

“Direct use of PV panels”

Presenter and author: Prof. Alex Van den Bossche

Ghent University, Electrical Energy Lab

Technologiepark 913, Zwijnaarde, Gent, Belgium

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“ Direct use of PV panels “

Abstract:

Against global warming more renewable energy should be used [1,6]. The **direct use of PV** can be cost effective and help reducing it. It can be **stand-alone or as a complement** of the grid. In the early stage of photovoltaic panels already pumps worked “**as and when the sun shines**”. Gradually PV was used to inject in the grid and at off grid using batteries. However a lot of appliances can operate directly on DC without injecting in a grid, nor batteries. There are a lot of appliances that use **SMPS**: switched mode power supplies. They often use a rectifier at the input and can work also well in DC, but not mentioned nor guaranteed: so we need a label. Some loads such as laptops also store in their own battery. **Electric boilers** can also store energy, adaptation is needed as the thermostat and protection switches are not made for DC. Further on, also more industrial processes could be considered: flour mills, waste water pumps. Also charging **vehicles** and other applications emerge, such as **refrigerating** and **air conditioning**.

" Direct Use of PV Panels "

Contents:

- **Cost** of direct DC, grid, battery or heat storage.
- **History** of DC grids, voltage levels, range and losses.
- DC grids: **range** and losses at 2.5 mm^2 .
- DC grids **power at 25A/wire**, 4mm^2 dual system 300-600V.
- What **voltage level** can be used in direct DC, DC ready.
- **Common equipment** and switches.
- **Pulsed DC** principle.
- **Safety** of 230Vac compared to 300Vdc.
- **Emerging** applications with PV, or excess PV, without battery nor grid.
- Conclusion
- Bibliography

Cost of direct DC, grid, battery or heat storage.

Table 1 Cost

	Direct use of PV	AC grid	Battery storage	Hot water storage cost	Other storage
Investment	Cost of only PV panels. Private: 380 €/kWp VAT incl, <i>Company, large farms</i> 200 €/kWp VAT excl	Connection costs, Grid installation, Power plants.	Li-ion type 300 €/kWh, Pb-acid: 150 €/kWh,	Warm water from 85-45°C = 40K 2 €/liter (300 €/200 l) $2 \times 3.6 / (4.18 \times 40) =$ 43 €/kWh stored 4.18 kJ/kg/K	Hydrogen: high storage cost under pressure. Low round trip efficiency. Methanol: low storage cost, low round trip efficiency.
€/kWh	Over 25 years, without interest, at 1000 kWh/kWp/year 20% average degradation 1000 is Belgium, $385 / (800 \times 25) = \mathbf{0.019 \text{ €/kWh}}$ Egypt: 1.5 times lower cost <i>Company</i> $200 / (800 \times 25) =$ <i>0.01 €/kWh, but transport cost</i>	If not subsidized and not abnormally taxed energy bill: Private: 0.1...0.3 €/kWh Companies: 0.06...0,15 €/kWh (Excl VAT.)	1500 equivalent full charges (EFC) Li-ion $300 / 1500 =$ 0.2 €/kWh Pb-Acid 150/500: 0.3€/kWh	15 years, “emptied” 2 times/week $43 / 2 / 52 / 15 =$ 0.0275 €/kWh <i>Ice: equivalent to 80°C temp change:</i> <i>10,8 kg/kWh thermal</i>	Carbon capture to methanol could become the cheapest summer-winter storage. 36.5 GJ/tMeOH [5] = 8.03 kWh/liter MeOH

“Naked” PV panels are considered: *no inverter, no installation, no interest, no benefit, no maintenance.*

The table is for efficiency or COP coefficient of performance =1, one can fill in other numbers as well.

Provisional conclusion: **“Direct PV use is the cheapest energy of today”**, if directly used...

Battery storage can increase the cost of ownership by a factor 10 compared to naked PV. Thermal storage in hot water or ice, does not add too much to the cost. However, compared to battery storage, the grid is still competitive...

