net balance with the grid.

The design and the simulation for the different scenarios were carried out in SAM by using the detailed PV model (but the detailed PV-battery model for Scenario B, with Li-ion:Ni–Mn–Co/graphite batteries[38]). The specific parameters and considerations for PV plant simulation in SAM are presented in Table 1.

The PV plant was assumed to be located near the bioenergy plant in Gabès (Tunisia), for which the typical meteorological year (TMY) was retrieved from the PVGIS database.[39] It was assumed that the bioenergy plant operates 7000 hours per year, distributed between February and November to take advantage of the periods with higher solar radiation (with December and January for technical maintenance). Following the above-mentioned requirements and considerations, the information obtained from the PV plant simulation in SAM is presented in Table 2.

2.2. Life cycle costing approach

Regarding the economic evaluation of the bioenergy system through Life Cycle Costing (LCC), considerations consistent with the original system were made:[27] 7000 h per year of operation, 20 years of operation, 2 years of construction, and 6.25% loan interest rate. On the other hand, in this work the addition of the PV plant was considered. In order to ease the interpretation and comparison with the base (*i.e.* original) case, the PV facility was considered apart from the bioenergy plant. Thus, capital expenditures (total investment cost, TIC)

Table 2 Main information from PV plant simulation for each case study

Parameter	Unit	Scenario A	Scenario B	Scenario C
PV power capacity	kW_p	5500	5500	10 700
Number of PV modules	—	18	18	35
PV field area	ha	2.89	2.89	5.63
Number of inverters	—	6	6	12
Battery capacity	kW h	—	1300	—
Load	MW h y^{-1}	25 095	25 095	25 095
PV to load	MW h y^{-1}	9900	9900	11 068
PV to battery	MW h y^{-1}	0	327	0
Battery to load	MW h y^{-1}	0	277	0
PV to grid	MW h y^{-1}	3136	2809	14 401
Grid to load	MW h y^{-1}	15 201	14 917	14 040
PV direct supply	%	39.5	39.5	44.1
PV + battery supply	%	39.5	40.8	44.1
PV + battery + grid balance	%	51.9	51.9	101.5

and operational costs remain unchanged in the biofuel production plant, except for the electricity cost, which was obtained from the cost estimation of the PV plant. This estimation was performed using the SAM costs database (PV modules, inverters, batteries, labour, *etc.*, with constant unit costs) according to the definition of the PV plant detailed in Section 2.1.2. The obtained levelised cost of energy (LCOE) was assumed to be the cost of the electricity in the bioenergy plant, which involves the modification of the total production cost of the biofuels (assessed life-cycle economic indicator). The latter was calculated per GJ of produced synthetic diesel and gasoline, which corresponds to the functional unit of the LCC study. The main considerations for the dedicated PV plant cost estimation include: 20 years plant lifetime, 20 years mortgage (6.25% loan rate), 2.5% per year inflation rate, and 6.4% discount rate. Moreover, an electricity price of 0.089 $ per kW h was considered for net consumption from the grid (when PV cannot provide power to the process) as well as for PV electricity fed to the grid (selling).[27]

2.3. Environmental evaluation approach

Regarding the environmental dimension, this study explores the potential suitability of the proposed modifications in the bioenergy system through the Life Cycle Assessment (LCA) methodology.[40] The functional unit was redefined as 1 GJ of synthetic diesel and gasoline combusted as a whole (lower heating value basis), thus including fuel use for comparative reasons. Accordingly, a cradle-to-grave approach was followed in the LCA study, covering date palm waste generation, pretreatment, conversion, and fuel use (Fig. 2). It is important to note that the present study modifies the original system boundaries set in ref. 27 (from date palm waste generation to biofuel production) to include the manufacture, installation, and operation of the solar PV plant (with/without battery storage) for the three scenarios considered. Additionally, oxygen supply by a local producer that uses PV electricity was considered in every scenario of the novel bioenergy system. Capital goods were included in this analysis. For benchmarking purposes, two reference systems were used: the base case (*i.e.*

