IMPACT OF SOLAR PANEL MANUFACTURING PROCESSES ON THE CONCENTRATION OF NO_X IN THE ATMOSPHERE

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Abstract. Considered the environmental aspects of producing photovoltaic modules, including the emission of nitrogen oxides (NO_x) into the atmosphere. The main stages of the technological process and their potential contribution to air pollution are analyzed. The main stages of production are considered, sources of NO_x emissions are analyzed, and their potential impact on the environment is assessed. Measures are proposed to reduce the negative impact on the environment.

Keywords: solar panels, emissions, nitrogen oxides (NO_x), energy, air pollution, environmental impact, cleaning, selective catalytic reduction (SCR).

Анотація. Розглянуті екологічні аспекти виробництва фотоелектричних модулів, зокрема емісія оксидів азоту (NO_x) в атмосферу. Проаналізовано основні етапи технологічного процесу та їх потенційний внесок у забруднення повітря. Розглянуто основні етапи виробництва, проаналізовано джерела викидів NO_x та оцінено їх потенційний вплив на навколишнє середовище. Запропоновані заходи для зменшення негативного впливу на навколишнє середовище.

Ключові слова: сонячні панелі, викиди, оксиди азоту, енергетика, забруднення повітря, екологічний вплив, очищення, селективна каталічна редукція.

Introduction. Solar energy is one of the most promising areas of renewable energy, actively developing worldwide, and is an essential step in the fight against climate change and reducing dependence on fossil fuels. The production of solar panels involves complex technological processes, each of which is a source of nitrogen oxide (NO_x) emissions into the atmosphere.

Nitrogen oxides, such as nitrogen oxide (NO) and nitrogen dioxide (NO_2), are among the most problematic air pollutants. They play a significant role in forming photochemical smog, acid rain, and ground-level ozone, which negatively impact human health and ecosystems. In addition, NO_x is an indirect greenhouse gas contributing to global warming. In the context of solar panel production, NO_x emissions may seem paradoxical. After all, solar energy is positioned as a clean and environmentally friendly energy source. However, like any industrial process, producing photovoltaic modules is not without environmental challenges.

Analysis of the state of the issue. The production of solar panels involves several stages (Fig. 1). Solar panels themselves do not emit NO_x during electricity generation, but the production process requires measures to reduce emissions.

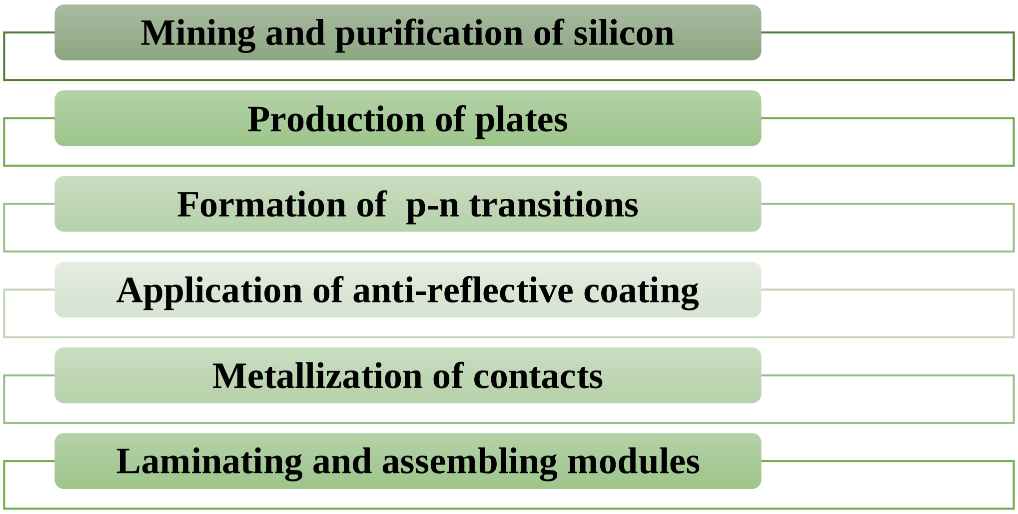

Fig. 1. Technological processes that are potential sources of NO_x emissions

Each stage is accompanied by the formation of NO_x due to high-temperature processes, the use of nitrogen-containing chemicals, or fuel combustion in power plants [2].

