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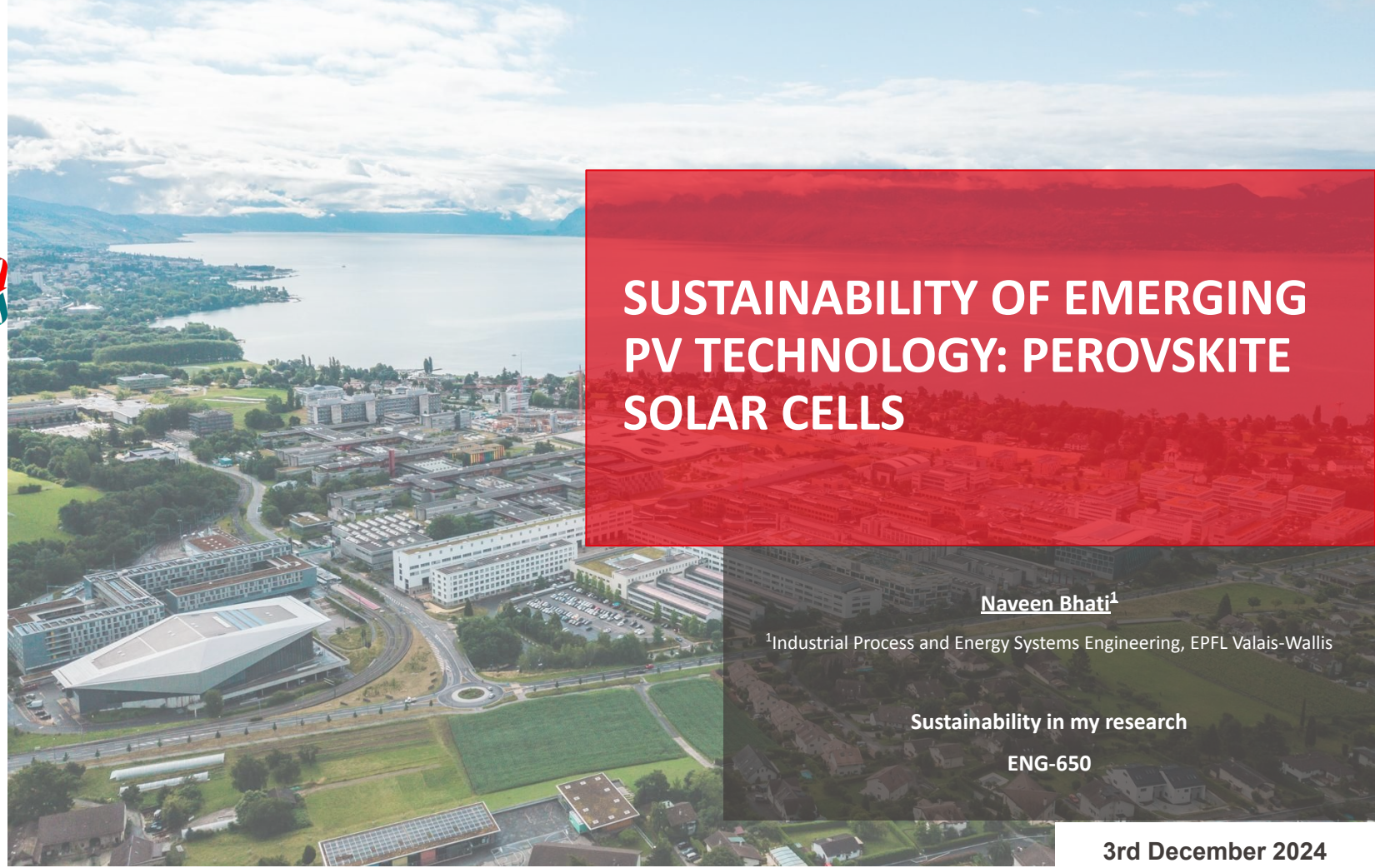

# SUSTAINABILITY OF EMERGING PV TECHNOLOGY: PEROVSKITE SOLAR CELLS


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**Sustainability in my research**

**ENG-650**

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# Photovoltaic (PV) Technologies

- Renewables -> dominate the electricity supply in future
- Solar PV -> 50% of the total renewable production capacity to meet the COP targets

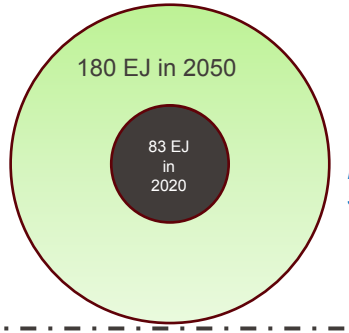



*Fig. Electricity demand to meet 1.5°C scenario (WETO 2023)*

**PV technologies:**

1st generation (thickness> 150um)

- Monocrystalline-Si, polycrystalline-Si

2nd generation (thin-film PV, thickness< 10um)

- CIGS, CdTe, CIS, a-Si, etc.