-- Cheapest large scale PV at high voltage 0.0179 \$/kWh: a bid in UAE [6] --

History of DC grids and voltage levels, range and losses

Table 2: History of voltage Levels

Approximate period	Application	Nominal DC Voltage
1900-1930	Radio (lead acid)	4.2 V direct heated filament 80 V Anode
1900-1930	very local use	55 V (arc lamp)
1900-1930	small grid	110 V (two arcs in series, or with gap feedback)
1900-now	emergency reserve	120 V (still “safe” DC in dry conditions)
1920-1960	Cars, small Tractors	6 V
1950-now	Cars	12 V (14V alternator)
1950-now	Trucks, busses larger tractors	24 V (28 V alternator)
1995-2000	Automotive <i>project</i> of car voltage	42 V (3x14V)
1900-now	Telecom	48 V
2010-?		300 V+ converter (also higher voltages are used)
1960-now	Digital IC	5 V down to 1.1 V
1960	Analog -- control	12 V, 15 V -- 24V
1960	Measuring	9 V
1980-now	Rectified 220-230 Vac	300 V
1980-now	Rectified 380-400 Vac	550 V
1950-now	Forklifts	48 V
1990-now	Newer forklifts	72 V, 96V, 120 V, 300 V
2000-now	Power factor controller output	380-400 V
2010-now	Automotive, mild hybrid	48 V
2010-now	Automotive, small car	300 V
2010-now	Automotive, large car	375 V Tesla 360 (240-403 V) Renault Zoe
2010-now	Automotive: bus, truck	500-900 V

What voltage level can be used in direct DC?

DC-voltage ranges of common old equipment

Electronic valves around 1925, right two triodes and socket (own)

Left: diode with direct heated cathode 4V (4 wires) Philips Milliwatt

Middle: a triode (4 wires) 1930 Onyx Philips

Right: SBR (4 wires) **20-150V** 3021V



80V battery for anode: 4 rows of 10 Pb-acid cells

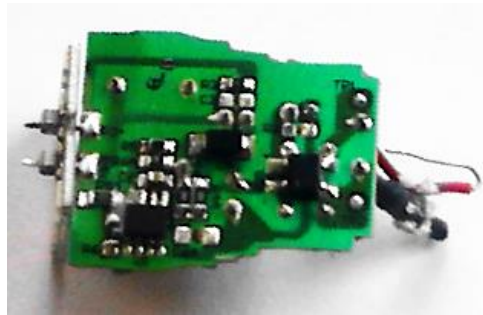
Tudor, around 1925 left: closed, right: open (own)



What voltage level can be used in direct DC?

DC-voltage ranges of common old and new equipment

Inside a wide voltage input LED lamp:
the internal PCB e.g. **80-370Vdc** ↓



DAB+ radio, SMPS supply
Listed 100V-240Vac 50, 60 Hz 5Vdc out
In practice it is **44-370Vdc** input range ↓



DC grids: range and losses at 2.5 mm²

Table 3: distance and power output at 10% drop in a 2.5mm² cable, used at 15A

2.5mm ² Cu wire, 10% voltage drop, $\rho=20 \cdot 10^{-9} \Omega \text{m}$ 16 m Ω /m cable giving 0.24V/m drop at 15A			
DC Voltage [V]	# Panels in series of each 60 Si-PV cells	Length [m]	Power out [W]
12		5	162
24		10	324
48		20	648
96		40	1296
120	4	50	1620
240	8	100	3240
(230 Vac)		(95.8)	(3105)
300	10	125	4050
350	12	145.8	4725
400		166.7	5400

For grids, at 300Vdc: significant more cable length is possible than 230Vac
 300 Vdc is already sufficient for “garden” or as extension cable for hand tools
 For 2% cable loss (= “ECO”-use) divide length by 5 or the power by about 2.3
 120 V and more permits to put it also on a carport or “at the end of the garden”

Table 3: Dual system in DC 300/600 V

Example: (4+PE)x4mm ² Cu cable, 25A/wire, For single phase and DC two wires are used in parallel. in three phase, the three lines, neutral not used (resistivity 20 mΩ m/mm ²) The PE (protective earth does not carry current).		
Voltage	Power [kW]	Loss W/m
(230 Vac)	(11.5)	12,5
(400 Vac 3ph+N)	(17.3)	9.375
300 /600 Vdc	15.0 / 30.0	12.5
350 /700 Vdc	17.5 /35.0	12.5
400 /800 Vdc	20.0 /40.0	12.5

Using 600 Vdc = +and- 300Vdc 10% tolerance grid, 20% tolerance appliances

Charging vehicles at 30 kW is possible with still a light cable (4+PE)x4mm²,

A neutral is needed in the 600 V grid, but not in the cable to the vehicle

But for 30kW the installation should be rather at 10 mm² instead of 4 mm² to limit losses.