The purpose of the work. Identification of the main sources of NO_x emissions in the production of solar panels, assessment of NO_x concentrations at different stages of the production process, analysis of the impact of NO_x emissions on air quality, development of recommendations for reducing NO_x emissions in the production of solar panels.

Methods, materials and research results. Sources of NO_x emissions in the production of solar panels are diverse and associated with different stages of the production process. They include both direct emissions from production processes and indirect emissions related to energy consumption and logistics [1].

It is important to understand that the amount and intensity of NO_x emissions can vary significantly depending on the specific technologies, equipment, and practices used in production [2].

High temperature processes

- Smelting and purification of silicon, the amount of NO_x depends on the temperature, the time the gases stay in the high-temperature zone, and the concentration of oxygen.
- Cultivation of monocrystalline silicon.

Chemical reactions using nitrogen-containing compounds

- Diffusion process for creating p-n transitions: nitrogen-containing compounds of the $POCl_3$ type are used (phosphorus oxychloride), which leads to the formation of NO_x. In the interaction of $POCl_3$ with oxygen at high temperatures (about 800 - 900 °C), nitrogen oxides are formed as by-products.
- Surface texturing of silicon wafers: When HNO_3 reacts with silicon, nitrogen oxides are formed, which can evaporate and enter the atmosphere.

Fuel burning at power stations

- Production of electricity for production needs: if production uses electricity from traditional sources (for example, coal-fired power plants), this indirectly leads to NO emissions. In the process of burning coal, both “thermal NO_x”and “fuel NO_x” (from nitrogen-containing compounds of coal) are produced.
- Use of natural gas for heating: When natural gas is burned, mainly “thermal NO_x” is formed, but “fast NO_x” can also be formed through the reaction of atmospheric nitrogen with hydrocarbon radicals.

Cleaning processes

- Plasma chemical vapor deposition (PECVD): This process used to apply anti-reflective coatings can produce NO_x, especially when nitrogen-containing gases are used. During the decomposition of such gases in the plasma, active forms of nitrogen are formed, which then react with oxygen, forming NO_x.

Coating processes

- The use of nitric acid or other nitrogen-containing compounds to clean equipment and materials can be a source of NO_x emissions. When nitric acid interacts with organic contaminants or metals, oxides can form nitrogens that evaporates into the atmosphere.

Modern technologies and emission control methods can significantly reduce NO_x emissions compared to earlier production processes. For example, using catalytic converters, optimizing combustion processes, using alternative chemicals, and implementing closed cycles can significantly reduce NO_x emissions.

Quantifying NO_x concentrations is critical to understanding the scope of the problem and developing effective emission reduction strategies. However, it is worth noting that these concentrations can vary significantly depending on the stages of operation used in production. Let's look at the available data on NO_x concentrations at key stages of the production process (Fig. 2).

Data taken from:

- production of polycrystalline silicon: study by Fthenakis et al. (2008), this is due to high-temperature silicon purification processes [4];
- growing single crystal silicon: according to Peng et al. (2013) [7];
- diffusion process to create p-n junctions: the study by Stegemann et al. (2013), this is due to the use of nitrogen-containing compounds such as $POCl_3$;
- application of anti-reflective coating by PECVD: according to Blakers et al. (2013), these emissions are associated with the use of nitrogen-containing gases in the deposition process [8];
- metallization of contacts: according to Fthenakis (2012), it is related to high-temperature sintering processes of metal pastes [4];
- production of glass for solar panels: according to Jungbluth et al. (2012), it is associated with high-temperature glass melting and molding processes [9].

Modern emission control technologies, such as selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR), can significantly reduce NOx concentrations in emissions.

