This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

goPV

June. 23rd

7. Economic & Environmental Aspects

(09:00-16:30)

co-organized with Università di Catania

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

Economic & Environmental Aspects.
LCOE Analysis, TECNALIA

Agenda

1. LCOE definition and insights
2. LCOE for PV systems. Evolution, comparatives, sensitivity analysis
3. Example of LCOE calculation. GOPV
4. R&D activities for LCOE improvements in PV plants

1. LCOE definitions and insights

- **Levelized Cost of Energy (LCOE, €/kWh) allows the comparison of different energy sources , conventional or renewable** and used to make fair comparison with electricity prices.
- **LCOE** includes all the costs and profit margins of the whole value chain including manufacturing, installation, project development, O&M, inverter replacement, dismantling, etc.
- Usually, **residual value** not included, although can be modelled.

GENERAL/SIMPLIFIED EXPRESSION

$$LCOE = \frac{Total\ cost\ for\ the\ whole\ PV\ plant lifetime}{Total\ energy\ production\ for\ the\ whole\ PV\ plant lifetime}$$

- $$LCOE = \frac{CAPEX + OPEX\ (PV)}{EP\ (PV)}$$

CAPEX: Capital Expenditure
OPEX: Operational Expenditure
EP: Energy/Electricity Production
PV: Present value

1. LCOE definitions and insights

Detailed EXPRESSION

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX\ (t)}{(1+WACC_{Nom})^t}}{\sum_{t=1}^{n} Yield(0) * \frac{(1-Degr)^t}{(1+WACC_{Real})^t}}$$

t is year number ranging from 1 to the economic lifetime of the system
CAPEX is total investment expenditure of the system, made at ***t*** = 0 in €/kWp
OPEX(t) is operation and maintenance expenditure in year ***t*** in €/kWp
Yield(0) is initial annual yield in year 0 in kWh/kWp without degradation
Degr is annual degradation of the nominal power of the system
$WACC_{nom}$ is nominal weighted average cost of capital per annum
$WACC_{real}$ is real weighted average cost of capital per annum

Other definitions

$$LCOE = \frac{C_0 * (1+\tau)^{nt} + C_1}{\left(PVP_{np} * \eta_{SYS} * H * \sum_1^{nt} (1-d)^{j-1}\right)}$$

Here C_0 are all the initial capital sensitive costs, C_1 are all the costs accrued along the PV plant lifetime, PVP_{np} is the nominal PV plant power expressed in kWp while η_{sys} is the system efficiency whose value can be assumed, nowadays, between 80% and 90%, H are the annual sun hours in the site where the PV plant is located and, finally, d is a degradation term, taking into account that during the 25 years of PV plant operating lifetime, panels conversion efficiency tends to diminish mainly as a result of the interaction with the environment [9]. Degradation can be considered linear with time at any practical purpose and, in general it can be assumed d=0.7%/yr for the solar technologies here considered.

1. LCOE definitions and insights

Financial definitions

El **WACC is the discount rate used for discounting future cash-flows** in an investment project, so to calculate the **Net present Value (NPV)** of a business or investment

$$WACC_{Nom} = \frac{D}{D+E} * (1-T) * k_d + \frac{E}{D+E} * k_e$$

with E = equity financing; D = % debt financing; k_d= interest rate of debt financing; k_e = equity financing; T = Corporate Tax rate

$$WACC_{Real} = \left(\frac{1 + WACC_{Nom}}{1 + Inflation} - 1\right)$$

If inflation = 0, $WACC_{nom}$ = $WACC_{real}$

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX(t)}{(1+r)^t}}{\sum_{t=1}^{n} Yield(0) * \frac{(1-Degr)^t}{(1+r)^t}}$$

Discount rate (r): in investing financing, the discounted cash-flow (equivalent to WACC)

1. LCOE definitions and insights

CAPEX inputs (Capital Expenditure)

All-inclusive turnkey PV system price to be paid upfront. CAPEX is fully paid during the year of installation t=0 and the PV system starts producing electricity from the following year.

CAPEX = Cost Modules + Cost BoS

Main Component costs:

1. **Module**
2. Inverter
3. Tracker/structure
4. Rest of BOS elements
5. Cost of installation

(Items 2–5: BoS)

- BOS: **efficiency-related** (cabling, structures, transport…) and **non-efficiency related** (combiner box, transformers, fuses, protections, monitoring tools, etc.). For a instantaneous "photo", not necessary to see evolution, **for sensitivity analysis, it's necessary to consider it**.
- Installation
  1. Administrative costs (e.g. permissions, local taxes, documentation)
  2. Cost for planning, engineering and project management
  3. Cost of PV plant construction (mounting, cabling, installation) and development
  4. Installer's margin

1. LCOE definitions and insights

OPEX and other costs (Operational Expenditures)

OPEX is usually associated with O&M costs as no fuel cost related to PV generation exists. Annual cost in €/MWh, €/kWp

1. Cost for O&M
   - Fixed costs: Preventive and Predictive O&M
   - Variable costs: corrective O&M. Only when a problem occurs.
2. Other costs for **Operation**: asset management, insurance, security, billing, monitoring
3. Inverter replacement (it would be included in Preventive O&M and even CAPEX)

   1 per system lifetime at the discounted cost of an inverter in 15-25 years
4. Land cost (only for ground-mounted, it could be considered CAPEX, if purchased)
   - Rental price: constant at xxx €/Ha yearly
   - Module efficiency increase → less area needed
5. Network access fee
6. Dismantling and Recycling cost: simplification, assumed to be zero and constant as it is either:
   - Financed in advance through the PV CYCLE program
   - Financed in advance through a company specific recycling program

1. LCOE definitions and insights

OPEX and other costs (Operational Expenditures)

$$NDC_{PV} = \frac{[(DC_T + IC_T + MR_T + LF_T) - SV_T - LV_T]}{(1+r)^T}$$

Decommissioning (source: PVTech, 2017)

- NDC_{PV} = present value of the net cost to decommission a PV power plant
- $DC_T + IC_T$ = Direct cost (labor, equipment) and indirect cost of PV plant de-installation, demolition, recovery, and land reclamation in year T.
- MR_T = PV module recycling cost in year T.
- LF_T = Landfill disposal cost in year T, including landfill tipping fees and hauling, of non-salvageable material.
- SV_T = Scrap value of steel, copper and aluminum recovered during PV solar field and power equipment removal and sold to recyclers at prices prevailing in year T.
- LV_T = Value of reclaimed land in year T.
- r = Rate of annual discount applied to costs and revenues realised in year T.