The consumption of electric cars to be a bit “ECO” should be rather below 15 kWh/100 km.

What voltage level can be used in direct DC?

DC-voltage ranges of common equipment today

Only AC ranges are given by the manufacturers. However a lot of equipment

❖ **Wide input voltage electronic equipment:** Laptop (I tried DELL and Apple)

Japan: 100 V, -10% 15% ripple: $90 \cdot 2^{0.5} \cdot 0.85 = 108.2$ Vdc

Australia: 240V +10% peak voltage: $240 \cdot 1.1 \cdot 2^{0.5} = 373.3$ Vdc

So, **often** worldwide sold equipment could work from **110 Vdc up to 370 Vdc**

More than 370Vdc could damage the equipment.

Up to now I did not get equipment damaged by a too low voltage:

It means that the designers did design well the brownout case.



❖ **SMPS** (switched mode power supply) in general.

Can be embedded and sold as AC-DC but with DC-DC specifications.

Inrush currents exist in both AC and DC, may be higher with batteries

Without PFC, a possible DC switch is protected by the back-emf of the internal capacitor.

In 50 Hz 20% ripple at 300 V, $\approx 60\text{V}/10\text{ ms}$, below 30V arcing does not easily occur

→ 5ms below 30V, in 230V the AC voltage remains $\approx 0.5\text{ ms}$ below 30V at a zero crossing..

If the power is above 75W, a PFC power factor controller is used to limit the harmonics in AC. It is not clear how these react on DC voltage.

Scooter example:



What voltage level can be used in direct DC, DC ready?

DC-voltage ranges of common equipment

❖ The power of **resistive loads** will reduce quadratic with voltage, a 100 liter, 2.2 kW boiler needs $4.04 \times 40 \times 100 / 3600 = 4.49$ kWh to rise 40K, **at 115Vdc instead of 230Vac it may take 8 hours instead of 2 hours**. Above 250V the resistor must be chopped to avoid overheating

❖ **Led Lamps**, direct use: for basement, underground parking place, inside deep offices...

Non-dimmable may have a wide input DC-Wide voltage range.

As they use a buck converter inside.

Some even give a range between 60-370Vdc giving about the same light,

Thanks to power electronics...

❖ **USB chargers:**

Mobile phones, but also DAB+ radios might be DC compatible.

Their output is often USB.

What voltage level can be used in direct DC, DC ready?

DC-voltage ranges of common equipment

Conclusion for voltage levels:

- A lot of worldwide sold small appliances work from 110-370Vdc (as extreme values)
- Too high voltages may destroy equipment.
- Too low voltages will not operate well, but no damages if the brownout is well designed.
- Manufacturers could give a **DC-label**, e.g. ***DC ready 110-370 Vdc***
- **Higher DC grid voltages:** 350, 400V $\pm 10\%$ should only be used with **an inserted buck converter**
- DC-DC and pulsed converters have a lower B.O.M. and have a much higher efficiency than DC-AC,
the no-load consumption of DC-DC can be 1W or even lower (1.5-3 mA)
- **Pulsed DC** is a solution to retrofit boilers, and other thermostat operated resistors, they should be operated in a dedicated circuit, but if needed still plugged in a conventional wall plug, so backwards compatible for periods of low sunshine.