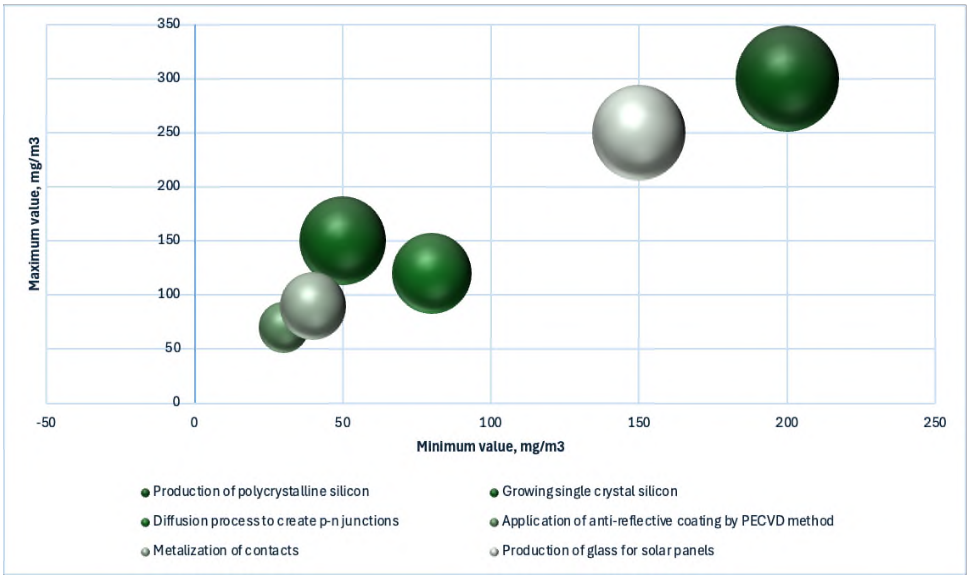

Fig. 2. Concentration of NOx emissions during key stages of solar panel production

Comparing these data with air quality standards, it can be concluded that without proper treatment systems, NOx emissions from solar panel production can pose a significant risk to the environment [5].

For example, the World Health Organization (WHO) recommends that the average annual concentration of NO_2 should not exceed 40 μg/m³. These data emphasize the importance of implementing effective emission control systems and optimizing production processes to minimize NO_x production in solar panel manufacturing [10].

Modern emission control technologies, such as selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR), can significantly reduce NO_x concentrations in emissions. Air pollution is a double whammy for our health and the environment. In cities, it creates smog, that brown haze, and when it rains, it turns into acid rain, damaging both forests and oceans. Inhaling this pollution irritates the lungs and can worsen respiratory problems, especially for those already at risk.

NO_x deposited in the oceans acts as a nutrient source for phytoplankton, potentially worsening problems such as red tides and harmful algal blooms. By acidifying surface waters, acid rain disrupts ecosystems, reducing the diversity of life and killing fish.

Inhalation of nitrogen oxides, nitric acid, and ozone can harm the lungs, especially delicate tissues. Even short bursts can irritate healthy lungs, while it is extremely dangerous for asthma sufferers. Living near major roads greatly increases exposure to these pollutants, increasing the risk of respiratory diseases such as pulmonary emphysema and bronchitis, especially for vulnerable populations such as children and the elderly.

NO_x can impact both locally and nationally, as it is a widespread pollutant and can be absorbed into the atmosphere.

● Local: creates localized air quality problems, especially in areas with a high concentration of sources: power plants, factories, and heavy traffic. These areas can experience high levels of NO_x that exceed national air quality standards, leading to respiratory problems for residents.

● Regional: due to prevailing winds, NO_x emissions can spread over long distances, contributing to regional air quality problems. Acid rain also helps to transport hazardous substances over long distances.

● National: most countries set national air quality standards for NO_x to protect public health. However, exceeding these standards can become a national problem that requires broader changes in policies and strategies to reduce emissions in different sectors (power generation, transportation, industry).

Optimization of technological processes

- **Temperature reduction:** using more efficient melting and processing technologies that lower the required temperatures will significantly reduce NO_x emissions.
- **Substitution of nitrogen-containing compounds:** use of alternative chemicals that do not contain nitrogen or have a lower tendency to form NO_x .
- **Vacuum coating:** the application of vacuum coating allows to reduce process temperature and, accordingly, reduce emissions.

Cleaning of emissions

- **Selective catalytic reduction (SCR):** this method allows you to reduce the concentration of NO_x in emissions by converting them into harmless nitrogen and water.
- **Adsorption:** use of adsorbents to absorb NO_x from flue gases.