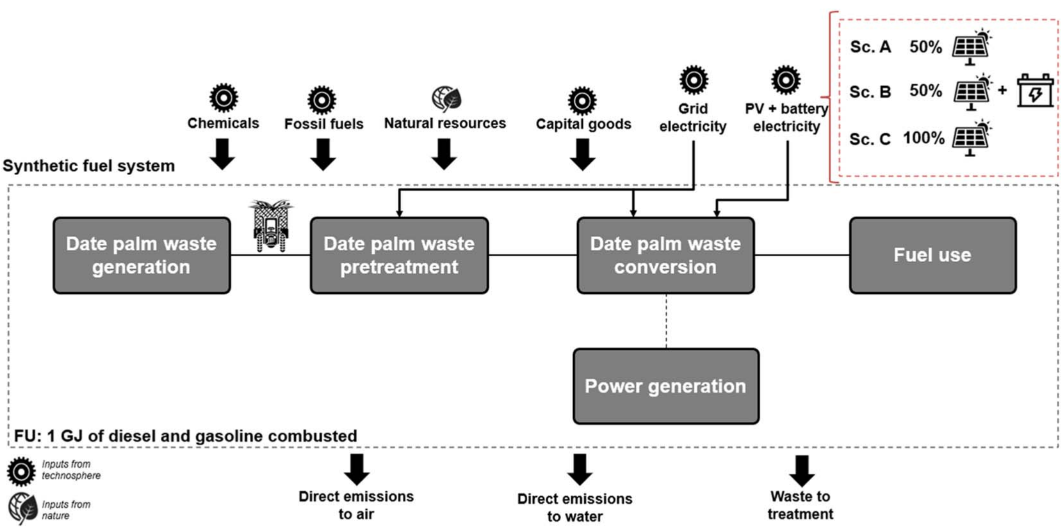

Fig. 2 Synthetic biofuel system with PV integration.

Table 3 Inventory data for synthetic biofuel production including electricity demand according to the specific scenario (values expressed per functional unit)

INPUTS			OUTPUTS		
From the technosphere	**Amount**	**Unit**	**To the technosphere**	**Amount**	**Unit**
Date palm waste	312.13	kg	*Products*		
Process water	357.54	kg	Diesel	14.80	kg
Methanol	0.27	kg	Gasoline	8.51	kg
Sand	3.88	kg	Hydrogen	0.46	kg
N_2	0.15	kg	*Waste to treatment*		
O_2	19.28	kg	Ash	1.52	kg
Calcium carbonate	32.08	g	Wastewater	357.54	kg
FT catalyst	13.02	g	Waste to recycling	$2.74 \cdot 10^{-2}$	kg
WGS catalyst	0.22	g	Waste to landfilling	3.91	kg
ATR catalyst	0.17	g	**To the environment**		
Electricity	87.04[a]	kW h	*Emissions to air*		
From the environment			O_2	25.49	kg
Air	618.62	kg	N_2	80.51	kg
Cooling water	2.44	t	H_2O	54.46	kg
			CO	1.50	kg
			CO_2	243.84	kg
			CH_4	3.90	g
			N_2O	0.76	kg
			NO	0.56	kg
			H_2S	16.92	g
			SO_2	34.30	g
			Acenaphthene	0.19	kg
			Anthracene	0.22	kg
			Hydrochloric acid	8.43	g
			Methanol	0.27	kg
			Naphthalene	0.17	kg
			Phenanthrene	0.22	kg
			Emissions to water		
			Acenaphthylene	5.72	g
			Anthracene	3.51	g
			Diphenylacetylene	1.50	g
			Naphthalene	28.91	g
			Pyrene	2.02×10^{-2}	g
			Water	2.44	t

[a] Electricity consumption is satisfied in each case study as follows: base case: 87.04 kW h from grid. Scenario A: 43.52 kW h from grid + 43.52 kW h from PV. Scenario B: 43.52 kW h from grid + 43.52 kW h from PV with battery storage. Scenario C: 87.04 kW h from PV.

the original bioenergy system up to fuel use without improvement actions) and the conventional fuels case (*i.e.* fossil-based production and use) as developed in ref. 27. Regarding the impact assessment method, the Environmental Footprint 3.0 method was used to characterise the potential life-cycle environmental impacts of every system under evaluation.[41,42] In particular, the following environmental indicators were evaluated: climate change, particulate matter, acidification, freshwater eutrophication, use of fossil resources, and use of minerals and metals.

Table 3 presents the inventory data associated with the production of synthetic biofuels, including the electricity demand and sources modelled in the different scenarios. Inventory information for the cultivation and transport of the biomass feedstock as well as for conventional fuel systems can be consulted in ref. 27. In order to streamline the presentation of the inventory data used in this article, only modified and new life-cycle inventories (LCIs) with respect to those found in ref. 27 are presented below.