Common equipment and switches

Common equipment and switches

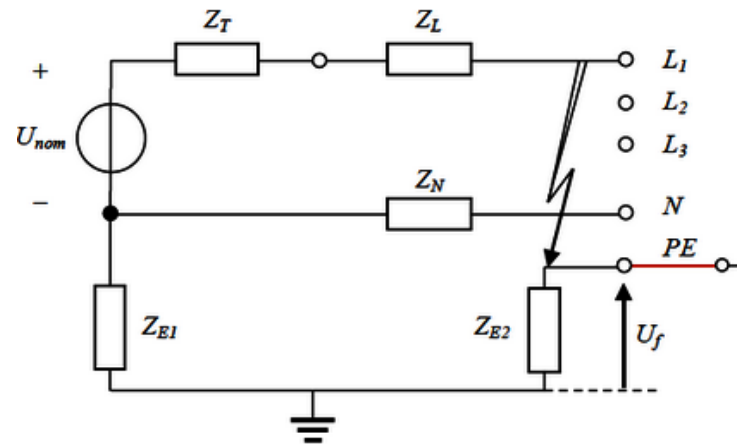
- ❖ In inductive apparatus the problem is arcing at the switch, some have a triac, but that remains “on” after the first trigger.
- ❖ Pure Resistors? The resistors themselves often work as good in DC or AC
The normal plugs seem not to arc when disconnected: the distance is large and even the internal child safety additionally cuts the path. So this can be the case with a simple soldering iron, may be nice for installing PV.
- ❖ Magneto-thermal protection is already widely used in PV strings. They often include magnets to deflect the arc. Some other types try to detect arcing and switch electronically off before mechanic separation.
- ❖ Problem: RCD, differential protection is not common for DC, the ones used with grid inverters switch at the AC side...



Common equipment and switches

Common equipment and switches

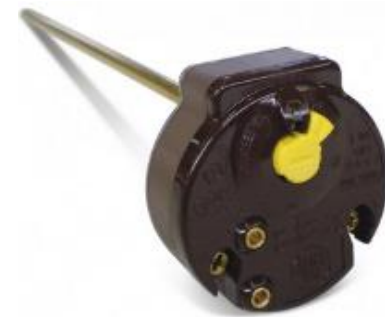
- ❖ Possibly using an IT type of local PV grid:
Insulated and resistance earthed 100 k Ω , seems possible.



- ❖ The problem with resistors is that *thermostats*, switches, will arc.

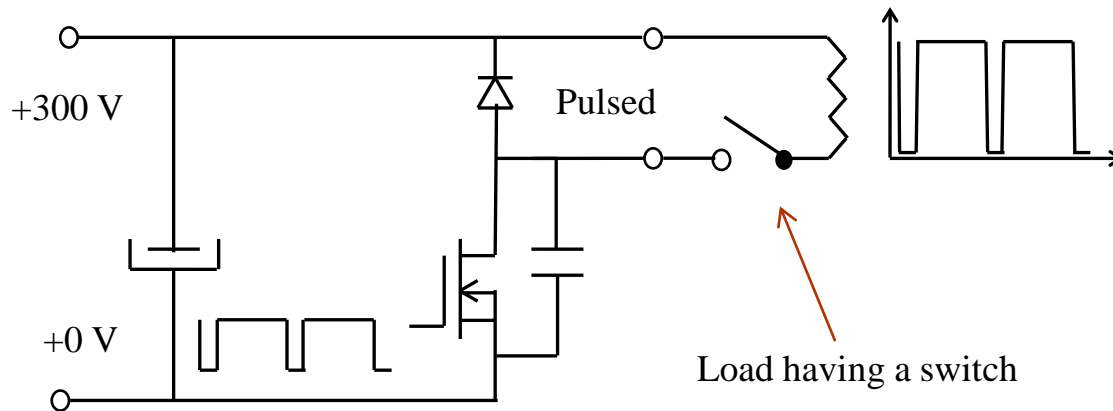
This is a typical problem with boilers and heating devices (form 50Vdc)

This not only the thermostat, (single contact) but also the safety back-up, that disconnects both wires to avoid steam pressure in a boiler.



Pulsed DC principle

Pulsed DC = solution for retrofit equipment with switches/thermostats?



A chopper added to a non-compatible appliance?

If some 1-2 ms interruption is created, the arc has the time to cool down (de-ionize),

This can be created by pulsating the current.

(Limited slopes for radio interference)

- Avoiding problems with switches
- Adapt to the correct voltage using duty ratio
- May be needed inside cooking appliances

Pulsed DC principle

Pulsed DC = solution for retrofit equipment with switches/thermostats?