- Models give negative values of NDC_{PV} *(incomes from recycling greater than decommissioning)* - US$1.58 per module area
- **Other scenarios: 0.01-0,02 USD/Wp net revenues**.

1. LCOE definitions and insights

ENERGY YIELD (adapted to bifacial technology)

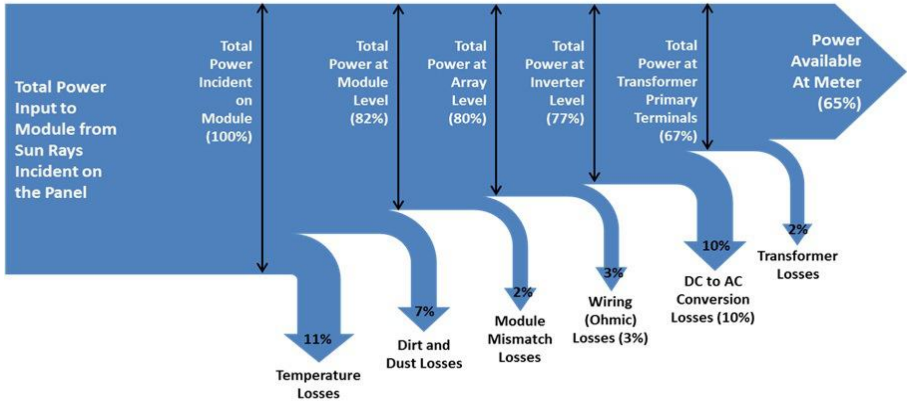
Dependent on local irradiation (kWh/m2.year), Performance Ratio (PR), degradation (%), lifetime (years), f(G, h, Pitch, Soil color)

$$E_{AC} = P*G_{eff}*PR*(1+BG)*EA$$

E_{AC} is annual energy production (kWh)
P is nominal power (kWp) = Area x effiency at STC
G_{eff} is annual in-plane irradiation in annual sun hours, kWh/m2 at STC.
PR is Performance Ratio
EA is Energy Availability
BG is Bifacial Gain = Module bifaciality* bifacial ratio

$$BG = \frac{P_{mpp\ rear}}{P_{mpp\ front}} * \frac{G_{rear}}{G_{front}}$$

PR defined as ratio between electricity actually generated by the PV system and the electricity that an ideal lossless PV system would produce with the same amount of irradiation and 25ºC cell temperature.



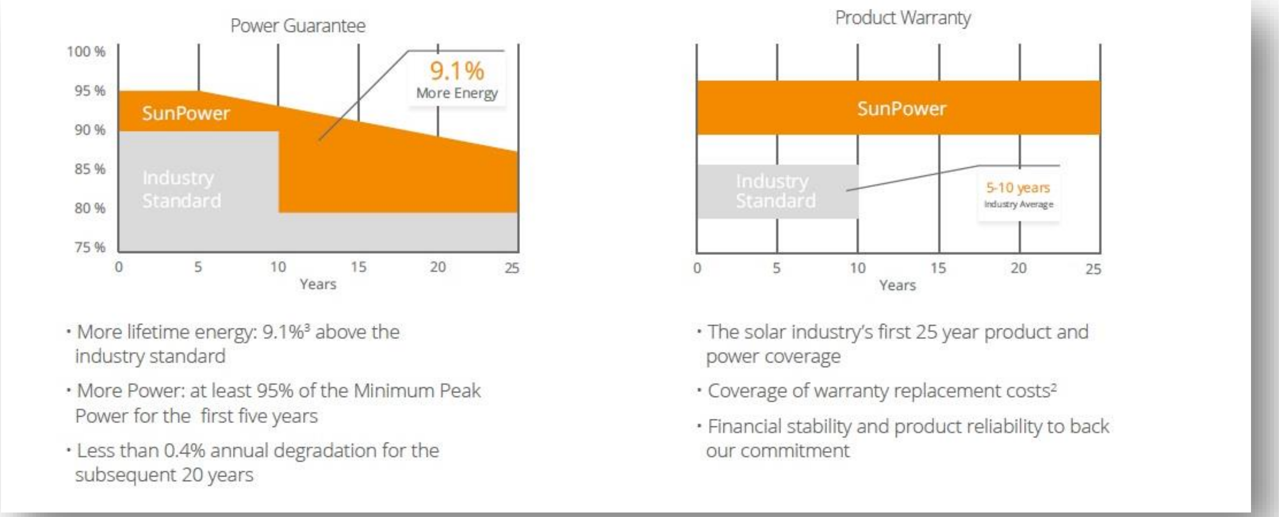
1. LCOE definitions and insights

ENERGY YIELD (adapted to bifacial technology)

$$PR = 1 - L_G - L_T - L_{dirt} - L_{miss} - L_{inv} - L_{tr} - L_{clip} - L_{ohm}$$

PR is Performance Ratio
L_G - low irradiance losses
L_T - temperature losses
L_{dirt} - dust and dirt losses
L_{miss} - mismatching losses
L_{inv} - DC to AC losses in inverter, including MPPT
L_{clip} – clipping losses, inverter saturation
L_{ohm} - ohmic loss in wiring,
L_{Tr} - transformer losses

