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ORIGINAL ARTICLE — OPEN ACCESS

Prioritizing circular economy strategies for sustainable PV deployment at the TW scale

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Abstract. Global decarbonization requires an unprecedented scale-up of photovoltaic (PV) manufacturing and deployment. The material demand and eventual end of life management associated with multi-TW scale deployment poses many challenges. Circular Economy (CE) and it's associated R-Actions (Reduce, Reuse, Recycle) have been proposed to mitigate end of life management and material sourcing concerns. However, CE metrics typically focus on a single product and only consider mass, excluding energy flows. This work leverages the PV in Circular Economy (PV ICE) tool to quantify the deployment, mass, and energy impacts of R-Actions and proposed sustainable PV designs in the context of achieving energy transition deployment goals (75 TW in 2050). 13 module scenarios are established and evaluated across 6 capacity, mass and energy metrics to identify tradeoffs and priorities. We find that increasing module efficiency can reduce near-term material demands up to 30% and improve energy metrics by up to 9%. Material circularity (recycling) can minimize lifecycle wastes and reduce material demands at the cost of higher energy demands. Increasing module lifetime, including reliability improvements and reuse strategies, is effective at reducing both material (>10%) and energy demands (24%). Uniquely, lifetime improvements maximize benefits and minimize the harms across all six metrics while achieving multi-TW scale deployment.

Keywords: Photovoltaics / circular economy / energy balance / energy transition / longevity / efficiency / recycling / remanufacturing

1 Introduction

PV deployment to support the Energy Transition and Decarbonization is expected to reach up to 75 TW by 2050, requiring a massive scale up of manufacturing [1]. To keep the global average temperature rise below 1.5 °C, these PV capacity goals are non-negotiable and must be achieved before mid-century. Although PV modules enable a massive reduction in the carbon intensity of electricity compared to the current fossil-fuel based system, the manufacturing of photovoltaic (PV) modules, including material extraction and refinement, entails environmental impacts [2], and there is concern over availability of required materials, energy, and resulting emissions to meet and maintain capacity targets [3–7] and eventual end of life management [8,9]. Circular Economy (CE) has been proposed as a solution to end of life material management challenges, such as recycling end of life PV [8,9], and to reduce material, energy, and carbon intensity from the manufacturing.

CE is a set of actions and principles which aim to design out waste and keep products and materials in use, among other goals [10–12]. Actions which move a product or system toward a CE are categorized by the R-actions, such as "reduce", "reuse", and "recycle", which are presented in ranked order of priority [13]. Progress toward CE can be measured by a variety of tools or indicators such as the Material Circularity Indicator and recycling rates [14]. Unfortunately, CE metrics and tools have several shortcomings for measuring renewable energy technology deployment for energy transition; typically, CE metrics only measure mass flows, de-prioritize the use phase in favor of mass circularity when scoring, and tightly focus on a single product scale [12,14,15]. The use phase and energy flows of renewable energy technologies, including PV are of central importance. Moreover, correlating product scale to system scale is necessary for quantifying the material, energy, and carbon impacts of energy transition.

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Furthermore, it is widely assumed that increased circularity implies reduced environmental impacts, however as of this publication, only two studies have computed life cycle assessment (LCA) and CE metrics of a product. Brändström and Saidani [16] found that CE metrics do not align with energy or toxicity impacts. Zubas et al. [17] demonstrated agreement between a CE metric and a weighted aggregated single LCA score. However, the study only considered silicon (excluding other materials) and found that agreement was primarily attributable to industry practice of recycling silicon manufacturing scrap (not end of life) and improved PV module lifetime assumptions.

An alternate method to evaluate circularity incorporating energy impacts is exergy analysis, or tracking the quality of energy [18,19]. This has the significant advantage of being able to account for material downcycling when examining circular pathways, provides society-scale perspective on circular choices at the product scale, and is decarbonization oriented [18–20]. However, as noted in the literature, exergy analysis has poor adoption, requires obtainable but detailed inputs [18,20], and may obfuscate tradeoffs or stakeholder decision points between material and energy impacts by combining both into energy-based values.

R-actions are aimed at further improving product sustainability. Definitions of sustainability include low material and energy demands, low environmental impacts, low toxicity, low carbon, low waste, eco-efficient, and providing socio-economic benefits, and different stakeholders emphasize different priorities [10,21–23]. As such, proposed R-actions have identified varying priorities including high-yield, high-efficiency paradigms, short-lived but fully recyclable module designs, and long-lasting, reliable, durable modules [24–26]. Most proposed R-actions for PV have focused heavily on “Recycle” and end of life material management, which is the last and lowest priority R-action [9,27]. Reduce actions for PV include deploying fewer modules and using less material per Wh generated. Reuse actions for PV include reselling installed systems or modules on a secondary market or reuse in place by selling power after the planned end of the project, are enabled by long component life and low degradation.

Ideally, a renewable energy technology would be high efficiency, long-lived, and closed-loop—however, such a PV module does not yet exist, and aspects of one design priority may interfere with another (e.g., remanufactureable vs. indestructible). Therefore, we need a decision support tool for PV that can capture the material and energy impacts of circular strategies and PV designs across scales from a single PV module to a whole energy system to inform and enable stakeholders to understand and prioritize potential tradeoffs. Such an analysis would help identify a most responsible strategy for implementing energy transition, including minimizing harms of raw-material extraction, peaks in carbon emissions, and maximizing availability of clean-electric power.

In this work, we quantitatively compare proposed sustainable PV module design and lifecycle management strategies in the context of achieving global energy transition. Specifically, we explore 13 PV module scenarios quantifying module performance across six metrics covering total deployment, mass, and energy, leveraging the PV in CE tool (PV ICE) [28,29]. Module designs span current technologies, government and industry technology targets, and several low Technology Readiness Level (TRL) emerging PV technologies and their potential evolutions of lifetime, efficiency and material circularity. Our analyses emphasize the importance of examining a suite of metrics encompassing mass and energy flows to identify tradeoffs and inform design or lifecycle management decisions holistically.

PV ICE is an open-source, Python-based, dynamic mass and energy flow analysis tool and set of baselines capturing and modeling the evolution of PV modules and their constituent materials historically and into the future [28]. The system boundaries include raw material extraction through end of life and support several PV-specific circular pathways for modules and materials throughout the lifecycle. Material intensity is dynamic with time, including material extraction, refinement, module composition, and market share of historically deployed cell and module technologies. This study focuses on crystalline silicon (c-Si) technology, which is the dominant deployed technology (97% global market share), and captures 7 major component materials of the c-Si module package.

First, we define the module scenarios explored and their alignment with different circular actions. Next, the metrics of success are defined. The results of the 13 scenario analysis are presented in a metric table, the implications of the results discussed, and takeaways identified. Methods for the analyses, covering energy flow tracking in PV ICE, deployments and replacements schedule, and other assumptions can be found in Appendix A. Appendix B documents the results of the sensitivity analyses conducted on the 3 design aspects and the deployment schedule. Detailed results of the 6 metrics are elaborated upon in Appendix C, as well as a normalized metric results table.

2 Scenarios

Section 2.1 describes the 3 aspects of PV module design explored in this analysis; lifetime, efficiency, and material circularity. These sections outline how these aspects align with circular economy principles and how they are modeled in the PV ICE tool. Section 2.2 then describes the 13 module scenarios, why these scenarios were developed, and their current analogs or feasibility. Figure 1 provides a simple graphical relationship between circular economy actions, PV module design aspects, and how the developed scenarios relate to R-actions and each other. The details of these scenarios are elaborated upon in Figures 2 and 3.

These scenarios represent PV potential futures, and allows exploring the impacts of prioritizing different design aspects during energy transition. Each of these scenarios is modeled with a deployment schedule which achieves global energy transition; 75 TW in 2050 [1] followed by a steady increase to 86 TW in 2100. These scenarios are evaluated and compared for their success at achieving energy transition in six metrics covering deployed capacity, mass, and energy.

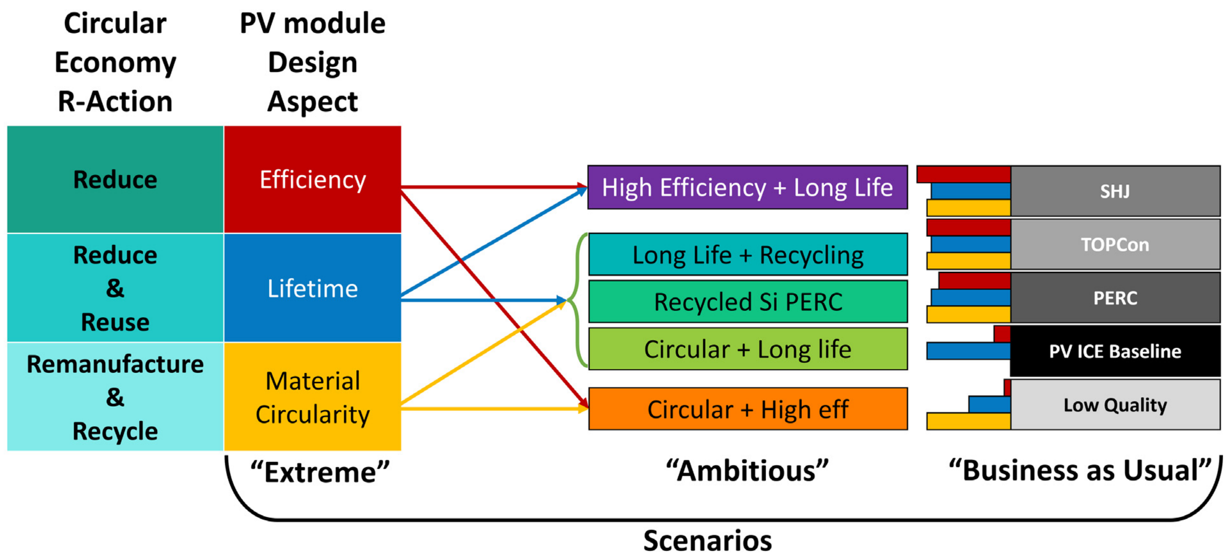

Fig. 1. A diagrammatic relationship between the Circular Economy R-actions, PV module design aspects, and the 13 scenarios explored in this study. Efficiency aligns with a Reduce action, Lifetime with Reduce and Reuse actions, and Material Circularity with Remanufacture and Recycle. These three design aspects are explored at respective theoretical limits in the Extreme Scenarios (e.g.; 99% remanufacture and recycling). Then, combinations of two design aspects are explored in the Ambitious scenarios, where scenario colors are the combination of the two design aspects. Finally, these Extreme and Ambitious scenarios are compared to a set of Baseline scenarios, which blend modest improvements all three design aspects and are based on currently available technologies. The small bars represent the blending of design aspect in each baseline scenario relative to the PV ICE baseline. The details of these scenarios are elaborated upon in Figures 2 and 3.

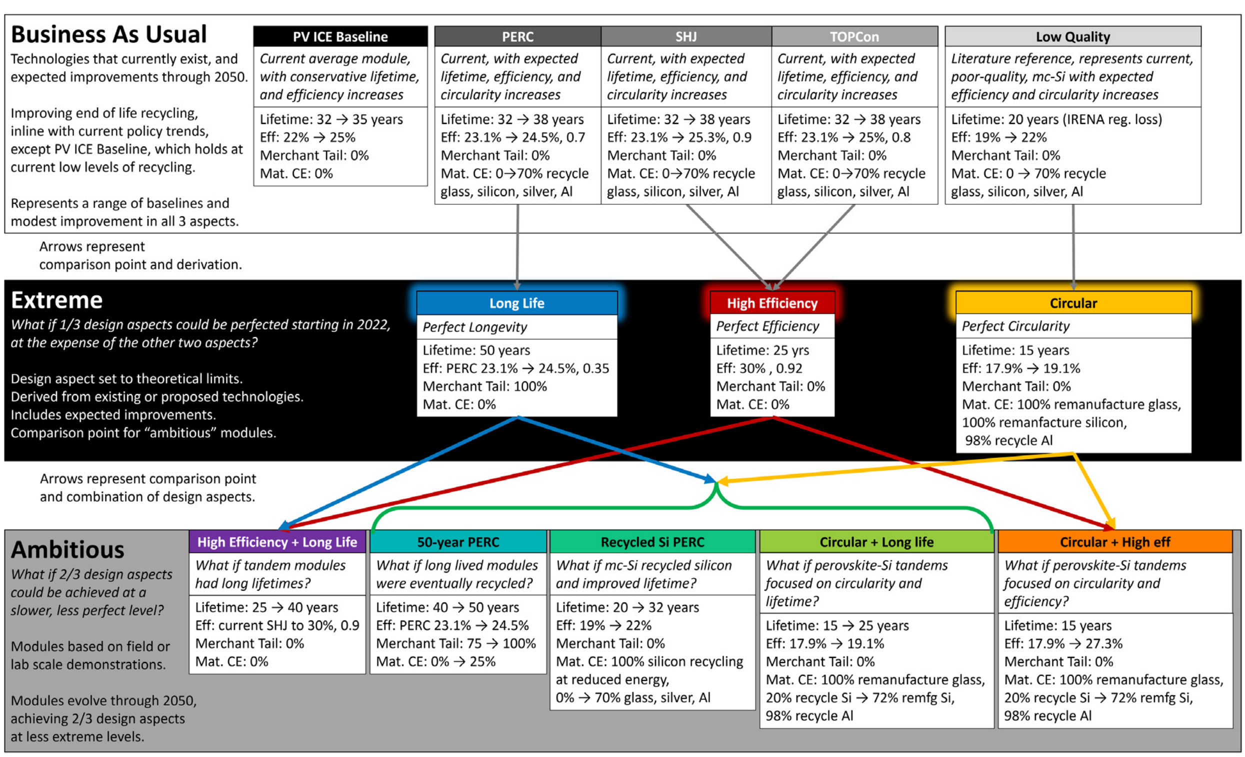

Fig. 2. A diagram showing the three categories of module scenarios, "Business as usual", "Extreme", and "Ambitious", the details of each module design, and relationships between module scenarios. "Lifetime" is the module technical lifetime including degradation, failures, and project lifes, "Eff" is module efficiency and bifacial factor (where applicable), "Merchant Tail" is the rate of in-place reuse, "Mat. CE" is closed-loop material circularity including remanufacturing (remfg) and recycling. Ranges of numbers are the 2022 value and 2050 value, respectively. Arrows represent connection for scenario comparisons and colors represent combinations of design aspects (e.g.; lifetime blue and efficiency red combine to purple).

