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THE CARBON FOORPTINT OF INTEGRATED PHOTOVOLTAICS

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CONTEXT and SCALE

Solar photovoltaic (PV) electricity is deemed to play a pivotal role in Europe to achieve climate neutrality by 2050. By this horizon, from 5 to 10 TW_p of PV must be installed across Europe corresponding to yearly installation rates of 150-300 GW_p/y (for a comparison, the newly added global solar capacity in 2022 was ~270 GW_p). The challenge is therefore huge. To minimize land exploitation, a massive deployment of PV should occur through the **integration of PV in buildings and infrastructures**, including surfaces with sub-optimal orientations. Hence, the question whether this may be justifiable from a carbon footprint perspective arises. Here we show that the carbon intensity of solar electricity in buildings already today is much lower than that of the local electricity mixes for most European countries. The manuscript takes an original perspective on the subject and makes use of the latest figures available for both the carbon footprint of PV and the national electricity mixes in Europe.

SUMMARY

To assess the meaningfulness of installing solar photovoltaics in buildings and infrastructures, we consider a carbon intensity (CI) balance perspective and assess whether installing PV at different orientations acts as a net CO_2 sink or source, when compared to the same amount of carbon that would be emitted using the local electricity mix. The mean values obtained for the CI of PV in buildings in Europe correspond to 41 gCO_2-eq/kWh for a generic rooftop installation. For facades this corresponds to: 51.4, 71, and 214 gCO_2-eq/kWh, respectively, for S-, W/E-, and N-facing facades. Notably, the potential to halve these figures by 2030 already exists. These figures are compared to CI mean values for national electricity mixes: 374.5 gCO_2-eq/kWh. The results indicate that for most countries the integration of PV in facades (often including N-facing PV façades) would not penalize - and conversely support - a transition towards a carbon-neutral electricity mix.

***Keywords**: Photovoltaics, Building-Integrated PV, BIPV, Integrated PV, IPV, Infrastructures-Integrated PV, IIPV, Carbon Intensity, Carbon footprint, Buildings, Energy transition*

INTRODUCTION

The global commitment to reduce greenhouse gas (GHG) emissions and achieve the 2015 Paris Agreement to keep global warming below 2°C – while pursuing efforts to limit the increase to 1.5°C – is not on track. Hence, the European Commission is setting ambitious targets to achieve climate neutrality by 2050, requiring a massive electrification of the mobility and heating sectors, coupled with a major shift towards renewable energy generation sources, among which solar photovoltaic (PV) electricity is deemed to play a pivotal role. By this horizon European member states may have to install from 5 to 10 TW_p of PV power across the Old Continent [1], corresponding to yearly installation rates of 150-300 GW_p/y (for a comparison, the newly added global solar capacity in 2022 was ~270 GW_p). This urgency - in the middle of an energy crisis and with the need to become energy independent from third countries - has presently become even more pressing.

In countries with limited availability of land (e.g. the Netherlands, Malta, Switzerland), however, the full deployment of PV on land conflicts with other land uses, such as agriculture, pastures, forestry. Also in larger countries, the deployment of large solar parks on agricultural land is nowadays increasingly facing resistances from national and local administrations because of land use conflicts. A situation, which in some countries (e.g. Italy) creates serious bottlenecks in the permitting phase, leading to considerable delays in the execution of solar projects and the adoption of national targets. For these reasons, the adoption of PV projects leading to a double land or space use - as for example so called *agri-PV* (i.e. on agricultural land) or *floating-PV* (on water reservoirs) projects – are highly welcomed and presently becoming targeted applications with a considerable market potential.

Nevertheless, a massive deployment of PV in Europe should primarily occur through the integration of PV in urbanized settings and into the built environment [2, 3, 4], including residential, tertiary, commercial and industrial buildings and warehouses, and more in general all available infrastructures. The latter may include: noise barriers along roads and railways, car-parks, water treatment plants, bus and train stations, harbors, and many others. Two examples of building-integrated PV are given in Figure 1, whereas examples of *infrastructure-integrated PV* (IIPV or IPV) and *landscape-integrated PV* are given in the Supplemental Information Section.

However, as opposed to large utility-scale plants, for which it is generally easier to have an optimal (or close to optimal) PV array exposure, this becomes more difficult when integrating PV in buildings or infrastructures, as the constraints will typically be set by the physical arrangement of the building skin or surface. Hence, the lifelong energy yield of a "solar active skin" will be impacted by the sub-optimal orientation [5, 6].

To assess the meaningfulness of installing PV in surfaces with sub-optimal orientations, we do not take an economical perspective - a topic recently reviewed by Gholami and Rostvik [7] - but that of a carbon intensity (CI) balance. To do this, we first asses the generating potential (insolation and PV energy yield) of non-optimally exposed surfaces in buildings (and elsewhere) for different European cities distributed at different latitudes (from 35° to 60° N); and then assess for all European countries whether – on a time horizon of 30 years – installing PV at different exposures acts as a net CO_2 sink or source, when compared to the same amount of carbon that would be generated over the same timeline using the local electricity mix. Since the solar electricity generated in buildings is generally consumed on site (or on its proximity), for a fairer comparison we focus here on country's electricity consumption - rather than generation - figures at the low-voltage (LV) grid, therefore including transmission and distribution losses.

Both CI figures for PV and the national electricity mixes make use of the most updated life cycle estimates available in the literature. For solar PV, we make as well use of a *greener-PV* scenario (in which carbon emissions from PV are halved), which is consistent with a further reduction of the carbon embedded in the construction of solar PV expected in the coming years.

In short, our primary research question can be summarized as follows: *is the integration of PV in sub-optimal orientations justifiable from a carbon-balance perspective?*

The results are somehow surprising for most countries and clearly laydown the pathway for a massive adoption of solar electricity into the built environment. Finally, we come out with indications and recommendations for the policy maker to help them achieve this target. The perspective adopted in this manuscript is primarily European but could easily be transferred to other countries and regions of the word.

As per the solar PV potential in European buildings (and infrastructures), as recalled in the Supplemental Information Section, some numbers are available in the literature, but would require the implementation of a dedicated solar cadaster to obtain more reliable figures.

Figure 1- South- and north-facing BIPV facades: The top row shows the south- (left) and shaded north- (right) facing BIPV facades of a high-rise office building in Milan (Italy). The building has undergone a major renovation process in year 2020. The bottom row shows the east- and north-facing façade (left) of a building of

the life-science department at the University of Neuchâtel (Switzerland), renovated in 2021 and (right) cladded on all surfaces with integrated solar panels.

RESULTS

Solar resources and PV system energy yield

For three different cities spanning most latitudes in Europe (Malta, Milan, Oslo), Figure 2 shows the ratio of H and EY for different PV system exposures, normalized over the same parameters calculated for an optimal exposure, i.e. south-facing at S-opta. This includes values for a flat roof (*flat*), for an average rooftop PV installation (*Avg roof*), and for installation facing the different cardinal points at 45°- and 90°- (facades) tilt, respectively. *Avg roof* values represent an average value for PV systems integrated or applied onto rooftops applying a constant 17% loss rate, which accounts for misalignments with respect to an optimal exposure (i.e. S-opta). This loss rate is computed by averaging the yearly EY of a south-, west-, and east-facing PV system at 45°-tilt.

With respect to an optimal PV energy yield, as can be observed in Figure 2, the potential of facades in Europe varies from **60% to 76%** for Malta (35°N) and Oslo (60°N), respectively, for **S-facing facades**; from **46% to 49%** (*idem*) for facades with a **W and E orientation**; and from **13.1% to 17.6%** (*idem*) for **N-facing facades**. The corresponding values for Milan (45°N) lie between these two extremes. Differences between E and W orientations are generally low and, for a given location, may be due to the presence of different horizons, weather conditions or far-shading. Similarly, for a mid-latitude city as Milan, the difference in the yearly electricity generated of a PV system installed in a *flat roof* or for an *avg-roof* is negligible. This difference is slightly larger in Oslo or in Malta, but as a first approximation, we can consider the two values to correspond. In the following, for conciseness we will present data for flat roofs only.