3rd generation (emerging PV, thickness < 10um)

- Organic materials, **perovskites**, Dye-sensitized, Quantum dots,
- multi-junction, tandems
- PSCs reached >26% efficiency in single junction devices and 33.9% in tandem (Si) devices

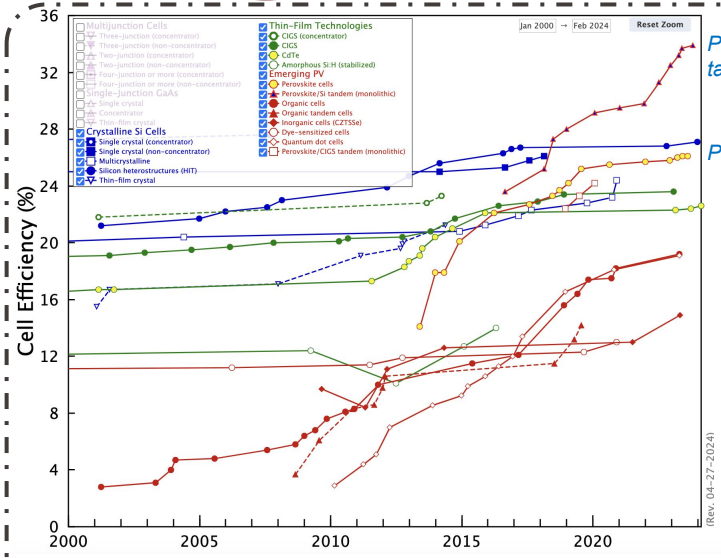



*Fig. Cell efficiency chart (NREL 2024)*

# Perovskite solar cells (PSCs)

- Infinite space for the chemical composition ($ABX_3$) optimization
- Complex manufacturing process with a plethora of cell architecture options
- Range of materials and fabrication processes for all active layers

