Energy transition: an analysis of agrivoltaic utilities suitability in terms of Levelized Cost of Electric Energy.

Girolamo Di Francia, ENEA,
P.le E. Fermi 1, 80055 Portici Napoli, +390817723277, girolamo.difrancia@enea.it.
Saverio De Vito, ENEA,
P.le E. Fermi 1, 80055 Portici Napoli, +3908177232364
Grazia Fattoruso, ENEA,
P.le E. Fermi 1, 80055 Portici Napoli, +390817723266
Arturo Matano, ENEA,
P.le E. Fermi 1, 80055 Portici Napoli, +390817723235

Introduction

Large, *utility scale*, photovoltaic plants have a power capacity typically ranging from 10 MW to 100 MW requiring surface areas for the installation from tens to hundreds hectares. There is therefore a concern of subtracting surfaces to food crops production, with a growing, longer term negative impact on the sector.

In this respect *agrivoltaic* photovoltaic (APV) allowing the dual use of the land and the implementation of both farming activities and solar energy production, is a very interesting and innovative concept. Agrivoltaic systems have rapidly become a popular and trendy topic of discussions. Government, local authorities, and stakeholders (electric utilities, installers, farmers, commercial and financial brokers, citizens' associations) are devoting a growing attention to the approach because the economic impact of the decisions to be made are relevant.

In Italy, for instance, the energy transition would require the installation, by 2050, of about 150 GW of photovoltaic power capacity. As each MW corresponds to more than EUR 1 million in terms of capital costs and provides about 100 kEUR/yr of revenues [1] for each of the more than 25 years of plant lifetime, the transition is expected to mobilize more than EUR 6 billion/yr.

Financial analysts such as Goldman and Sachs (2023) consider therefore investment in the photovoltaic sector among those currently most profitable.

Comparison among cropland revenue (EUR/ha) and revenue from electricity production (EUR/kWh) provides a further insight. Each hectare allows the construction of a 1 MW plant whose revenues are, as above recalled, about 100kEUR/year. The corresponding land farming revenue is, on the average, less than 15 kEUR/year. Di Francia and Cupo (2023) have indeed shown that strictly from a financial point of view there is hardly any benefit in building agrivoltaic plants in terms of preservation of the agricultural revenues.

Therefore, without the adoption of suitable supporting schemes, farming activities might lose any specific interest and agrivoltaic would readily reduce to standard photovoltaic. Moreover, integrating electricity production with agriculture requires considering that their simultaneous operation could originate a number of drawbacks, as it will be discussed below.

On the other hand there is no doubt that agrivoltaic can be the most sustainable of any possible choice in terms of both preserving the pristine farming land use and providing, at the same time, the area required for PV installations.

In this work we will compare the levelized cost of electricity from photovoltaic, LCOE, in EUR/kWh, for agrivoltaic new installations in the Italian case, considering various regulatory scenarios proposed for the sector. Here we solely refer to utility scale plants using, as a reference case, a 1 MW plant and compare the LCOE costs derived from the different possible solutions. We will also consider systems characterized by the same technology, single-side silicon modules on fixed supports. As we will show, the methodology we use will make the result independent on this choice.

Problem Description

Agrivoltaic plants In Italy various types of photovoltaic plants realized in agricoltural areas can be considered as agrivoltaic solutions according to the classification proposed by the ministerial MASE guidelines (2021). Basically all such plants have to be realized so that they perform some synergic function with agricultural activity (e.g. the possibility of crop protection during extrema weather events, of optimizing irrigation process, etc.), the different types being characterized by their compliance to the different guidelines criteria, as below specified:

A.1) Minimum cultivated area larger than 70 % of the total land area;
A.2) LAOR (Land Occupation Ratio, that is the ratio between the surface of the modules to the total land area) less than 40%;
B.1a) Preserving the yield of agricultural and/or pastoral activity for the plot of land considered for APV installation (in EUR/ha or EUR/LU-Unit of Adult Livestock);
B.1b) Preserving the continuity of agricultural and pastoral activity;
B.2) The electrical producibility of the agrivoltaic plant has not to be less than 60% than a standard PV plant;
C) A minimum ground - PV modules distance, MMH, has to be respected (2.1 m agricultural activity, 1.3 m pastoralism);

---

[1] Considering an electricity market reference price equal to 15 cEUR/kWh

D) The installation of monitoring systems to verify water saving, agricultural productivity, continuity of agricultural activity have to be considered;
E) Advanced monitoring techniques to verify the recovery of soil fertility, microclimate effects, resilience to climate changes have to be implemented.
Table 1 shows the different types of agrivoltaic systems classified according to the above criteria. For this work, the criteria referred in B will not be taken into account because they can be considered, as a first approximation, negligible for LCOE determination.