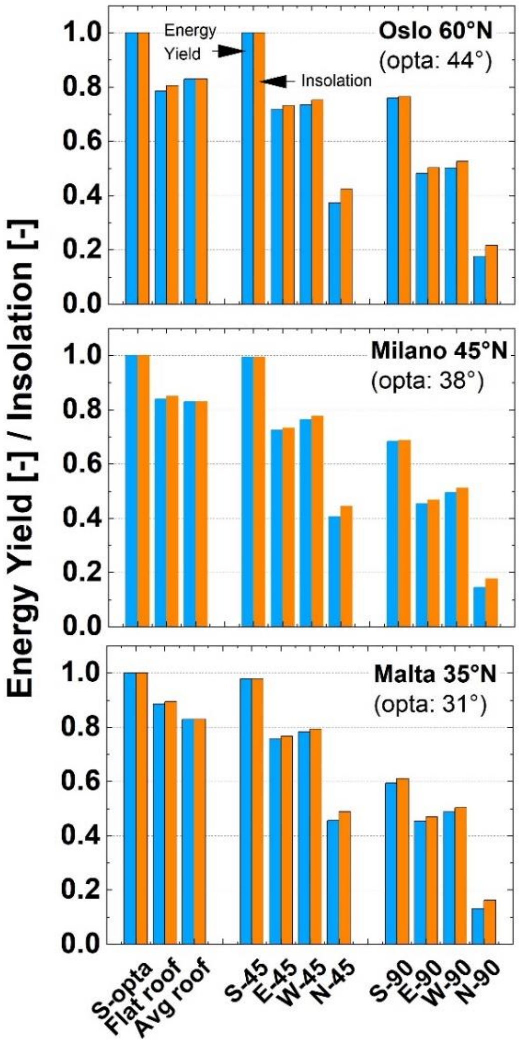

Figure 2 - Solar resources and PV energy yield (three cities). Ratio of the insolation H [kWh/m^2·y] (orange) and the yearly energy yield EY [kWh/kWp·y] (blue)) of a PV system for different exposures normalized over the same parameters calculated for an optimal orientation (S-opta) for three cities in Europe located at different latitudes (from Ref. [8]).

Carbon balances

Out of the European capital cities listed in Table I and III, we select three cities emblematic of different cases:

a. **Oslo**: a high-latitude city (60°) with a low insolation (1'130 kWh/m^2·y) and a very low CI of the national electricity mix (31 gCO_2-eq/kWh);
b. **Bratislava**: a mid-latitude city (48°) with the insolation of a typical Central European location (1'509 kWh/m^2·y) and the CI of the national electricity mix (346 gCO_2-eq/kWh) close to the European average (i.e. 374 gCO_2-eq/kWh);
c. **Athens**: a Mediterranean city (38°) with relatively high insolation (1'932 kWh/m^2·y) and high CI of the national electricity mix (780 gCO_2-eq/kWh);

Understandably, as can be inferred by the data in Table I and III, Oslo and Athens represent two extreme cases, whereas the results for Bratislava are representative of a large number of European cities and countries. For these three cities we compute:

1. The cumulative energy yield (MWh/kW_p) generated by a PV plant under the assumption of a 30-year-long service lifetime (and an annual degradation rate of -0.7%/y);

2. The amount of CO_2 that would be emitted by the same plant over the same lifespan using current PV CI figures (*PV-2021*) and under a scenario with reduced PV GHG emissions (*greener-PV*). These values are compared to - and normalized over - the amount of CO_2 that would be emitted to generate the same amount of electricity using the present CI of the local electricity mix.

The results are presented in Figure 3 for these three cities. For Oslo it becomes obvious that a carbon intensity balance is not in favor of PV, not even for good system exposures (i.e. S-opta, *flat*, S-90°). This situation would change in the *greener-PV* scenario with a reduced CI of PV, for which only E-, W- and N-facing facades would not be fully justifiable from a carbon-balance perspective.
On the contrary, in Bratislava, and understandably even more in Athens, the carbon balance is largely in favor of PV, even - and not without a surprise - for the N-facing facade. In the case of S-opta and N-90° PV installations in Bratislava, the carbon emissions would correspond to only 10% and 62% of that that would be emitted over the same lifespan using the present CI of the national electricity mix.
In Athens the corresponding ratios would be only 3% and 24%, respectively, and in Oslo 146% and 830%.
In the previously mentioned *greener-PV* scenario, a reasonable target for 2030, all these figures would be halved. Therefore, in Bratislava, Athens and the vast majority of European countries (as demonstrated in the next Section), even a N-facing PV façade (receiving on average only approximately 15% of the yearly cumulative irradiance received by a surface with an optimal exposure) can be fully justified if a carbon-balance perspective is considered.

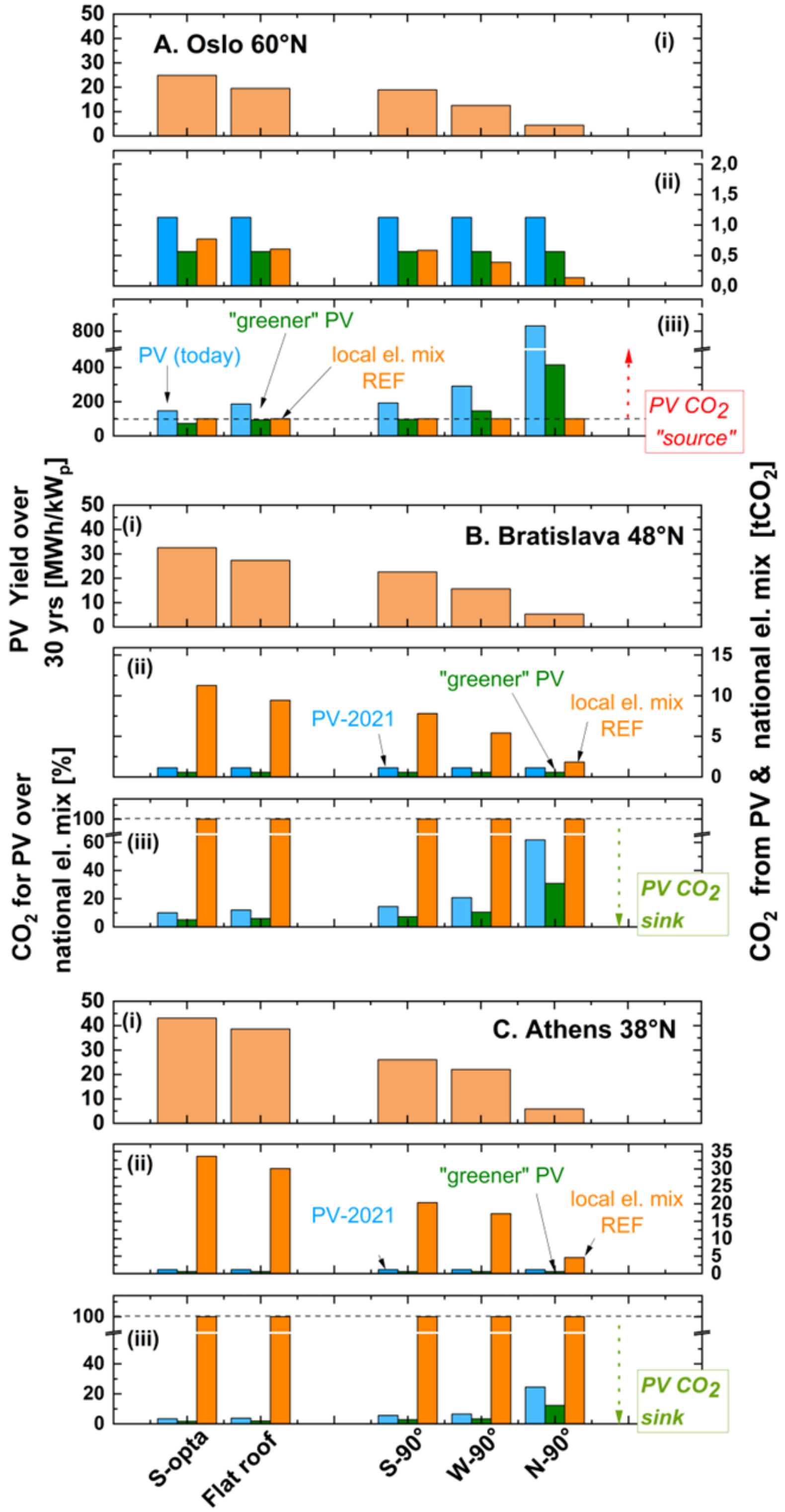

Figure 3 – Carbon emission of PV vs local electricity mix (three emblematic cases). A. Oslo (60°N); B. Bratislava (48°N); C. Athens (38°N). (i) Cumulative energy yield (kWh/kW$_p$) over 30 years – as a function of different orientations - for a PV system; (ii) shows the amount of CO_2 that would be emitted by the same plant over its service lifetime using current PV CI figures (*PV-2021)* and under a scenario with a reduced (i.e. 50%) PV CI (*greener-PV*). The amount of CO_2 that would be emitted to generate the same amount of electricity using

the CI of the national electricity mix is shown as well for a comparison (orange bars) and is used to normalize the corresponding values in (iii). The results for an E-facing facade are well aligned to the case of a W-facing façade and are therefore omitted.

Carbon intensity of PV vs national electricity mixes

By adopting the same methodology and dividing the lifetime CO_2 emissions of a PV system (which are nearly entirely attributable to the manufacturing of the different components, with a smaller contribution from their shipment) over the energy yield [kWh/kW$_p$·y] of the PV system installed at different exposures, we can compute the CI of PV for the different capital cities of Table I.