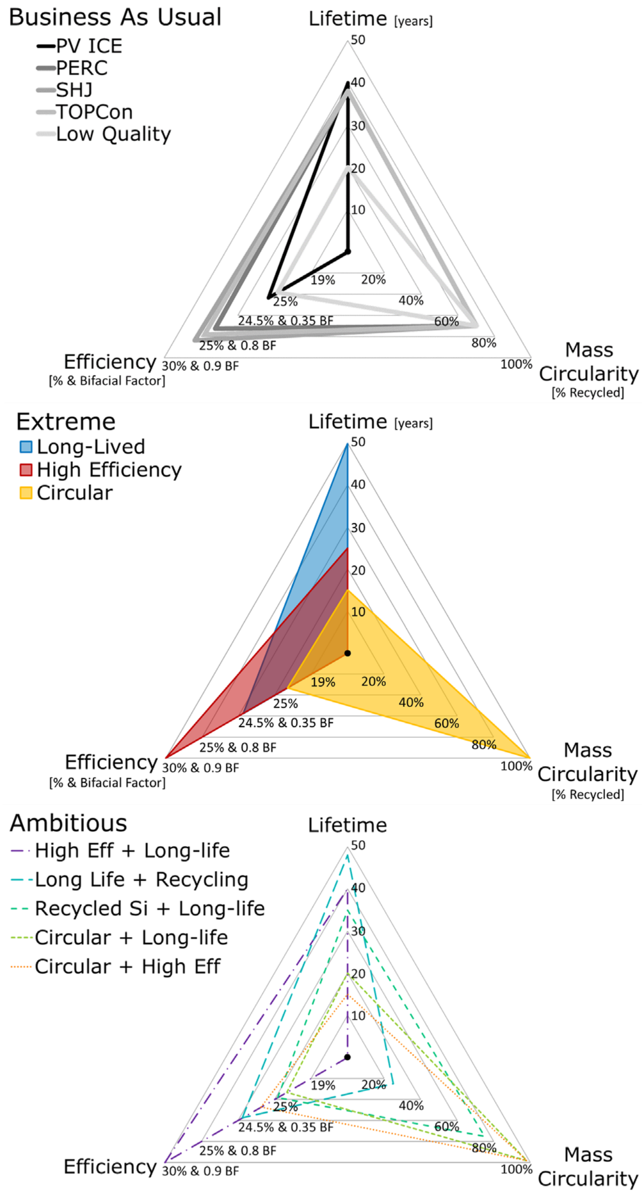

Fig. 3. Three spider plots by scenario category (BAU, Extreme, Ambitious) comparing the scenarios on design aspects, Lifetime, Module Efficiency, and Mass Circularity. Axes have been normalized to the maximum value in each aspect and are identical between the three plots. Efficiency includes both module efficiency and bifacial factor (BF). Lifetime is controlled by project life, degradation rate, and failure probability. Material Circularity has been simplified to a single value, see Figure 2 for material details.

2.1 Design aspects and their contribution to circular economy

In this analysis we examine the effects of prioritizing or combining 3 design aspects of module technology. These design aspects are common areas of research, targets, and proposals, and align with different CE R-actions. Design aspects can be influenced by technological changes, legislation or policy, and economic factors. The three explored design aspects and their circular correlations are:

2.1.1 Lifetime (R-action: reduce, reuse)

The useful life of a PV module during which it generates electricity. Lifetime is subject to both technological (e.g., degradation, failure) and non-technological (e.g., power purchase agreement, reuse standards) constraints. Extending module useful lifetime is an effective method of reducing the total quantity of modules required to achieve energy transition; lower degradation rates maintain higher power generation for longer, reducing the number of modules required to generate a certain amount of energy. Additionally, long-lived modules enable reuse strategies for PV, including reselling on a secondary market, or the “merchant tail”, which is a practice where a system is left in place to participate on the grid power market after it’s power purchase agreement period or other economic project lifetime ends.

In our model, PV ICE, module useful lifetime is controlled by three parameters in PV ICE [28]; degradation rate, Weibull probability of failure, and economic project lifetime or warranty. Scenario lifetimes are referred to by their economic project lifetimes (e.g.; 30-years). Scenario-unique degradation rates are calculated such that modules reach 80% of nameplate power 5 years after the economic project lifetime (this degradation rate is also accounted for in energy generation calculations). Similarly, the failure rates, as controlled by Weibull probability functions, are calculated such that 10% of modules suffer failure by the economic project lifetime, and 90% module failure by 10 years past project lifetime [30]. Finally, the merchant tail is expressed as the fraction of deployed systems which are left in place continuing to generate energy until they fail or degrade to 50% of nameplate power (as opposed to 80%).

2.1.2 Efficiency (R-action: reduce)

Module efficiency represents the rate at which solar radiation is converted to electricity by the module. Module efficiency is primarily controlled by technological improvements, but economics can play a role in what actually gets deployed (e.g.; cost effectiveness). Increasing module efficiency is another form of reduce; fewer high power or yield modules are required to achieve the same target capacity. c-Si technology has a fundamental upper limit of 30% efficiency, which can be overcome by stacking multiple cells (tandem, hetero- or multi-junction). Bifaciality effectively increases the energy yield of the module, and current industry practice does not include bifaciality in the nameplate power rating of the module.

In the analysis, scenarios have dynamic module efficiency, leveraging literature-sourced predicted efficiency improvements. In addition, for applicable technologies (e.g.; PERC, SHJ, TOPCon), bifacial factors are included in the energy generation calculation, and are ignored for calculating capacity deployment per current industry practice.

2.1.3 Material circularity (R-action: recycle, remanufacture)

Material circularity is material which is captured from manufacturing yields and end of life modules and returned to the PV supply chain to offset virgin material demand (i.e. closed-loop). Alternatively, if the material is used in other products it is “open-loop”. Material circularity can include remanufacture, a higher level R-strategy [13] in which a material component, such as the glass, silicon wafer, or aluminium frame, is recovered whole and intact, cleaned, and then used in the manufacture of a new module. Remanufacturing offsets virgin material demands and has a lower energy demand than recycling, but may have reverse logistics and backward compatibility challenges.

Material circularity is influenced by technological advancements (e.g.; sorting, separations), policy (e.g.; landfill bans, recycled content targets), and economics (e.g.; cost of recycling). Increasing PV recycling rates beyond current low levels would likely require changes to technology, policy, and economic factors. Agent-based modeling can project which stakeholders could be the dominant driving force toward increased PV recycling [31]. Our dynamic system model does not assert how remanufacturing or recycling is implemented, instead focusing on the impacts of achieving various levels of material circularity.

Our scenarios include both remanufacture and recycling, both open- and closed-loop, for targeted materials (e.g.; recycle glass and silicon but not plastic encapsulants). When expressing an overall “material circularity”, we are referring to the closed-loop remanufacture and recycling rate, which can be dynamic with time. Each material is subject to a recycling yield in addition to the recycling rate. Recycled material availability is time resolved to accurately calculate required virgin material demands over time. If recycled material is at an oversupply, it is assumed to be retained for use in new PV modules.

The following module scenarios we explore are ultimately complex combinations of these three design aspects. Therefore, we also explored the sensitivity of the metrics to each design aspect and their combinations of changing two design aspects to understand interactions. The results of this analysis can be found in Appendix B.1. The analysis demonstrated that lifetime and efficiency improvements improve all metrics, while worsening lifetime and efficiency have an out-sized negative effect on metrics. Material circularity (modeled as recycling) primarily effected the mass metrics. If recycling is closed-loop, i.e. used to offset virgin material demands, energy savings are achieved. These results were found to be consistent with results from the module scenarios described below.

2.2 Module scenarios

In this exploration of potential PV futures, we employ three categories of scenarios further described below, and in Figures 2 and 3. Scenarios combine the three design aspects in different ways, which could be achieved through a combination of changes to technology design and lifecycle management (legislation, economics). Our dynamic system model does not assert how change is implemented, instead focusing on the impacts of achieving various levels of lifetime, efficiency, or material circularity. Figure 2 describes the categories, assigns module scenarios to categories, and provides details of the module design in each scenario. Arrows represent derivation or comparison points, while colors of the “Ambitious” category are combinations of the colors from the “Extreme” category scenarios (e.g.; lifetime blue and efficiency red combine to purple). Figure 3 compares the scenarios in the three design aspects. The axes have been normalized to the maximum value in each design aspect to show the relative change between scenarios.

2.2.1 Business as usual

The Business as usual (BAU) category presents a range of evolving baselines of currently commercialized module designs and their expected improvements in lifetimes, efficiencies, and material circularity from technology and legislative trends. These scenarios can be considered a spectrum of baselines for comparison.

- PV ICE Baseline (black): the most conservative prediction of module improvement in the 3 design aspects, and serves as a universal baseline of comparison. This represents the average deployed module (i.e. including market shares of different technologies). No improvements to end of life recycling are assumed, but lifetimes and efficiencies improve modestly through 2050.
- PERC, SHJ, TOPCon (greys): the PERC (passivated emitter rear contact), SHJ (silicon heterojunction), and TOPCon (tunnel oxide passivated contact) scenarios capture three current cell technologies and their expected improvements through 2050 [5,32]. Each scenario assumes only that technology is deployed 2022 through 2100. PERC, SHJ, and TOPCon scenarios also assume increasing end of life recycling rates, nearly achieving current EU WEEE mandates by 2050 (70% recycling rate for glass, silicon, silver and aluminium) [33].
- Low Quality (lighest grey): the Low Quality module scenario represents a high failure rate, low upfront cost, multicrystalline-Si module. It serves as a literature comparison, leveraging the IRENA regular loss Weibull parameters [8,34]. We assume improving end of life recycling rates on the same schedule as PERC, SHJ, and TOPCon (70% recycling rate for glass, silicon, silver and aluminium by 2050), and modest efficiency improvements.

2.2.2 Extreme

Extreme scenarios represent if a single aspect of module design (lifetime, efficiency, material circularity) could be perfected at the expense of other design aspects, and deploy beginning in 2022. Isolating the design aspects allows exploration of different circular strategies, R-actions. Critically, the Extreme scenarios do not evolve the design aspect; this should result in maximum and minimum values in metrics, outlining the extreme boundaries of potential futures.

- Extreme Long-life (blue): this scenario deploys a 50-year PERC module (Reduce), a target of the U.S. Department of Energy [24]. The scenario includes expected efficiency improvements and current bifaciality of PERC modules, and implements merchant tail (Reuse) for all modules, retaining them in the use phase until 50% of nameplate power (as opposed to 80%). Material circularity is non-existent (per current practice).
- Extreme High Efficiency (red): improved module efficiency (Reduce) has long been a priority for the PV industry, thus this scenario emulates silicon-based tandem technologies deploying 30% efficiency module with a 0.92 bifacial factor. Module lifetimes are kept at a conservative 25 years, and material circularity is non-existent (per current practice).
- Extreme Circular (gold): this scenario prioritizes closed-loop materials (remanufacture, recycle), and takes design concepts from emerging technologies such as silicon-perovskite tandems [25,35] and direction from the increasing requirements for PV developers to plan for recycling modules at end of life [36]. Glass, silicon, and aluminium frames are remanufactured or recycled into new modules. Lifetimes are only 15 years and module efficiency evolves from 17.9% to 19% [35,37,38].

2.2.3 Ambitious

The Ambitious category explores potential, ambitious futures, where module design prioritizes two of the three design aspects. These scenarios evolve from current analogs to potential futures through 2050, and future designs are based on field and lab demonstrations. Achieving module designs in this category entails a strong and focused technology research and development push with complimentary lifecycle management support to realize this potential future PV. Exploration of these different design priority combinations will help identify optimal pathways for implementing energy transition, minimizing negative impacts and maximizing clean energy yield.