Table 1 The different types of agrivoltaic systems investigated in this work, classified according to the MASE guidelines criteria. *Actually, guidelines take into consideration also the installation of vertically mounted PV modules as possible advanced systems.

Criteria	A1	A2	B1a	B1b	B2	MMH	D	E	With agricultural entrepreneur	Absence of concrete foundations	Name
Type 0 (T0)	No	No	No	No	No	No	No	No	No	No	Photovoltaic installed in agricultural and non-agricultural areas.
Type I (T1)	>70 %	<30%	No	No	No	No	No	No	No	No	Basic agrivoltaic
Type II (T2)	>70 %	<40%	Yes	Yes	Yes	Yes*	Yes	Yes	No	No	Advanced agrivoltaics
Type III (T3)	>70 %	No	Yes	Yes	Yes	Yes*	Yes	Yes	No	No	Advanced agrivoltaics similar to T2. LAOR is neglected.
Type IV (T4)	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Advanced agrivoltaics PNRR

Beyond to TI-TIII types, defined according to the guidelines descriptions, a Type IV, an agrivoltaic plant defined according to a recently approved law, DL 21 aprile 2023 n. 41, so called DL PNRR 3, is also reported. Finally, for comparison, T0, a type of plant that can be theoretically still installed in agricultural areas but that cannot be defined as agrivoltaic since it has no synergic functions with the farming activity and which is here essentially used for comparison and discussion, is reported. Here below the different types are described in more detail, according to the regulatory requirements.

Type 0 It is a photovoltaic system built in an agricultural area where no farming activity is pursued. The PV plant and the installation area are designed to optimize the energy production.

Type I Photovoltaic systems installed in areas intended for agricultural activities that have to operate in synergy with the farming activities. Panels installation far high from the ground is not strictly required. Here however, criteria as in A (surface of the plant) and B (agricultural and electrical yield) of the guidelines, should be considered, although it is worth to remind that both criteria are not mandatory since not yet included in any specific legal frame. Similarly, the same guidelines suggest that the agrivoltaic plant should be tailored so that the UE support to the agricultural sector, the Common Agricultural Policy, CAP, revenues, should be at least 5% of the PV electricity revenue.

Type II Photovoltaic systems installed in areas intended for agriculture and that have therefore to operate in synergy with the farming activities. The installation of panels elevated from the ground or in any case in such a way as to ease the farming activities, is required. Here, as it is for Type I, criteria A and B and constraints related to the CAP support should be considered. Moreover, monitoring of agricultural activity, of its sustainability and resilience to climate change, as it is described respectively in criteria D and E of the guidelines, are also to be considered.

Type III It is type II with the removal of the constraints related to the LAOR.

Type IV They are photovoltaic systems installed in areas intended for agriculture and that have therefore to operate in synergy with the farming activities. The installation of modules elevated from the ground is here mandatory. Moreover, monitoring of agricultural activity, of its sustainability and resilience to climate change, as it is described respectively in criteria D and E of the guidelines, are mandatory too. CAP constraints are not addressed, but farmers have to be involved into APV plant management.

LCOE methodology $LCOE$, whose dimension is EUR /kWh, is defined as the ratio between the PV plant cost and the electric energy produced in its total lifetime. This methodology of energy cost estimation was first proposed by Short, Packey, and Holt (1995) in order to introduce a technique suitable to compare the costs of different sources of energy and then thoroughly reviewed by Branker, Pathak and Pearce (2011) and Campbell (2010), as far as PV is concerned. Here we use the expression for *LCOE* defined by Vartiainen, Masson, Breyer, Moser and Román Medina (2020) for large PV plants:,

$$LCOE = \frac{\left(CAPEX_{PV} + \sum\left[\frac{OPEX_{PV}(t)}{(1+WACC_{nom})^t}\right] + \frac{InvRepl}{(1+WACC_{nom})^{N/2}} - \frac{ResVal}{(1+WACC_{nom})^N}\right)}{\sum\left[\frac{Yield(0)*(1-d)^t}{(1-WACC_{real})^t}\right]} \quad (1)$$

In Equation (1), N is the lifetime of the PV system, t is the year number ranging from 1 to N, $CAPEX_{PV}$ is the total capital expenditure of the system, made at t = 0 in EUR/kWp, $OPEX_{PV}(t)$ is the operation and maintenance expenditure in year t in EUR /kWp, InvRepl is the cost of the inverter replacement, made at t = N/2 in EUR /kWp, ResValue is the residual value of the system at t = N in EUR /kWp, Yield(0) is the initial annual yield in year 0 in kWh/kWp without degradation, d is the annual degradation of the nominal power of the system, $WACC_{nom}$ is the nominal weighted average cost of capital per annum and $WACC_{real}$ is the real weighted average cost of capital per annum. The relation between $WACC_{nom}$ and $WACC_{real}$ is:

$$WACC_{real} = \left[\frac{(1+WACC_{nom})}{(1+i)}\right] - 1, \quad (2)$$

where *i* is the annual inflation rate.