The carbon intensity of PV in the different capital cities as a function of the CI of national electricity mixes for all European countries is presented Figure 4 for different orientations and tilts: *i.* south orientation at optimal tilt (S-opta); *ii.* flat roof; *iii.* 90°-tilt façades with orientation to the south (S-90°), to the west (W-90°) and to the north (N-90°). Results for east-facing facades are generally very similar to west-facing ones and are therefore omitted. The dashed line corresponds to a CI of PV = CI of electricity mix. For the points (i.e. countries and orientations) lying above or below the dashed line, PV has a larger or lower CI, respectively, when compared to the current electricity mix of the specific country.

Figure 4 (a) is divided into three sections, which are then magnified for more clarity. Fig. 6 (b) shows the low end of the abscissa scale (0-300 gCO_2-eq/kWh). In this chart a restricted subsection of countries (AL, IS, NO, SE) lies above the straight line for all orientations, although only slightly for the S-opta orientations. These countries (with the exception of Albania) are all high latitude countries with low CI electricity mixes due to a large use of renewables (and some nuclear in the case of Sweden). For another restricted group of countries (CH, FR, FI, DK) with low CI electricity mixes, PV is below the threshold (dashed line) for all orientations with the exception of the N-facing façade. The other countries in this portion of the original chart (BE, AT, ES) all lie below the dashed line for all orientations, including N-facing façades. Meaning that in these countries the carbon footprint of the electricity generated by a N-facing PV façade over its entire life span (i.e. 30 years) is already lower than that of the local electricity mix.

This is the same situation for all the countries lying in Figure 4 (b) (abscissa: 300-600 gCO_2-eq/kWh), where most countries are represented, and (c) (abscissa: 600-1000 gCO_2-eq/kWh), which represents countries with very large CI of electricity mixes, largely due to an extensive use of coal.

The same values of Figure 4 are listed in Table I and - normalized over the CI of the national electricity mixes - summarized in Table A.1 (see Supplemental Information Section)

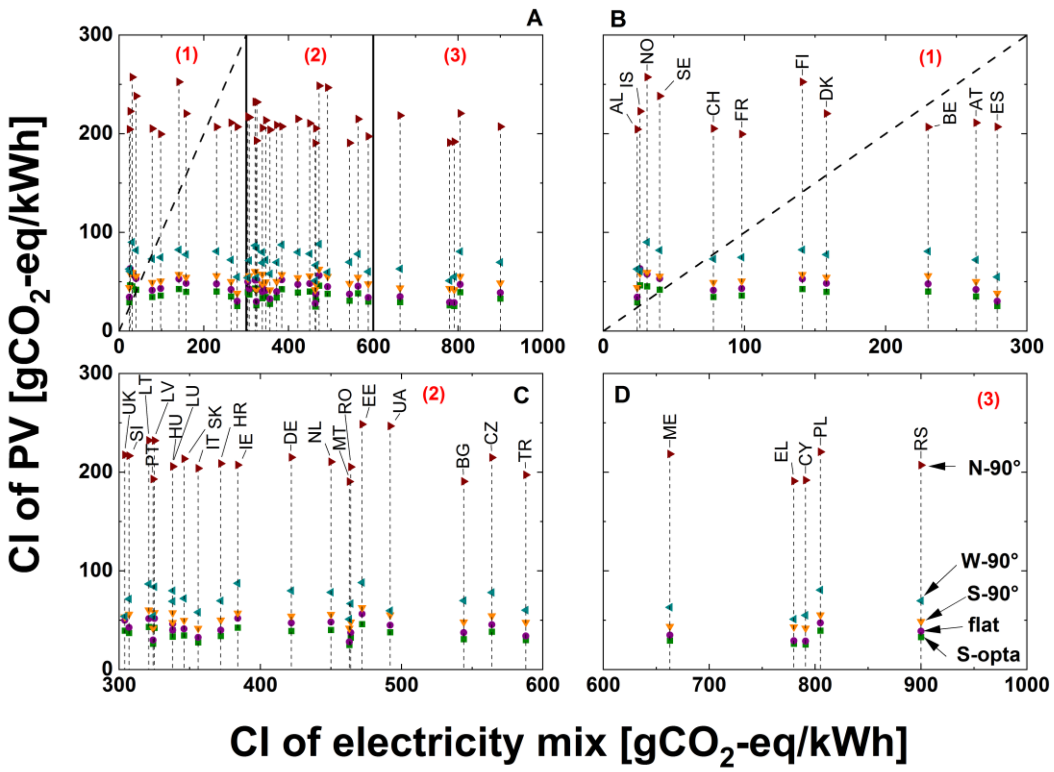

Figure 4 - Carbon emission of PV vs local electricity mix (all Europe). Carbon intensity of PV in the different capital cities vs the CI of national electricity mixes for all European countries as a function of different exposures (orientation and tilt): i. south orientation at optimal tilt (S-opta); ii. flat roof; iii. 90°-tilt façades with south- (S-90°), west- (W-90°) and north-orientation (N-90°). Results for E-facing facades are very similar to W-facing ones and are therefore omitted. Fig. 4 (a) is divided into three sections (1, 2, 3), which are magnified for more clarity. The dashed line corresponds to a f(x)=x line: i.e. for the points lying above or below the straight line, PV has a larger and lower CI, respectively, when compared to the electricity mix of the same country. Note that the four charts have the same scale in the ordinates but differ in the abscissas. In the *greener-PV* scenario (for 2030 and beyond) all values for the CI of PV would be halved (see Figure 5 (A)).

Table I: Carbon intensity of the national electricity mixes (i.e. consumption figures at the low-voltage grid), compared to that of PV in the different capital cities of EU-27 member-states and other European countries as a function of different exposures (orientation and tilt): i. south orientation at optimal tilt (S-opta); ii. flat roof; iii. 90°-tilt façades with orientation to the south (S-90°), to the west (W-90°) and to the north (N-90°). Results for E-facing facades are very similar to W-facing ones and are therefore omitted. The last row presents the mean values of the distributions. The same values – normalized over the CI of the national electricity mix – are listed in Table A.1. In the *greener-PV* scenario all values for the CI of PV would be halved. The same values – normalized over the CI of the national electricity mix – are listed in Table A.1 (see Supplemental Information Section).

Country	Country code	Capital	CI elect. mix	S-opta	Flat roof	S-90°	W-90°	N-90°
			[gCO_2-eq/kWh]	[gCO_2-eq/kWh]	*[idem]*	*[idem]*	*[idem]*	*[idem]*
Austria	AT	Vienna (48.2N, 16.4E)	264	35.1	42	50.2	72.2	211
Belgium	BE	Brussels (50.8N, 4.4E)	230	40.1	47.9	56	80.8	206.9

Bulgaria	BG	Sofia (42.6N, 24E)	544	30.8	37.4	48.1	69.9	190.6
Cyprus	CY	Nicosia (35.1N, 33.2E)	791	25.5	28.9	41.8	55.1	192
Czechia	CZ	Prague (50N, 14.5E)	564	38.3	45.5	54.4	78.1	214.8
Germany	DE	Berlin (52.5N, 13.4E)	422	39	47.3	54.2	79.9	215.1
Denmark	DK	Copenhagen (55.7N, 12.6E)	158	39.8	48.3	54.5	77.6	220.5
Estonia	EE	Tallinn (59.4N, 24.8E)	472	46	56.5	62.8	88.1	248.6
Greece	EL	Athens (38N, 23.7E)	780	26.1	29.1	43.2	51.1	191.1
Spain	ES	Madrid (40.4N, 3.7W)	279	25.5	30.4	38.3	54.8	207
Finland	FI	Helsinki (60.2N, 24.9E)	141	42.6	52.9	57.3	82.5	252.5
France	FR	Paris (48.9N, 2.3E)	98	36	43.2	50.7	74.7	199.7
Croatia	HR	Zagreb (45.8N, 16E)	372	34.1	40	50.2	69.8	208.8
Hungary	HU	Budapest (47.5N, 19.1E)	338	33.3	39.9	47.6	69.2	205.8
Ireland	IE	Dublin (53.3N, 6.3E)	384	42.5	52	57.1	87.5	207.4
Italy	IT	Rome (41.9N, 12.5E)	356	27.6	32.6	41.8	58.1	204
Latvia	LV	Riga (56.9N, 24.1E)	325	42.3	51.8	57.7	83.8	232
Lithuania	LT	Vilnius (54.7N, 25.3E)	321	43.2	51.5	60.5	86.7	232.2
Luxembourg	LU	Luxembourg (49.7N, 6.1E)	338	39.7	46.2	57.6	79.9	205.7
Malta	MT	Valletta (35.9N, 14.5E)	463	25	28.2	42	51.1	190.4
Netherlands	NL	Amsterdam (52.4N, 4.9E)	450	40.1	48.2	55.9	78.2	210.6
Poland	PL	Warsaw (52.2N, 21E)	805	39.4	47.3	55.3	80.7	220.5
Portugal	PT	Lisbon (38.7N, 9.1W)	324	26.1	30	41.8	54.3	193
Romania	RO	Bucharest (44.4N, 26.1E)	464	32.2	37.5	48.2	66.9	205.4
Slovakia	SK	Bratislava (48.1N, 17.1E)	346	34.6	41.2	49.9	72	213.6
Slovenia	SI	Ljubljana (46N, 14.5E)	307	37.2	42.6	56.2	71.5	216.6
Sweden	SE	Stockholm (59.3N, 18.1E)	40	41.9	53.2	55.6	81.9	238.2
Iceland	IS	Reykjavik (64.1N, 21.9W)	26	46.4	63.3	58.7	60.6	222.8
Norway	NO	Oslo (59.9N, 10.6E)	31	45.3	57.7	59.6	90.2	257.4
Switzerland	CH	Bern (46.9N, 7.4E)	78	34.7	41.3	49.4	73.1	205.2
United Kingdom	UK	London (51.5N, 0.1W)	304	39.4	50	53.5	54	217.5
Ukraine	UA	Kiev (50.4N, 30.5E)	492	37.8	45	55.4	59.7	246.7
Serbia	RS	Belgrade (44.8N, 20.4E)	900	33	38.9	48.7	69.7	207.1
Albania	AL	Tirana (41.3N, 19.8E)	24	29.3	34.3	44.1	62.9	204.4
Montenegro	ME	Podgorica (42.4N, 19.3E)	663	29.4	34.9	43.7	63.1	218.5
Turkey	TR	Istanbul (41N, 29W)	588	30	34	47.9	60.3	197.4
Mean (all)	-	-	**374.5**	**35.8**	**43.1**	**51.4**	**70.8**	**214.2**
Mean (greener-PV, 2030+)				**17.9**	**21.5**	**25.7**	**35.4**	**107.1**