- The High Efficiency+Long-life scenario (purple): derived from concern over the lack of lifetime data for silicon-based tandems coming onto the market, explores the impact of lifetime extension for a high efficiency module. The module starts from the module efficiency of the BAU SHJ scenario (the highest baseline), achieves the efficiency of the Extreme High Efficiency (30% and 0.92 bifaciality) while increasing lifetimes to 40 years.
- The 50-year PERC (turquoise): targeted by U.S. DOE [24] and PV manufacturers, prioritizes improving module lifetime and belatedly incorporates increasing recycling trends. The scenario evolves from the BAU PERC, achieving lifetimes and merchant tail rates of the Extreme Long-Lived scenario, and ramps up recycling to 25% closed loop by 2050.
- The Recycled Si PERC (teal): this scenario is based on a lab scale demonstration of lower energy silicon recycling [39]; the silicon wafer is cleaned and sent directly as polysilicon into the Czochralski ingot growth process (current recycled silicon enters as metallurgical grade silicon to be processed through the energy intensive Siemens process). This scenario evolves from the BAU Low Quality scenario, retains expected improvements in module efficiency, leverages this low energy recycling process and prioritizes improving module lifetime.
- The Circular+Long-life (lime green): this scenario expands to include proposed silicon-perovskite tandems, assuming that the addition of the perovskite material and processing is negligible additional mass and energy. Most silicon-perovskite tandem designs are targeting high levels of material circularity through both remanufacturing glass and silicon and recycling [26,40,41], following in the footsteps of CdTe lifecycle management [42]. This scenario explores one potential future for silicon-perovskite tandems in which improvements to lifetime are prioritized. The module evolves from the Extreme Circular, and achieves lifetimes slightly better than the BAU Low Quality.
- The Circular+High Efficiency (orange): this scenario forms a strategy comparison point for the Circular +Long-life scenario. Instead of prioritizing lifetime

extension, this scenario pursues efficiency gains [35] in combination with high levels of material circularity. This module also evolves from the Extreme Circular, achieves efficiencies of 25%, while lifetimes remain at 15 years.

3 Metrics of success

To expand the scope of CE metrics to effectively evaluate renewable energy technologies in the energy transition, we calculate six performance metrics for each module scenario, covering capacity, mass and energy. These metrics are total deployed capacity, virgin material demand, lifecycle wastes, energy demands, net energy, and energy balance. Greenhouse gas emissions are tied to these metrics but are not explicitly calculated in this study. Metric details are described in the following sections.

3.1 Total deployed capacity

To firmly seat this analysis in the context of energy transition, all scenarios must achieve and maintain capacity targets of energy transition (see Fig. A.5). In theory, if PV modules had infinite lifetimes and no degradation, deploying 86 TW would achieve energy transition. However, modules are subject to expected power degradation, susceptible to extreme weather and random failures, and economic and other non-technical factors can cause modules to reach end of life. Different lifetimes and degradation rates in each scenario entail a different quantity of replacements; i.e. a short-lived module will require more replacements than a long-lived module between now and 2100.

We will examine both the maximum annual deployment rate and **total deployment requirement** (cumulative) 2000 through 2100 including capacity expansion and replacements. Maximum annual deployment is also annual manufacturing requirement. Because, generally, increased manufacturing has negative environmental impacts, we seek to minimize the annual and total deployment requirement. However, different stakeholders may prefer to maximize manufacturing requirement, as it can provide economic benefits – here we only consider mass and energy.

PV ICE can take in any deployment schedule, thus a sensitivity study of the deployment schedule was conducted, and can be found in Appendix B.2. The conclusions of this paper are found to be robust to deployment schedule changes.

3.2 Mass

Literature CE metrics are effective at accounting for mass impacts, and are typically derived by combining virgin material demands and life cycle waste flows into a single circularity metric. Here, we keep them separate (as opposed to using them to calculate circularity [12]) to elucidate the effects of the scenarios on each individually. Both mass metrics should be minimized. We calculate the **virgin material demand** (not sourced from PV waste flows) for each scenario, and **lifecycle waste** calculations include yields and inefficiencies in the module and material extraction, refining, manufacturing and end of life processes [28].

3.3 Energy

It is critical to understand the energy flows (energy demands and energy generation) when considering circularity and sustainability of renewable energy technologies. Moreover, to consider the implications of PV module design on energy transition, we need to examine all deployed PV, not just a single system or module. Therefore, using the energy calculations in PV ICE (see Appendix A.1), we calculate the energy demands and energy generation of all the PV modules deployed between 2000 and 2100 for use in metric calculations. Using the cumulative values 2000–2100, we can calculate the following metrics [43].

- **Energy Demands**: Energy demands are the sum of all direct process energy (electrical and fuel) required for modules and materials throughout the lifecycle of the PV module and it's constituent materials. This includes mining, refining, processing, installation, and end of life processes for modules and materials. All recycling energy demands are attributed to the PV module even if the material is not used closed-loop; no avoided product credits are considered. Transportation demands are not included, thereby scoping the analysis to manufacturing processes and electrification. Energy Demands should not be confused with embedded energy, embodied energy, primary energy demand or cumulative energy demand. Our energy demand metric for this analysis is the sum of all energy demands for all deployed modules for energy transition, 2000–2100. Energy demands should be minimized.
- **Net Energy**: Net energy is energy generated minus energy demands. Net energy represents how much energy is gained by society from the manufacture of a module. Our net energy metric is the sum of all energy generation of all deployed PV modules 2000–2100 minus cumulative energy demands (above). Net Energy is shown normalized to the PV ICE baseline and should be maximized.
- **Energy Balance**: Energy Balance is a metric we propose here. It is inspired by energy return on investment (EROI) [43–45], but as with our other metrics, we apply the concept to all PV modules deployed for energy transition. Therefore, Energy Balance is cumulative energy generated by all the systems deployed for energy transition divided by cumulative energy demands. Energy balance should be maximized.

4 Results and discussion

A PV ICE simulation was run, requiring all 13 scenarios to achieve and maintain energy transition target capacities (75 TW by 2050, 86 TW in 2100, Appendix A.2). Replacements, virgin material demands, lifecycle wastes,

	Scenario	Total Deployment *TW*	Raw Material Demand *bmt*	Lifecycle Wastes *bmt*	Energy Demands *TWh*	Net Energy *TWh*	Energy Balance *Unitless*	Benefits	Harms
Business as Usual	PV ICE	191	10.1	5.1	144,000	7,044,000	50	0	2
	PERC	188	8.2	2.1	122,000	7,569,000	63	4	0
	SHJ	188	7.8	2.0	116,000	7,719,000	67	4	0
	TOPCon	188	8.0	2.1	119,000	7,644,000	65	4	0
	Low Quality	265	11.0	4.2	193,000	6,995,000	37	0	4
Extreme	Long-Lived	145	8.7	3.2	107,000	7,333,000	70	3	0
	High Efficiency	263	12.2	8.1	150,000	7,699,000	52	1	2
	Circular	401	9.3	1.2	154,000	7,034,000	47	1	2
Ambitious	High Eff + Long-life	189	9.0	4.7	110,000	7,740,000	71	3	0
	Long Life + Recycling	152	8.8	2.9	112,000	7,328,000	66	3	0
	Recycled Si + Long-life	227	8.2	1.3	147,000	7,041,000	49	2	1
	Circular + Long-life	272	8.9	1.5	148,000	7,040,000	49	1	1
	Circular + High Eff	401	7.2	1.9	137,000	7,051,000	52	2	2
		Minimize				Maximize		Maximize	Minimize

bmt = billion metric tonnes

Benefit — Harm

Fig. 4. A comparison of the PV module design scenarios (rows) across the six mass and energy metrics (columns). The first 4 metrics should be minimized while the last two metrics should be maximized. The numbers in cells are the cumulative result in each metric for each module scenario, rounded to 3 significant figures. The color scale (teal to black) is proportional to the range of results within each metric; most intensely teal is the best performing while black is the worst performing module scenario. Two final columns, Benefits and Harms, summarize module scenarios by counting the number of intensely teal or black metrics for each module scenario, and are color ranked from 0 to 6 (the number of metrics). This comparison matrix highlights tradeoffs between mass and energy metrics within module designs, and emphasizes that increasing lifetime increases benefits while minimizing harm.

and energy demands and energy generation were calculated annually for each scenario. Annual results of capacity, deployment, and virgin material demands are shown in Figure C.14. The cumulative of each metric 2000–2100 was then calculated; these cumulative results are shown in Figures C.15 and C.16. A detailed discussion of the scenario results in each metric is presented in Appendix C. The analysis is open-source and available in the "17–Energy Results Paper[1]" Jupyter journal on the PV ICE GitHub [29].

To evaluate these 6 metric results, a weighted-color scale matrix was created. Figure 4 shows a comparison matrix rating each scenario against the others in each metric. Color scales are proportional to the range of results within a metric; the most intensely teal is the best performing scenario, black is the worst performing module scenario. The first four metrics (total deployment, virgin material demands, life cycle wastes and energy demands) should be minimized, while net energy and energy balance should be maximized. Finally, Benefits and Harms are tallied for each module scenario by counting the number of intensely colored teal and dark grey/black metrics for each module, and color rated from 0 to 6 (the number of metrics).

First and most apparently, the BAU Low Quality module scenario performs poorly in all metrics, resulting in no benefits and 4/6 harms. This module's lifetime and efficiency are similar to early PV modules [46] or current poor quality modules, however, most modern modules have higher efficiencies and longer lifetimes, and warranty times have been steadily increasing [34,47,48]. As described in Figures 1 and 2, the BAU Low Quality module explores "is it ok to deploy cheap crap if we recycle it?". The poor performance in all metrics of this low quality module emphasizes the importance of deploying reliable modules, and shows that material circularity alone (at 70% closed-loop recycling) cannot compensate for poor lifetime and efficiency.

Second, Figure 4 highlights tradeoffs between different metrics if a single design aspect is prioritized. For example, the scenarios prioritizing material circularity (Extreme Circular, Ambitious Circular+Long life, Ambitious Circular+High Efficiency, Ambitious Recycled-Si+Long life)

[1]https://github.com/NREL/PV_ICE/blob/main/docs/publications/10a - Energy Results Paper.py

perform well in the mass metrics (virgin material demands and life cycle wastes), but perform poorly on the energy metrics and total deployment. The scenarios prioritizing high efficiency (Extreme High Efficiency, High Efficiency +Long Life) maximize net energy at the cost of increased material impacts. All scenarios which have some amount of bifaciality (PERC, SHJ, TOPCon, Extreme High Efficiency, Extreme Long-life, Ambitious High Efficiency +Long-life, Ambitious 50-year PERC) perform well in energy metrics, but vary widely in mass metric performance. As noted in the annual results shown in Figure C.14b, improved efficiency can slightly curb pre-2050 material demands (more efficient modules require fewer to achieve a certain capacity), but prioritizing efficiency alone cannot decrease cumulative virgin material demands. Understanding these tradeoffs is critical to proactive planning for an optimal, lowest impact pathway to decarbonization. For example, a laser-focus on improving recycling rates may come at the cost of increasing energy demands. An over-emphasis on module efficiency could increase material demands and life cycle wastes, resulting in supply chain challenges.

Prioritizing two design aspects, even at modest levels, can improve overall metric performance. This is most obviously observed in comparisons between related module scenarios (Figs. 1 and 2). For example, while the Extreme Circular scenario minimizes life cycle wastes, the addition of either efficiency or lifetime enables the Ambitious Circular scenarios to outperform the Extreme Circular scenario in all other metrics. The addition of efficiency maximizes benefits while the addition of lifetime minimizes harms. Comparing the BAU Low Quality scenario to it's improved counterpart, Ambitious Recycled-Si+Long life, we see significant reductions in mass impacts, due to reduced deployment from improving lifetimes and slightly higher silicon recycling rates. Total deployment and energy metrics are also marginally improved. Moreover, the number of benefits increases to two and, critically, the number of harms are decreased from 4 to 3–again we see harm minimization through the addition of lifetime. If we add lifetime improvements to efficiency improvements (Extreme High Efficiency vs. Ambitious High Efficiency +Long Life), large reductions in total deployment and mass metrics are observed and the combination of lifetime and efficiency significantly outperforms in all energy metrics, despite a slow evolution to the higher efficiency. Unsurprisingly, this addition of lifetime increases the number of benefits from 1 to 3 and minimizes harms to 0. Finally, the increasing to a 50% recycling rate of long-lifetime modules (Extreme Long life vs. Ambitious 50 year PERC) results in a small worsening of the energy metrics without compromising the overall maximizing of benefits and minimizing of harms. The Extreme scenarios perform best in only one metric (with the exception of the Extreme Long life), highlighting the tradeoffs inherent in pursuing only one design aspect, and demonstrating the benefits of improving module lifetime.

Overall, the modules which maximize benefits and minimize harms are those with improved lifetimes. Modules scenarios with lifetimes in excess of 35 years minimize harms and achieve the largest number of beneficial metrics. Long-lived modules deployed sooner reduce the number of replacements required; while a 25-year module deployed now will need to be replaced in 2050, a 50-year module will not exit the field until nearly 2080, decreasing manufacturing and deployment requirements. This extra 20–30 years of delayed end of life PV modules can also facilitate an improvement in material circularity, by providing time for circular end of life management practices to be developed and scaled up. These end of life materials then can provide the source materials for following generations of deployments and replacements. Attempting to massively scale up recycling while simultaneously scaling up manufacturing increases the challenge of short term energy transition by adding additional energy demands, logistics, and environmental controls for recycling processes.

PV module lifetime extension needs to be underpinned by reliable modules with low degradation rates. However, to truly achieve a 50-year lifetime, it is likely that management practices or economics will also need to change, as useful lifetimes can be dictated by non-technical factors, such as land leases, power purchase agreements, or repowering decisions. Finding ways to incentivize systems with long lifetimes and/or safe and equitable reuse strategies will need to complement continuing work in PV reliability.