In the following equation, residual PV plant value and inverter replacement costs are considered to mutually compensate each other, which is very realistic since a modern PV plant's operating lifetime is now in the range of 30 years while, for these calculations, N is still assumed to be 25 years following International Energy Agency guidelines (2016). Thus, if we multiply both numerator and denominator of Equation (3) by the total peak power of the PV plant, G, we then obtain:

$$LCOE = \frac{\left(CAPEX_{PV,total} + \sum\left[\frac{OPEX_{PV,total}(t)}{(1+WACC_{nom})^t}\right]\right)}{G*\sum\left[\frac{Yield(0)*(1-d)^t}{(1+WACC_{real})^t}\right]}, \quad (3)$$

where $CAPEX_{PV,total}$ is the total capital expenditure of the system, made at t = 0 in EUR and $OPEX_{PV,total}(t)$ is the operation and maintenance expenditure in year t and in EUR for the whole plant. $OPEX_{PV,total}(t)$ is generally assumed to be only dependent on the power size of the PV plant throughout its whole operating lifetime. Finally, $G \times Yield(t) \times (1-d)^t$ is the total plant electric energy production in the year t.

Following the recommendation of the European Commission (2020) in Italy, for long-term investments, $WACC_{nom}$ is presently set at 5%, and a 2% inflation rate is considered, Arera (2021). Recalling that according to NREL (2018) on the average d ≈ −0.05%/yr, with straightforward calculations, it can be shown that Equation (5) turns into:

$$LCOE = \frac{\left(CAPEX_{PV,total}*(1+WACC_{real})^N + N*OPEX_{PV,total}\right)}{N*Yield(0)*G}, \quad (4)$$

This expression for LCOE is particularly useful for this analysis, since, according to Di Francia (2013), it allows to simply highlight the effect of the capital and operation and maintenance expenditures related to the power of the PV plant, $CAPEX_P$ and $OPEX_P$ with respect to those that are area intensive: $CAPEX_A$ and $OPEX_A$:

$$CAPEX_{PV,total} = CAPEX = CAPEX_P + CAPEX_A, \quad (5)$$

$$OPEX_{PV,total} = OPEX = OPEX_P + OPEX_A, \quad (6)$$

$CAPEX_P$ are all the capital expenditures related to the capacity size of the PV plant in Watts. The expenditures are related to the modules cost, combiners, switch gears, fuses, ground fault detectors, charge controllers, batteries, transformers, and grid connection equipment. In $CAPEX_P$, additional costs related to plant design, test, and start-up, as well as the installation profits and any other administrative or financial costs are, in general, also included.

$CAPEX_A$ are all the capital expenditures related to the area of the PV plant in m^2. They include costs related to the supporting structures, the transport up to the installation site, the site preparation and any civil work required for the realization of the mounting structures, such as a reinforced concrete base or a fence.

$OPEX_P$ are all the yearly costs accrued throughout the PV plant's lifetime that depend on the capacity size of the plant, such as, for instance, costs related to module and electric equipment operation and maintenance, replacement included and to module cleaning.

Finally, $OPEX_A$ are all the yearly costs depending on the area of the plant, such as, for instance, those related to land rental and to its maintenance, to the supporting structure maintenance, to surveillance and monitoring.

Since, for this analysis, any of the plants is considered to be characterized by the same total peak power, G, then the total electric energy production E_{pr}, in kWh, along the whole operating lifetime of any of the plants considered will be:

$$E_{pr} = G * \sum Yield(0) * (1-d)^t, \tag{7}$$

and LCOE can be, therefore, rewritten as:

$$LCOE_{TX} = \frac{\left((CAPEX_P^{TX} + CAPEX_A^{TX}) * (1 + WACC_{real})^N + N * OPEC_P^{TX} + N * OPEX_A^{TX}\right)}{N * G * Yield(0)} \tag{8}$$

where TX is one of the PV plant typos above considered.

Results

In Tab. 2 T0-T4 typos are listed, reporting: where the PV plant can actually be installed, the type of authorizations required for each typology, the possibility of accessing to financial supporting tools and, finally, the (basic) legal reference frame.

Tab. 2 Where and how the different types of PV plants considered in this work, can be installed. *The legal frames for VIA (Environmental Impact Assessment) and VA (Evalutation for VIA request), are not detailed.