Degradation curve provided by module manufacturer = power guarantee (example from SunPower)



1. LCOE definitions and insights

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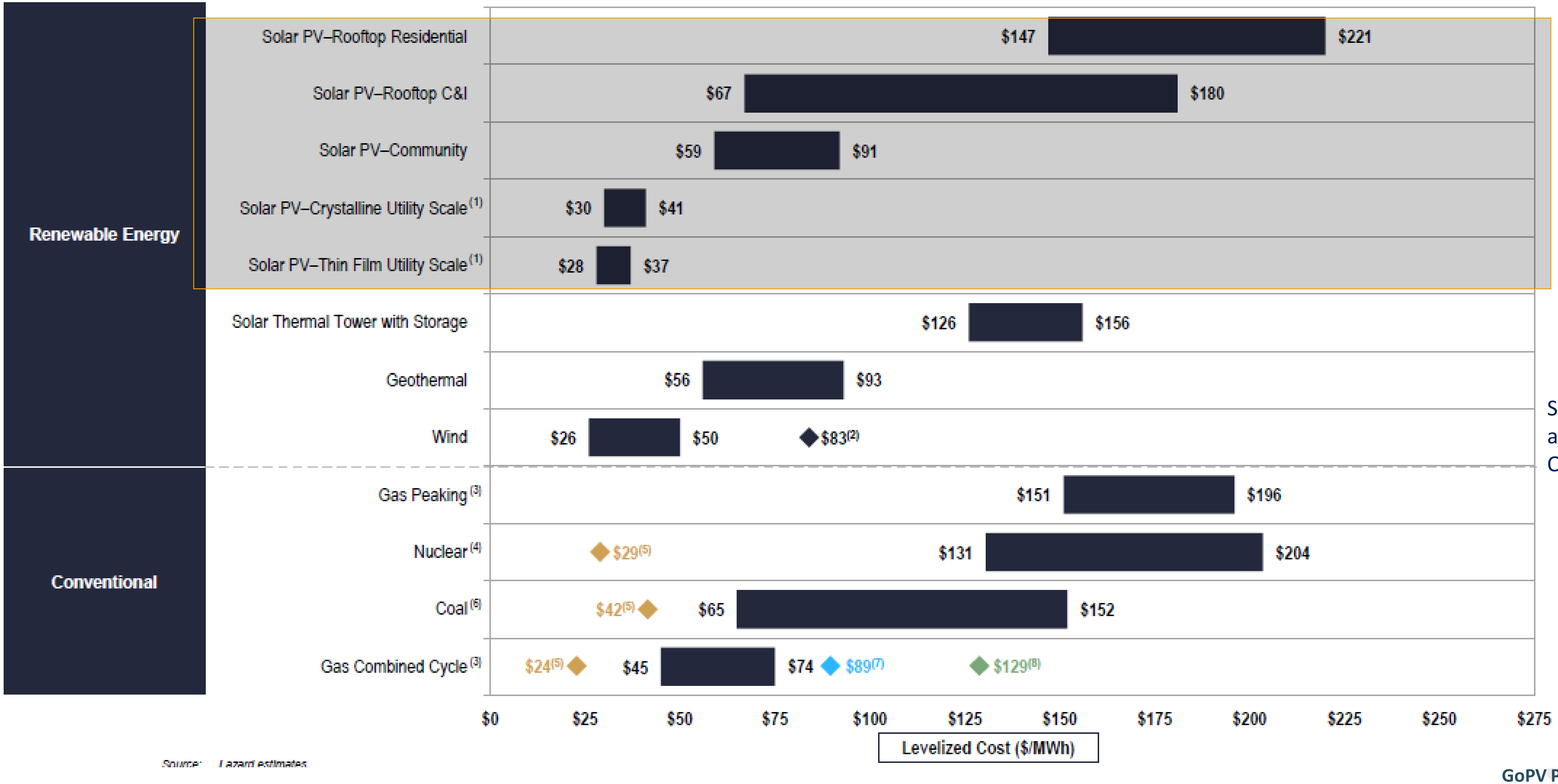
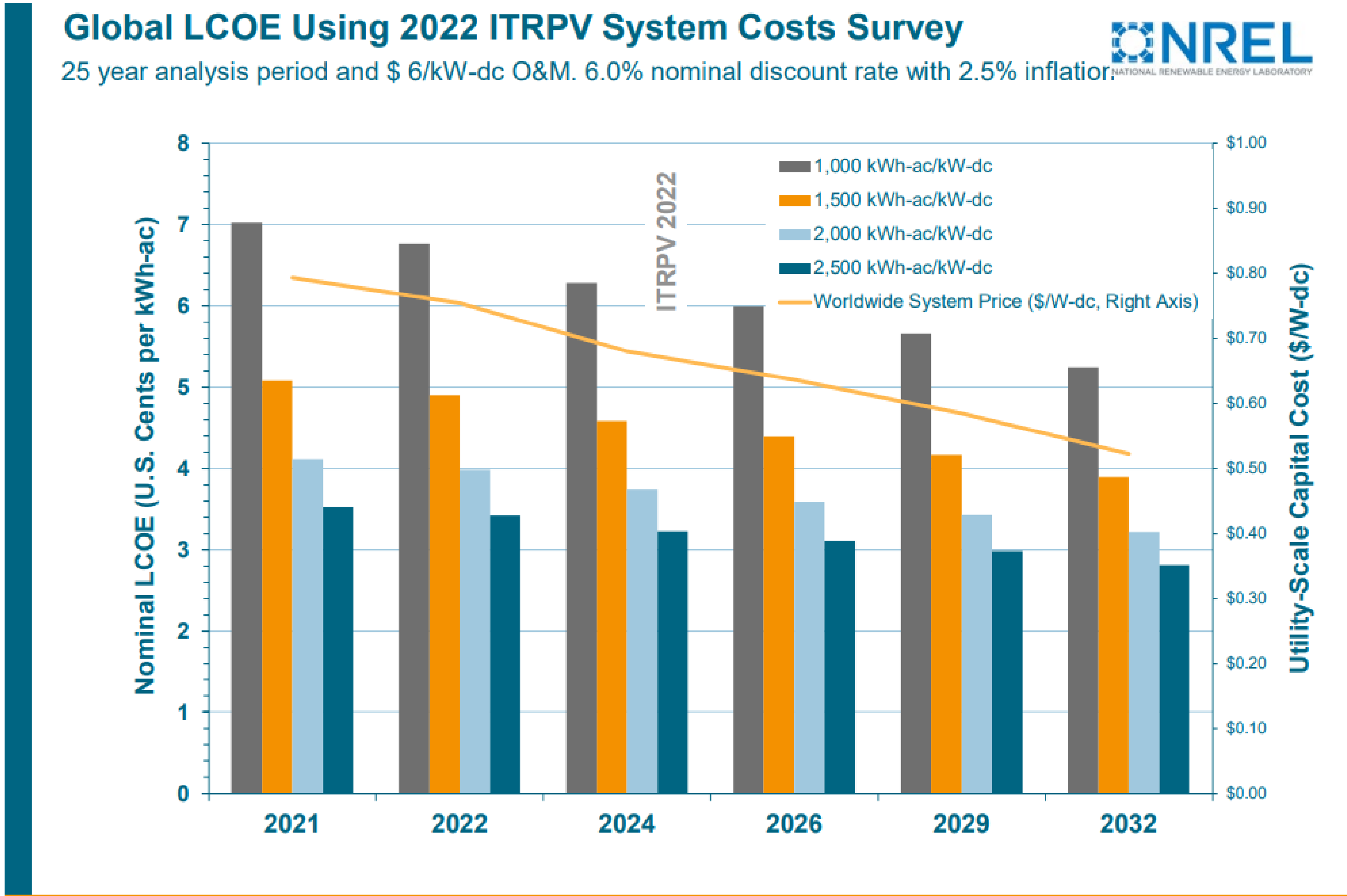
2. LCOE in PV systems, evolution