5 Conclusions

Global decarbonization requires an unprecedented scale-up of PV manufacturing and deployment. The material demand and eventual end of life management associated with multi-TW scale deployment has caused concern [3–8]. Circular Economy (CE) has been proposed as a potential solution to the twin challenge of material sourcing and end of life management, but most CE metrics critically overlook energy intensity, do not correlate to all environmental impact categories [16,17], and focus overly on material Recycling at the expense of higher priority R-actions, Reduce and Reuse. These R-actions align with PV improvement strategies including increasing module efficiency (Reduce), lengthening lifetimes (Reduce and Reuse), and/or increasing material circularity (Remanufacture and Recycle).

To evaluate proposed sustainability strategies and circular economy R-actions for PV in the energy transition, we established 13 scenarios of potential module futures and quantified their performance in achieving energy transition across 6 metrics (total deployment, virgin material demands, life cycle wastes, energy demands, net energy, and energy balance). These 13 scenarios were evaluated using the open-source PV ICE dynamic system model, and run with an energy transition deployment schedule, achieving 75 TW in 2050 and 86 TW in 2100.

A sensitivity analysis of the three design aspects (see Appendix B.1) demonstrated that lifetime and efficiency improvements improve all metrics, while worsening lifetime and efficiency have an out-sized negative effect on metrics. Material circularity through recycling primarily affected the mass metrics. If recycling is closed-loop, i.e. used to offset virgin material demands, energy savings are achieved. Additionally, a sensitivity analysis of the deployment schedule demonstrated the robustness of the scenario results on the path to energy transition.

From our 13 scenario analyses, we found that a focus on material circularity (Remanufacturing and Recycling) improves mass-based metrics, reducing virgin material demands and lifecycle wastes at the expense of energy metrics. This demonstrates why it is critical for energy metrics to be included when combining Circular Economy and renewable energy technologies like PV, whose purpose is to achieve energy transition. Improving module efficiency and energy yield through bifaciality (Reduce) is an effective strategy to improve energy metrics, but can come at the expense of increasing material impacts. Uniquely, improving module lifetime (Reduce and Reuse) has a positive impact in all metric categories, and supports further improvements when combined with material circularity or efficiency. These results are consistent with the rank ordered R-actions of CE [13]. A sensitivity of the scenario metric results to deployment schedule demonstrated the robustness of the identified design aspect prioritization.

None of the examined scenarios were able to eliminate the need for virgin materials to achieve energy transition. Therefore, regardless of the module design, the short term material needs should be met with low-carbon, conflict-free material sourcing. Efforts toward this goal are already underway in industry groups, such as the Ultra Low-carbon Solar Alliance [49]. Circular sourcing from adjacent industries could further improve sustainability, support recycling industries, and increase diversity and security of material supply chains.

Finally, these analyses expand upon previous investigations of Circular Economy for PV by adding energy metrics, however, the carbon intensity must also be considered as we attempt to mitigate the greenhouse gases causing climate change. Future work will consider the carbon intensity of material sourcing, PV module designs, and lifecycle management strategies to more holistically evaluate sustainable strategies for PV modules while achieving energy transition.

Increasing module lifetime minimizes harms while supporting benefits across all metrics. Longer module lifetimes reduce the required number of replacements, and therefore manufacturing demands, lowers energy demands and improves the energy balance of achieving multi-TW scale deployment. Moreover, long lifetime plays well with others; for example, long lived modules provide extra time for end of life material circularity processes (such as remanufacturing and recycling) to be developed and scaled. Therefore, it is recommended that in addition to whatever module design aspect is prioritized, don't forget to make it last.

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Conflicts of interest

The authors have declared that no competing interests exist.

Data availability statement

All files and analyses are available in from the GitHub repository: https://github.com/NREL/PV_ICE.

The PV ICE tool is version controlled and can be cited with: Ovaitt S, Mirletz H. NREL PV_ICE. NREL; 2021. https://doi.org/10.5281/zenodo.10855015

Author contribution statement

Conceptualization, Methodology, Formal Analysis, Software, Investigation, Visualization, Writing (Original Draft), Writing (Review & Editing), Data Curation, Resources, H.M.; Software, Writing (Review & Editing), S. O.; Supervision, Funding Acquisition, Writing (Review & Editing), T.M.B. and S.S.

Inclusion and diversity

One or more of the authors of this paper self-identifies as an underrepresented ethnic minority in science. While citing references scientifically relevant for this work, we also actively worked to promote gender balance in our reference list.

Appendix A: Methods

For this research, we developed new capabilities in the PV ICE tool to quantify energy flows, explained below. Some comments on assumptions, limitations and scope are provided.

A.1 PV ICE energy flows

Building on our previous work [28,50], we developed the energy flows of the PV ICE model to parallel the mass flows. For each step throughout the life cycle of a PV module and its constituent materials, the direct process electrical and fuel energy intensity are summed on a kWh/m^2 or kWh/kg basis. For example, the electricity and fuel (heat) energy demands to manufacture a piece of rolled glass are the sum of the mining, beneficiation, batch preparation, melting and refining, forming and post-forming processing. The energy intensity is multiplied by the area or mass entering a particular step to calculate how much energy is demanded by that process in a particular year. Like the mass intensities, the energy intensities are dynamic with time, accounting for changing cell and module designs, more challenging extraction, and improving refinement and manufacturing processes. Transportation associated energy demands are not included, and the energies captured here are the direct process (electricity and fuel) requirements; this focuses the scope on manufacturing processes and electrification, and energy intensities presented here should not be confused with embedded energy, embodied energy, cumulative energy demand, or primary energy demand.

To capture the evolution of manufacturing technologies over time, market share weighting was used to calculate the annual average energy intensity. For example, mono-crystalline ingot growth uses the Czochralski method, while multi-crystalline silicon uses a direct solidification method. Both process have improved energy efficiency over time [51–54], and have comprised widely varying portions of the market share [28]. Therefore, the energy intensity of each ingot growth process was multiplied by its manufacturing market share to determine the market share weighted average energy intensity of silicon ingots grown each year. For all materials and the module package, historical market share weighted manufacturing energies are documented and available in individual Jupyter journals on the PV ICE GitHub[2].

Annual energy generation is calculated using the effective capacity of the PV installed. Effective capacity represents what is available on the grid to generate energy, accounting for new deployed modules, annual module degradation, and annual decommissions. The yearly insolation considered for this calculation is an annual average for the US of 4800 Wh/m^2/day [55]. The annual energy generation considers current market transitions to bifacial modules. Bifacial modules have higher energy yields due to converting light from both front and rear sides of the module. Our energy generation calculation includes a bifaciality factor, which is the ratio of the rear side efficiency to the front side efficiency [56,57]. A system performance ratio (PR) of 0.8 is also applied to account for system losses between DC and AC [43].

A.2 Deployment schedule

To understand the implications of energy transition in the long term, we analyze the mass and energy flows of PV modules globally 2000 through 2100. All scenarios use the deployment schedule shown in Figure A.5. Historical deployment 2000 through 2022 is drawn from IRENA [58]. We target a cumulative (orange shaded, right axis) 75 TW_{dc} by 2050, inline with many 100% renewable energy projections [1]. After 2050, we project an increase in cumulative capacity to 86 TW_{dc} in 2100, which accounts for increasing energy demand (related to population growth and development) based on historical energy demand increases [59].

To achieve 75 TW and 86 TW cumulative capacity targets on a defined schedule, we take the derivative to calculate the theoretical minimum annual deployments (Fig. A.5, black line, left axis). At minimum, annual deployments linearly increase to nearly 5 TW_{dc} by 2050. Because modules are not immortal, replacements must be deployed in addition to these minimum annual capacity expansions. The quantity and timing of replacements is dependent on module efficiency, lifetime, and degradation, and will be unique for each scenario examined.

The sensitivity of the capacity, mass, and energy metrics to the deployment schedule was tested. Two alternate deployment schedules were simulated. The results in all metrics are robust to changes in the deployment schedule, and the details of this sensitivity are presented in Appendix B.2.

A.3 Assumptions, limitations, scope, data availability

For this study, we assume that each scenario deploys only the type of module modeled. We focus on the module package (glass, silicon, silver, aluminium frame, copper, encapsulant, backsheet); balance of system materials and junction box are currently excluded. Another aspect of PV design proposed for improved sustainability is material intensity or light-weighting [15,60,61]. Lightweighting is becoming more common as PV modules increase in area [62]; thinner glass and frames can be used to reduce weight and cost, which can have a significant tradeoff in durability. The scope of this analysis is limited to silicon-based technologies (including silicon tandems) and to the best of our ability PV module designs are based on commercialized or laboratory scale demonstrations. Future work will include comparison to thin films, such as CdTe.

For the energy flow calculations, we have placed our system boundary to include the direct electricity and direct thermal fuel-based demands only. We do not include cumulative energy demand, primary energy demand, the embodied energy of processing materials (ex: solvents), or transportation demands. This system boundary differs from standard life cycle assessment methodology. Focusing

[2] https://github.com/NREL/PV_ICE/tree/main/docs/baseline%20development%20documentation

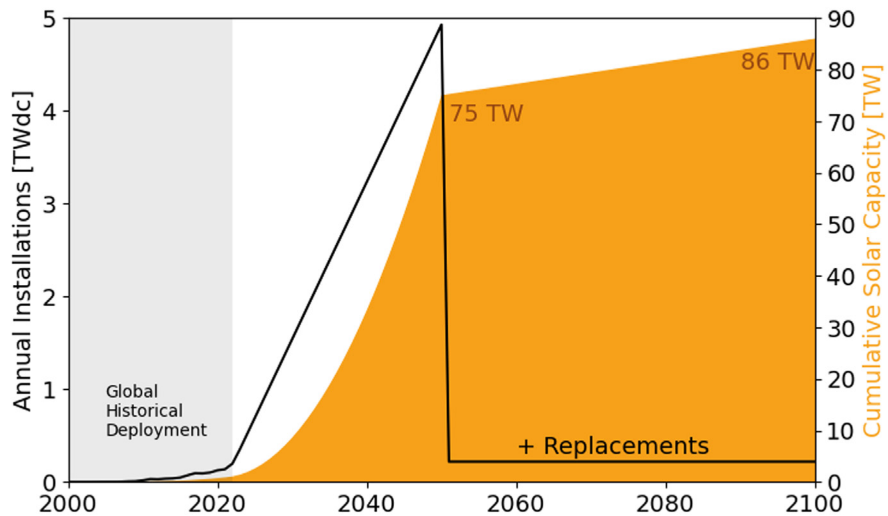

Fig. A.1. The global PV deployment schedule used in this study showing cumulative capacity (shaded orange, left axis) and theoretical minimum annual installations (black, right axis) in TW_{dc}. 75 TW in 2050 achieves 100% renewable energy [1], and the increase to 86 TW in 2100 assumes increasing energy demand based on historical rates [59]. Pre-2022 installations are the global historical PV installations from IRENA [58]. Annual installations will be adjusted for each scenario for required replacements to achieve capacity targets.

purely on the energy demands of the system align to energy transition goals; we focus on the impacts to the current energy system directly attributable to PV deployment for energy transition, and analyzing how that might change across different scenario futures, i.e. will a particular module design or life cycle management increase or decrease the energy demands in the near term, making transition more or less challenging.

All methods and results are open-source and can be found in the "17–Energy Results Paper[3]" and "10b - Energy Sensitivity - Lifetime, Efficiency, Material, Circularity[4]" Jupyter journals on the PV ICE GitHub [29].

Appendix B: Sensitivity analyses

B.1 Design aspects

We conducted a sensitivity analysis to understand the effects and trends of modifying module lifetime, efficiency, and material circularity on our metrics (see Sect. 3). Using the baseline, experiments were run increasing and decreasing the lifetime by 10 years (blue), increasing and decreasing the efficiency by 5% (absolute) and adding a bifacial factor of 0.9 (red), and, using recycling as a proxy for material circularity, varying all material recycling rates to 100%, 25% and down to 0% (gold). For the sensitivity analysis, we used the 86 TW deployment schedule (see Fig. A.1) and modified only modules deployed after 2022.

[3]https://github.com/NREL/PV_ICE/blob/development/docs/publications/10a%20-%20Energy%20Results%20Paper.ipynb
[4]https://github.com/NREL/PV_ICE/blob/main/docs/publications/10b%20-%20Energy%20Sensitivity%20-%20Lifetime%2C%20Efficiency%2C%20Material%20Circularity.ipynb

Figure B.1 shows the relative percent improvement or worsening of each metric, as compared to the baseline. Metrics appear along the x-axis, and the grey background indicates a worsening of the metric. Darker colored bars are improvement in the design aspect and paler colors are worsening the design aspect.

Improving either lifetime (blue) or efficiency (red) improves all metrics, which is consistent with previous results [28]. Overall, improving efficiency has a greater positive impact than improving lifetime. Notably, the addition of a bifacial factor (darkest red) is a significant improvement over increasing the module efficiency. A bifacial module results in higher effective capacity and energy generation than that of a higher efficiency module – bifaciality is essentially bonus capacity and energy.

On the other hand, worsening lifetime (pale blue) or efficiency (pale red) has an outsized negative effect. This is due to the study constraint requiring PV module deployment meet energy transition targets for capacity on a set schedule in a fixed period. If module lifetime is decreased or modules become less efficient, more modules must be manufactured to meet the same capacity targets, demonstrating the opposite of Reduce R-action. Conversely, the improvements in module lifetime and efficiency appear smaller because there are diminishing returns given the study constraint of achieving 75 TW by 2050 and because benefits are only partially captured by examining a fixed time period – the lifecycle of the longer-lived module extends past 2100.