The data of Table I (and Figure 4) are rearranged in Figure 5 showing the probability distribution (and box and whisker plots) of the CI of PV systems for all exposures and all European countries. These distributions are primarily affected by the different availability of solar resources in the different capital cities and are largely symmetric. The mean values of the distributions are listed in the last line of Table I. For the same countries, Figure 5 (b) compares the same set of values to the present distribution of the CI of national electricity mixes. In the greener-PV scenario – a target potentially at reach for 2030 (see Methodology Section) - all values for the CI of PV would be halved.

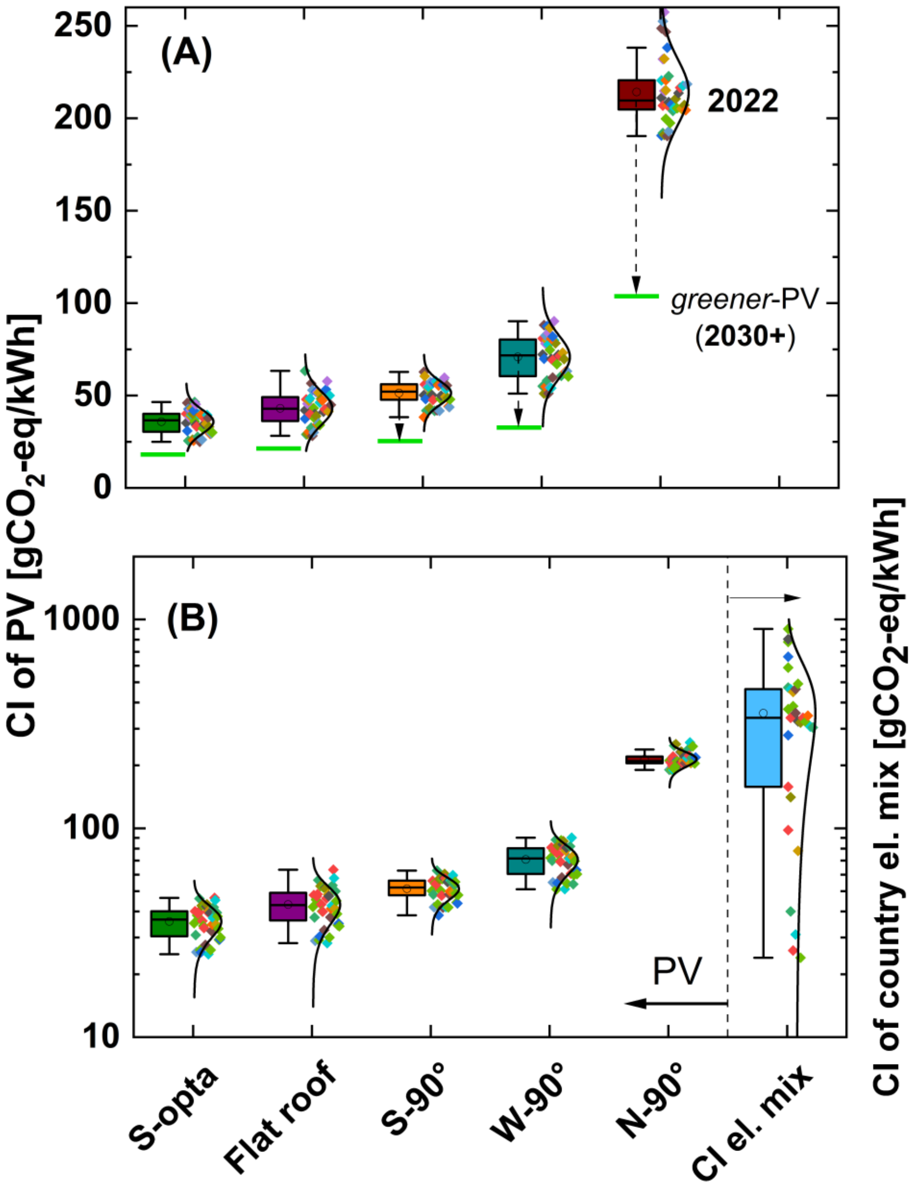

Figure 5 - Carbon emission of PV vs local electricity mix (all Europe). (A) Probability distributions (and box and whisker plots with mean, median, and quartiles) of the CI of PV systems for all orientations and all

European countries. The distribution is largely affected by the different annual insolation levels of the different capital cities. In the *greener-PV* scenario all values for the CI of PV would be halved (for more clarity only the mean values of the distributions are shown). The same values are compared in (B) to the distribution of the CI of national electricity mixes (note: the scale of the y-axis is here logarithmic).

Finally, for the different European countries Figure 6 shows the CI of the national electricity mixes plotted as a function of the yearly cumulative irradiance for an optimally oriented PV system (S-opta) in the capital city of that country. In the plot, the two dashed lines correspond to the mean values (taken from Table I) of the CI distributions for PV in a West- (70 gCO_2-eq/kWh) and North-facing façade (214 gCO_2-eq/kWh) and help us divide the chart into three sub-sections: (1) a very restricted pool of countries (four and labeled: *(PV) not in the first place*) for which the CI of PV is slightly higher (even at the optimal exposures) when compared to the CI of the national electricity mix; (2) a similar number of countries for which only an installation in N-facing facades would lead to a higher CI for PV (i.e. *No N-facing (PV)*); (3) the vast majority of the countries (i.e. *PV everywhere*) or which PV would act as a net carbon sink irrespective of the exposures (including N-facing facades).

These results clearly indicate, not without surprise, that for the vast majority of European countries a N-facing PV façade would not penalize a transition towards a carbon-neutral electricity mix and would therefore be fully justified if a carbon balance perspective is considered.