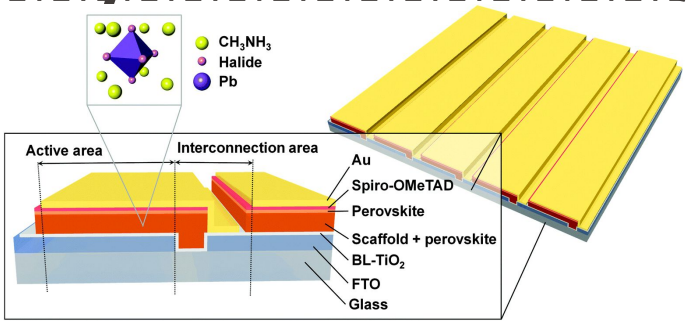



*Fig. Typical perovksite substrate (Jacobsson et al., 2015)*

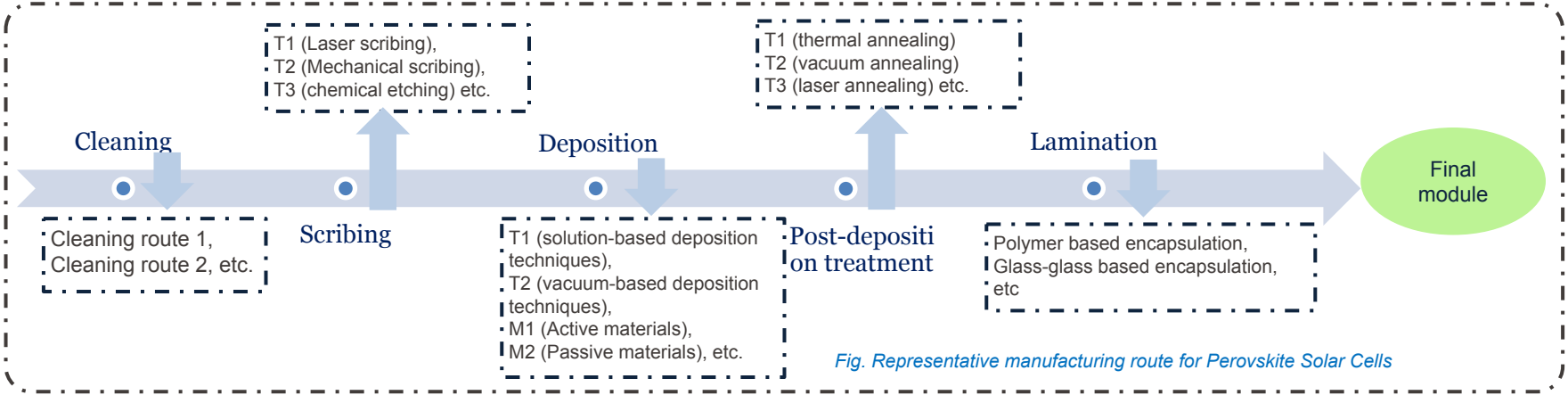
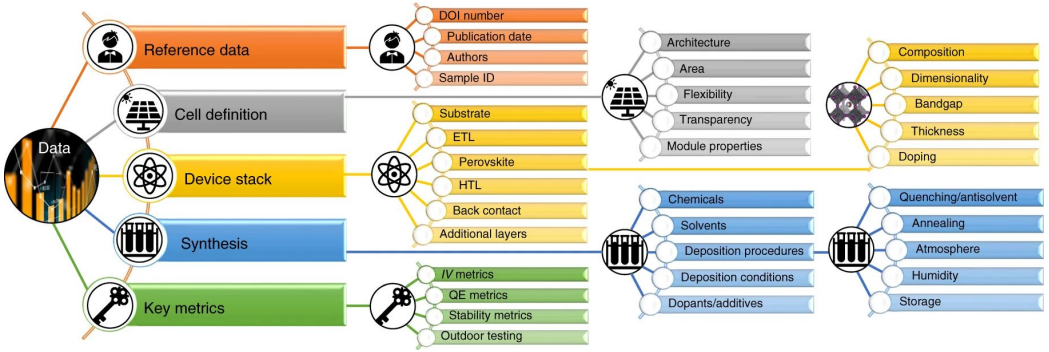



*Fig. Representative manufacturing route for Perovskite Solar Cells*

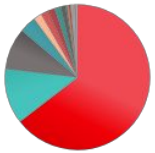
# PSCs Recipes

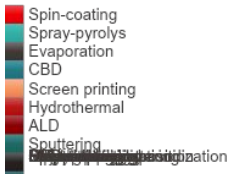
**FAIR database of perovskite solar cells recipes (Jacobsson et al. 2022)**

- >42400 cell recipes
- >100 deposition process sequence for each layer
- > 1000 stack sequence for each of the active layers (i.e., Electron transport layer (ETL), Perovskite, Hole transport layer (HTL))