Changes in material circularity (golds) primarily impact mass metrics. Improving recycling has a 1:1 impact on lifecycle wastes, and a less than 1:1 impact on virgin material demands. There is less potential to reduce virgin material demands due to the study constraint of achieving 75 TW by 2050–materials are needed to make modules for energy transition.

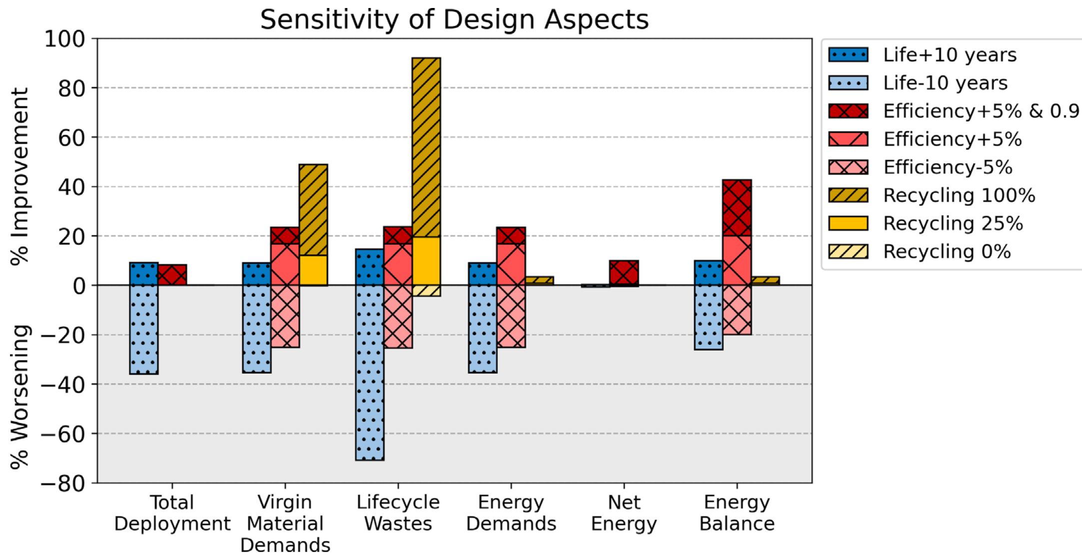

Fig. B.1. A bar plot showing the relative change in each metric as compared to the baseline due to varying each considered design aspect; lifetime +/−10 years, efficiency +/− 5% (absolute) and with bifaciality factor of 0.9, material circularity 100%, 25%, and 0%. For each design aspect, the more intense color indicates improvement. A grey background indicates a worsening of the metric. All metric changes are present, however, when the changes are insignificant they are not resolved in the graph.

Energy metrics are relatively insensitive to recycling rate – it takes 100% recycling rate to change energy demands by 15%. This is because recycling still entails energy, especially to obtain a high enough quality or purity sufficient for closed-loop recycling. Increasing recycling always worsens energy demands and energy balance. We expect energy demands to decrease slightly when recycling is set to 0% because the baseline captures current low levels of open-loop glass and aluminium recycling.

To better understand the relationship between recycling rate and energy demand, an additional sensitivity was conducted. Recycling rate was varied between 0% and 100% in increments of 10%, and the material was either used to offset virgin material demand (closed-loop) or returned to the material market (open-loop). Recycling was considered for only glass, silicon, silver, and aluminium frames, as per current recycling processes and the established scenarios. Figure B.2 shows the change in energy demands relative to the baseline as a function of changing the recycling rate. Two sets of bars are shown; grey for open-loop recycling, and gold for closed-loop recycling.

In both cases, energy demands of both virgin material and recycling are summed. The open-loop recycling shows the additional energy required for recycling on top of virgin material extraction, essentially attributing the benefits of recycling to outside our system boundary. We chose to examine this energy increase from recycling demands to understand the effect of changing recycling rate on the energy demands associated with PV lifecycle management. This also scopes the potential scale of energy impacts of current industry recycling practices (which are mostly downcycling or open-loop).

The closed-loop recycling demonstrates the potential energy savings of recycling to offset the energy associated with mining and refining the material. Despite still requiring some energy to recycle the material, energy savings are achieved. Closed-loop recycling achieves energy savings by offsetting virgin material manufacturing, thereby improving the metric up to 15%.

Because the established module scenarios we explore are ultimately a complex combination of the three design aspects, we also explored the sensitivity of metrics to combinations of changing two design aspects. Figure B.3 shows the sensitivity analysis of the combination of design aspects alongside the three solo design aspects of Figure B.1. Combination scenarios are shown in the blended color (e.g. blue lifetime and gold circularity make green) and dotted. Grey backgrounds indicate a worsening of the metric relative to the baseline, and more intense colored bars indicate improvement of the design aspect.

Overall, when improvements or worsening of design aspects are combined, their effects are additive. For example, improvements to lifetime & efficiency (purple) is roughly the addition of lifetime impacts (blue) and efficiency impacts (red). This means the benefits of both reduce actions can be gleaned together. This additive trend holds in both the positive and negative direction. When combining efficiency & recycling (orange), effects are additive for mass metrics and dictated by efficiency for energy metrics. Similarly, combining lifetime & recycling (green), mass metric effects are slightly less than additive in the positive direction and dictated by lifetime in the negative direction. For the energy metrics, the combination of lifetime & recycling (green) is mostly dictated by lifetime impacts, with a small counter-acting influence from recycling; improving lifetime improves energy metrics, but improving recycling to 25% slightly worsens energy metrics, thereby slightly curtailing the positive effect when combined. This is a demonstration of a tradeoff – to improve the mass metrics, the benefit of the improved energy metrics is slightly curtailed. Put another way,

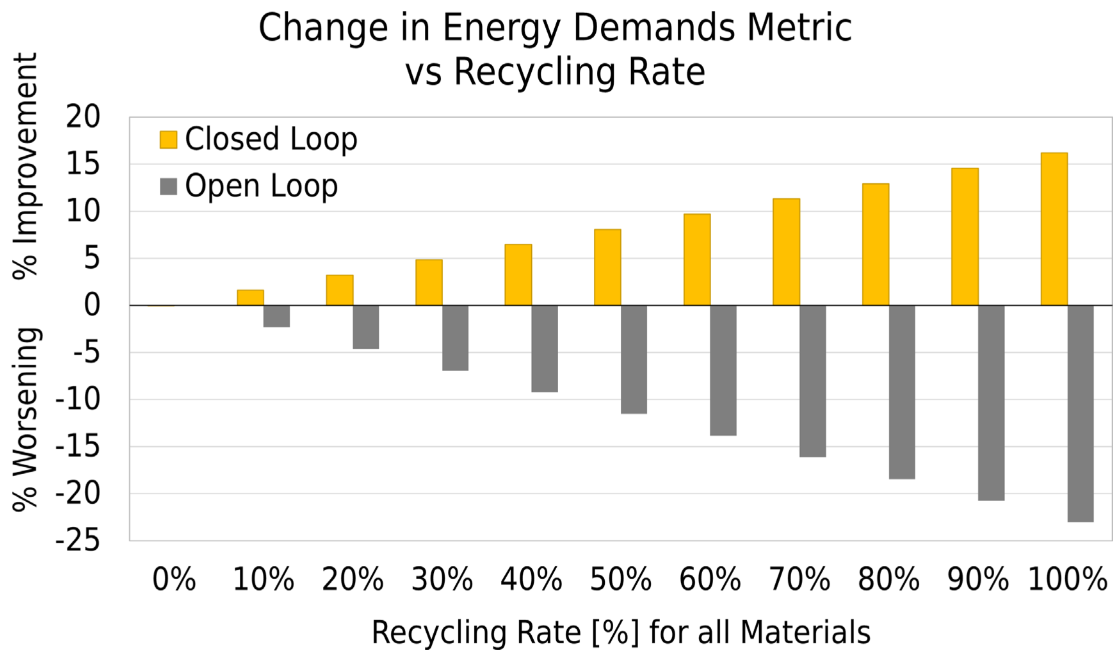

Fig. B.2. A bar plot showing the change (improvement or worsening) in cumulative Energy Demands (as compared to the PV ICE baseline) as a function of material recycling rate (glass, silicon, silver, aluminium frames only). Gold bars are closed-loop recycling, which offset virgin material demand, grey bars are open-loop recycling. Closed-loop recycling gleans energy savings by offsetting virgin material demand.

combining either efficiency or lifetime improvements with recycling counteracts the negative effect of recycling on energy metrics.

B.2 Deployment schedule

To test the robustness of the scenario results to how we achieve energy transition, the same 13 scenarios were modeled following three deployment schedules. The minimum annual deployment curve comparison is shown in Figure B.4.

All deployment curves achieve 75 TW in 2050, and continue increasing to 86 TW in 2100. The black curve is a simple linear increase in annual deployments until 2050, and used for the results presented in the body of this work. The green curve is sourced from Hieslmair [34], which increases deployment following a sigmoidal curve peaking around 2040. The blue curve represents the fastest possible increase to a steady annual deployment; a steep exponential curve over 3 years to reach 3 TW of annual deployment which holds through 2050. For all deployment curves 2050 through 2100, we assume a minimum annual deployment around 250 GW to continue increasing cumulative capacity. These deployment schedules are again the minimum annual deployment, each scenario will deploy replacements in a time-resolved manner in addition to these capacity requirements. These three deployment schedules explore a wide range of how we reach 75 TW of cumulative installed capacity in 2050; deployment sooner or later.

All 13 scenarios were simulated with each deployment curve and all metrics calculated. Figures B.5 and B.6 show the metric results tables of the exponential to 3 TW and sigmoidal adoption curve respectively. These are compared to the linearly increasing metric results in Figure 4. Because the color scale is relative to the results in each table, we can glean that because the heatmap pattern is the same between the three metric results tables (i.e. the same number of harms and benefits in the same categories), the overall trends and comparative conclusions of the scenario analysis hold true regardless of the deployment schedule.

There are numerical differences between the metric results from the different deployment schedules. This is due to the changes in when modules are deployed; essentially the cycles of deployment and replacement are being shifted. However, the priority is to check that the relative differences (number of harms and benefits) between scenarios is consistent. This will validate the overall conclusions about relative prioritization of design priorities.

To quantify if scenarios had notably different results relative to one another due to the deployment curves, each scenario was normalized to it's respective PV ICE baseline. Then the absolute difference between results from the alternate deployment curves and the linear deployment curve was calculated. Figures B.7 and B.8 are in the format of the metric tables, and show the difference in normalized scenario results relative to the linear deployment schedule. These figures thereby identify which scenarios changed relative results changed and in which metrics.

These figures demonstrate that while there are some minor effects on the energy demands, energy balance, and lifecycle wastes, the difference between scenarios is at most 16% across all deployment schedules. This is considered within uncertainty. Moreover, the relative ranking of each scenario within the deployment schedule does not change. Therefore, from these sensitivity results, we can conclude that the insights into design aspect prioritization gleaned from comparing the scenarios will hold true regardless of the schedule on which we achieve energy transition.

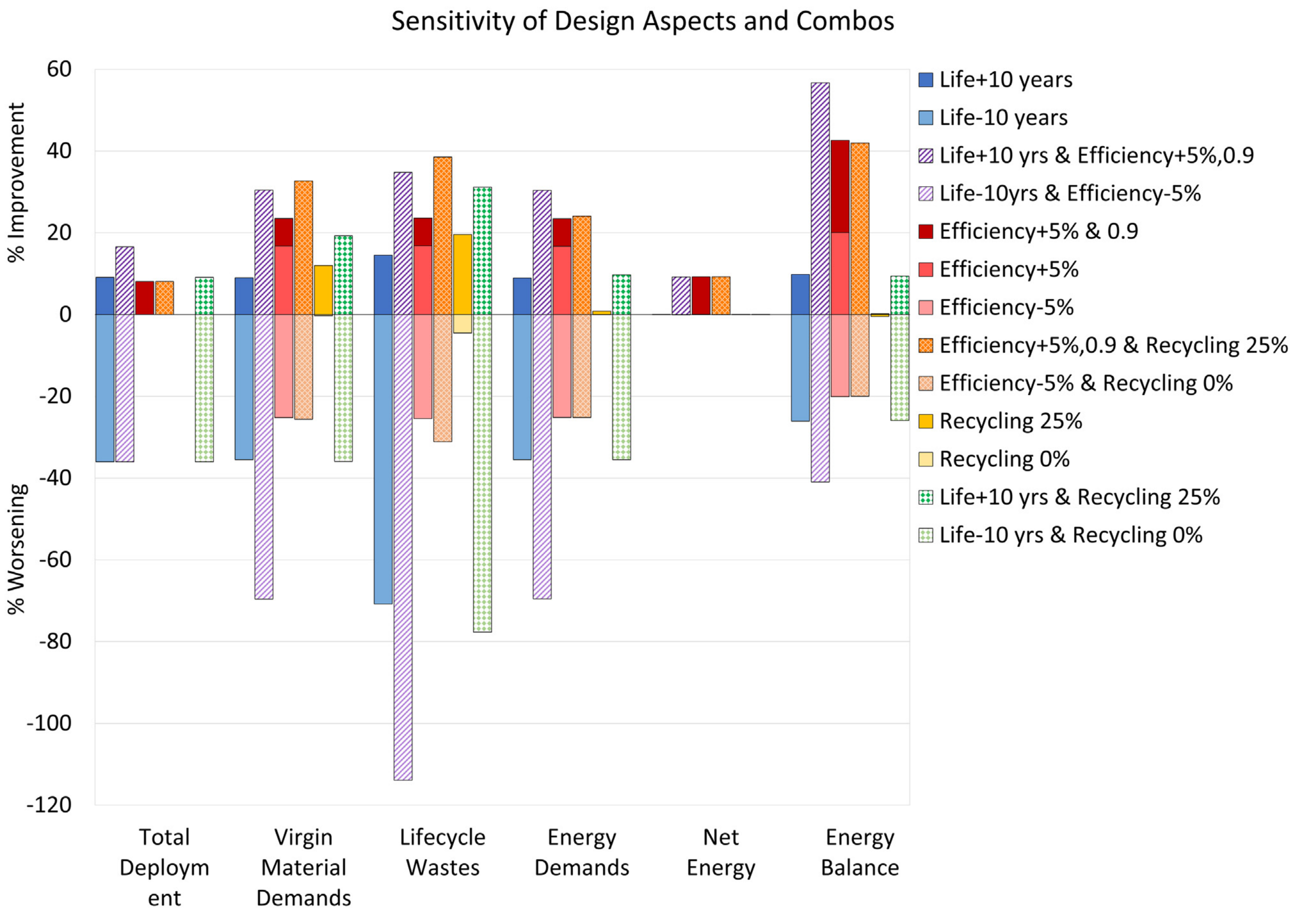

Fig. B.3. A bar plot showing the relative change in each metric as compared to PV ICE Baseline due to varying the three design aspects and their combinations. Combinations are shown in the blended color of the solo design aspect (e.g.; blue and red makes purple) and hatched. The combinations display either a domination from one aspect, for example, lowering module lifetime increases required replacements with no affect from lowering efficiency, or additive affects, such as the improvement in energy balance from improved lifetime and improved efficiency.