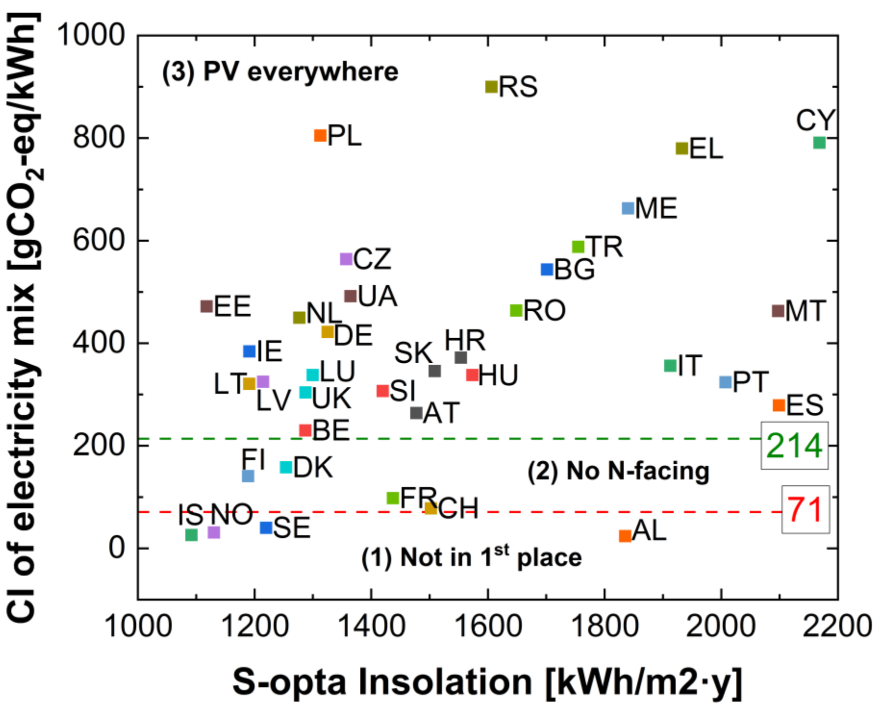

Figure 6 – where does PV go first? CI of the national electricity mix as a function of the yearly cumulative irradiance for an optimally oriented PV system (S-opta) in the capital city of that country. The two dashed lines correspond to the mean values for European countries of the CI distributions for PV in a W- (71 gCO_2-eq/kWh)

and N-facing façade (214 gCO_2-eq/kWh), highlighting three sections: (1) *(PV) not in the 1st place*; (2) *No N-facing (PV)*; (3) *PV everywhere*.

DISCUSSION and RECOMMENDATIONS

PV at sub-optimal orientations

Massive integration of solar electricity in buildings and infrastructures will need to be pursued through the integration of PV onto/into surfaces with sub-optimal orientations, as the availability of ideal surfaces will understandably be limited, or not possible because of the presence - for example - of persisting shading. If we focus on buildings or infrastructures, several reasons may lead us to promote the integration of PV in facades:

(1) **South-facing PV façade**s (or high-tilt orientations) have a more stable generation profile throughout the year, as shown in Figure 7 (a) which plots the monthly generation profile – as a function of different orientations and tilts - for a 1 kW_p PV system located in Milan (Italy, 45° N). This helps maximizing PV production in winter [9] – a season in which several mid- or high-latitude countries may have shortages of supply from renewable energies – and prospectively reduce the impact of high PV generation in summer months during the central hours of the day.

(2) **East- or west-facing PV façades** may help shaving and shifting peaks of PV generation throughout the day, generating power during periods of the day when the electricity may be more valuable, due to supply-demand imbalances, and potentially alleviating stresses to the grid that may arise during the periods of high PV electricity injection into the grid (i.e., summertime at midday). The hourly generation profile on the 21st of March of a 1 kW_p located in Milan is shown in Figure 7 (b), clearly highlighting that, despite the lower daily electricity production, E- and W- facing facades maximize the generation of electricity in the early and late hours of the days, respectively.

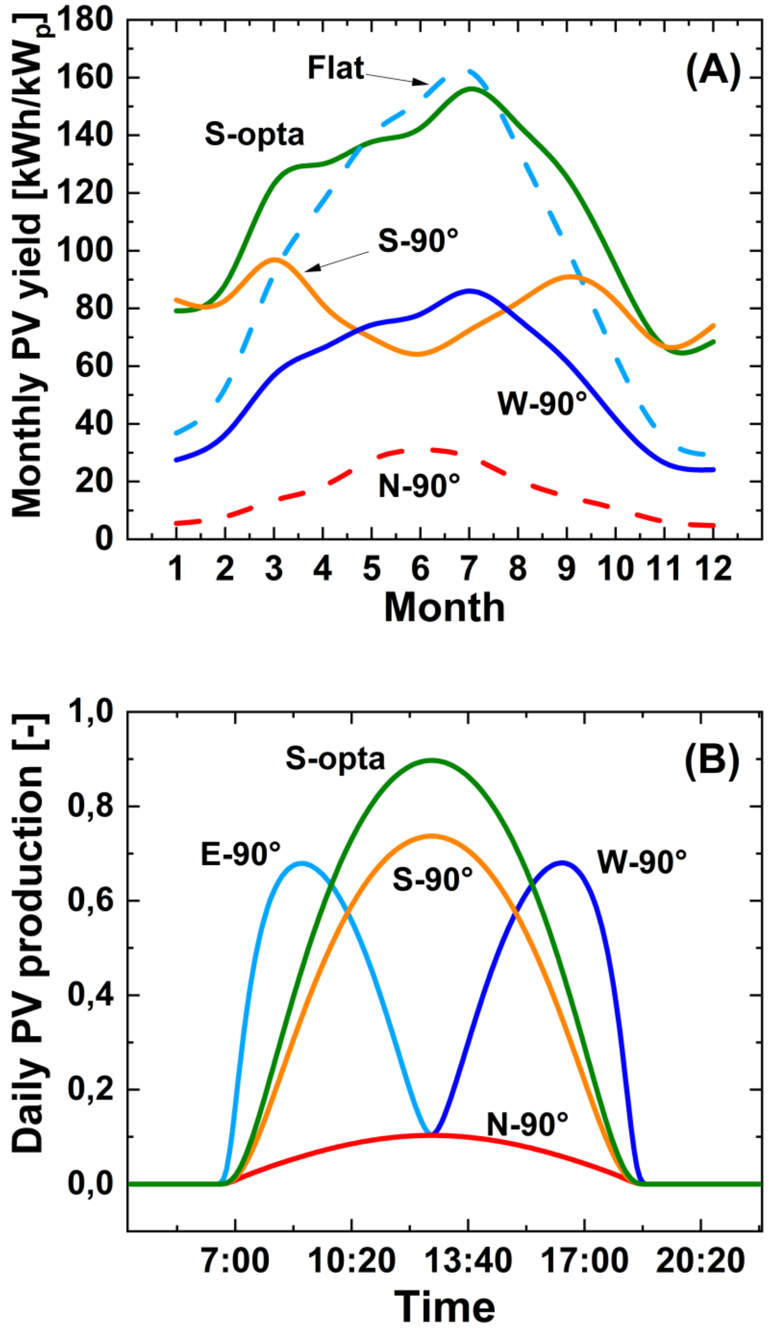

Figure 7 – Monthly and daily generation profiles of PV for different orientations. (a) Average monthly electricity generation of a $1kW_p$ PV system installed in Milan (Italy, 45° N) as a function of different orientations and tilts; (b) hourly generation profile (in arbitrary units) on the 21st of March for the same plant as a function of different orientations and tilts (source: JRC's PV-GIS [8]).

(3) North-facing PV façades: as shown in the previous Section, carbon footprint considerations for PV tell us that solar electricity today is fully justifiable in the vast majority of European countries and for most orientations, including – most of the time – north-facing facades, which receive on average only approximately 15% of the yearly cumulative irradiance received by a surface with an optimal exposure.

Finally, if we consider the countries that are placed in the two lowest quadrants of Figure 6, the CI of PV compared to the CI of local electricity mix, may serve as a first (but not unique) discriminant to incentivize the adoption of PV in buildings and infrastructures, pointing out that in countries with a low CI of the national electricity mix - and massively relying on nuclear power for their electricity supply (e.g. France, Switzerland, Sweden, …) - other elements should simultaneously be weighted. Citizens in these countries may in fact oppose the use of a technology (nuclear fission), which will leave a huge burden and dangerous legacy to the coming generations in terms of disposal of nuclear fuels and infrastructures and of the costs needed for the decommissioning of the nuclear power plants. In addition, in countries planning nuclear phase-outs (Germany, Switzerland, …) PV will clearly be in the future a valid alternative to other energy sources to lower or preserve a low CI budget of the national electricity mix.

Finally, we should mention that there are no supply limits for photovoltaics. Hence, installations penalizing energy-yield should not be avoided. This understandably would not be the case if the production of silicon or panels was limited.

Caveats: BIPV and moving targets

In this section, we want to highlight a few shortcomings of our analysis. Firstly, when considering the integration of PV in buildings (or more in general in infrastructures), we generally differentiate between Building-Added PV (BAPV) and Building-Integrated PV (BIPV). This distinction is generally not clear to the layman. In the case of a rooftop installation, for example, a BAPV system is added on top of an existing roof. In the case of BIPV, the PV system is fully integrated into the building envelope, therefore replacing (and providing the functionalities) of a building element, as tiles in a roof.

In the case of full integration (i.e. BIPV), the PV modules are therefore replacing some building elements (the roof tiles of our example) that have an embedded carbon-footprint related to the materials and processes used in manufacturing them. This should ideally be considered and balanced by offsetting the CI of the PV system with that of the replaced building element. Therefore, allowing to further reduce the CI of actual BIPV systems. On the other hand, BIPV modules may often have a lower *total-area efficiency* (depending on cell and edge spacing) or in some cases (mostly in facades, to become complaint with building regulations) may require the adoption of much thicker cover glasses, which would successively require the adoption of more robust mounting structures, in turn partly penalizing the carbon-footprint of BIPV when compared to conventional PV modules and systems. The energy yield of BIPV solutions (and consequently the CI of the electricity generated by them) may also be penalized by the adoption of coloring techniques (or other *transformative* approaches).

