2021 IEEE 48th Photovoltaic Specialists Conference (PVSC) | 978-1-6654-1922-2/21/$31.00 ©2021 IEEE | DOI: 10.1109/PVSC43889.2021.9518632

Comparing the carbon footprint of monocrystalline silicon solar modules manufactured in China and the United States

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***Abstract*— This work discusses the life-cycle impact of manufacturing silicon monocrystalline (c-Si) (PV) panels in the United States compared to China. We compare the results using country average and regional data accounting for the location of each manufacturing stage. The carbon footprint based on the national average for the USA is 515 g CO_2/kWp compared to 740 g CO_2/kWp for China. Producing c-Si modules in China from US polysilicon reduces the carbon footprint by 9.5% compared to Chinese modules. Manufacturing modules entirely in the US modules could reduce the carbon footprint by 30%. PV modules supply chain is in regions with slower decarbonization than the rest of the country for both US and China, slowing down the reduction in carbon footprint for c-Si in the future.**

Keywords*— *Life cycle assessment, silicon photovoltaics, United States manufacturing

I. Introduction

The installation of solar photovoltaic modules (PV) is motivated in part to reduce the carbon footprint of current electricity production. However, solar panels, in particular silicon modules which account for most of the current market, are energy-intensive to produce, and therefore, depending on the energy mix for electricity production, the impact on the environment differs among solar panels. The location for silicon manufacturing is changing very quickly. Figure 1 shows the location of polysilicon cells, panels in 2013 compared to 2019 [1][2]. Chinese production has increased for each manufacturing stage, particularly for polysilicon (30%) while installations have decreased (5%). By comparison, most of the manufacturing in the USA was for polysilicon production, and its share has reduced by 13% over the same period while installations have remained constant. The USA still produces polysilicon, but it is exported to produce cells and panels in other countries. This work compares the life cycle carbon footprint of manufacturing c-Si modules in China and the USA using country-specific electricity and material production. In addition to country carbon footprint, this work includes a regional analysis that impacts the carbon footprint and transportation assumptions. A future scenario is developed to evaluate the impact of grid decarbonization and expected module efficiency improvement over the next decade.

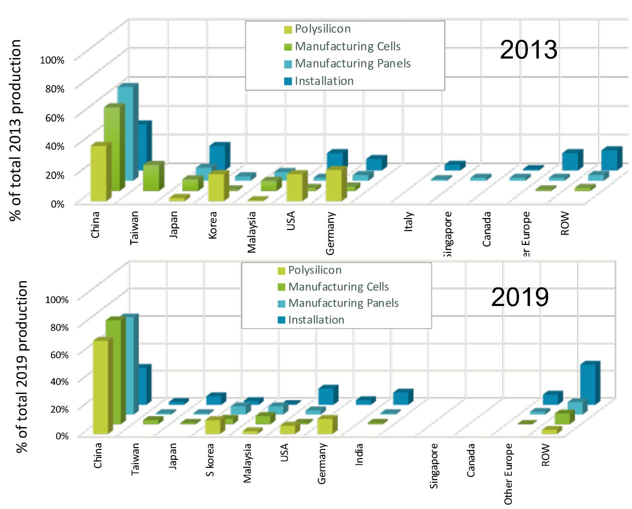


Fig 1: Manufacturing location for polysilicon, cells and panels as well as installation in 2013 and 2019 (adapted from [1-2])