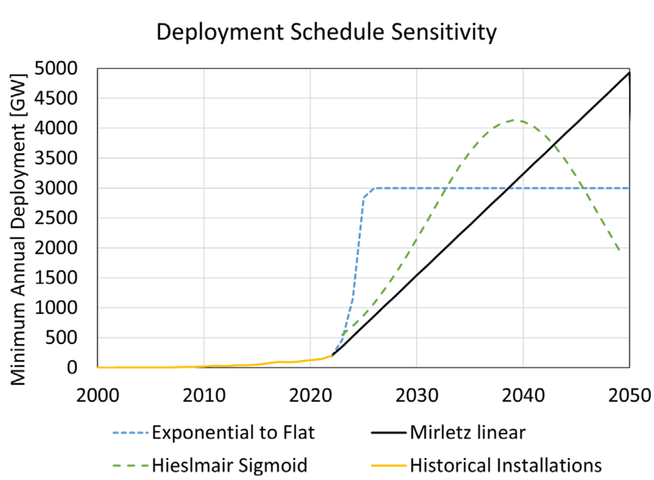

Fig. B.4. A graph comparing the three minimum annual deployment schedules modeled with the 13 scenarios to assess the robustness of the results to the rate of deployment. The black line is what is used for the results presented in the body of this work. The green is sourced from Hieslmair based on a sigmoidal adoption. The blue follows a 3 year exponential increase to 3 TW then holds constant through 2050. These represent the minimum annual deployment; replacements to maintain capacity are calculated for each scenario based on lifetimes.

	Scenario	Total Deployment (TW)	Raw Material Demand (bmt)	Lifecycle Wastes (bmt)	Energy Demands (TWh)	Net Energy (TWh)	Energy Balance (Unitless)	Benefits	Harms
Business as Usual	PV ICE	206	10.9	5.8	156,000	7,611,000	50	0	2
	PERC	202	8.8	2.4	141,000	8,170,000	59	4	0
	SHJ	202	8.3	2.3	134,000	8,332,000	63	4	0
	TOPCon	202	8.5	2.3	137,000	8,251,000	61	4	0
	IRENA reg. loss	282	11.7	4.6	227,000	7,541,000	34	0	4
Extreme	Long-Lived	159	9.6	4.0	117,000	7,922,000	69	3	0
	High Efficiency	276	12.9	8.6	158,000	8,324,000	54	1	2
	Circular	431	9.7	1.3	167,000	7,601,000	47	1	2
Ambitious	High Eff + Long-life	205	9.8	5.4	120,000	8,362,000	71	3	0
	Long Life + Recycling	166	9.5	3.4	124,000	7,915,000	65	3	0
	Recycled Si + Long-life	247	8.8	1.5	181,000	7,587,000	43	2	1
	Circular + Long-life	292	9.5	1.8	160,000	7,607,000	48	1	1
	Circular + High Eff	431	7.8	2.3	151,000	7,617,000	52	1	2
		Minimize				Maximize		Maximize	Minimize

bmt = billion metric tonnes

Benefit — Harm

Fig. B.5. Metric results table of the exponential to 3 TW deployment schedule.

	Scenario	Total Deployment (TW)	Raw Material Demand (bmt)	Lifecycle Wastes (bmt)	Energy Demands (TWh)	Net Energy (TWh)	Energy Balance (Unitless)	Benefits	Harms
Business as Usual	PV ICE	193	10.2	5.3	146,000	7,239,000	51	0	2
	PERC	190	8.3	2.1	132,000	7,770,000	60	4	0
	SHJ	190	7.9	2.0	126,000	7,924,000	64	4	0
	TOPCon	190	8.1	2.1	129,000	7,847,000	62	4	0
	IRENA reg. loss	270	11.2	4.3	217,000	7,169,000	34	0	4
Extreme	Long-Lived	153	9.2	3.8	113,000	7,531,000	68	3	0
	High Efficiency	265	12.4	8.2	151,000	7,913,000	53	1	2
	Circular	412	9.4	1.3	160,000	7,225,000	46	1	2
Ambitious	High Eff + Long-life	192	9.1	4.8	112,000	7,953,000	72	3	0
	Long Life + Recycling	160	9.2	3.3	120,000	7,524,000	64	3	0
	Recycled Si + Long-life	237	8.4	1.5	173,000	7,212,000	43	2	1
	Circular + Long-life	276	9.0	1.6	151,000	7,234,000	49	1	1
	Circular + High Eff	412	7.3	2.0	142,000	7,243,000	52	2	2
		Minimize				Maximize		Maximize	Minimize

bmt = billion metric tonnes

Benefit — Harm

Fig. B.6. Metric results table from sigmoidal deployment schedule.

Exponential to 3 TW	Total Deployment	Virgin Material Demands	Lifecycle Wastes	Energy Demands	Net Energy	Energy Balance
PV ICE	0%	0%	0%	0%	0%	0%
PERC	0%	-2%	-1%	6%	0%	-8%
SHJ	0%	-1%	0%	5%	0%	-8%
TOPCon	0%	-1%	0%	5%	0%	-8%
Low Quality	-2%	-2%	-3%	11%	0%	-6%
Long-Lived	1%	1%	5%	1%	0%	-2%
High Efficiency	-3%	-4%	-10%	-3%	0%	3%
Circular	-1%	-3%	-1%	-1%	0%	1%
High Eff + Long-life	0%	1%	1%	1%	0%	-1%
Long Life + Recycling	0%	0%	2%	2%	0%	-3%
Recycled Si + Long-life	1%	-1%	0%	14%	0%	-12%
Circular + Long-life	0%	-1%	2%	0%	0%	0%
Circular + High Eff	-1%	0%	3%	1%	0%	-1%

Fig. B.7. The difference in scenario results when using the exponential to 3 TW deployment schedule as compared to the linear deployment scenario. The energy demands for several scenarios are higher (and therefore lower energy balance) due to the higher deployment of modules early (i.e. less efficient and less recycled content). These results are within uncertainty and overall comparative trends are not changed.

Sigmoidal	Total Deployment	Virgin Material Demands	Lifecycle Wastes	Energy Demands	Net Energy	Energy Balance
PV ICE	0%	0%	0%	0%	0%	0%
PERC	0%	0%	0%	6%	0%	-8%
SHJ	0%	0%	0%	6%	0%	-9%
TOPCon	0%	0%	0%	6%	0%	-9%
Low Quality	1%	0%	1%	14%	0%	-7%
Long-Lived	3%	4%	9%	3%	0%	-6%
High Efficiency	0%	0%	-1%	0%	0%	0%
Circular	3%	-1%	0%	2%	0%	-2%
High Eff + Long-life	0%	0%	0%	0%	0%	0%
Long Life + Recycling	3%	3%	7%	4%	0%	-7%
Recycled Si + Long-life	4%	1%	2%	16%	0%	-14%
Circular + Long-life	0%	0%	0%	1%	0%	-1%
Circular + High Eff	3%	0%	1%	2%	0%	-2%

Fig. B.8. The difference in scenario results when using the sigmoidal deployment schedule as compared to the linear deployment scenario. The energy demands for several scenarios are higher (and therefore lower energy balance) due to the higher deployment of modules early (i.e. less efficient and less recycled content). Two scenarios have slightly higher lifecycle wastes, similarly due to early deployment of less recyclable modules. These results are within uncertainty and overall comparative trends are not changed.

Appendix C: Results

This section dives into details of the performance of the established module scenarios in our each of our metrics. The metrics are evaluated in the order presented in Section 3 and in the final metric table Figure 4. Each section details the comparison between scenarios to glean insights into design aspect prioritization. We also present the metric table normalized to the PV ICE Baseline, which provides a sense of which scenarios improve upon the expected BAU scenario.

C.1 Total deployed capacity

Now that we understand the trends and interactions of these three design parameters on our metrics, we will examine the effects of the complex, technology specific scenarios established to understand potential tradeoffs and advise research priorities for PV module technology improvement to achieve energy transition while minimizing harms and maximizing clean energy yield.

We begin by examining deployment requirements to meet and maintain capacity targets on schedule for global decarbonization. Figure C.1a shows the Energy Transition capacity targets (black dashed) compared with the Effective Capacity (installations minus all end of life and degradation) of each module scenario without any replacement modules. This figure demonstrates the capacity shortfall of each module type. Effective capacity trends with module lifetime and all scenarios require replacements to meet and maintain capacity targets. Therefore, required replacements were calculated annually for each module scenario. Figure C.1b shows the actual required annual installations for each module scenario compared to the theoretical minimum deployment of 86 TW (black dashed line). Post-2050 the annual deployments are the average annual deployment rate during the decade. From these graphs, we see that:

- Capacity can be boosted by module bifaciality. The BAU PERC, SHJ, and TOPCon scenarios (greys) bifaciality factors enable their effective capacity to be higher in 2050 than the target capacity (75 TW) because bifaciality increases the effective capacity but not the nameplate which is used for deployment. This demonstrates the ability of high high energy yield to Reduce deployment.
- Short lived module designs do not meet capacity targets without large quantities of replacements before 2050. This is seen in the BAU Low Quality (lightest grey), Extreme Circular (gold), and Ambitious Circular +Efficiency (orange) scenarios, with lifetimes of 20 and 15 years respectively, which do not meet the 2050 capacity targets (a), and have increased annual deployment 2035-2050 (b). These short-lived module scenarios require increasing manufacturing and deployment (b) to over 8 TW/year by 2050.
- Conversely, longer lifetimes maintain a higher effective capacity further into the century. The two longest lived scenarios, the Extreme Long-lived (blue) and the Ambitious 50-year PERC (turquoise) do not require significant replacements until 2080.
- Short-lived modules also require maintaining higher levels of deployment through the end of the century. The Extreme Circular (gold) and Ambitious Circular & High Efficiency (orange) scenarios average over 6 TW/year of manufacturing and deployment 2050-2100, compared to 2-3 TW/year for BAU or less than 2 TW/year for long lived module scenarios.
- Long module lifetimes deploy the fewest modules (Reduce), coming the closest to theoretical minimum. Extreme Long-lived (blue) and Ambitious 50-year PERC (turquoise) scenarios at peak require an annual deployment of 5 TW, in line with previous estimates of annual manufacturing capacity requirements [1,5], and delay the need for significant replacements until after 2080, averaging around 2 TW/year 2050–2100.

Currently globally, we have 567.4 GW of PV module manufacturing capacity globally [63], less than 20% of the required 3–5 TW of annual manufacturing capacity. Short-lived module scenarios entail TWs of extra manufacturing capacity a decade sooner, increasing the magnitude of the required short term manufacturing and deployment ramp-up by 6 TW. We consider large quantities of near-term replacements to be a negative impact, keeping with the CE R-action Reduce, as they are directly correlated to manufacturing demands and infrastructure, logistics, and supply chains. From a different perspective, manufacturing can mean jobs and economic benefit to the regions in which manufacturing takes place, but it can also result in localized environmental impacts, increased transportation demands, etc.