In addition, the full integration of PV in the building skin generally exposes the modules to higher operating temperatures that to a given extent penalize the energy yield of the PV system, if compared to a free-standing or to a partly-ventilated BAPV system. Similarly, the operation of PV systems in the built environment (which statistically are more affected by the presence of shading, compared to ground-mounted plants) may in some cases considerably penalize the energy yield of the system [[10]].

In this work, to avoid adding excessive complexity and keep the right focus on our primary research question (i.e. is the integration of PV in sub-optimal orientations justifiable from a carbon-balance perspective?), we do not differentiate between BAPV or BIPV systems. We are therefore: (1) neither offsetting the carbon-footprint of BIPV modules when they are replacing other building elements; nor, when applicable, (2) penalizing the energy yield of the PV system due to a full building integration.

Secondly, the numbers on which our analysis relies on (i.e., the CI of PV and of the national electricity mixes) are both understandably moving targets.

The CI of PV can be further reduced in by further technological progress or -already today -by moving PV manufacturing (particularly the most upstream processes of silicon, wafer and solar cell manufacturing) in countries using electricity with low carbon (C) footprints. This has led us to propose a "*greener-PV*" scenario for 2030 or beyond (see Methodology Section), in which the present CI of PV is halved. This scenario is already within reach, but will highly depend on: (a) the ability of moving a considerable portion of global PV manufacturing outside of China, in countries using electricity mixes with a much lower C footprint than that presently used in China today; or (b) rely on a very rapid transition in China towards a low-carbon electricity mix, a target that does not presently seem to be in sight, despite the considerable progresses made in the country in the last decade.

Analogously, the carbon intensity of electricity shows on average a clear reduction trend since 1990 for most European countries. In the European Union (EU27), the carbon intensity of the electricity used at low voltage decreased from 641 gCO2eq/kWh in 1990 to 334 gCO2eq/kWh in 2019 [27]. This trend is expected to continue in the coming years, particularly in view of the 2050 carbon-neutral targets presently under discussion.

We are therefore aware that with this analysis, we are taking a snapshot at the current situation and that the estimates presented in this work will have to be fine-tuned at regular intervals in the coming future. Nevertheless, in view of the massive integration of PV in the built environment, the outcome of this work clearly indicates that already today in the vast majority of European countries solar electricity is certainly a cost-effective and reliable technology that can be a key enabler for full decarbonization of the energy sector.

Challenges and solutions

We would simultaneously like to put some emphasis on the fact that the massive integration of PV in urban and building contexts will pose some threats in terms of:

1. PV system design;
2. Potential grid imbalances and infrastructure investment costs.

PV system design

A massive integration of solar PV in the built environment may require the adoption of different PV plant design practices, such as:

a. The adoption of micro-inverters or power optimizers (i.e. DC-DC converters) to minimize the impact of shading on the energy yield of PV arrays: Despite the impact on the energy yield, the constant solicitation of by-pass diodes may lead to diode failures and potentially lead to the generation of hot-spots in modules that are exposed to frequent or persisting shading. The integration of module-level electronics or the development of shading-tolerant modules may therefore allow a smoother operation of solar arrays installed in buildings or more in general in urban contexts.

b. Because a PV array rarely produces power close to its STC (standard test conditions) DC rating, it is common practice and economically advantageous to size the AC power of the inverter to be lower than the DC power of the PV array. This ratio of PV array to inverter power is called the DC/AC ratio and it is a good practice to vary it from 1.1 to 1.25. If the PV array generates more energy than the inverter can handle, the inverter will reduce the voltage of the electricity and limit the power output. This mechanism and the consequent power loss are known as *clipping*. Certainly, the DC/AC ratio for the integration in surfaces with a sub-optimal orientation may be much more aggressive and speculatively vary from 1.5 to 2 for east/west facing and north facing facades, respectively.

Low- and medium-voltage grids

The full coverage of roofs in residential areas is expected to require, in many cases, an important and costly reinforcement of the LV grid infrastructure. The latter is in general dimensioned to cope with the potential maximum electric load, but is not designed to sustain high PV generation peaks, especially when the electric consumption is low. High reverse power flows at the MV to LV transformer, exceeding the latter rated limits, and overvoltage situations are emblematic effects of large PV penetration [11, 12, 13]. Installation of PV on most facades is expected to exacerbate the situation and further stress LV grid operation. Fortunately, as shown in Figure 7 (a), roof-top and façade PV systems do not exhibit their maximum power at the same time, reducing the magnitude of the grid impact. S-facing façade production maximum takes place during the winter season when roof-top production is reduced. W- and E- facing facades show their maximum in the evening, respectively in the afternoon, when again roof-top production is lower.

On the other hand, the detrimental effect of the high PV penetration on the LV operation and needs for grid reinforcement can be mitigated by different solutions. *Curtailments* of the PV production by limiting the power that can be injected in the LV grid at all time is the cheapest measure to implement [14]; a relatively severe curtailment can be implemented without affecting too much the yearly production of a PV system. A limit of the injection set at 50% of the PV nominal power only affects the yearly production, in many cases, by less than 10% [13, 15]. *Reactive power control* is another solution to increase PV hosting capacity [13, 16]. As an alternative solution, *electricity tariffs*, on the import and export (i.e. feed-in tariff), can be tailored to reduce PV surplus injection, improving the self-consumption and, incentivizing the deployment of local electricity *storage* [17]. The latter can be provided by a central grid battery, but this option is currently costly and does not alleviate all grid limitations (beside the one set by the MV to LV transformer) or using distributed storage systems at the building level [13, 18]. Storage can be provided by electro-chemical batteries or in the form of thermal storage (e.g. water tanks for the domestic hot water) or by using thermal inertia of building when heating or cooling [19].

Additionally, other form of demand-side management can be implemented to use PV surplus [47, 44]. As an example, the deployment of *electric mobility* is expected to offer much of the flexibility needed for a large penetration of PV. As most of the cars are idle most of the time, their large battery capacity could be used for the storage of excess PV production and therefore use to minimize the impact on the grid [[20],[21]].
Renewable energy communities [[22], [23]] and *microgrids* have also been proposed to help integrate PV at the level of LV grids [[24],[25]]. Energy communities help increasing self-consumption by balancing production and consumption, benefiting of the aggregation of the latter. While such communities offer an easier management of the energy flows to balance production and consumption and potentially attractive economics (for these communities), they do not offer considerable advantage in terms of PV hosting capacity (in comparison to the solutions already mentioned) and marginally reduce exchanges at the transformer level. Nevertheless, they reduce the overall size of energy storage or flexible assets (total capacity for the LV grid) for optimized operation. In short, they modify the grid operation without modifying substantially the total energy exchanged between LV and MV grids.

In addition, one should note that the impact of a large PV deployment on facades is expected to be low on MV grid. PV systems in facades are in general smaller than the ones on rooftops and connected to LV grids. Large system connected to MV include mostly industrial or large commercial sites with large self-consumptions and reduced grid injections.

Recommendations for policy makers

With over 90% of European rooftops and facades unused, a strong need for regulations that encourages all new and renovated residential, tertiary, commercial, and industrial buildings - including infrastructures - in the EU to include PV systems. By 2050 (or better earlier) these systems need to be installed on every appropriate rooftop (or façade) to enable all citizens to become active consumers. At the European level, policy drivers, such as the Energy Performance of Building Directive (EPBD) - amended in 2018 and for which an additional revision is pending to reflect higher ambitions and the more pressing needs for Europe on how to achieve a zero-emission and fully decarbonized building stock by 2050 [[26]] - already exist, and are presently boosting the adoption of renewable electricity generation sources (mainly solar PV electricity) in the built environment. Particularly, in the case of new buildings and in the case of deep renovations. Member states impose directives at the national level, and the requirements are implemented (and can become more stringent) at the regional or municipal levels.

For this reason, based on the analysis presented in this work, we come out with a list of recommendations that should help local authorities adopting favorable building codes and the right policies (including proper incentive schemes) to foster and maximize the diffusion of PV in buildings and infrastructures. These include:

(1) In most European countries, PV installations should be mandatory (in the case of new buildings and renovations) and incentivized by different means (being investment tax credits, feed-in tariffs, direct contributions or net metering schemes, etc.) for all the cases (building or infrastructure) when a surface is exposed to an insolation higher than 40-50% (net of shadows) of that of a south-facing surface exposed at an **optimal tilt** for a given location. This threshold should be country, or even region-dependent and should

be tailored to allow the inclusion of E- and W- facing facades. Particularly, incentives are urgently needed for all the situations where such solar systems cannot contribute significantly to self-consumption (an incentive per-se), which considerably increases the return on investments for this kind of projects.