For higher voltage the on-time should be limited to lower the rms voltage

For lower voltage a minimal off time can be used.

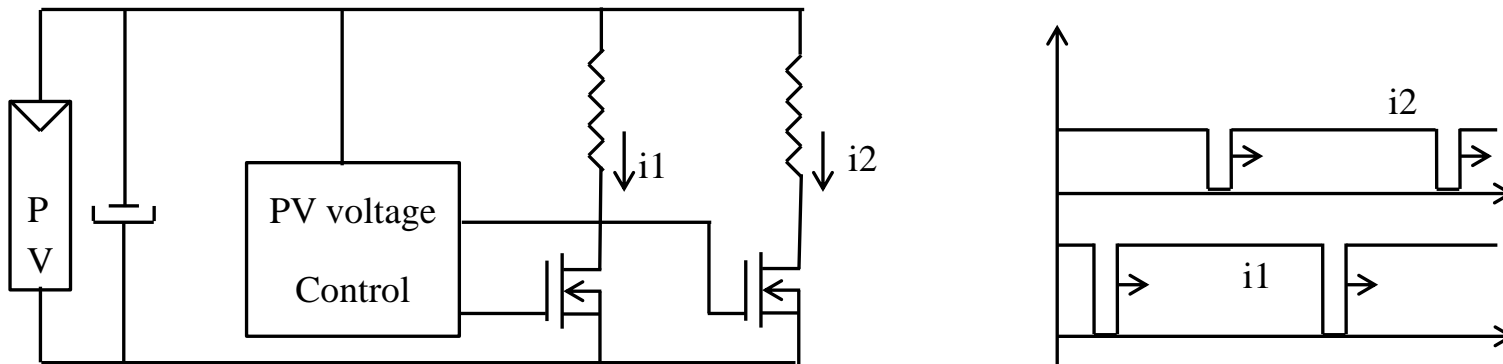
-- even cooking with 300W is possible, (tried out), heat loss to ambient has to be reduced (double cover) and using a minimal water quantity --

**Pulse length for 10 ms period:
Avoid arcing and to correct rms voltage**

DC Voltage [V]	Pulse [ms]	Pause [ms]	Pulsed V [Vrms]
300	5.9	4.11	230.4
330 (= +10%)	4.9	5.1	231.0
360 (= +20%)	4.1	5.9	230.5
270 (= -10%)	7.3	2.7	230.7
240 (= -20%)	8	2	214.7

Pulsed DC principle

Pulsed DC = solution for retrofit equipment with switches/thermostats?



A two phase chopper reduces the AC current in the capacitor: less capacitance needed, and less losses,
Even if the loads are not equal
(e.g. sanitary and sink boiler)

-- This controls the PV voltage, if the voltage increases,
increase the duty ratio. MPP is possible but it works even
without. --

Pulsed DC for storage boilers

1) Often more than one water heater could be present in a dwelling. If only one of 2300 W, it cannot absorb 5 kW if the a full 5 kWp PV is installed. Also to avoid long conducts and may be also a hot fill of laundry, dish washing. May be rain-water for laundry...

- Absorbs the power that is not used by other instruments at that moment.
- It stabilizes the voltage
- The boiler controller should not fully be operated as MPPT (maximum power point tracker): a perfect MPPT would remove most of the power given to other appliances.

2) Cooking plates could be used in “slow cooking”, at noon.
The mechanic thermostat should not be operated in pure DC,
Even 50V is not allowed, but can work with pulsed DC.

Notes:

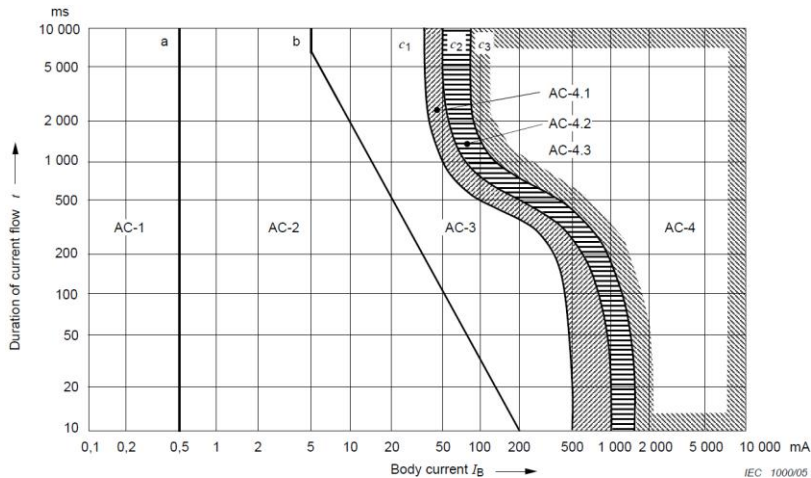
- Standard water boilers have only a limited insulation thickness of 40-60 mm PU, some 120-200mm glass wool should be added.
- Cooking, using one or better two covers need less energy.



Safety of 230Vac compared to 300Vdc

Safety aspects

<http://slideplayer.com/slide/3190614/>



Touch Voltage	5 th percentile		50 th percentile		95 th percentile	
	Hand-hand	Hand-foot	Hand-hand	Hand-foot	Hand-hand	Hand-foot
25	1750	1225	3250	2275	6100	4270
50	1450	1015	2625	1838	4375	3063
75	1250	875	2200	1540	3500	2450
100	1200	840	1875	1313	3200	2240
125	1125	788	1625	1138	2875	2013
220	1000	700	1350	945	2125	1488
700	750	525	1100	770	1550	1085
1000	700	490	1050	735	1500	1050
Asymptotic	650	455	750	525	850	595

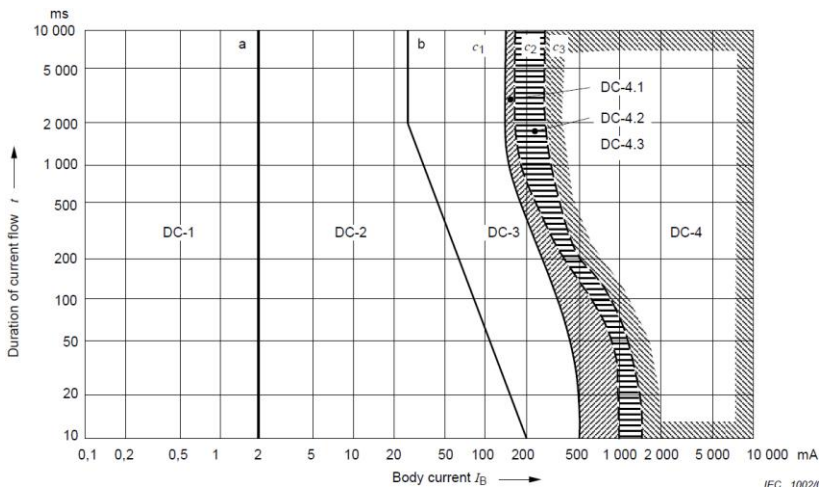
Body impedance typical 800-2000 ohm depending on contact surface

300Vdc, 1000 ohm is below 200 ms, good enough

DC: less risk in long contact time at small contact surface

But the voltage level should not be much higher than 300Vdc

Make connections in PV circuits in the evening...



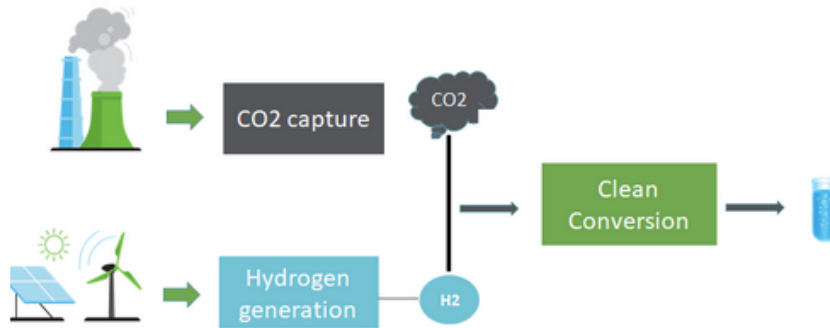
<https://electronics.stackexchange.com/questions/327341/safety-of-current-with-duration> IEC graphs