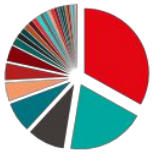


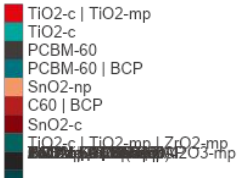

**ETL Deposition techniques**



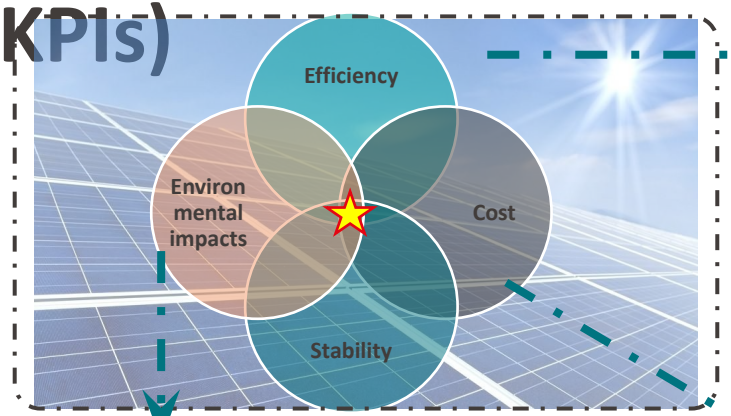



**ETL STACKS**





# Key performance indicators (KPIs)



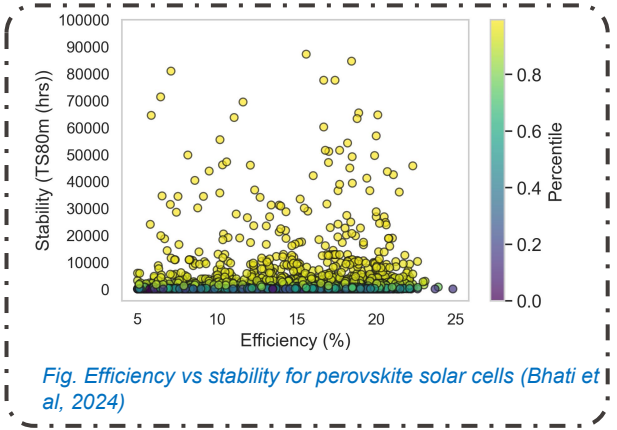




*Fig. Efficiency vs stability for perovskite solar cells (Bhati et al, 2024)*

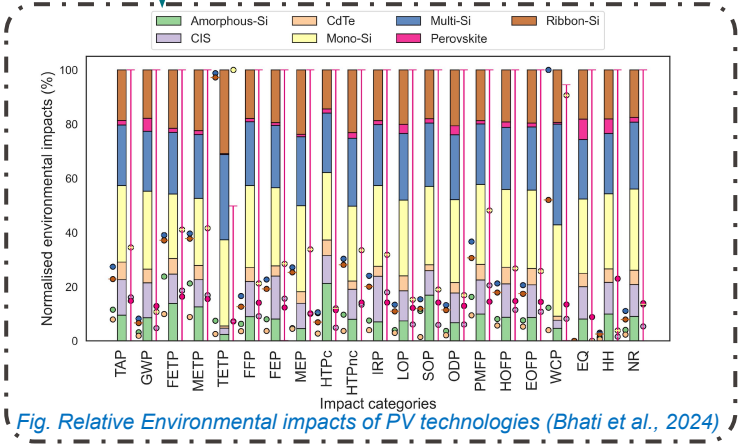



*Fig. Relative Environmental impacts of PV technologies (Bhati et al., 2024)*

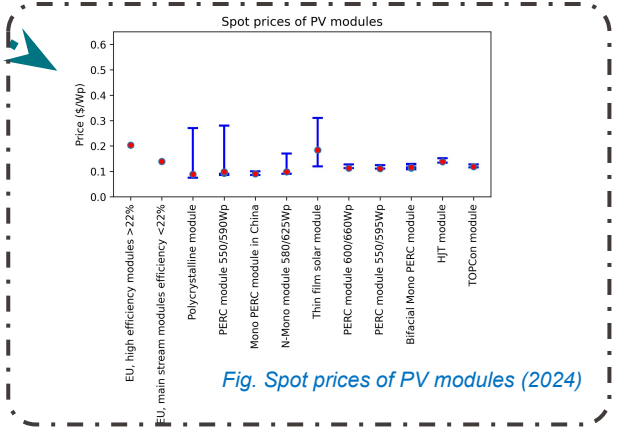



*Fig. Spot prices of PV modules (2024)*

# $CO_2$ budget and Environmental impacts of PV Technologies

- Cumulative CO2 emissions of PV production to meet the energy demand by 2050 at 20% growth rate till 1.2 TW/annum production level will significantly consume the overall CO2 budget
- However, with significant research, this footprint can be reduced to 1.5% by 2050
- Further, a carbon-neutral PV production by transforming the energy infrastructure will keep impact below 1% of the cumulative budget

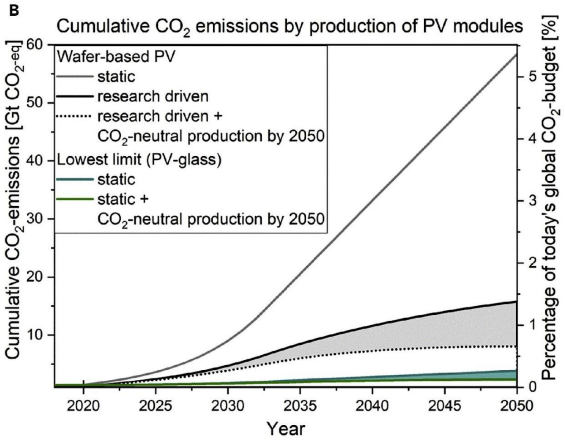



*Fig. Carbon emissions scenarios for PV industry: cumulative CO2 emissions from the PV sector (Wagner et al. 2020)*