(2) **Exceptions** to the mandatory installations of PV in buildings/infrastructures should be granted if the above criterium is not met, as well as in the case of impossibility for urban, architectural, or heritage reasons.

(3) Installations in surfaces with **less optimal orientations** (e.g. N-facing facades) should possibly not be incentivized in the first place, but not expressly "prohibited" (or abandoned), as we have demonstrated that, in several countries, they are fully justifiable from a CI perspective. In addition, this may still help in promoting and creating ***PV-awareness*** among citizens, help architects in preserving building harmony/aesthetics, and push market deployment for BIPV and integrated PV (I-PV). Furthermore, they could still make sense from an economical perspective (not considered in this work) in the case of a new building or major renovation project, as they may avoid the adoption of different mounting structures and cladding elements for the different surfaces of the building. With consequently the possibility to simplifying and streamlining the overall building project. Economic considerations for sub-optimal orientations in buildings can be found in Ref. [7].

(4) Finally, we firmly take a firm position against **minimum requirements**, as they are usually set in local codes. A recurrent limitation in existing municipal building codes is that of referring to minimal requirements expressed in terms of nominal capacity per building ground area (e.g. 2 kW_p per 100 m^2). These requirements sometimes lead to the absurd situations where only limited-size PV systems are deployed in surfaces with a much greater potential. This situation is well represented in Figure 8, which shows an aerial view of a newly-built residential housing project recently realized in Canton Vaud (Switzerland). In this specific case, only 10 m^2 of solar PV was installed on most single-family houses when in reality 100+ m^2 (of well oriented PV) could have been installed on most roofs. The situation of such roofs will likely be locked-up for the next 30 years, despite the optimal orientations and solar yield potential of all the neighbourhood. This image is therefore emblematic of a situation in which the integration of PV in a building project (or infrastructure) could have been maximized - due to the clear potential of the area - to avoid an unnecessary exploitation of land elsewhere. The philosophy behind requiring minimal requirements is fully understandable, but relevant incentives should be put in place – as discussed earlier - to consider this as a minimum threshold and incentivize citizens to maximize, whenever possible, the adoption of PV in the built environment.

Figure 8 – Against minimal requirements. Aerial view of a newly built residential housing project recently realized in Bussigy (Switzerland). In this specific case, only 10 m^2 of solar PV was installed on most single-family houses – being fully compliant with the local building requirements - when in reality 100+ m^2 (of well oriented PV) could have been installed on most roofs (credits: Thomas Söderström).

APPROACH, DATA and METHODOLOGY

Solar resources and energy yield of PV systems for different orientations

Insolation (H, [kWh/m^2·y]) and yearly energy yield (EY, [kWh/kWp·y]) data for PV as a function of different exposures are obtained by JRC's (Joint Research Center – European Commission) PV-GIS, a free on-line tool, which uses satellite-derived data to estimate the availability of solar resources [8]. The EY values are obtained for PV systems made with conventional crystalline-silicon (c-Si) and fixed system losses set at 14% (a default PV-GIS value). H and EY for south-facing surfaces at optimal tilt angle (S-opta) - the orientation that maximizes the annual energy yield of a PV plant in the Northern atmosphere- are shown in Table II for the capital cities of EU 27-member states and other European countries.

Table II: Carbon intensity CI of the national electricity mixes (i.e. consumption figures at the low-voltage grid [[27]]), insolation and energy yield for a S-facing PV system at optimal tilt (S-opta, [8]) located in the capital cities of EU27-member states and other European countries.

Country	Country code	Capital	CI elect. Mix [gCO$_2$-eq/kWh]	S-opta Insolation [kWh/m^2·y]	S-opta Energy Yield [kWh/kWp·y]
Austria	AT	Vienna (48.2N, 16.4E)	264	1477.5	1179.9
Belgium	BE	Brussels (50.8N, 4.4E)	230	1287.1	1034.1
Bulgaria	BG	Sofia (42.6N, 24E)	544	1701.3	1343.7
Cyprus	CY	Nicosia (35.1N, 33.2E)	791	2168.2	1623.2
Czechia	CZ	Prague (50N, 14.5E)	564	1357	1082.7

Germany	DE	Berlin (52.5N, 13.4E)	422	1325.3	1061.7
Denmark	DK	Copenhagen (55.7N, 12.6E)	158	1254	1041.4
Estonia	EE	Tallinn (59.4N, 24.8E)	472	1117.7	900.2
Greece	EL	Athens (38N, 23.7E)	780	1932.5	1587
Spain	ES	Madrid (40.4N, 3.7W)	279	2098.9	1625.8
Finland	FI	Helsinki (60.2N, 24.9E)	141	1188.9	972
France	FR	Paris (48.9N, 2.3E)	98	1437.2	1151.3
Croatia	HR	Zagreb (45.8N, 16E)	372	1553.6	1214.3
Hungary	HU	Budapest (47.5N, 19.1E)	338	1573.2	1245
Ireland	IE	Dublin (53.3N, 6.3W)	384	1191.1	975.5
Italy	IT	Rome (41.9N, 12.5E)	356	1912.6	1499.7
Latvia	LV	Riga (56.9N, 24.1E)	325	1214	980.7
Lithuania	LT	Vilnius (54.7N, 25.3E)	321	1191	959.8
Luxembourg	LU	Luxembourg (49.7N, 6.1E)	338	1299.6	1042.9
Malta	MT	Valletta (35.9N, 14.5E)	463	2097.4	1659.8
Netherlands	NL	Amsterdam (52.4N, 4.9E)	450	1276.7	1033
Poland	PL	Warsaw (52.2N, 21E)	805	1312.9	1051.8
Portugal	PT	Lisbon (38.7N, 9.1W)	324	2007.3	1585.4
Romania	RO	Bucharest (44.4N, 26.1E)	464	1648.5	1287.2
Slovakia	SK	Bratislava (48.1N, 17.1E)	346	1508.7	1197.7
Slovenia	SI	Ljubljana (46N, 14.5E)	307	1419.8	1114.3
Sweden	SE	Stockholm (59.3N, 18.1E)	40	1219.7	988.6
Iceland	IS	Reykjavik (64.1N, 21.9W)	26	1091.8	892.3
Norway	NO	Oslo (59.9N, 10.6E)	31	1130.5	915.2
Switzerland	CH	Bern (46.9N, 7.4E)	78	1502.3	1195.5
United Kingdom	UK	London (51.5N, 0.1E)	304	1287.4	1050.8
Ukraine	UA	Kiev (50.4N, 30.5E)	492	1364.5	1095.3
Serbia	RS	Belgrade (44.8N, 20.4E)	900	1606.3	1254.8
Albania	AL	Tirana (41.3N, 19.8E)	24	1835.3	1416.4
Montenegro	ME	Podgorica (42.4N, 19.3E)	663	1840.1	1409.5
Turkey	TR	Istanbul (41N, 29E)	588	1754.9	1382.5

Carbon intensity of solar PV electricity

Life cycle analysis (LCA) is a well-established methodology to evaluate the environmental impact caused by products or processes throughout their entire life cycles [28]. The relevant ISO (International Standard Organization) standard 14040–44 [29, 30] is supported by European guidelines [31] and by PV-technology specific best practices [32, 33]. LCA figures for PV are, however, often outdated, as they do not often reflect the large progress made for this technology in recent years all along the value chain, as well as the massive manufacturing shift to Asia (mostly China) in the last decade. The limits of existing carbon inventories for PV and differences between databases (e.g. electricity mixes, material consumption and energy requirements) is reviewed by Müller and coworkers in Ref. [34].

Several technological improvements have in fact allowed a remarkable reduction in the carbon footprint (per installed W_p or generated kWh of electricity) of crystalline silicon (c-Si) based PV, the dominant PV market technology. This has been achieved over the years through a considerable increase in solar cell and module efficiencies, reduction in material consumption (thanks for example to the use of thinner wafers, reduced wafering losses and lower silicon and silver consumption), and the adoption of more efficient manufacturing processes, including polysilicon production, as recently reviewed by [35]. Just to make two examples, over the last thirty years (1990 to 2020), Si wafer thicknesses have been reduced by at least a factor of two (from 400 to 180 µm) and Si usage per watt-peak by a factor of four (from 16 to around 3 g/W_p). In parallel, with module prices today in the range of 0.2 $\$/W_p$, the combination of technological innovation and economies of scales have led to a cost reduction of the PV technology larger than a factor of 100 since the early 80's of the last century, making solar photovoltaic electricity a major and cost-effective enabler of the ongoing energy transition towards a low-carbon-emission society.