	Where	Permitting	Incentives	Ref.
T0	Any cropland area	AU VIA*	No	AU-D.Lgs. 387/2003, art. 12; D.Lgs. n. 387/2003 (inst. in cropland); inc.- art. 65 del D.L. 24/01/2012, n. 1;
T0	Suitable areas (so called: aree idonee, solar belt)	PAS up to 20 MW VA <20 MW	No	PAS-D.Lgs. 28/2011; D.Lgs. n. 387/2003; inc- art. 65 del D.L. 24/01/2012, n. 1; inc-art. 11 del D.L. 01/03/2022; art 12 n. 17; D.L. 01/03/2022, n. 17; suit. Areas, art. 20, comma 1, DL 8 novembre 2021, n. 199;
T1	Any cropland area	AU VIA	No	AU-D.Lgs. 387/2003, art. 12; D.Lgs. n. 387/2003 (inst. In cropland); inc.- art. 65 del D.L. 24/01/2012, n. 1;
T1	Suitable areas (so called: aree idonee, solar belt)	PAS up to 20 MW VA <20 MW	No	PAS-D.Lgs. 28/2011; D.Lgs. n. 387/2003; inc- art. 65 del D.L. 24/01/2012, n. 1; inc-art. 11 del D.L. 01/03/2022; art 12 n. 17; D.L. 01/03/2022, n. 17; suit. Areas, art. 20, comma 1, DL 8 novembre 2021, n. 199;
T2-T3	Any cropland area	AU VIA	Possible for high installations	AU-D.Lgs. 387/2003, art. 12; D.Lgs. n. 387/2003 (inst. In agri); inc.- art. 65 del D.L. 24/01/2012, n. 1; art 12 n. 17; D.L. 01/03/2022, n. 17,
T2-T3	Suitable areas (so called: aree idonee, solar belt)	PAS up to 20 MW VA<20 MW	Possible for high installations	PAS-D.Lgs. 28/2011; D.Lgs. n. 387/2003; inc- art. 65 del D.L. 24/01/2012, n. 1; inc-art. 11 del D.L. 01/03/2022; art 12 n. 17; D.L. 01/03/2022, n. 17; suit. Areas, art. 20, comma 1, DL 8 novembre 2021, n. 199;

T4	Any cropland area	AU VIA	Possible for high installations	AU-D.Lgs. 387/2003, art. 12; D.Lgs. n. 387/2003 (inst. In agri); inc.- art. 65 del D.L. 24/01/2012, n. 1; art 12 n. 17; D.L. 01/03/2022, n. 17,
T4	Suitable areas (so called: aree idonee, solar belt)	No AU, No PAS; VIA not required up to 30 MW	Yes	PAS-D.Lgs. 28/2011; D.Lgs. n. 387/2003; inc- art. 65 del D.L. 24/01/2012, n. 1; inc-art. 11 del D.L. 01/03/2022; art 12 n. 17; D.L. 01/03/2022, n. 17, DL 21 aprile 2023 n. 41 (DL PNRR 3)

The main characteristics of the plot of land area considered for PV plant installation are reported in Tab. 3. For the sake of clarity, the plot of land hereafter considered is a square area. The surface required for type T0 is mainly related to the optimum plant design. Assuming south facing, 35° tilted modules, a feasible average choice for Italy, and considering 400 W, 2 m^2 modules, the total number required for a 1 MW plant is 2500 modules, for a ground projection of 4075 m^2. In the case of a multi-rows plant, a 3 m gap should be considered to minimize shadowing effects so that for a square plot of land, the optimal design is a 110 x 110 m^2 plant consisting in 23 rows each made by 109 modules. It is worth to note that only for type I a wider installation area is required to take into account for A1 and A2 criteria, since the area under the modules cannot be used for agricultural activity. For type II to IV the minimum area required is very similar to the area required for type T0, except for the areas occupied by foundations, here considered, for simplicity, negligible. It is worth to note that type T0 is also different in that an intrinsic limitation in the type of cultivated crops exists due to the fact that tall plants could shade PV modules. Finally, note that the optimization of the cropland activity could require an increase of the gap for instance to take into account the use of agricultural machinery. That will result in an increase of area related capex and opex costs and, in turn, in the LCOE increase.

Tab. 3 Main characteristics of plot of land area characterizing the various solutions investigated.