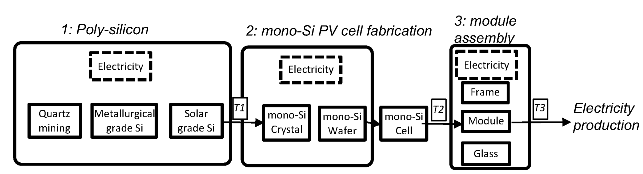


Fig 2: Scope of the study

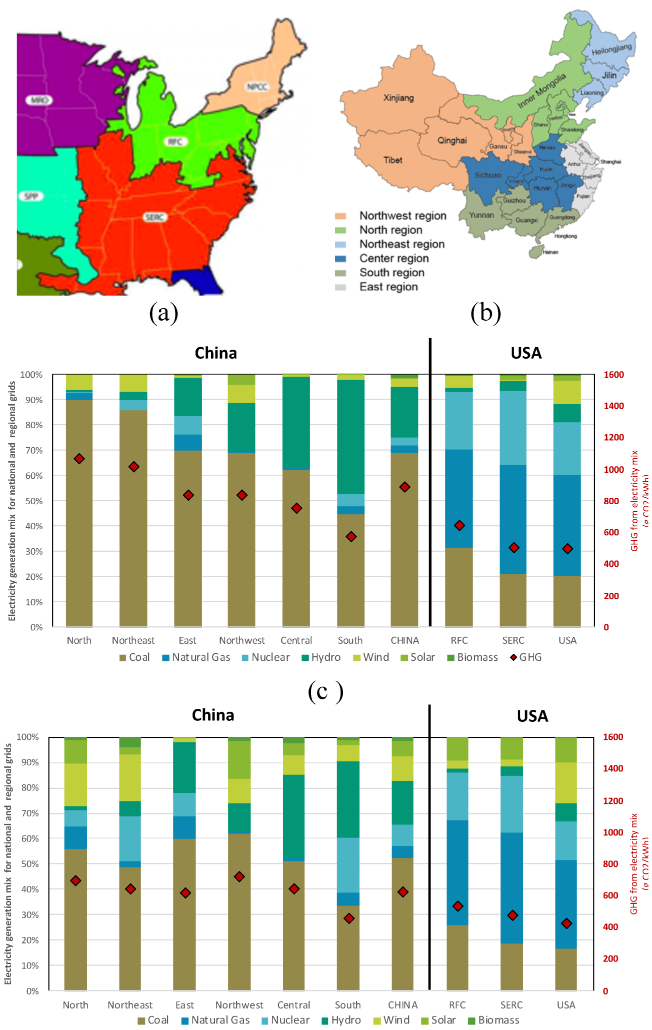
II. Methods

The scope of the study is shown in Fig 1. We consider all stages from polysilicon production to electricity production under standard conditions. The regional analysis includes the specific location of each manufacturing stage and the transport required between the regions. The life cycle inventory was updated based on the 2020 IEA PVPS inventory data [3] as well as other reports on change in polysilicon consumption [4] and module fabrication [5]. The electricity grid for China was modeled using a recent regional grid study that accounts for the addition of renewables and specific electricity production performance for China [6]. The US electricity was updated using the US current and future electricity mix from the EIA Annual Energy Outlook 2021 [7]. This approach is preferred to using existing inventory data from Ecoinvent [8], which is outdated and overestimates the carbon footprint of the grid. The module efficiency was assumed to be 20% in 2020 and 21.5% in 2030 based on current and future c-Si module efficiency [9].

In the regional analysis, the manufacturing location and annual production were used to calculate an average carbon electricity carbon footprint per manufacturing stage. For China, the location for each manufacturing stage is based on a recent report from NREL about the silicon supply chain [10]. For the US scenario, polysilicon production considers Michigan and Tennessee locations. Due to the low volume of wafer, cell, and panel manufacturing, the US average is used for those stages.

III. Results and Discussions

The electricity production for each region and the associated carbon footprint is shown in Figure 3. For polysilicon in the US, Wacker Chemie and Hemlock have similar manufacturing capacities in Tennessee (SERC) and Michigan (RFC). The average grid carbon footprint of these two regions is used in the analysis. By comparison, the carbon footprint for each of the Chinese regions is required since there are photovoltaic module components produced in most areas.



(d)

Fig 3: (a) Electricity regions in the USA and (b) China (c-d) Electricity generation mix for each region and country average and associated lifecycle carbon footprint for 2020 and 2030

The share in manufacturing for each stage of the silicon module is shown in Fig 4. Most of the polysilicon production is in the Northwest, then most of the wafer, cell, and module production is in the East region. The location change has minimal impact on the carbon footprint from the electricity in 2020, ranging from 847-853 g CO_2/kWh, but is slightly lower than the average Chinese value for the grid.