According to the context of the study, regionalised datasets from the ecoinvent database were directly used in the case of the PV plant, involving manufacture of solar panels, support systems, inverters and electrical systems, as well as operation.[43] Regarding battery storage, the work by da Silva Lima *et al.*[44] was used as the main source of information. In this sense, inventories concerning the production of the battery cell, battery tray and rack housing were directly retrieved from ref. 44, while adaptations to the present case study were conducted in relation to the transport and operation of the manufactured battery (Tables 4 and 5, respectively). The road and ship transport from the battery manufacturer in The Netherlands to Gabès in Tunisia was taken into account (Table 4). Additionally, the operation of the battery was adapted by including the abovementioned regionalised PV datasets (Table 5). Finally, regarding the modification of background processes, the ecoinvent dataset *Oxygen, liquid {RoW}* was regionalised by using 100% PV electricity (from Tunisia) in the oxygen production process instead of grid electricity.

Table 4 Inventory for the assembly and transportation of one lithium-ion battery

INPUTS			OUTPUTS		
From the technosphere	Amount	Unit	To the technosphere	Amount	Unit
Battery rack filled, lithium-ion battery	13 900.00	kg	*Products*		
Intermodal shipping container	1.00	p	Assembled battery, lithium-ion battery	1.00	p
Transport, by lorry	1790	t km			
Transport, by ship	80 357.54	t km			

Table 5 Inventory for the use phase of the lithium-ion batteries (values per MW h assuming a lifetime of 20 years)

INPUTS			OUTPUTS		
From the technosphere	Amount	Unit	To the technosphere	Amount	Unit
Assembled battery, lithium-ion battery	3.47×10^{-4}	p	*Products*		
Electricity, from PV (energy for operation)	1.65×10^{-1}	MW h	Electricity	1.00	MW h
Electricity, from PV (energy for charging)	1.93×10^{-1}	MW h			
Inverter	4.52×10^{-4}	p			

3. Results and discussion

3.1. LCC results

The main economic results for the bioenergy scenarios are presented in Table 6. As stated in Section 2, the PV plant (and thus its associated economic parameters) was considered apart from the bioenergy plant. For the PV plant, the highest TIC was found for Scenario C, which considers the supply of all the power required in the bioenergy plant, hence requiring higher PV power capacity. It is followed by Scenario B, whose TIC is 1.55 M$ higher than that estimated for Scenario A, which is associated with the costs of the batteries system.

Regarding the obtained electricity cost, the lowest values were found for Scenarios C and A, indicating that the consideration of the batteries in Scenario B penalises the economic performance of the system. In any case, the LCOE estimated for the three scenarios was found to be lower than that assumed for grid electricity, which suggests the feasibility of the PV plant in the specific location. This finding is aligned with the values reported prospectively in ref. 45 as well as with current tenders.[46]

Regarding the influence of PV electricity on the bioenergy plant, the production cost per GJ of gasoline and diesel was found to be reduced around 5 $ compared with the base case. In particular, higher reduction percentages were found in Scenarios A and C (>16.5%) than in Scenario B (*ca.* 15%), which is linked to their associated LCOE. These values are in agreement with other values reported in the scientific literature.[19] When compared with their fossil counterparts, the cost values achieved in the present study are close to the upper edge for conventional diesel and gasoline in Tunisia (around 18–22 $ per GJ (ref. 47 and 48)). This suggests that further improvements and optimisation of the bioenergy plant in the near future could make it cost-competitive with fossil-based products, regardless of the potential consideration of any externalities or carbon-related taxes.

Overall, the installation of a PV plant to produce the electricity required by the BtL process was found to improve the economic performance of the biofuel plant, while proving the feasibility of such a strategy in the specific location.

3.2. LCA results

Fig. 3 shows the impact assessment results and the comparison between the different cases under the six selected environmental indicators. The values in this figure were obtained through the implementation of the modified and new LCIs (Section 2.3) in SimaPro.[49] The squares in Fig. 3 represent the life-cycle impact assessment results for the three bioenergy scenarios with PV integration and renewable oxygen, while the

Table 6 Main LCC results of the bioenergy plant for each scenario

Parameter	Unit	Base case	Scenario A	Scenario B	Scenario C
TIC PV plant	$M\$_{2020}$	—	5.65	7.20	11.00
Discounted payback PV	year	—	4.5	6.1	4.5
LCOE	¢$_{2020}$ per kW h	8.96	2.79	3.36	2.78
TIC bioenergy plant	$M\$_{2020}$	52.09	52.09	52.09	52.09
Electricity cost	$M\$_{2020}$ per year	2.20	0.70	0.84	0.70
Total production cost	$\$_{2020}$ per $GJ_{diesel\ and\ gasoline}$	30.87	25.70	26.19	25.69

red and grey lines allow benchmarking against the bioenergy base case and the conventional fossil fuels case, respectively.