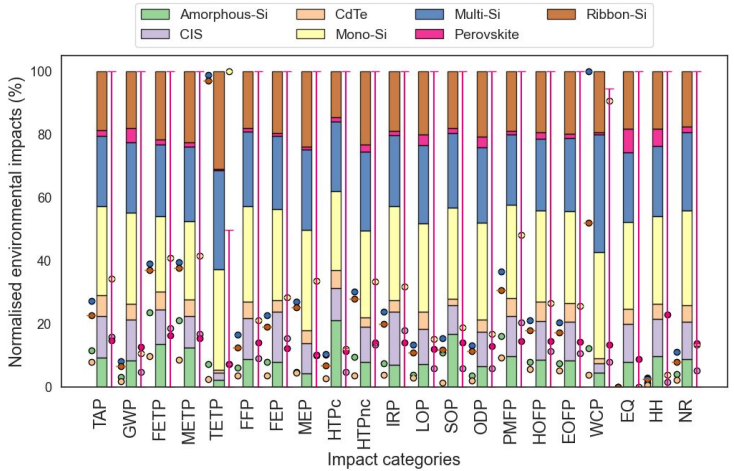



*Fig. Comparison of normalized environmental impacts of different classes of PV technologies based on Recipe method (Bhati et al. 2024)*

- On a median values basis (shown as bar) perovskite solar cells are having relatively less impact in all categories except HH and EQ
- On average (shown as scattered plots with error bars), PSCs are not significantly better moreover can be worse than si cells in categories like HH, EQ and NR

# Hotspots in PSCs manufacturing

## Hotsopts in the fabrication process:

- Based on hotspot analysis, on average, the etching stage contributes minimum to the overall fabrication process except in FETP, METP, HTPnc, EQ, and HH indicators
- Substrate+TCO selection and preparation stage has maximum impact in human health category
- Cleaning stage has maximum impacts in almost all categories
- Among active layers, perovskite layers have slightly higher values than ETL and HTL which are comparable to each other

## Strategies to reduce impacts:

- Recycling of solvents used in the cleaning process (acetone has the maximum impact)
- Electricity consumption during ultrasonication also have high impact in certain cases
- Gold and gold-based electrodes should be avoided
- Certain ETLs like PCBM and perovskite layers like CsPbBr should be avoided to reduce the impacts in HH category

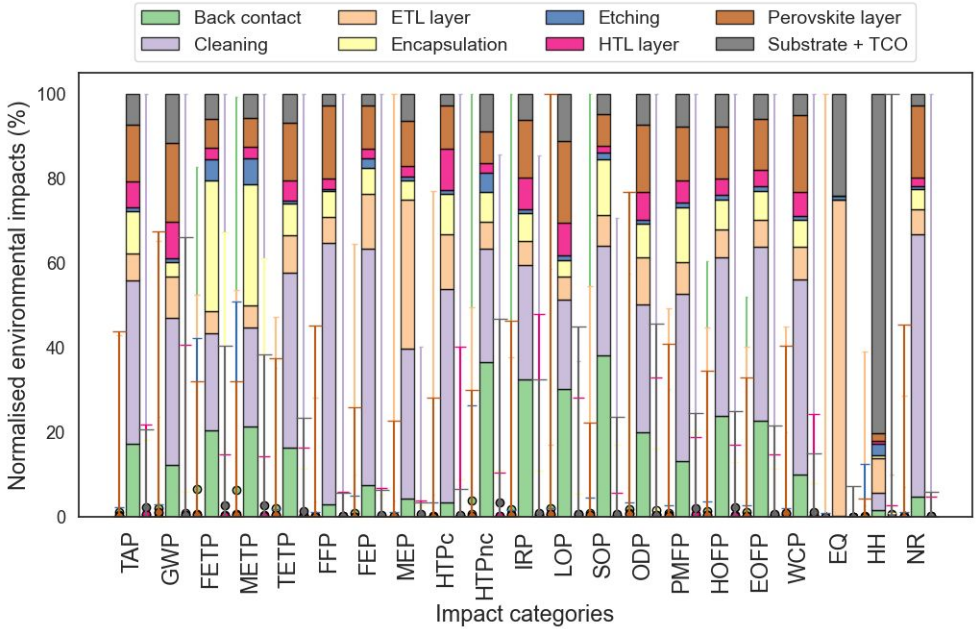



*Fig. Relative environmental impacts of different fabrication steps for perovskite modules based on Recipe method (Bhati et al. 2024)*