DC-4 ¹⁾	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1 - c_2	DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2 - c_3	DC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50 %

Future applications with PV or excess PV

Industrial or semi-industrial use of excess energy in sunny periods or “as and when the sun shines”

- **Methanol** : e.g. <http://www.carbonrecycling.is/george-olah/> Iceland since 2011 → solar instead of hydro?
- **Flour mills**
- **Electrolysis and may be other use:** <https://decarbeurope.org/solutions>



Making methanol from renewables



<https://www.youtube.com/watch?v=Bm0q29xv-z0>
Veljibhai Desai Published on Oct 29, 2015

4 frames of 10 panels, 60 cells each
Almost half million such flour mills of 2 HP to 10 HP
for wheat and grain grinding are working in **India**



<https://decarbeurope.org/solutions>
20 fields of solutions....

Future applications with PV or excess PV

Vehicle charging for commuting PV2V

- PV at home: **charges** in the weekend and more **boiler** + other loads during the week
- PV at job: charges during the week and more boiler during the weekend
- **Two times PV is cheaper and less CO2 than a second set of batteries** --

Vehicle charging



Use PV on the roof of vehicles and trailers



<https://www.gprosys.com/why-plasma/>
<http://naturallypowerful.co.uk/solar-services/solar-carports/>

Sono motors Sion

<https://phys.org/news/2010-10-i-cool-solar-air-conditioning-trucks.html>

The remainder should go local to boilers, or still grid.

Within 10 years > 50% of vehicles?

Using low weight PV cells:

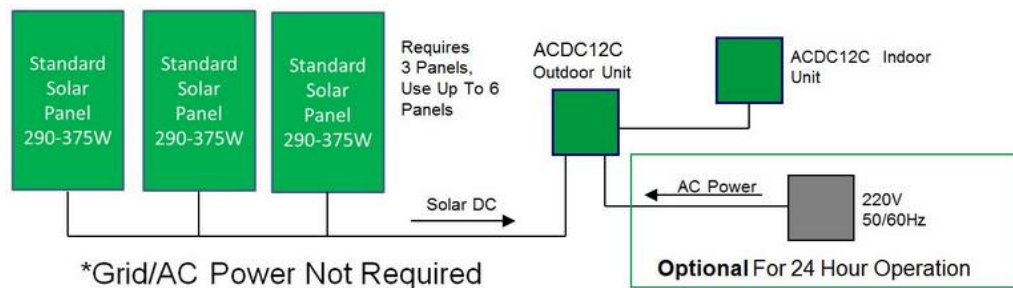
up to 100 Wp/kg in plastic cover type?

Cooling with solar PV without grid nor battery

- **Refrigerator:** a need to store in ice, but could be developed. Small items can use Peltier.
- **Freezer:** if well insulated it can retain for 48-72 hours, could work using the thermal time constant
 - it is not so difficult to oversize the PV so that a fridge or freezer could be used on/off.
- **Compressed air storage: expansion generates cold and power at the same time**
 - It should be changed to “as and when the sun shines”: not well developed yet --

Cooling with solar PV without grid nor battery

- **Air conditioning:** Ice storage cooling systems, to cover needs in the evening or clouds. Reduces the stress on the grid: at maximal sun the distribution transformers run hot. Is more or less state of the art.
- **Air conditioning:** storage in physical ice cubes?
It needs a development “as and when the sun shines”, similar to boilers.



<https://www.hotspotenergy.com/solar-air-conditioner/>
No ice storage: still AC power required for the evening.

<https://www.youtube.com/watch?v=T9CcPZMK-bc>
DIY Solar Ice Maker but uses still a battery

Combined and changed to “as and when the sun shines”

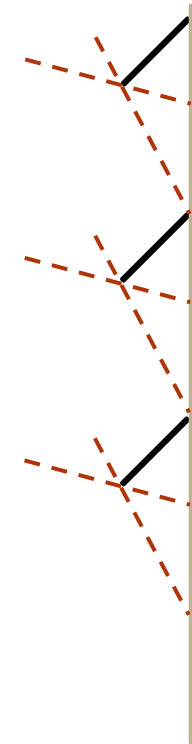
Combine solar PV with shadow

In Belgium the solar PV for south orientation can be designed

- * To allow all sunlight November-February
- * Screen all sunlight at noon in June-July