One of the main findings of the environmental assessment can be directly drawn from Fig. 3: the impact categories do not follow a general trend, but the environmental suitability of the proposed modifications depends on the specific indicator under study and the reference target. When the focus is placed on mitigating climate change and reducing the use of fossil resources (both impact categories are closely linked), the strategy that achieves a more favourable environmental performance is the use of solar PV to cover all the electricity demand of the synthetic fuel plant (Scenario C). Particularly, this scenario reaches impact reductions above 70% for both indicators (climate change and fossil resource use) compared to both the base case and the conventional fuels case. However, Scenario C, in turn, involves the largest use of minerals and metals, with the associated concerns on upstream impacts on ecosystems and biodiversity and socio-economic issues related to mining and refining.[50]

For the remaining impact categories (particulate matter, acidification, and freshwater eutrophication), the three novel bioenergy scenarios show, to a similar extent, an enhanced performance with respect to the base case. This finding is closely linked to the substitution of oxygen from a global market by a local supplier that uses PV electricity for its production. Despite this behaviour, it should be noted that the environmental performance of the synthetic biofuels from the novel bioenergy scenarios under these three indicators remains unfavourable compared to conventional fuels.

3.3. Joint interpretation and final remarks

When the synthetic biofuel scenarios are compared under environmental and economic aspects, Scenarios A and C could be seen as trade-off solutions generally outperforming both Scenario B and the bioenergy base case. If the comparison is extended to the conventional (fossil-based) fuels case, the interpretation is more complex since conventional fuels present a lower production cost and a more favourable performance in four (out of six) impact categories. However, it is important to further discuss some aspects associated with climate change mitigation.

One important consideration is the long-term cost of climate change. The Intergovernmental Panel on Climate Change (IPCC) has stated that the costs of climate change, including damages from extreme weather events, rising sea levels and