1 MW PV plant	**T0**	**T1**	**T2=T3**	**T4**
P (kW)	1000	1000	1000	1000
Plant neat surface (module 400 w, 2x1 m^2, inclination 35°, Set Back Ratio =3 m), ha	1,2	1,36	1,2	1,2
Plant total surface (including service areas), ha	1,25	1,43	1,25	1,25
Power plant density, W/m^2	80	70	80	80
Module number	2500	2500	2500	2500
Modules total surface, m^2	5000	5000	5000	5000
Ground modules projection, m^2	4075	4075	4075	4075
LAOR	NA	0,4	0	0
Total surface (to take LAOR into account according to the guidelines), ha	NA	1,43	1,2	1,2
Plot of land perimeter (assuming a square plant), m	440	480	440	440

The installation and the operation and maintenance costs of the photovoltaic systems above described are reported in Fig. 1 and Fig.2. Costs are classified in terms of power and area related costs and refer to the year 2022. They derive from interviews with Italian operators and from public data as far as agrivoltaic costs are concerned as reported by Trommsdorff, Kang, Reise, Schindele, Bopp, Ehmann, Weselek, Högy and Obergfell (2021).

Fig.1 Capacity dependent CAPEX and OPEX costs of the photovoltaic systems, in EUR/kWp

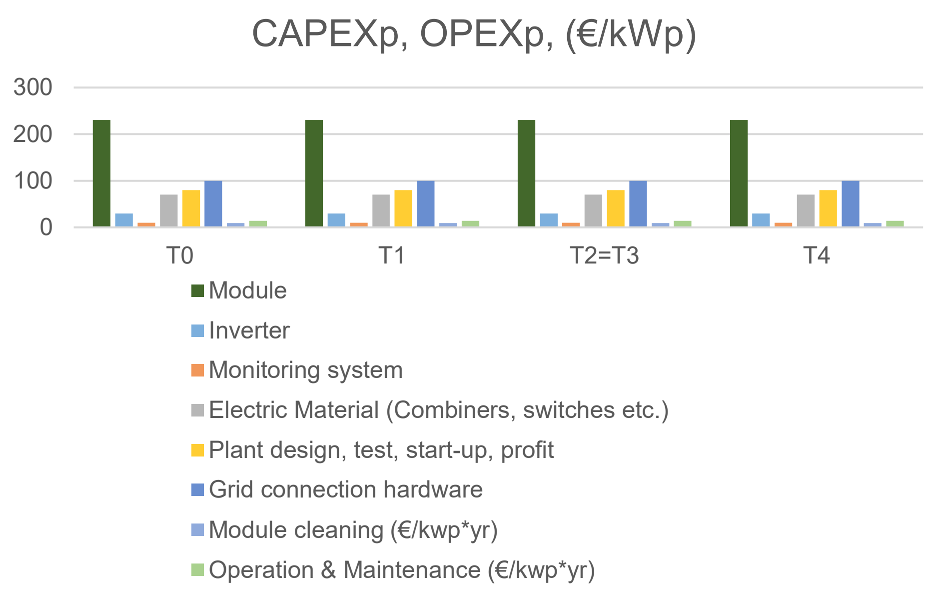
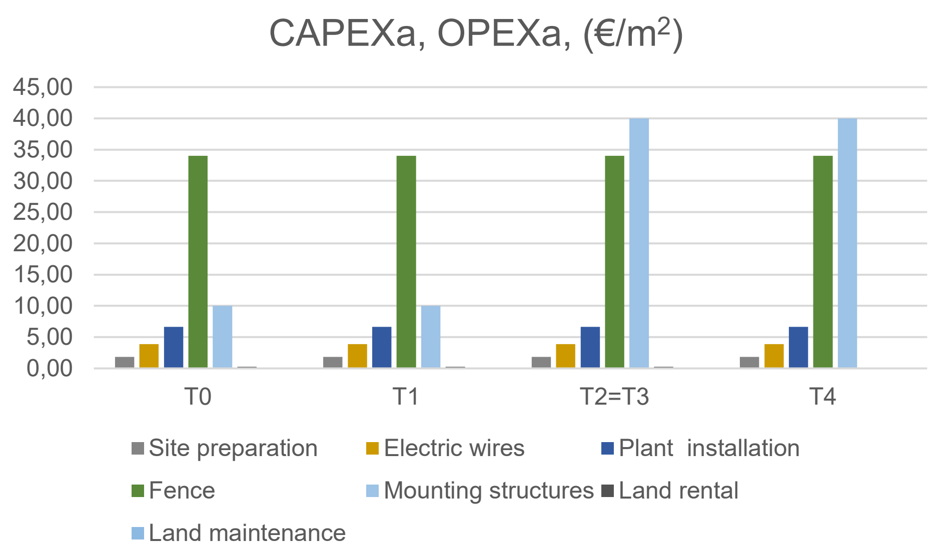


Fig.2 Area dependent CAPEX and OPEX costs of the photovoltaic systems, in EUR/m²



Using these data and assuming an average productivity in Italy of 1250 kWh/kWp as measured by the National Electric Services Manager, GSE (2022) the LCOE values shown in Table IV in cEUR/kWh are obtained.

Tab. IV Levelized cost of photovoltaic electricity in €/kWh, for the different types of plants here investigated.