Photograph of EELAB, Gent, front
18th December = low sun



extreme positions of sun

Conclusion

Conclusion

- ❖ **The naked PV panels** make **cheaper electrical energy than all other means**, it gets expensive if stored in batteries, PV could be the roof, may be cost effective even if all energy is not used
- ❖ **DC use is cheaper** and less no-load than first converting to AC.
- ❖ Much more **home appliances** could work in DC if the instantaneous power is larger than appliance
- ❖ Non used energy could be “dumped” in boilers or similar adaptable loads.
- ❖ There are problems with **switches** for resistive loads, but solutions exist.
- ❖ No RCD residual current circuit breakers for DC
- ❖ Emerging/future **direct use** is growing: Flour mills, methanol...
- ❖ Needed: air conditioning “as and when the sun shines” without grid, with ice storage ?

**A warm/cool
Thank You**

Conclusion

Most of links are in the text, but a bibliography is added to know more about global warming and some proposed results.

BIBLIOGRAPHY – REFERENCES - LINKS

1. Global Warming Potential Values fifth report, IPCC Intergovernmental Panel on Climate Change, <https://www.ipcc.ch/report/ar5/wg1/> Total 1535 pages, 375MB, look at chapter 8, Fig 8.30 for CO₂, CH₄
2. Arctic Sea Ice Graphs <https://sites.google.com/site/arcticseaicegraphs/>
3. Piomas 30% ice remaining in September since 1979
http://iwantsomeproof.com/extimg/siv_monthly_average_percentage_of_79.png
4. New energy solutions for 1.5°C Pathways and technologies to achieve the Paris Agreement, World Business Council for Sustainable Development.
https://docs.wbcsd.org/2018/12/WBCSD_New_Energy_Solutions%20for_1.5C.pdf
5. MarPérez-Fortes, Jan C.Schöneberger, Aikaterini Boulamanti, EvangelosTzimas, “Methanol synthesis using captured CO₂ as raw material: Techno-economic and environmental assessment.
<https://www.sciencedirect.com/science/article/pii/S0306261915009071>
6. LeAnne Graves, 2017, The National A.E. Business, “World’s Cheapest Prices Submitted for Saudi Arabia’s First Solar Project” October 3, <https://www.thenational.ae/business/energy/world-s-cheapest-prices-submitted-for-saudi-arabia-s-first-solar-project-1.663842>
7. Alex Van den Bossche, “Global warming and sea level rise : faster than expected”, International Conference on Advanced Engineering in Petrochemical Industry ICAEPI’17At: Skikda Algeria, keynote paper, November 2017.
https://www.researchgate.net/publication/320961809_Global_warming_and_sea_level_rise_faster_than_expected
8. Alex Van den Bossche , "Electric cars compared to ultra-light electric vehicles and global warming“, The 3rd Renewable Energy Sources - Research and Business conference (RESRB) June 2018.
https://www.researchgate.net/publication/325903828_Electric_cars_compared_to_ultra-light_electric_vehicles_and_global_warming
9. Alex Van den Bossche , “How to reduce the energy needs of electrical and conventional vehicles Conference: Workshop on Electric Mobility WELMO, at: Faculty of Science and Technology– Marrakech – Morocco September 2015
https://www.researchgate.net/publication/281584740_How_to_reduce_the_energy_needs_of_electrical_and_conventional_vehicles

Addendum



<https://www.youtube.com/watch?v=VXKnS0qGjmY>

ADDENDUM:

F2E “for two electric” at Ghent University.

Ultralight closed vehicle under construction, (master student 1m90)

Side windows are not yet mounted in.

Vehicle about 140 kg.

96 V LiFePO₄ battery, about 3kWh/100 km, so much less than 15 kWh/

Design for max speed 90 km/h; 50 km/h in 8 seconds

Two outer rotor BLDC motors, front wheel drive,

Charger can be DC-compatible...



3.24 kWp PV (12 panels of 270Wp) PV used in direct DC use, combined with wood storage, mounted on wooden frame.