Source: Lazard's LCOE analysis, version 15.0. October 2021

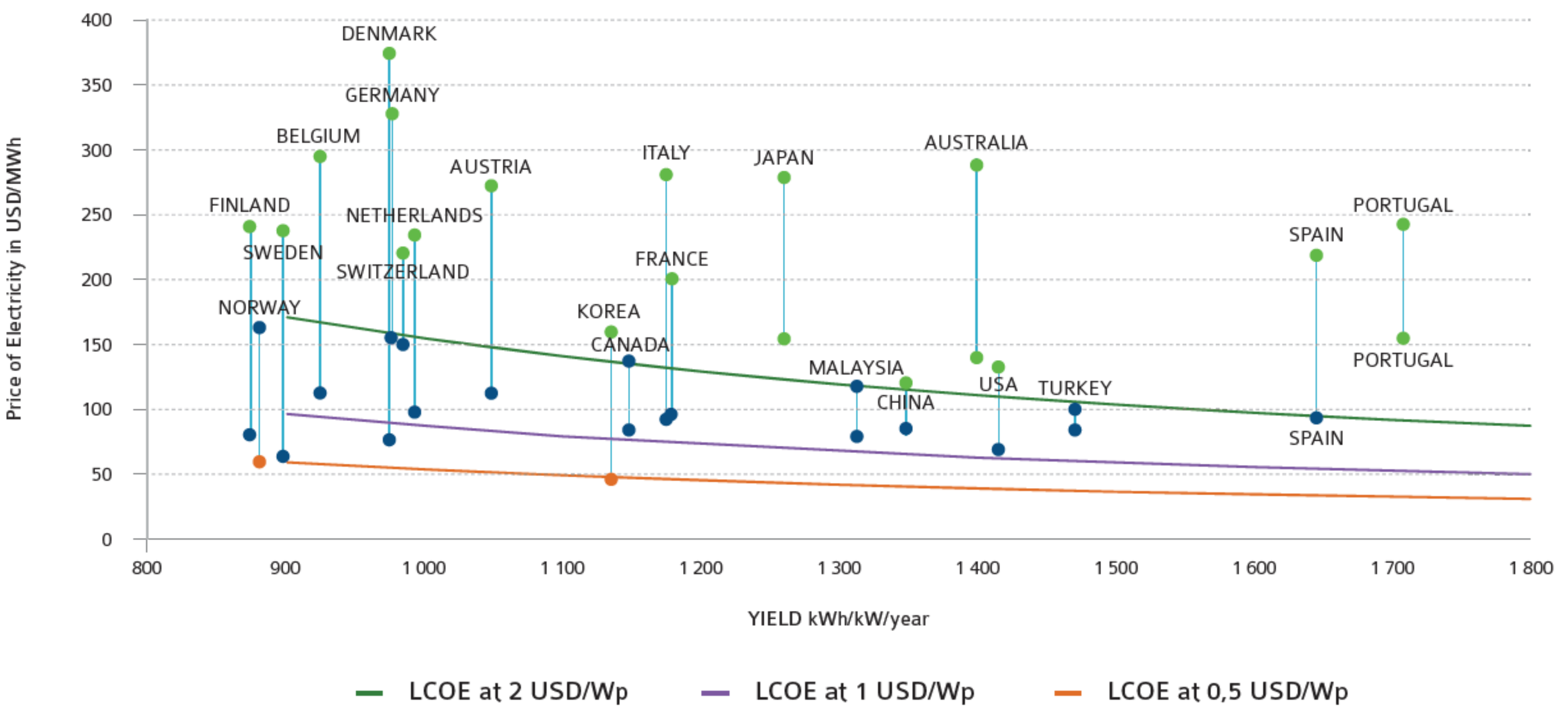
2. LCOE in PV systems, evolution



Source: ITRPV 13th Edition April 2022

2. LCOE in PV systems, evolution

FIGURE 6.7: LCOE OF PV ELECTRICITY AS A FUNCTION OF SOLAR IRRADIANCE & RETAIL PRICES IN KEY MARKETS*



*NOTE THE COUNTRY YIELD (SOLAR IRRADIANCE) HERE SHOWN MUST BE CONSIDERED AN AVERAGE.