Use of renewable energy sources

- **Going green:** powering solar panel production with electricity from renewable sources such as solar, wind or hydro will avoid the NO_x emissions associated with burning fossil fuels.

Implementation of monitoring and control systems:

- **Regular monitoring of emissions:** constant monitoring of NO_x level in emissions will allow timely detection of any deviations from the norms and taking the necessary measures.

Different types of filters can be used to reduce NO_x emissions in the production of solar panels [3]:

1. Diesel Particulate Filters (DPF): used to capture particulate matter (soot) from NOx waste.

2. Catalytic converters (SCR): use catalysts to react with NO_x, which converts it into safe compounds such as nitrogen and water.

3. AdBlue filters are used to introduce the AdBlue reagent, which reacts with NO_x and reduces its content in the waste.

For example, although the well-known company Yara specializes in fertilizer production, it also has technology to reduce the amount of nitrogen oxide emissions into the environment, such as catalytic converters. Their patented ammonia injection mesh provides efficient mixing in the flue gas stream, maximizing the conversion of NO_x into harmless nitrogen (N_2) and water (H_2O) with minimal ammonia slippage (Fig. 3).

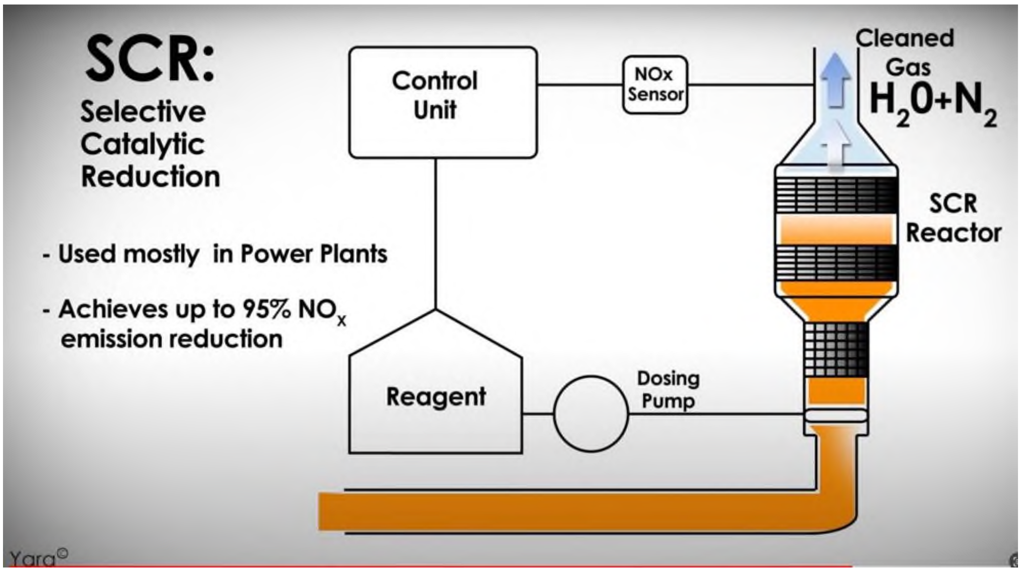

Fig. 3. The cleaning technology installed at YARA

This innovative mesh design allows for the industry-leading performance of up to 98 % NO_x reduction while keeping ammonia emissions (NH_3 release) below 2 ppmv. Yara recommends SCR systems for optimum performance when flue gas temperatures are between 180 °C and 450 °C and minimal catalyst poisons are present. Yara's transition to green ammonia production using renewable electricity for electrolysis significantly reduces the dependence on fossil fuels for ammonia production. This can lead to a reduction in overall NO_x emissions [6].

Conclusions. Although current levels of NO_x emissions do not lead to exceedance of air quality standards, there is potential for their reduction. Reducing NO_x emissions in solar panel production is an important step towards creating a cleaner and more sustainable energy sector. Using modern technologies, filters, optimization of production processes and renewable energy sources can significantly reduce the negative impact on the environment and make solar energy an even more attractive alternative to traditional energy sources.

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