# Mapping effects on absolute scale

- Based on the results of LCA, PSCs have the potential to reduce the impacts of PV technologies significantly
- However, the results are still relative and cannot be taken as guiding measures for designing or fabricating PSC
- For the same, the Environmental footprint method can be used to estimate the impacts under different categories
- Finally, these impacts can be translated into contribution to different planetary boundary (PBs) budgets
- However, there is still a need to allocate the budget for this technology against different PBs so the transgression can be measured specific to these technologies

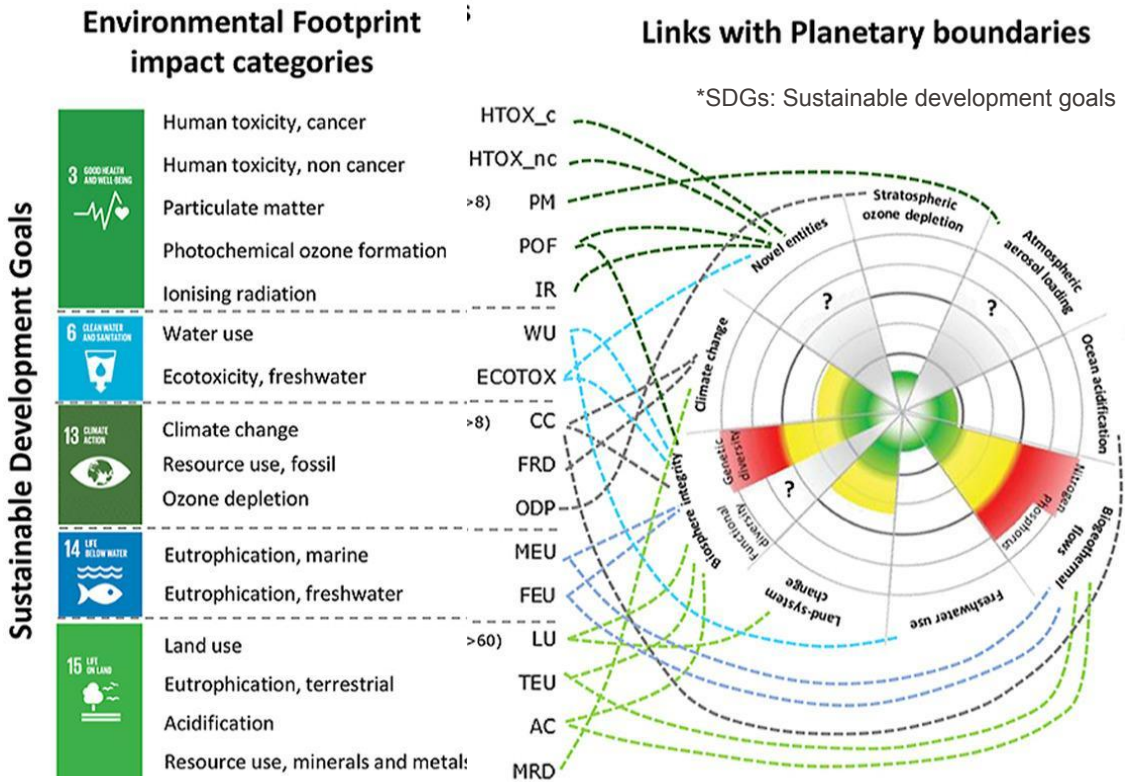



*Fig. Connection between the LCIA impact categories of Environmental Footprint (EF) method, PBs and SDGs (Sala et al. 2020)*

# Trade-offs between various objectives

- Multiple criteria for designing these cells (like different PBs) and hence we need a mathematical framework to design the optimal recipes

- For the same, we can use multi-objective optimization to generate the optimal recipes by balancing the weights of different recipes

- Finally, with the generated recipes we can do a screening and evaluate the most potential candidates in the experimental setting to reduce the time in finding the optimal solutions