SOURCE IEA PVPS & OTHERS.

TRENDS 2021 IN PHOTOVOLTAIC APPLICATIONS.
Report IEA-PVPS T1-41: 2021.

2. LCOE in PV systems, evolution

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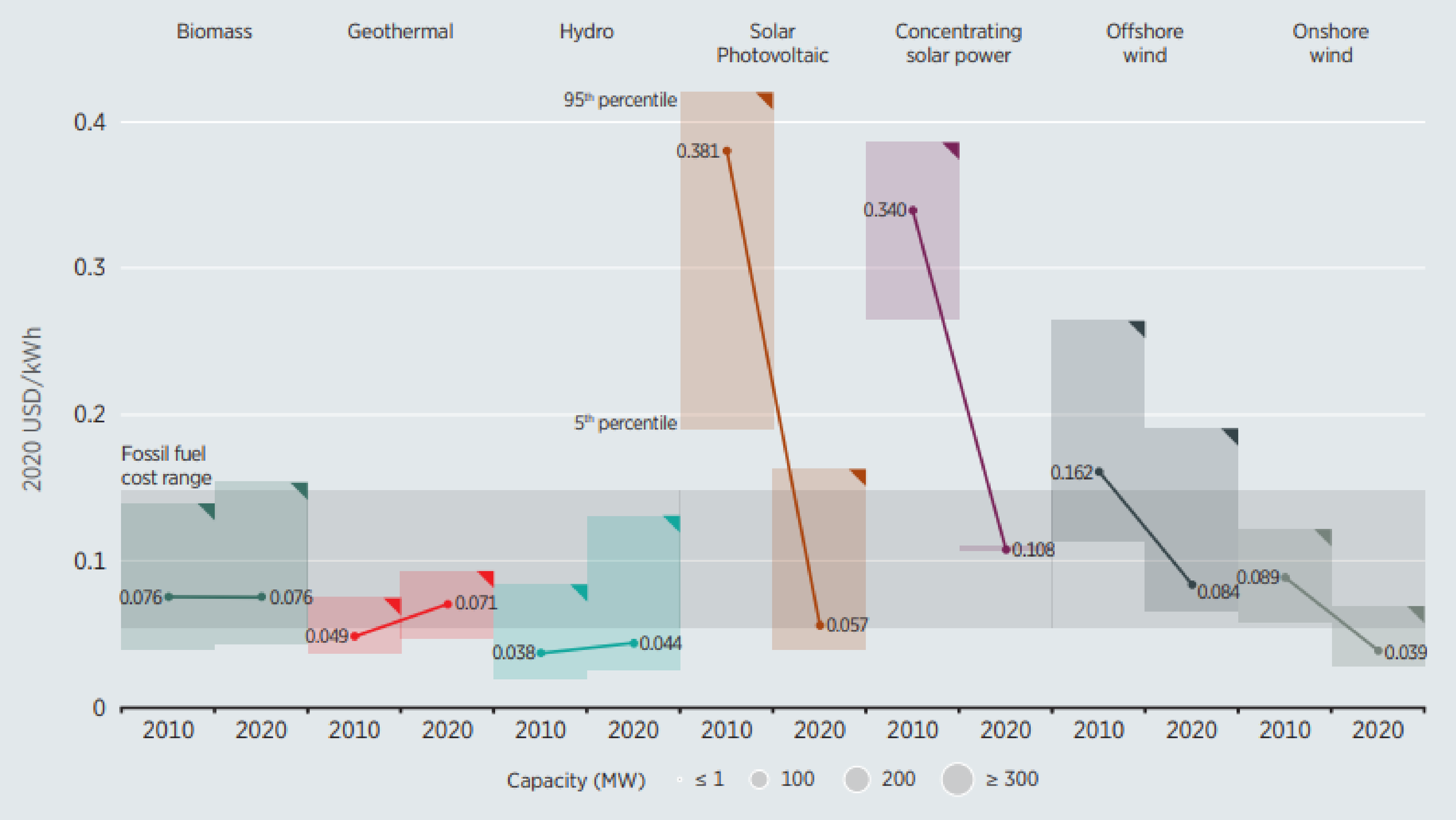
Figure ES.2 Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020



Source: IRENA, Renewable Power Generation Costs in 2020.