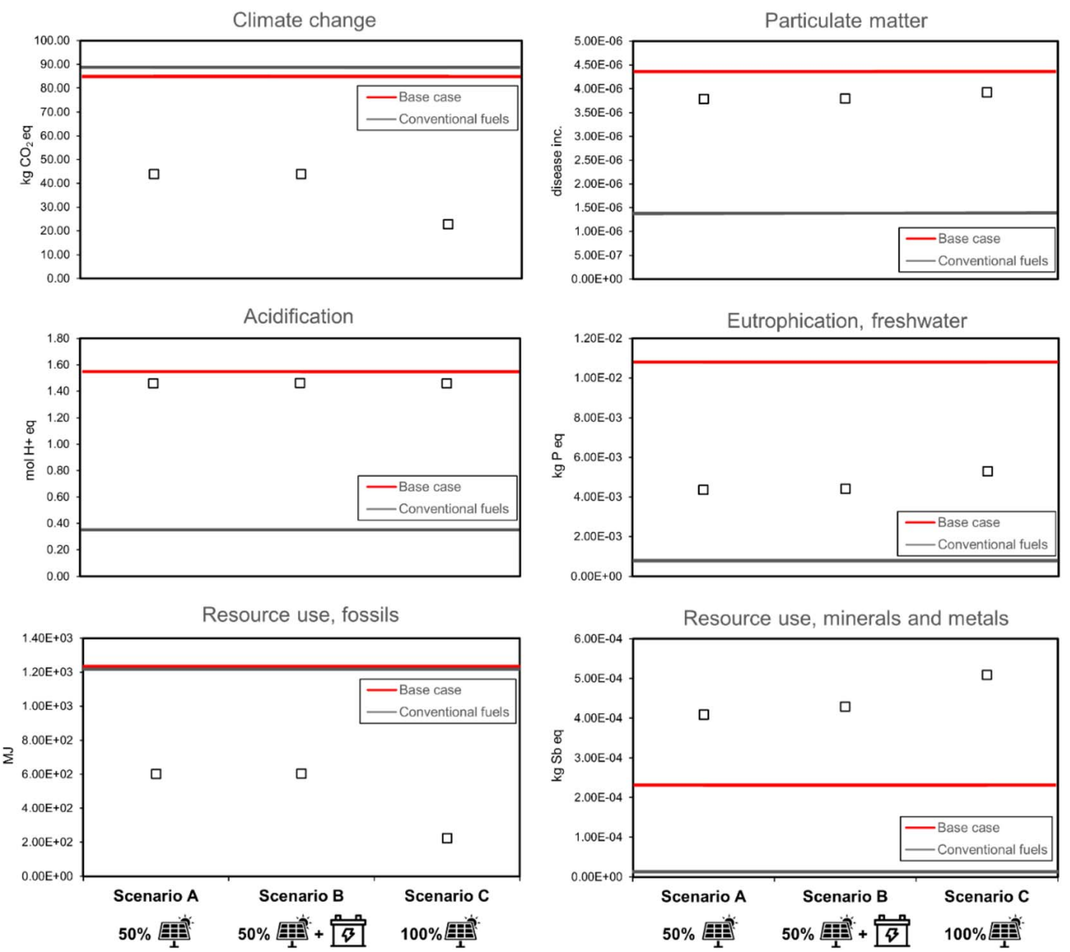

Fig. 3 Environmental life-cycle profile of the novel bioenergy scenarios (values per GJ of fuel combusted). The red and grey lines additionally report the values for the bioenergy base case and the conventional fossil fuels case, respectively.

reduced crop yields, should not be ignored.[51] The costs of inaction on climate change are usually underrated, while they are likely to exceed the costs associated with mitigation and adaptation efforts.[52] Hence, if inaction costs are taken into account, an energy system as proposed in Scenarios A and C, which reduces life-cycle GHG emissions and slows the rate of climate change, could be deemed more cost-effective in the long term than its fossil-based counterpart. Another relevant consideration is that the cost of the synthetic fuels can potentially decrease in the near future as technology improves and economies of scale are achieved, making these fuels increasingly competitive with conventional ones, especially if the current context of energy crisis continues. Additionally, it is important to consider the potential social and economic benefits of transitioning away from fossil fuels. Synthetic biofuels can create jobs and boost economic growth in those regions where their supply chain is located, and can also help improve energy security in areas where fossil fuels are currently the primary energy source.

Overall, while some aspects such as production costs could penalise the short-term production of the synthetic biofuels under study, long-term benefits in terms of avoided climate change damages and the current decarbonisation targets and climate policy frameworks of many countries could favour the deployment of this enhanced biofuel pathway. This leads to acknowledging sustainability as a pivotal concept within the complexity of decision-making processes, evaluating and prioritising those alternatives and measures that slow the rate of climate change while investing in sustainable infrastructure and equipment that promote long-term socio-economic benefits.[53,54]

4. Conclusions

This article addresses, from a life-cycle perspective, the economic and environmental suitability of an enhanced bioenergy plant producing synthetic gasoline and diesel from date palm waste in Tunisia with PV-based supply of electricity and oxygen. The consideration of a dedicated PV plant is concluded to improve the economic performance of the original bioenergy plant (*i.e.* base case without PV electricity and without renewable oxygen), reducing the production costs of the fuels due to the lower electricity costs, however involving higher investment costs. The additional consideration of a battery system to ensure 40% off-grid operation was found to lead to increased electricity costs, yet lower than the base case.

From an environmental perspective, the consideration of the PV plant and renewable oxygen is concluded to improve all the evaluated impact categories, except for the use of minerals and metals, compared to the base case. In particular, reductions above 70% would be achieved in terms of climate change and use of fossil resources in a 100% PV scenario, compared to both the base case and conventional fuels. Nevertheless, the studied alternative systems would still involve concerns in terms of use of minerals and metals, particulate matter, acidification and freshwater eutrophication when compared to conventional, fossil-based fuels. Overall, long-term benefits in terms of avoided climate change damages and the current context of the energy crisis and climate emergency could favour the deployment of this enhanced biofuel pathway.

Author contributions

Pedro L. Cruz: conceptualisation, methodology, formal analysis, investigation, and writing – original draft preparation. Mario Martín-Gamboa: conceptualisation, methodology, formal analysis, investigation, and writing – original draft preparation. Khaoula Ben Hnich: writing – original draft preparation. Javier Dufour: writing – review and editing. Diego Iribarren: conceptualisation, methodology, formal analysis, investigation, and writing – review and editing.

Conflicts of interest

No conflicts of interest to declare.

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