A direct comparison of the different figures available in the literature about the global warming potential (GWP) or CI of PV is further complicated by several factors:

a. Some authors report estimates about the GWP of PV referring to the system capacity (gCO_2-eq/W_p) and others to the electricity generated by the PV plant (gCO_2-eq/kWh).

b. Estimates for the CI of PV per kWh require assumptions about the electricity generated by a PV plant over its guaranteed lifetime (including assumptions about service lifetimes and degradation rates) and largely depend on the installation site, particularly on the local availability of solar resources. This figure is however the most adequate for comparing the GWP of different power generation technologies.

c. Some authors report CI numbers for the full PV system (including inverters and other BOS components) and others about solar modules only;

d. The methodology and the GWP inventories adopted by the different authors to estimate the CI and energy yield of PV during its entire life-cycle may largely affect the outcomes of the analysis.

Fortunately, some updated figures (listed in Table III) have recently appeared in the literature for the CI of PV allowing a more accurate and reliable analysis.

In this work we decided to use the estimates reported by Frischknecht et al. in a recent factsheet report from the IEA (International Energy Agency) [36, 37]. This are relative to a 3 kW_p residential rooftop PV system located in Switzerland. The assumptions used by the author are briefly summarized at the bottom of Table III and are based on a strong carbon mix for the electricity used for the sand to module manufacturing, reflecting manufacturing in China. Under these worst-condition assumptions, PV has a CI of **42.5 gCO_2-eq/kWh** for an energy-yield of 975 kWh/kW_p and assuming a 30-year-long lifetime for the PV plant with an average annual degradation rate of -0.7%/y. According to the same report, the environmental impact – in terms of GHG emissions - of PV systems made with c-Si modules has been reduced from 2011 to 2018 by a factor of 40%.

Table III. Review of recent literature reporting estimates for the CI of PV per installed capacity or per kWh of electricity for PV systems and modules.

Source	**PV module or system**	**CI of PV per capacity [kgCO_2-eq/kW_p]**	**CI of PV per kWh of electricity [gCO_2-eq /kWh]**	**Notes**
Fthenakis et al. [38].	System	1000 (mono, 2020)	40 23 17	Three insolation levels: 1000, 1700, 2300 kWh/m·y (from top to bottom)
Frischknecht et al. [36]	System		**42.5**	**Data used in this work**. Details given below: (*);
Golsdchmidt et al. [39]	System	1270 (mono, 2021)		
Müller et al. [35]	Module	810 580		(G/BS, China, 2021) (G/BS, EU, 2021)

G/BS = glass/back-sheet panel structure, mono: mono-crystalline Si, EU: manufacturing in Europe.

(*) Starting assumptions for the CI of PV ([3-4]): 42.5 gCO_2-eq /kWh for a residential 3 kW_p rooftop PV system (including panels, inverters, cabling, mounting structures) installed in Switzerland (46°N), yearly PV energy yield of 975 kWh/kW_p·y (corresponding to 83% of the energy yield of a S-facing system installed at the optimal angle in Bern i.e. 1175 kWh/kW_p·y); Service life: PV modules 30 years (with an annual degradation rate of -0.7%/y); inverter 15 years. Origin of polysilicon/ingots/cell/modules; CI of Chinese electricity mix: 1190 gCO_2-eq /kWh; Energy pay-back time of PV system: 1.2 years (Switzerland). Breakdown of emissions: 63.5% (panels), 23.5% (inverter), 11.7% BOS, 1.2% (other).

The green-house gas (GHG) emissions associated with the generation of 1 kWh of solar electricity from PV systems are far lower than the emissions from fossil fuel generators, which can emit up to 1000 gCO_2-eq /kWh in the case of coal-fired power plants. Almost all the emissions from the life cycle of PV originate from the manufacture of the different components. There is little impact from end-of-life activities and almost no impact at all from their operation. This is in direct contrast to fossil and nuclear power plants which release the majority of emissions through their ongoing operation and fuel supply.

For all the works reported in Table III, modules (as well as metallurgical-grade Si, ingots, wafers, cells and the aluminum frame [40]) are assumed to be manufactured in China, reflecting the fact that over 80% of global module shipments presently originate from this country.

Even though this share has been decreasing over the last decade, still 65% of Chinese electricity comes from burning coal [[41], 36]). This fact is reflected in the CI of the Chinese electricity mix (i.e. 1190 gCO_2-eq /kWh on the medium-voltage grid; the value used in the Ref. [36, [42], [43], [44]]), which is more than three times higher when compared to the European average (~374.5 gCO_2-eq /kWh on the low-voltage grid tough, see Table I).

Since the energy yield (kWh/kW_p) of a PV plant over its lifetime is strongly site-dependent (primarily depending on the availability of solar resources) and, for a given site, will largely be affected by the plant's orientation and tilt, we use the starting assumption of 42.5 gCO_2/kWh for the CI of PV systems in 2022 (975 kWh/kW_p, see details in Table III) and correct these values to reflect the energy yield of PV plants installed in different locations in Europe and for different orientations (see Table II). This is done by using the same assumptions: a plant service lifetime of 30 years with an annual performance degradation rate of -0.7%/y [45]. Understandably, the CI of solar electricity will highly depend on the lifelong generation of a PV plant, which is highly site-dependent and highly impacted by the system exposure.

Similarly, we make use of a scenario ("*greener-PV*") in which the CI of PV is halved (i.e. 21.2 gCO_2-eq/kWh, as base value). This is a scenario potentially reach 2030 (and beyond) reflecting two main drivers: (1) further reduction of GWP of PV following additional technological evolution and innovation; (2) manufacturing of PV panels and other components outside of China: in countries with a low-carbon electricity mix. This includes the possibility of reshoring manufacturing back to some European countries, presently a highly discussed and sensitive topic at the European level.

As previously shown in Table III, in the breakdown of emissions for PV systems (and under the same assumptions), the manufacturing of PV panels (silicon, wafer, cell and module) accounts for over 63% of overall GHG emissions. According to Ref. [35], detailing the overall and breakdown contributions of GHG emissions of solar PV modules, this value could already be reduced today – for modules in a glass/foil structure - from 810 gCO_2-eq/kWh (for manufacturing in China; i.e.100%) to 580 (72%) and 480 (60%) gCO_2-eq/kWh for manufacturing, respectively, in Germany and more in general in the European Union (EU).

Very recently a full "made-in-Europe" 566 W_p module with a carbon footprint of 317 kgCO2eq/kWp only has been reported by CEA (see Ref. [46]). This record has been achieved by using silicon-heterojunction solar cells, thinner glass and cells, a wooden frame (replacing the conventional aluminum frames) and sourcing most materials (including polysilicon) in Europe.

These numbers, clearly demonstrating the large potential that already today exists for the further reduction of the GWP of PV, tell us that a carbon tax on the imports of Asian solar panels would be fully justified in this perspective and could serve as a basis to support the reshoring of solar module manufacturing to Europe. Noticeably, many stakeholders of the PV value chain nowadays are engaging in using cleaner electricity in their production (in Asia as well) to address this issue.

Carbon intensity of European countries energy mixes

As the electricity generated by PV in buildings is generally consumed by or close to the end-user and it is injected into the LV or the medium voltage (MV) grid (depending on the size of the plant), to have a fairer comparison we make use - for CI figures of the local electricity mix - of consumption (rather than generation) figures at the LV grid.

CI figures for power generation, rather than consumption ones, are much easier to retrieve and can be generally accessed through European statistical databases (see e.g. Ref. [47]). The existing literature, however, shows a clear gap in the knowledge of the real green-house gas (GHG) emissions associated with the production and the use of electricity. In particular, there is a lack of studies clearly addressing GHG emissions produced across the whole life cycle of electricity production and use, including upstream emissions, operational and use-related emissions. In addition, few evaluations are available for the construction and decommissioning related emissions of the electricity generation facilities.

In the present work we use recently published (i.e. 2022) consumption figures by Scarlat and coworkers [27], who adopt a Well-to-Wheel (WTW, see Ref. [48]) methodology considering all the emissions that occur along the entire pathway, from fuel supply to the power plant, construction of the electricity generating facility, operational phase, plant decommissioning and waste management.

Further, the methodology proposed by the authors considers the impact of electricity trade (intra-country electricity imports and exports) on the carbon intensity that can impact considerably the CI of the electricity used, but which is in general not considered so far in existing assessments of the CI of electricity (see also Ref. [48] and [49]). Furthermore, the proposed methodology considers all sources of electricity, including renewable energy sources, type of plants, conversion efficiencies, own electricity consumption in the power plant, as well as transmission and distribution losses in the grid.

The CI figures for the electricity consumption at the LV grid used in this work are listed in Table I and III for all EU27 member states and other European countries. These numbers reveal significant variations between countries.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR'S CONTRIBUTIONS

AV conceptualized the analysis, searched for data and wrote the paper. ABB and AV performed data analysis. and prepared charts. NW wrote parts of the manuscript. ABB, NW, and CB have reviewed the paper. CB provided general guidance and supervision. AV and CB have secured funding for the research project.

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