Cumulatively through the end of the century, total deployed capacity follows annual installations. Figure C.2a shows total deployed capacity (including replacements) – our first metric – for each module scenario. As expected:

- Short module lifetime scenarios entail the largest cumulative installations. The Extreme Circular (gold) and Ambitious Circular+High Efficiency (orange) scenarios must deploy over 400 TW to meet and maintain capacity targets, more than 4× the theoretical minimum required 86 TW.
- Increasing module lifetime reduces required deployment. Comparing the Extreme Circular (gold) and Ambitious Circular+High Efficiency (orange) scenarios (15 year modules) to the Ambitious Circular+Long-life module (lime green) demonstrates the effects of increasing lifetime; required manufacturing and deployment is decreased from 400 TW to 272 TW.
- The Extreme Long-lived (blue) and Ambitious 50-year PERC (turquoise) modules require the fewest replacements, 145 TW and 152 TW respectively, less than double of the 86 TW theoretical minimum, demonstrating the Reduce (long lifetimes) and Reuse (merchant tail) R-actions of lifetime extension.
- Combining Reuse with long lifetimes is more beneficial than lifetime extension alone. The BAU scenarios (greys) and Ambitious High Efficiency & Long-life (purple) scenario reach 40 year module lifetimes, but are removed from use when degradation reduces them to 80% of

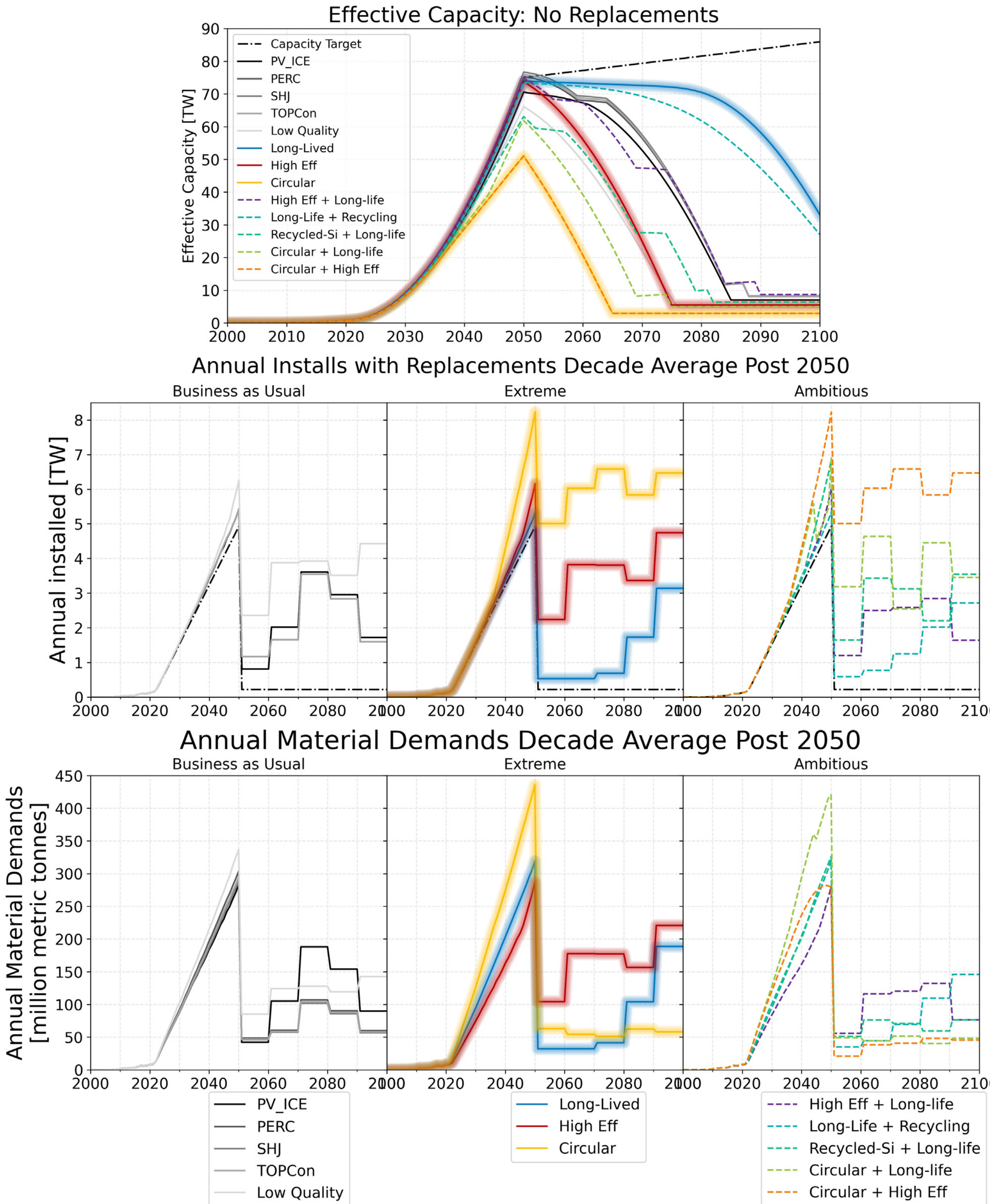

Fig. C.1. The (a) Effective Capacity (installations minus module degradation, failures, and end of life, and assumes no replacements) from 2000 to 2100 of each scenario compared to the capacity targets (black dashed line). The (b) annual installations including replacements to meet capacity targets and associated (c) annual virgin material demands accounting for material circularity for all scenarios 2000–2100. In (b), the theoretical minimum deployment (i.e. immortal modules) is shown in the black dashed line. Post-2050 installations and material demands are the average annual rate during each decade.

nameplate power, whereas the Extreme Long-life and Ambitious Long-Life+Recycling (turquoise), which make use of the merchant tail (i.e. stay in use phase until they reach 50% nameplate) in addition to 50-year lifetimes. This Reuse action has the additional effect of reducing the total deployment requirement, and can be seen in the higher maintained effective capacity in Figure C.1a.

C.2 Mass metrics

Next, we consider the mass metrics for each module scenario. The goal is to extract and waste the least amount of material possible while achieving multi-TW scale deployment and energy transition, therefore both metrics should be minimized.

Figure C.1c shows the annual virgin material demands for each scenario 2000–2100. Post-2050, the material demands are the average annual material demand during the decade. These virgin material demands are summed cumulatively 2000–2100 for our second metric, shown in Figure C.2b. From these virgin material demands, we can conclude:

- Improved efficiency can reduce annual material demands by achieving a higher energy yield from the same amount of material. Efficiency improvements in the Extreme High Efficiency (red), Ambitious High Efficiency+Long-life (purple), and Ambitious Circular+High Efficiency module (orange) scenarios enable reduced peak virgin material demand in 2050 (Fig. C.1c) compared to other scenarios, under 300 million metric tonnes per year. This Reduce R-action can be thought of as ecoefficiency – more power from the same amount of material.
- Conversely, low efficiency and short lifetimes result in the maximum annual material demands before 2050. The Extreme Circular (gold) and Ambitious Recycled Si PERC (lime green) scenarios have the lowest module efficiencies (under 22%) and short lifetimes (15–25 years) resulting in the highest peak virgin material demands before 2050. These scenarios peak virgin material demand is up to 40% higher than BAU scenarios, peaking over 400 million metric tonnes annually.
- Lifetime extension reduces cumulative virgin material demand. Evidence for this is seen in 3 scenario comparisons. The Extreme High Efficiency (red) scenario versus the Ambitious High Efficiency+Long-life (purple) scenario and the BAU Low Quality (lightest grey) scenario versus the Ambitious Recycled Si PERC (teal); the Ambitious scenarios add lifetime resulting in 3 billion metric tonnes reduction in cumulative material demand. The Extreme Circular (gold) compared to the Ambitious Circular+Long-life (lime green) scenario slightly decreases material demand. Moreover, the Extreme Long-lived (blue) module requires less virgin material input than the Extreme Circular (gold) module, demonstrating why in the ranked R-actions Reduce comes before Recycle.
- High levels of material circularity can reduce annual virgin material demands, especially after 2050. Demonstrated by the Extreme Circular (gold) and Ambitious Circular (lime green and orange) module scenarios, which require less than 50 million metric tonnes of virgin materials annually post-2050, a 40% lower average than the BAU scenarios.
- However, circularity is best in combination with other design aspects. The Ambitious Circular & High Efficiency (orange) scenario has the lowest cumulative material demand due to a combination of circularity and high efficiency. Similarly, the Ambitious Circular+Long-life scenario (lime green) reduces virgin material demands compared to the Extreme Circular scenario (gold). Looked at from the negative side, the BAU Low Quality module (lightest grey) and the Extreme Circular (gold) scenarios require the second and fourth most virgin material cumulatively because efficiency and lifetime are neglected. Recycling alone cannot compensate for the virgin material demands for energy transition.
- No scenario eliminates the need for virgin materials.

Even at the fastest cycle time (15 years) a short-lived, highly mass circular module (Extreme Circular, gold or Ambitious Circular+High Efficiency, orange) cannot offset the short-term material demands [50]. Materials will need to be sourced responsibly for the initial material input to energy transition. Irresponsible material sourcing in the silicon supply chain has already resulted in social (forced labor) and environmental (illegal mining) harms [64,65]. Additionally, avoiding extreme virgin material demand peaks will help prevent shortages, supply chain bottlenecks, and price instabilities. Obtaining silicon, glass, and aluminium from other circular sources would further improve PV sustainability, support recycling industries, and increase diversity and security of material supply chains.

Figure C.2c shows the cumulative lifecycle wastes for all module scenarios 2000 through 2100. Life cycle wastes include manufacturing scrap as well as end of life wastes for the 7 tracked component materials. Overall:

- Increased material circularity reduces lifecycle wastes. This is apparent in the Extreme Circular (gold) and Ambitious Circular (lime green and orange) scenarios achieving the lowest cumulative waste, and in the comparison between Extreme Circular (blue) and both the Ambitious Long-life+Recycling (turquoise) and Ambitious Recycled-Si+Long-life (teal), demonstrating reductions in wastes.
- Increased lifetime reduces lifecycle wastes. Three comparisons exemplify this trend; Extreme High Efficiency (red) to Ambitious High Eff+Long-life (purple), BAU Low Quality (light grey) to Ambitious Recycled Si PERC (teal), and Ambitious Circular+High Efficiency (orange) versus Ambitious Circular+Long-life (lime green), all demonstrating a reduction in waste with lifetime extension.
- The combination of circularity and lifetime most effectively decreases wastes in all scenarios, seen in the Ambitious Recycled-Si+Long-life (teal) and Circular +Long-life (lime green) scenarios.

These trends in virgin material demands and lifecycle wastes follow the ranked R-actions – increasing efficiency and lifetime reduces virgin material demand, increasing lifetime delays end of life, and material circularity manages modules whose use phase can no longer be extended with some potential for offsetting virgin material demand.

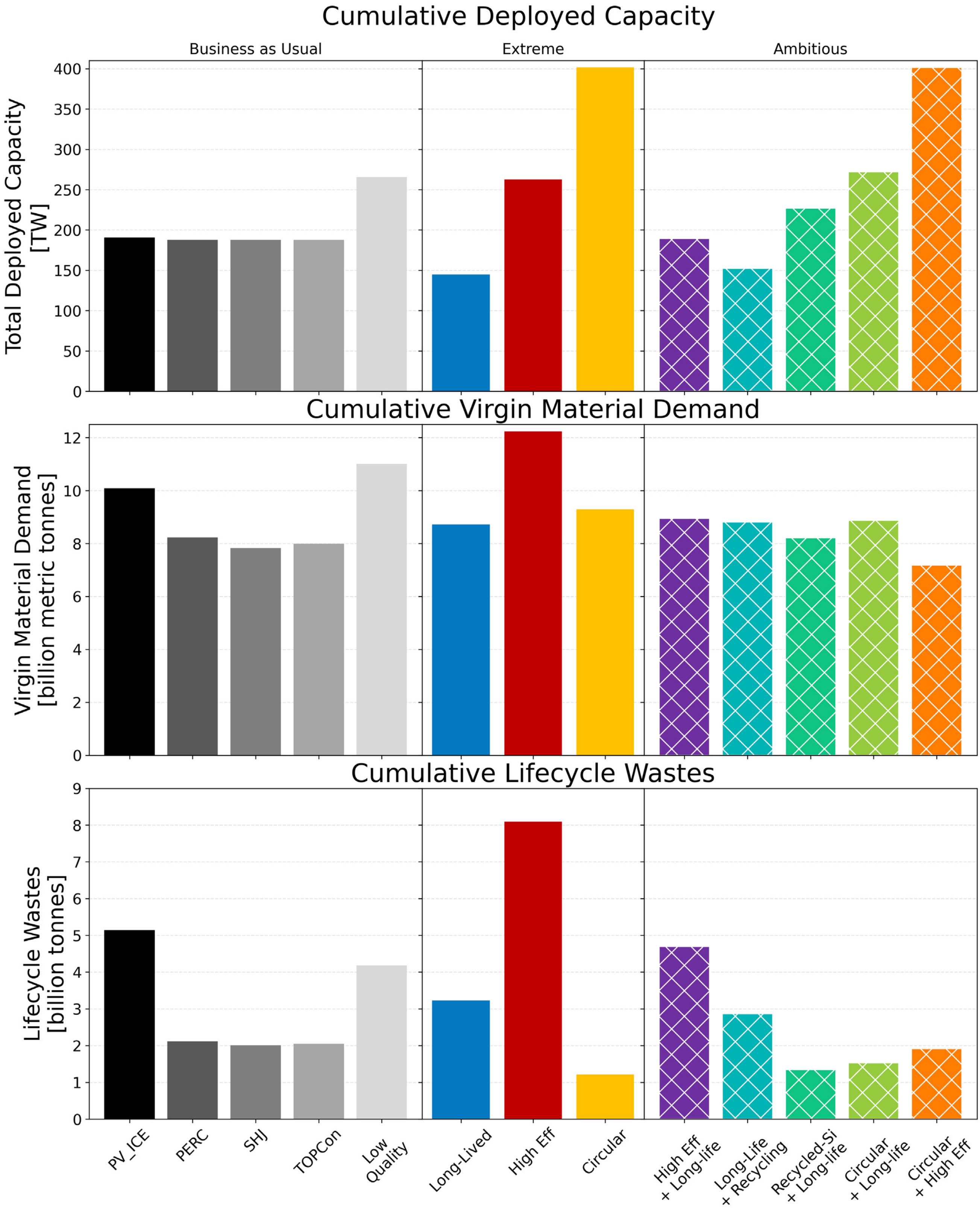

Fig. C.2. The cumulative (a) capacity manufactured and deployed in TWs, (b) virgin material demand, and (c) lifecycle wastes in billion metric tonnes 2000–2100 for each scenario. Despite the largest capacity deployments, the Ambitious Circular+High Efficiency (orange) has the lowest material demands. Long lifetimes (blue, turquoise) lower the capacity manufacturing and deployment requirements. High levels of circularity (gold, lime green) and long lifetimes (blue, teal) enable waste reduction.