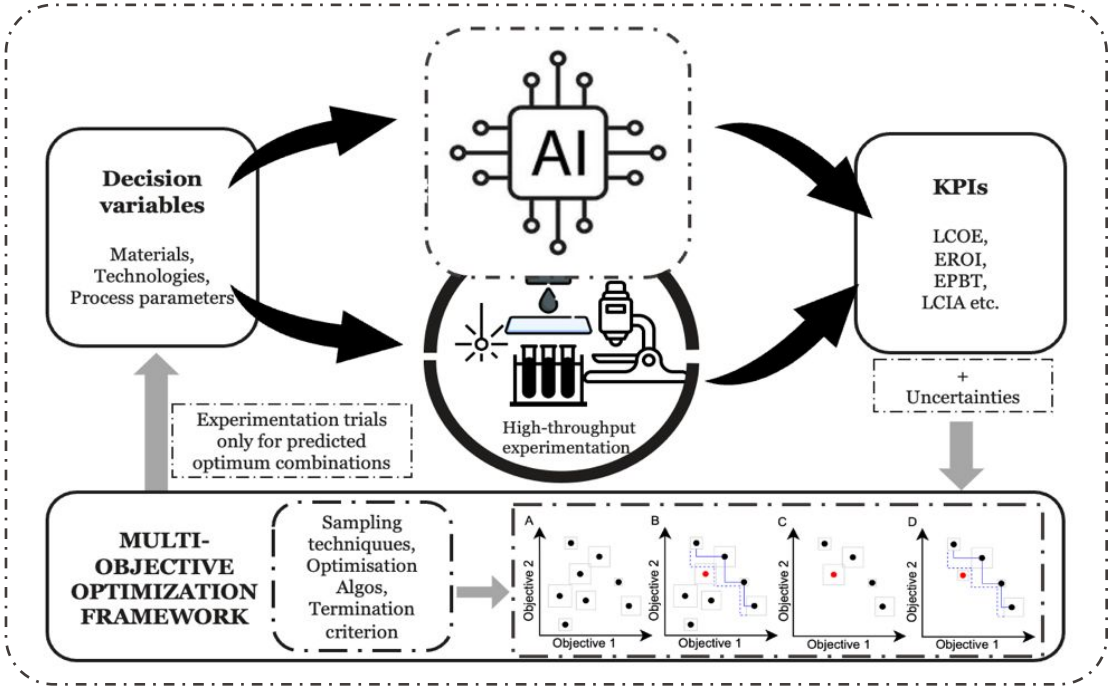
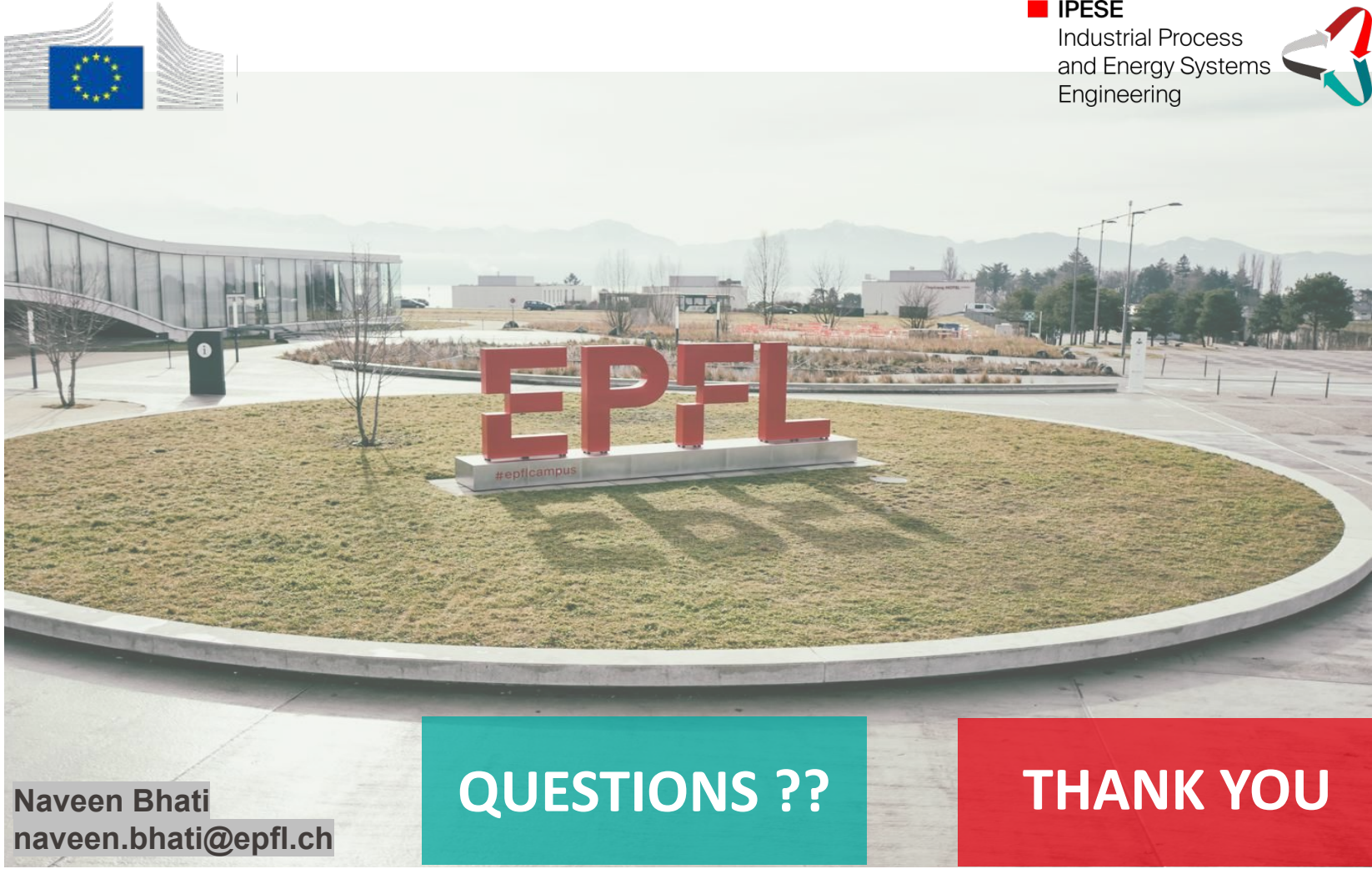