2. LCOE in PV systems, evolution

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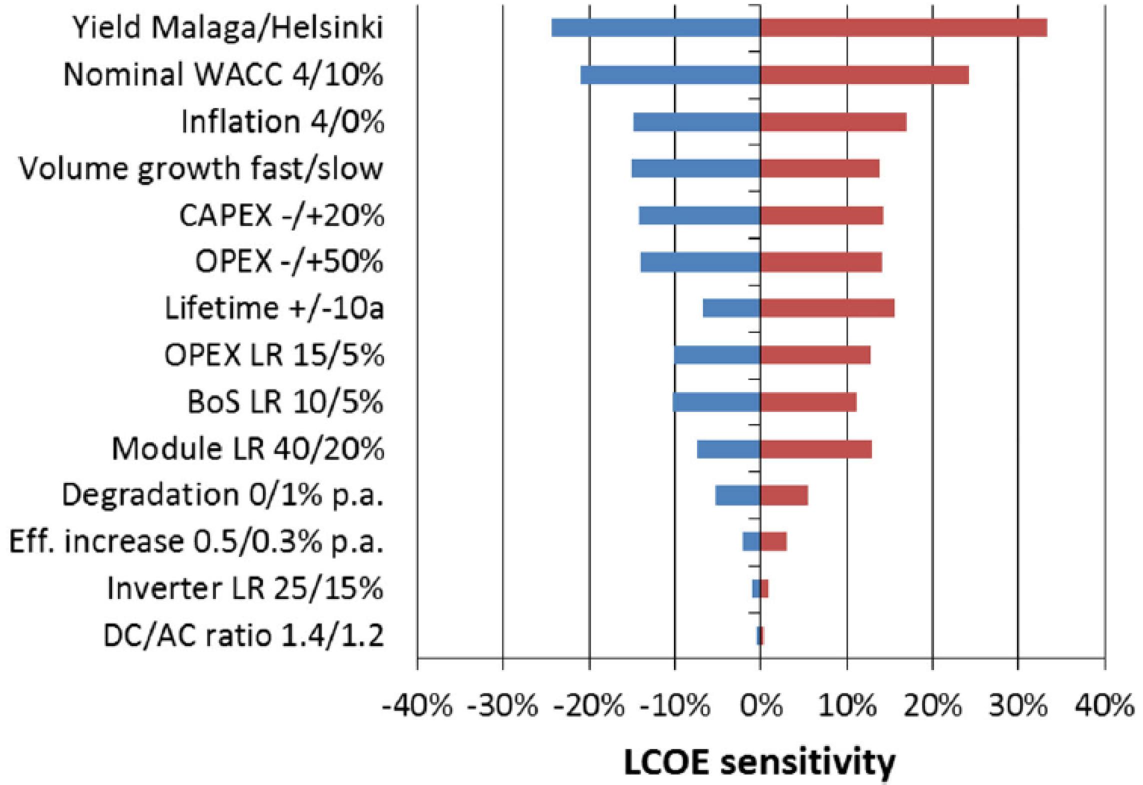
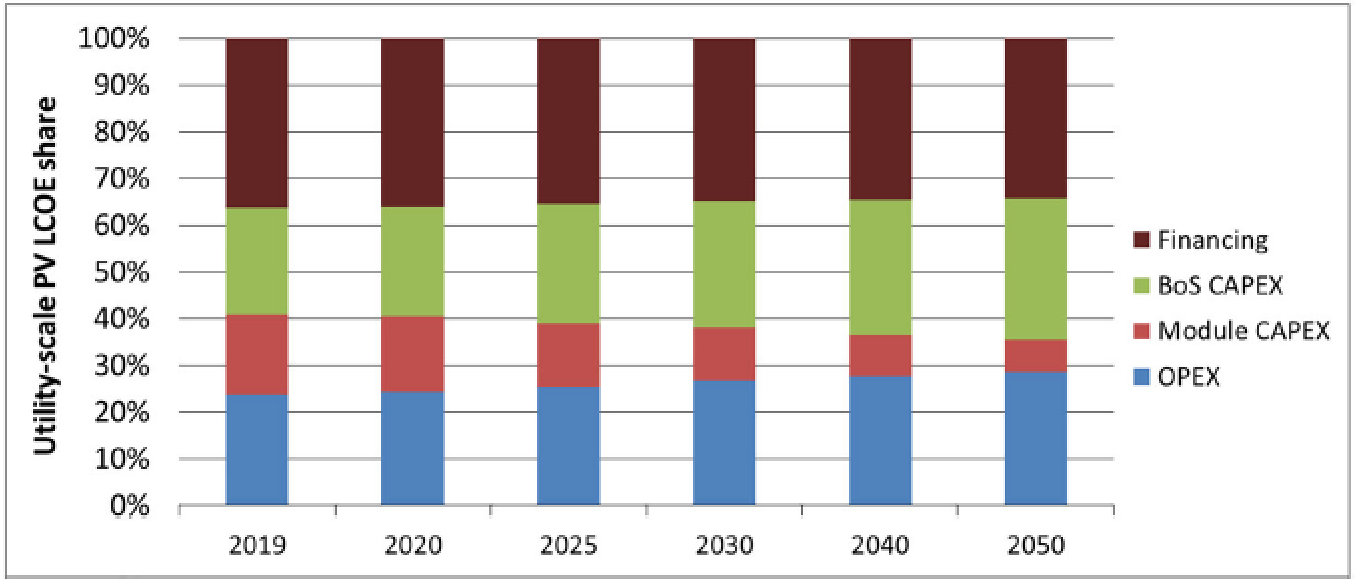


FIGURE 13 Sensitivity of photovoltaics (PV) levelised cost of electricity (LCOE) in 2050 on input parameters for a utility-scale PV system in Toulouse with 0.164 €/Wp capital expenditure (CAPEX), 4.2 €/kWp/a operational expenditure (OPEX), 7% nominal weighted average cost of capital (WACC), 2% inflation, 30 years lifetime, 0.5% annual degradation, 0.4%-points annual efficiency improvement, 1.3 DC/AC ratio, base volume growth scenario, and learning rate (LR) of 30% for PV modules, 20% for inverters, 7.5% for other BoS and 10% for OPEX [Colour figure can be viewed at wileyonlinelibrary.com]

Source: Vartiainen E, Masson G, Breyer C, Moser D, Román Medina E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. Prog Photovolt Res Appl. 2019;1–15. https://doi.org/10.1002/pip.3189