C.3 Energy metrics

As previously mentioned, CE metrics do not capture the energy impacts of R-actions. However, we show that R-actions have significant implications for energy metrics, and that these impacts are critical for evaluating PV module design priorities in the context of achieving energy transition.

C.3.1 Energy demands

Energy demands should be minimized—modules made sooner draw energy from a carbon intensive grid [66,67] and may increase required capacity targets. Figure C.3a shows the cumulative energy demands 2000–2100 by module scenario. We find that:

- Poor lifetime and efficiency result in the largest energy demands due to the high total deployed capacity requirements. This explains why the scenario with the largest energy demand is BAU Low Quality (lightest grey), followed by the Extreme Circular (gold)—these scenarios have the shortest lifetimes and lowest module efficiencies. Specifically, the BAU Low Quality (light grey) scenario entails the largest energy demands, due to a combination of high manufacturing demands (a result of low efficiency), high decommissioning rates (a result of short lifetimes and failures), and high recycling rates. This module scenario shows the result of skipping Reduce and Reuse R-actions and relying exclusively on Recycling; a large energy demand compounding the short term challenges of energy transition.
- Material circularity alone cannot minimize energy demands. This is demonstrated by the high energy demands of the Extreme Circular (gold) scenario, one of only 3 scenarios to have higher energy demands than the PV ICE Baseline.
- Increased efficiency lowers energy demands. The Ambitious Circular+High Efficiency (orange) reduces the energy demands of the Extreme Circular (gold) scenario. Additionally, the Ambitious Circular+Long-life (lime green) has slightly higher energy demands than the Ambitious Circular+High Efficiency (orange) – this is due to the higher virgin material demands of the Ambitious Circular+Long-life (lime green), and is consistent with our sensitivity analysis in which increasing efficiency has a slightly greater positive impact than increasing lifetime. Given the similarity of the energy demands of the two Ambitious Circular scenarios, there is likely an equivalency point; either increasing module lifetime by X or module efficiency by Y will save the same amount of energy.
- Increased lifetime minimizes energy demands most effectively. For example, the addition of improved lifetime in the Ambitious Recycled-Si+Long-life (teal) reduces the energy demands in comparison to BAU Low Quality (light grey). Similarly, the addition of longevity (Ambitious Circular+Long-life, lime green) mitigates the high energy demands of the Extreme Circular (gold) module. Finally, the low energy demands of the Extreme High Efficiency scenario (red) can be further improved by the addition of lifetime (Ambitious High Efficiency +Long-life, purple). The lowest energy demand is achieved in the scenarios with the longest lifetimes; Extreme Long-lived (blue), Ambitious High Efficiency +Long-life (purple), and Ambitious Long-life+Recycling (turquoise). This is directly related to the total deployed capacity v metric; these modules require the least deployment, leveraging low degradation and merchant tail, demonstrating the ability of Reduce and Reuse to lower energy demands.

C.3.2 Net energy

Net energy (energy generated minus energy demands) reveals how much energy is gained from the lifecycle of the module, and should be maximized. Figure C.3b shows the cumulative net energy of each module scenario normalized to the PV ICE baseline. Overall:

- Increased bifaciality or energy yield (Reduce actions) increases net energy. The Ambitious High Eff+Long-life (purple), the Extreme High Efficiency (red) and BAU SHJ (grey) module scenarios have the largest net energy and the highest bifaciality factors. All scenarios which have some bifaciality perform better than the baseline in net energy.
- Improving lifetime also improves net energy. Notably, net energy of the Ambitious High Efficiency+Long-life (purple) is higher than that of the Extreme High Efficiency (red), indicating the addition of lifetime improves this metric.
- Net energy is a relatively insensitive metric. All module designs are within 10% of the baseline. The Extreme Circular (gold) and Ambitious Circular (lime green and orange) modules have a comparable net energy to the baseline, and the worst performing BAU Low Quality scenario (light grey) is still within 2% of the baseline.

C.3.3 Energy balance

Energy balance, the EROI-inspired metric we propose, is a unitless measure of energy returned for energy invested, cumulatively across the energy transition timeline, and should be maximized. Figure C.3c shows the Energy Balance of each module scenario. Overall, energy balance is nearly the inverse of energy demands – this is expected since energy generated is similar between scenarios, differentiated by bifaciality, and energy demands are the denominator of energy balance. These trends show:

- Increased lifetime improves energy balance. Scenarios with long lifetimes, Extreme Long-lived module (blue), Ambitious High Efficiency+Long-life module (purple), and Ambitious 50-year PERC (turquoise) have the highest energy balance. Specifically, the improvement in lifetime of the Ambitious High Efficiency+Long-life module (purple) over the Extreme High Efficiency (red) significantly increases the energy balance.
- Increased efficiency improves energy balance. For example, the Ambitious Circular+High Efficiency (orange) scenario slightly outperforms the Ambitious Circular+Long-life (lime green) scenario. This is tied to the energy demands associated with the higher virgin material extraction necessary for the Ambitious Circular +Long-life (lime green) scenario.

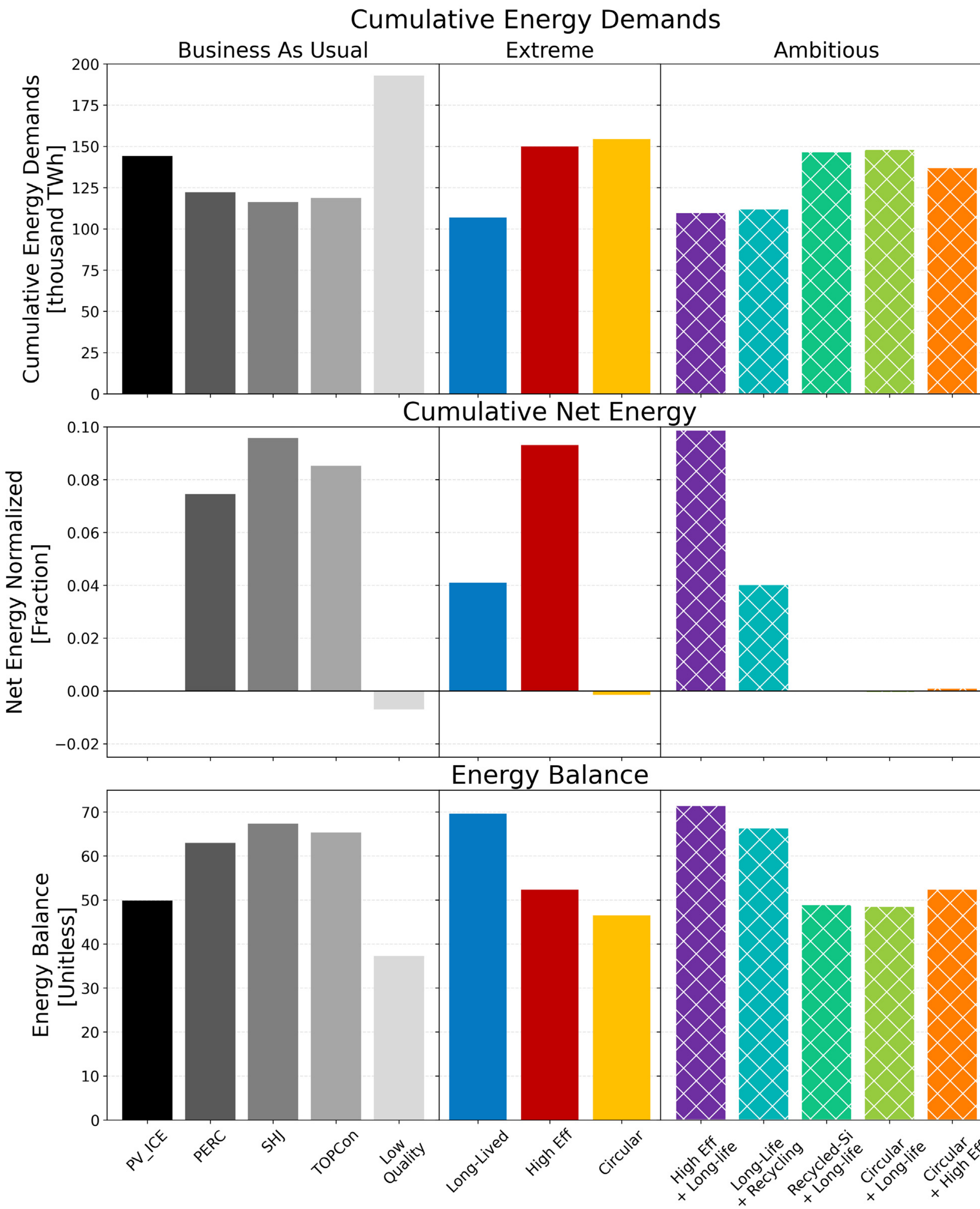

Fig. C.3. The energy metrics (a) energy demands, (b) net energy, and (c) energy balance, cumulatively for all deployed PV modules 2000–2100. Energy demands include full lifecycle energy demands of modules and materials and should be minimized. Net energy is the cumulative energy generated minus the cumulative energy demands, is shown normalized to the baseline, and should be maximized. Energy balance is cumulative energy generated divided by cumulative energy demands and should be maximized.

Normalized to PV ICE Baseline

	Scenario	Total Deployment *TW*	Raw Material Demand *bmt*	Lifecycle Wastes *bmt*	Energy Demands *TWh*	Net Energy *TWh*	Energy Balance *Unitless*
Business as Usual	PV ICE	1.00	1.00	1.00	1.00	1.00	1.00
	PERC	0.99	0.82	0.41	0.85	1.07	1.26
	SHJ	0.99	0.78	0.39	0.81	1.10	1.35
	TOPCon	0.99	0.79	0.40	0.83	1.09	1.31
	Low Quality	1.39	1.09	0.81	1.34	0.99	0.75
Extreme	Long-Lived	0.76	0.87	0.63	0.74	1.04	1.40
	High Efficiency	1.38	1.21	1.57	1.04	1.09	1.05
	Circular	2.11	0.92	0.24	1.07	1.00	0.93
Ambitious	High Eff + Long-life	0.99	0.89	0.91	0.76	1.10	1.43
	Long Life + Recycling	0.80	0.87	0.56	0.78	1.04	1.33
	Recycled Si + Long-life	1.19	0.81	0.26	1.02	1.00	0.98
	Circular + Long-life	1.43	0.88	0.30	1.03	1.00	0.97
	Circular + High Eff	2.11	0.71	0.37	0.95	1.00	1.05
		Minimize				*Maximize*	

bmt = billion metric tonnes

Benefit — Harm

Fig. C.4. A comparison of the PV module design scenarios (rows) across the six mass and energy metrics (columns) normalized to the PV ICE Baseline scenario results. The first 4 metrics should be minimized while the last two metrics should be maximized. The numbers in cells are the result in each metric for each module scenario normalized to the PV ICE Baseline, rounded to 2 decimal places. The color scale (teal to black) is centered on 1.0 (white), more teal is improvement relative to the baseline, more black is worsening. Normalizing the matrix emphasizes the poor performance of short life and low efficiency scenarios.

– Combining lifetime and efficiency maximizes energy balance. The Extreme Long-lived scenario (blue) and the Ambitious High Efficiency+Long-life scenario (purple) have the highest energy balance due to a combination of bifaciality and long life, both of which increase energy yield and reduce energy demands.
– Increased material circularity decreases energy balance. Notably, all highly circular scenarios have a worse energy balance than the BAU scenarios (except Low Quality, lightest grey). The addition of circularity between the Extreme Long-life (blue) and Ambitious 50-year PERC (turquoise) slightly lowers the energy balance due to increased energy demands. The third worst energy balance is the Extreme Circular scenario (gold). In comparison, increasing lifetime (lime green) or efficiency (orange) improves the energy balance relative to the Extreme Circular (gold). The BAU Low Quality (light grey) scenario is expected to have the lowest energy balance due to no bifaciality, low efficiency, short lifetimes, and high circularity. These results agree with the sensitivity analysis.

C.4 Metric table normalized

Figure C.4 shows the metric table normalized to the PV ICE baseline. Because the PV ICE baseline represents conservative expected future improvements, this figure demonstrates the potential of a module scenario to improve or worsen each metric in the path to achieving energy transition.

As noted, throughout, the Low Quality scenario continues to perform more poorly than BAU PV ICE, emphasizing that lifetimes need to be maintained or improved. Tradeoffs between mass and energy metrics are also demonstrated in this normalized table, with only the scenarios with lifetime extension prioritized outperforming the baseline in all categories.

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