*Fig. Framework for optimizing PSCs based on multiple objective functions*

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QUESTIONS ??

THANK YOU

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# Decision variables and design space

Decision variables affecting the Key performance indicators of perovskite solar cells/modules include:

- Perovskite absorber layer composition
- Charge transport layer materials (ETL, HTL)
- Manufacturing techniques
- Post-deposition treatment technique
- Solvent composition
- Overall cell architecture

Manufacturing Cost : $MC = Cost_{materials} + Cost_{ener} + Cost_{equip} + Cost_{build} + Cost_{labour} + Cost_{util} + Cost_{automate} + Cost_{waste}$

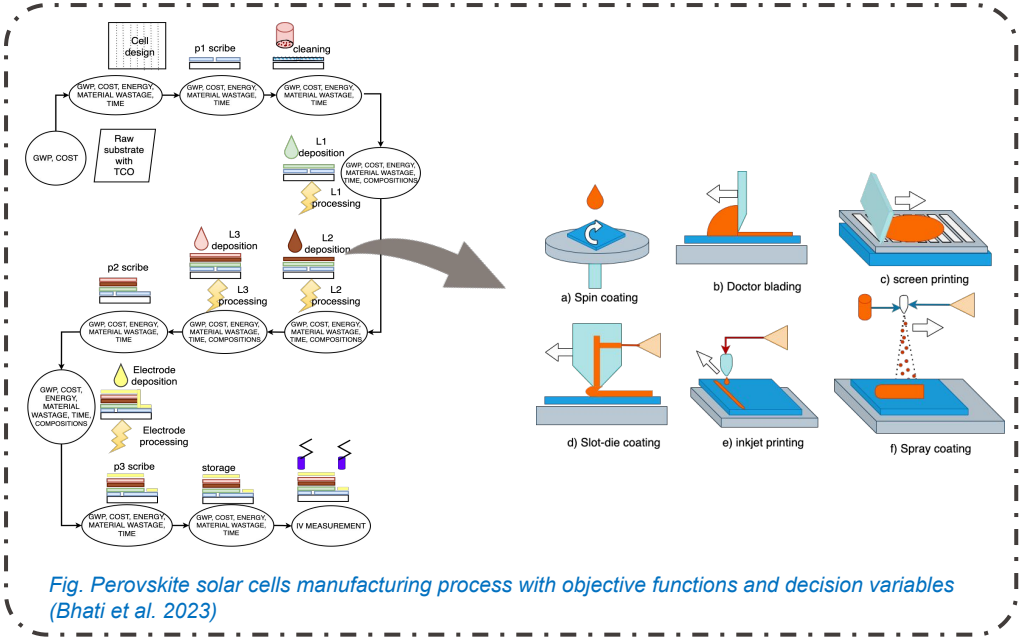


*Fig. Perovskite solar cells manufacturing process with objective functions and decision variables (Bhati et al. 2023)*