2. LCOE in PV systems, evolution

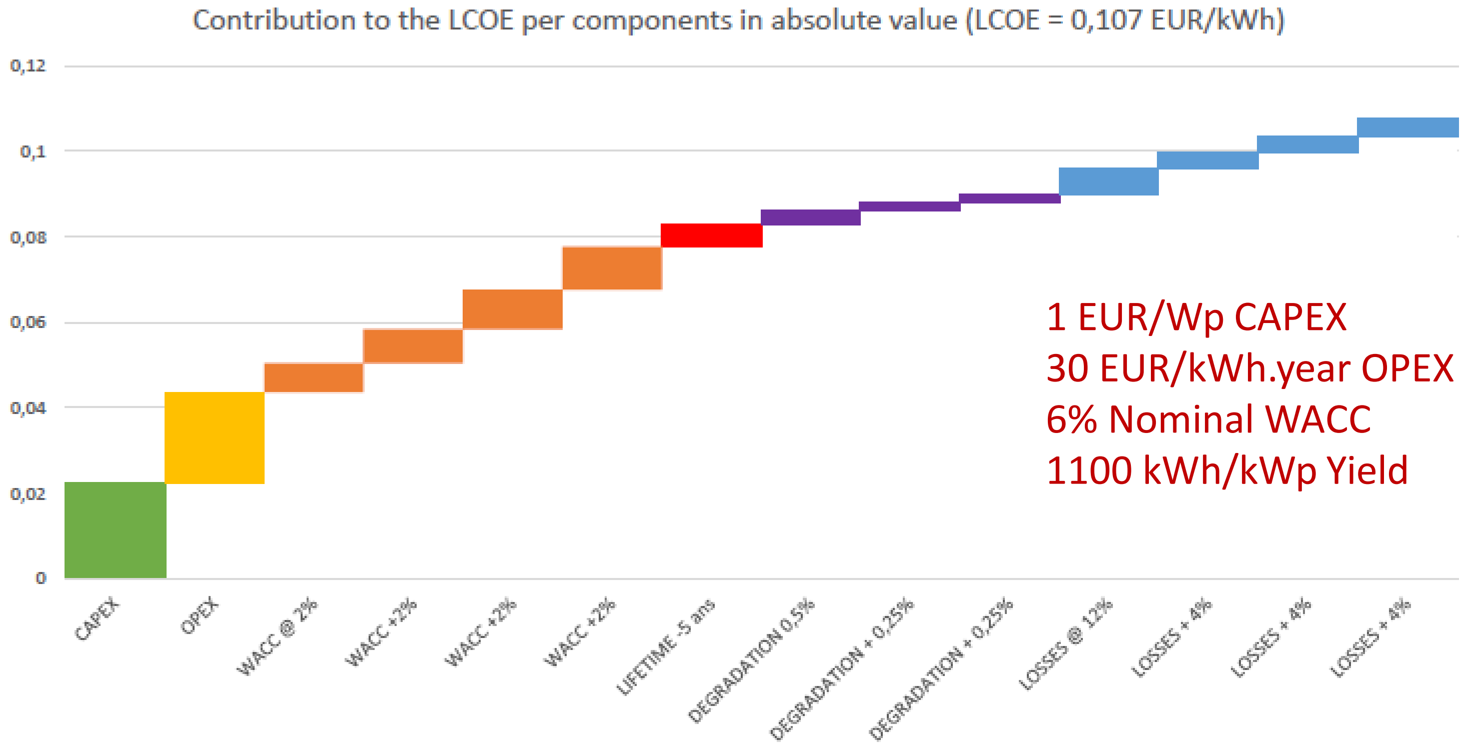


Source: Vartiainen E, Masson G, Breyer C, Moser D, Román Medina E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. Prog Photovolt Res Appl. 2019;1–15. https://doi.org/10.1002/pip.3189

FIGURE 14 Share of operational expenditure (OPEX), module, and BoS capital expenditure (CAPEX) and financing in a utility-scale system levelised cost of electricity (LCOE) in Toulouse with 7% nominal weighted average cost of capital (WACC) and 2% inflation for the years 2019 to 2050. Financing is the LCOE difference between 7% and 2% nominal WACC [Colour figure can be viewed at wileyonlinelibrary.com]

2. LCOE in PV systems, evolution

SENSITIVITY OF LCOE



Source: Becquerel Institute 2016

3. Example of LCOE calculation. GOPV

- Proposed LCOE

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX\,(t)}{(1+r)^t}}{\sum_{t=1}^{n} Yield(0) * \frac{(1-Degr)^t}{(1+r)^t}}$$

- Decision on **discount rate r** (value?) Simplification / no consideration of WACC
- Initial lifetime for the model = 35 years by 2023
- CAPEX:
  - market price of every component (tracker, inverter, module)
  - Land cost can be considered as CAPEX (or OPEX).
  - Dismantling (+recycling) to be considered during the project, with formula. At initial phase, incomes of 0,01 €/Wp, equivalent to consider a **residual value** for the PV plant.
- OPEX:
  - value for O&M (including fixed and variable costs, TECNALIA) and rest of Operational costs (e.g. insurance, asset management, surveillance). Main source: EGP-RSE.
  - Inverter / tracker programmed replacement during the project life? (lifetime) MTBF to be provided by REFU, 3SUN-EGP).
- Energy yield:
  - Module bifaciality (3SUN-EGP), degradation curve (3SUN-EGP), Energy availability (EA, 3SUN-EGP), inverter efficiency (REFU), module temperature coefficients (3SUN-EGP)