1 MW PV plant	**T0**	**T1**	**T2=T3**	**T4**
LCOE, EUR/kWh	0.069	0.073	0.095	0.092

Discussion

It is worth to note that the T0 LCOE cost is very similar to the cost officially reported for large utilities in Italy 2022 as per GSE (2022a). Data in Tab. IV show that, mainly due to the higher cost of the assembly structures, the LCOE cost for agrivoltaic plants (T2-T4) is generally 30% higher, the small difference between T4 and T2/T3 being related to the difference in land rental costs. T1 cost is slightly higher than T0 cost as a result of the total surface required for T1 to be considered fully agrivoltaic according to the guidelines. It should be noted that in calculating LCOE, several simplifications related to agrivoltaic plants have been performed:

a) - the installation costs have been considered the same for any PV systems, a rather optimistic assumption since agrivoltaic plants building should be more complex considering the higher and heavier structures involved;
 - the cleaning frequency of all the PV systems considered has been assumed similar and equal to one cleaning cycle per year, a frequency that may be considered typical only for T0 type PV plants according to Dawson (2019);
 - for an agrivoltaic plant, whose operation is expected to coexist with agricultural activities, the cleaning cycles should be dependent on, at least, the actual number of days worked on the cropland. In Italy, according to Delib. (2008) this number can vary from 3 d/yr up to 20/25 d/yr depending on of the specific cultivation. The few data reported in the literature by Arslan and Aybekhttps (2012) and Aroonsrimorakot and Laiphrakpam (2021) seem to indicate a specific and relevant problem in this respect and suggest the need to increase the cleaning frequency;

b) - it should be taken into account that cropland operation can produce significant quantities of dust that, beyond depositing on the panels, may reduce solar radiation as observed by Nocerino, Fattoruso, Sorrentino, Manna, De Vito, Fabbricino and Di Francia (2021) and, therefore, affect the electric yield of the systems. This effect has not been taken into account in the LCOE analysis as it has not been yet sufficiently investigated for consolidated data being available.

Indeed, agrivoltaics is nowadays characterized by a considerable lack of data related to the operation and management of this class of PV plants in real conditions. There are a number of open issues that can significantly impact on the specific costs of the electricity produced. In Table 5 some of such effects are reported.

Table 5. Issues still poorly known related to agrivoltaic utilities implementation and their effect on LCOE.

	Phenomenon	Cause	Effect	Remedy	Reference	LCOE effect
1	Increased tendency of photovoltaic modules to get dirty	Cropland activities tend to produce quantities of dust and processing residues that can soil the panels.	Electric efficiency decrease; possible hot spots;	More frequent cleaning of modules are required.	Delib. (2008), Arslan (2011), Massi Pavan (2011)	+n*0.6 c€/kWh, n= number of cleaning cycles;
2	Reduction of impinging solar energy due to dust from agricultural activity	Cropland activities tend to produce quantities of dust and processing residues that can shield the solar radiation.	Electric efficiency decrease;	Perform cropland activities requiring the minimum possible “on field” activities;	Delib. (2008), Aroonsrimorakot et al. (2019)	In Italy a 0.3%/ppm decrease in solar irradiance has been calculated as a result of environment pollution. No data yet exist for cropland activities.
3	Increased cost of assembly structure	High mounting structures cost 3-8 times more than standard ones.	Increase LCOE	None	Di Francia (2013)	+n*1 c€/kWh, n= doubling the base installation cost;
4	The cleaning of the system must be done taking into account farming.	PV plants cannot be cleaned with machines that are not compatible with agricultural processes (for instance trucks freely moving on the cropland).	Capex increase	This involves designing the APV plant taking into account specific automatic cleaning tools and optimizing the photovoltaic plant design.	None	Unknown
5	Potentially harmful cleaning products cannot be used in a land used for farming.	Cleaning products may be harmful to crops and/or may not be accepted by food authorities.	Opex increase	Probably an increased use of water has to be considered	None	Unknown