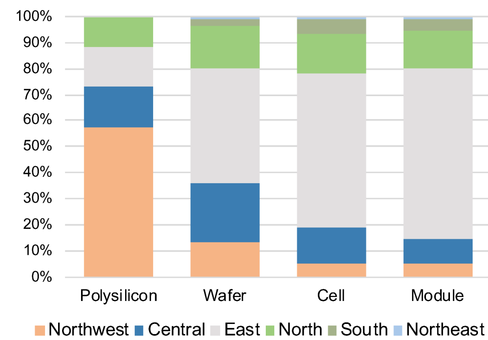


Fig. 4. Manufacturing location for each stage of module production and calculated carbon footprint of the grid for that stage.

The life cycle carbon footprint for modules completely manufactured in China, manufactured in China from USA polysilicon, and entirely in the USA is shown in Fig. 5. The carbon footprint based on the national average for the USA is 515 g CO_2/kWp compared to 740 g CO_2/kWp for China. For China from 2015 to 2020, this corresponds to a 58% carbon footprint reduction. Producing c-Si modules in China from US polysilicon reduces the carbon footprint by 9.5% compared to Chinese modules, while producing modules entirely in the US modules could reduce the carbon footprint by 30.4%. In 2015, this difference would have been 41.6% lower, but the rapid

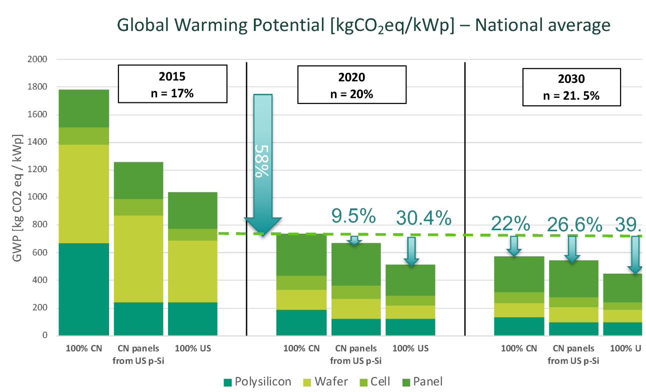


Fig. 5. Carbon footprint in 2015, 2020 and 2030 for modules produced in China, US and in China from US polysilicon.

decarbonization of the Chinese grid is reducing this gap. In 2030, the difference between US and China is expected to further reduce to 17.4%.

The results from the regional analysis are shown in Fig. 6. The results are slightly lower than with the country average for China and higher for the USA. However, manufacturing in both the US and China is in where grid decarbonization is expected to be lower than in the rest of the country. The regional results are 9% higher for China and 10% higher for the US in 2030

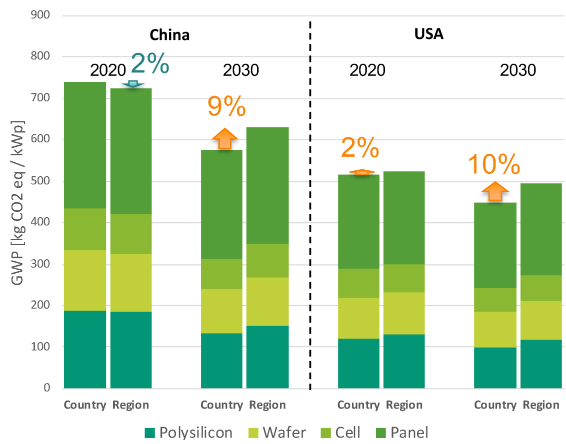


Fig. 6. Manufacturing location for each stage of module production and calculated carbon footprint of the grid for that stage.

compared to the country average.

IV. CONCLUSION

The carbon footprint of photovoltaics has decreased significantly in the last five years because of increased efficiency, reduction in material and electricity consumption. Silicon manufacturing requires a large amount of electricity, and therefore the manufacturing location has a significant impact on the overall carbon footprint of the module. The PV supply chain is currently located in regions where the decarbonization of the electrical grid is expected to be slower than in the rest of the country.

V. ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation grant number NSF-1801785.

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