3. Example of LCOE calculation. GOPV

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Energy calculation

SYSTEM INPUTS		System description		
		Front side efficiency	20,7%	
		Temp coeff Pmax	-0,25%	/ºC
		NOCT	44	ºC
		DC Total Power (P)	84730	kWp
		Module bifaciality	90,1%	
		Backside irradiance	8,50%	
DC losses modelling		**AC losses modelling**		
Soiling	0,50%	Inverter Nom power	84730	kW
Module mistmach	1,00%	Inv op. consumption	0	kW
Diodes and connection	0,75%	Inv night consumption	0	kW
Low irradiance	1,00%	Inv efficiency	98,40%	
DC wiring	2,00%	AC wiring	1,50%	
Tracking error	0,50%	Transformers no-load	93,90	kW
DC Availability	0,00%	Transformers load	1,49%	
Current meteo data:	*Totana*	AC availability	0,50%	

3. Example of LCOE calculation. GOPV

Energy calculation

SYSTEM OUTPUTS			
Total P * Geff	**229.624.891**	**kWh**	Losses from previous
Soiling losses	228.476.767	kWh	0,50%
Temp losses	218.304.539	kWh	4,45%
Rest of DC losses	**207.067.922**	**kWh**	5,15%
Inverter clipping losses	207.054.637	kWh	0,01%
After Inv consumption	207.054.637	kWh	0,00%
Inverter AC production	**203.741.762**	**kWh**	1,60%
After AC wiring & transformers	196.880.479	kWh	3,37%
After AC availability	195.893.957	kWh	0,50%
Final AC output	**195.893.957**	**kWh**	
Performance Ratio	**85,74%**		

LCOE 2.088 c€/kWh

3. Example of LCOE calculation. GOPV

OPEX

O&M	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
OPERATION SERVICES	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL SERVICES (kEUR/MW)	1,18	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,25	3,
MAINTENANCE SERVICES (KEUR/MW)	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL MAINTENANCE SERVICES (KEUR/MW)	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,24	1,
MATERIAL AND OTHER MACHINES (kEUR/MW)	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL MATERIAL AND OTHER MACHINES (kEUR/MW)	1,44	1,10	1,10	1,10	1,10	1,10	1,45	1,10	1,10	1,
TAXES	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
Taxes and charges (kEUR /MW)										
OTHER COSTS (kEUR /MW)	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL OTHER COSTS (kEUR /MW)	1,64	1,64	1,64	1,64	1,64	1,64	1,64	1,64	1,64	1,
PERSONNEL COSTS /MW	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL PERSONNEL COSTS /MW	0,47	0,47	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,
OTHER COSTS FOR OPERATION	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL OTHER COSTS FOR OPERATION										
LAND COST	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
Land Rental (kEUR/Ha)	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	
DISMANTLING	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
Dismantling and Recycling Costs										
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL OPEX (kEUR/MW)	10,56	12,30	12,82	12,82	12,82	12,82	13,17	12,82	12,82	
Absolute value	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	
TOTAL OPEX (kEUR)	895,00	1.041,88	1.086,58	1.086,58	1.086,58	1.086,58	1.116,23	1.086,58	1.086,58	

3. Example of LCOE calculation. GOPV

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Degradation		
	Year 1	2,000%
	Year2-year 5	0,500%
	Year6-year25	0,500%
	Year 26-year35	0,500%

	YEAR 0	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8	YEAR 9	YEAR 10	YEAR 11	YEAR 12	YE
CAPEX (€/kW)	532,03													
OPEX (t) (€/kW)		10,56	12,30	12,82	12,82	12,82	12,82	13,17	12,82	12,82	13,37	12,82	12,82	
WACC Nom	0,050													
1+WACC Nom	1,050													
(1+WACC Nom)^t		1,05	1,10	1,16	1,22	1,28	1,34	1,41	1,48	1,55	1,63	1,71	1,80	
OPEX (t) / (1+WACCNom)^t		10,06	11,15	11,08	10,55	10,05	9,57	9,36	8,68	8,27	8,21	7,50	7,14	
YIELD (0) (kWh/kWp)	2.325,39													
(1-Degradation)		0,980	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,995	0,995	
(1-Degradation)^t		0,980	0,990	0,985	0,980	0,975	0,970	0,966	0,961	0,956	0,951	0,946	0,942	
YIELD (0)*(1-Degradation)^t		2.278,88	2.302,19	2.290,68	2.279,23	2.267,83	2.256,49	2.245,21	2.233,98	2.222,81	2.211,70	2.200,64	2.189,64	2.
WACC Real	0,050													
1+WACC Real	1,050													
(1+WACC Real)^t		1,05	1,10	1,16	1,22	1,28	1,34	1,41	1,48	1,55	1,63	1,71	1,80	
YIELD (0)*(1-Degradation)^t/(1+WACCReal)^t		2.170,36	2.088,16	1.978,78	1.875,13	1.776,91	1.683,83	1.595,63	1.512,05	1.432,85	1.357,79	1.286,67	1.219,27	1.

LCOE 0,02088

4. R&D activities for LCOE improvements in PV plants

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PV innovations go in the direction of improving (reducing) LCOE

- Cost reduction (CAPEX) of cells, modules and BOS, even installation
- O&M measures to improve energy performance (O&M could increase but the total effect should be positive)
- Improvement of PR (Performance Ratio): efficiency, PV availability, durability (degradation)…

LCOE Formula

$$LCOE = \frac{CAPEX + PV(O\&M)}{PV(EP)}$$

CAPEX: Capital Expenditure
O&M: Operations & Maintenance Cost
EP: Electricity Production
PV: Present Value

4. R&D activities for LCOE improvements in PV plants

LCOE Formula

$$LCOE = \frac{CAPEX + PV(O\&M)}{PV(EP)}$$

CAPEX: Capital Expenditure
O&M: Operations & Maintenance Cost
EP: Electricity Production
PV: Present Value

What happens if an innovation…

- Improves efficiency but is more expensive?
- Is more expensive but extends the lifetime 5 years?
- Reduces the O&M activities but increases the OPEX?
- Reduces the cost.. But is less efficient ?
- Improves cost and OPEX, but produces less….?

Answer: Case by case analysis

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

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