6	The compatibility of pesticides used in agricultural practice must be evaluated	Compatibility of the chemicals normally used in the cropland activity with the PV plant components has to be verified in the long term.	Capex increase	Possible use of other tools.	Huang et al. (2023)	Unknown
7	Worsening crop growth control	AgriPV systems limit the use of satellite to control plant growth.	Cropland practices have to change. Capex increase	Possible use of other tools.	Huang et al. (2023)	Unknown
8	Safety issue for farmers.	Farmers actually work in a power plant characterized by high voltage and high current cables. Adequate training, specific PPE and possible revision (i.e. use of specific sensors) of agricultural equipment.	Increased capex and opex	Use proper PPE and specific equipments	INAIL (2016)	Unknown
9	Compliance with safety standards	Necessity that agricultural work does not take place in an area too close to HV lines	No effect on LCOE	Review safety rules	INAIL (2016)	Unknown
10	Crop shading	PV plant shades crops	Positive or negative effect depending on crops (has no effect on LCOE)	none	Ramos Fuentes et al (2023)	Poorly known
11	Soil evaporation mitigation	The soil is on average colder and holds water better	Can save irrigation costs (does not affect LCOE)	none	Altyeb Ali Abaker Omer et al (2021)	Poorly known
12	Inhomogeneity in the distribution of rainfall	An agrivoltaic system intrinsically produces a non-homogeneity in the distribution of rainwater	Increased probability of landslides	Study of specific plant topologies	Verheijen et al (2023)	Unknown
13	Increase in total area for cropland operation	Using agricultural machinery could require wider intra-rows spacing.	Require more wires and mounting structures, longer fences.	None	None	Unknown

For T2-T4 typos here investigated, LAOR is always less than 40%. This limit could only become of concern if the intra-row spacing were reduced, a rather unpractical situation at our latitudes. Therefore, LAOR effect is expected to be almost negligible in Italy. On the contrary increasing intra-row spacing, for instance to allow agriculture machinery use, will result in an increase of area dependent costs such as mounting structures, wiring, fence etc.

In addition to the above-mentioned effects, agrivoltaic systems could also bring unforeseen external costs. For instance, the risk of fire, if it were to concern an agrivoltaic system, would also put the crop harvest at risk. Of course, the reverse is also true. Furthermore, given that an agrivoltaic plant may be up to 4-7 meters high and taking into account that wind speed increases with height, the risk of damage from strong winds could result into damage and contamination of wide areas.

Conclusions

Ideally agrivoltaic is a brilliant solution to limit the use of agricultural land and at the same time to support the production of renewable energy from photovoltaics. However, this solution involves some problems:

1) The cost of agri-photovoltaic energy is higher than that of photovoltaic energy and will hardly significantly decrease, given that the building structures of agrivoltaic systems are more complex, taller, heavier and require more solid foundations than those of a standard photovoltaic system.
2) There are still many issues whose effect on the energy and agricultural yields of agrivoltaic systems have not yet been sufficiently evaluated.

It should therefore be reasonable to pay care in considering agrivoltaic utilities as a pillar of the energy transition especially recalling that, in Italy, even if all the photovoltaic capacity required up to 2050 would be set in agricultural areas, the land consumption would just be around 1% of the whole available croplands.

On the other hand, the construction of photovoltaic systems could be a chance for abandoned agricultural lands recovering in terms of their agrivoltaic implementation. Even in this case, only a few percent of abandoned lands could be sufficient to satisfy the full photovoltaic request. In summary, agrivoltaic is a very interesting and stimulating research field and as such it should be considered until the issues listed in Tab. 5 are not better investigated. Energy transition should probably better rely, at least for the next two three years, on more consolidated and well known standard technologies.

References

Goldman and Sachs (2023) https://www.goldmansachs.com/intelligence/topics/clean-tech-and-renewables.html, last accessed 15 june 2023.

Di Francia Girolamo and Cupo Paolo. (2023). "A Cost–Benefit Analysis for Utility-Scale Agrivoltaic Implementation in Italy". *Energies* 16(7):2991. https://doi.org/10.3390/en16072991.

https://www.mase.gov.it/sites/default/files/archivio/allegati/PNRR/linee_guida_impianti_agrivoltaici.pdf

Short Walter, Packey Daniel J., and Holt Thomas. (1995) "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies". Available on line: https://www.nrel.gov/docs/legosti/old/5173.pdf (accessed on 16 may 2023).

Branker Kadra, Pathak M.J.M.; Pearce Joshua M. (2011) "A review of solar photovoltaic levelized cost of electricity", *Renewable and Sustainable Energy Reviews*, Volume 1, pp. 4470–4482.

Campbell Matthew. (2010) "Levelized Cost of Energy for Utility-Scale Photovoltaics".In *Solar Cells and Their Applications*, Wiley publisher, pp 251-270. https://doi.org/10.1002/9780470636886.ch11

Vartiainen Eero, Masson Gaetan, Breyer Christian, Moser David and Román Medina Eduardo. (2020) "Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity", *Progress in photovoltaics: research and applications*, Volume 28, pp. 439-453.

IEA (2016. IEA-PVPS and IRENA, Photovoltaic Power Systems Programme of the International Energy Agency and International Renewable Energy Agency. End-of-Life Management; Solar Photovoltaic Panels, Report T12-06:2016, IEA PVPS, St Ursen, 2016.

European Commission (2020). Guide to Cost-benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020. 2014. doi:10.2776/97516

Arera (2021). Delibera 23 dicembre 2021 614/2021/R/comARERA. Available on line: https://www.arera.it/it/docs/21/614-21.htm# (accessed on 20/01/2023). Rapporto statistico solare fotovoltaico GSE 2022, pag. 39

NREL (2018. Lifetime of PV Panels. Available on line: https://www.nrel.gov/state-local-tribal/blog/posts/stat-faqs-part2-lifetime-of-pv-panels.html#:~:text=NREL%20research%20has%20shown%20that,climates%20and%20for%20rooftop%20systems (accessed on 20/01/2023).

Di Francia Girolamo (2013). The impact of recycling policies on the photovoltaic Levelized Cost of the Electricity. In *Proceedings of the International Conference on Renewable Energy Research and Applications* (ICRERA), 2013, pp. 979-983, doi: 10.1109/ICRERA.2013.6749894;

Trommsdorff Max, Kang Jinsuk, Reise Christian, Schindele Stephan, Bopp Georg, Ehmann Andrea, Weselek Axel, Högy Petra, and Obergfell Tabea (2021) "Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany", *Renewable and Sustainable Energy Reviews*, Volume 140, https://doi.org/10.1016/j.rser.2020.110694.

GSE (2022) Rapporto statistico solare fotovoltaico, p 39

GSE (2022a) Relazione trimestrale . Pag.68

Dawson Carla (2019), Solar Farm Cleaning Costs - Soilar Technologie, The Solar Panel Cleaning Business - Online Book,

Delib. (2008), Estratto da Delib. G.R. Lazio 11/07/2008, N. 506 (/NODE/2517825) Allegato 1 - Tabelle per il calcolo delle ore lavorative relative alle attività agricola ed agrituristica;

Arslan Selçuk and Aybekhttps Ali (2011), Particulate Matter Exposure in Agriculture, Selçuk Arslan and Ali Aybekhttps://www.intechopen.com/chapters/38344;

Aroonsrimorakot S.; Laiphrakpam, M. (2019) Application of solar energy technology in agricultural farming for sustainable development: A review article. Int. J. Agric. Technol., 685–692.
Nocerino Martina, Fattoruso Grazia, Sorrentino Giampiero, Manna Vincenzo, De Vito Saverio, Fabbricino Massimiliano and Di Francia Girolamo (2021), "Assessing the Impact of Haze on Solar Energy Potential Using Long Term PM2.5 Concentration and Solar Insolation Filed Data in Naples, Italy". In AISEM Annual Conference on Sensors and Microsystems, AISEM 2020: Sensors and Microsystems pp 125–130 First Online: 11 May 2021 Part of the Lecture Notes in Electrical Engineering book series (LNEE,volume 753).
Huang Kai, Lei Shu, Kailiang Li, Yuejie Chen, Yan Zhu, and Ravi Valluru (2023). "Sustainable and Intelligent Phytoprotection in Photovoltaic Agriculture: New Challenges and Opportunities" *Electronics* 12, no. 5: 1221. https://doi.org/10.3390/electronics12051221 https://doi.org/10.3390/electronics12051221
INAIL (2016), Lavori in prossimità di linee elettriche aeree Valutazione del rischio e misure di prevenzione,
Ramos-Fuentes Isaac A., Elamri Yassin, Cheviron Bruno, Dejean Cyril, Belaud Gilles, Fumey Damien (2023), "Effects of shade and deficit irrigation on maize growth and development in fixed and dynamic AgriVoltaic systems", *Agricultural Water Management,* Volume 280,2023,108187,ISSN 0378-3774, https://doi.org/10.1016/j.agwat.2023.108187.
Altyeb Ali Abaker Omer, Wen Liu, Ming Li, Jianan Zheng, Fangxin Zhang, Xinyu Zhang, Samia Osman Hamid Mohammed, Liulu Fan, Zhipeng Liu, Fangcai Chen, Yuxuan Chen, Jan Ingenhoff, (2022) Water evaporation reduction by the agrivoltaic systems development, *Solar Energy*, Volume 247, Pages 13-23,ISSN 0038-092X, https://doi.org/10.1016/j.solener.2022.10.022.
Verheijen Frank G.A. and Bastos Ana Catarina (2023). Discussion: Avoid severe (future) soil erosion from agrivoltaics, *Science of the Total Environment*, May 15;873:162249. doi: 10.1016/j.scitotenv.2023.162249. Epub 2023 Feb 15. PMID: 36804977.
Massi Pavan Alessandro, Mellit Adel, De Pieri Diamando, (2011) The effect of soiling on energy production for large-scale photovoltaic plants, *Solar Energy*, Volume 85, Issue 5, Pages 1128-1136,ISSN 0038-092X, https://doi.org/10.1016/j.solener.2011.03.006.