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Byproduct metal requirements for U.S. wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios

Nedal T. Nassar *, David R. Wilburn, Thomas G. Goonan

National Minerals Information Center, U.S. Geological Survey, USA

HIGHLIGHTS

- U.S. byproduct metal demand for solar PV and wind power are assessed in various scenarios.
- Requirements for Te and Dy seem to be of most concern.
- Cumulatively, the CPP may require 13–43% more byproduct metals by 2040.

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ABSTRACT

The United States has and will likely continue to obtain an increasing share of its electricity from solar photovoltaics (PV) and wind power, especially under the Clean Power Plan (CPP). The need for additional need for solar PV modules and wind turbines will, among other things, result in greater demand for a number of minor metals that are produced mainly or only as byproducts. In this analysis, the quantities of 11 byproduct metals (Ag, Cd, Te, In, Ga, Se, Ge, Nd, Pr, Dy, and Tb) required for wind turbines with rare-earth permanent magnets and four solar PV technologies are assessed through the year 2040. Three key uncertainties (electricity generation capacities, technology market shares, and material intensities) are varied to develop 42 scenarios for each byproduct metal. The results indicate that byproduct metal requirements vary significantly across technologies, scenarios, and over time. In certain scenarios, the requirements are projected to become a significant portion of current primary production. This is especially the case for Te, Ge, Dy, In, and Tb under the more aggressive scenarios of increasing market share and conservative material intensities. Te and Dy are, perhaps, of most concern given their substitution limitations. In certain years, the differences in byproduct metal requirements between the technology market share and material intensity scenarios are greater than those between the various CPP and No CPP scenarios. Cumulatively across years 2016–2040, the various CPP scenarios are estimated to require 15–43% more byproduct metals than the No CPP scenario depending on the specific byproduct metal and scenario. Increasing primary production via enhanced recovery rates of the byproduct metals during the beneficiation and enrichment operations, improving end-of-life recycling rates, and developing substitutes are important strategies that may help meet the increased demand for these byproduct metals.
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1. Introduction

On April 22, 2016, 174 countries and the European Union signed the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) thereby agreeing to strengthen their response to the threat of climate change by developing plans, pursuing actions, and stimulating investments aimed at reducing global anthropogenic greenhouse gas (GHG) emissions [1]. The Clean Power Plan (CPP), developed by the U.S. Environmental Protection Agency (EPA) in 2015, represents a central mechanism that the Obama Administration has established for the United States to meet its goals of reducing GHG emissions generated from power plants [2]. Although the U.S. Supreme Court has since issued a "stay" on the CPP, the "EPA firmly believes the Clean Power Plan will be upheld when the merits are considered because the rule rests on strong scientific and legal foundations" [2]. Regardless of whether or not the CPP is implemented in its current form or on its proposed timetable, the United States has and will likely

* Corresponding author at: 12201 Sunrise Valley Dr., MS 988, Reston, VA 20192, USA.
E-mail address: nnassar@usgs.gov (N.T. Nassar).

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continue to obtain an increasing share of its electricity from renewable energy technologies. Indeed, technological advancements, which have resulted in improvements in electricity conversion efficiencies and cost reductions, as well as U.S. federal production and investment tax incentives, have already helped make solar photovoltaics (PV) and wind power among the fastest growing electricity generation technologies in the United States. As illustrated in Fig. 1, although U.S. electricity generation capacities based on solar PV and wind power are small in comparison to those based on fossil fuels (i.e., coal, natural gas, and petroleum) they have increased rapidly both in absolute terms and on a relative basis. For example, the U.S. electricity generating capacity of solar PV from all sectors, excluding non-grid applications, increased from approximately 20 megawatts (MW) or 0.0025% of total capacity in the year 2000 to nearly 23,000 MW or approximately 2.1% of total capacity in 2015 [3]. Even more robust was the growth in wind power generation capacity, which increased from approximately 2450 MW or 0.3% of total capacity in the year 2000 to nearly 76,000 MW or 7% of total capacity in 2015 [3].

Fig. 1 also displays U.S. electricity generation capacity projections up to the year 2040 under two scenarios recently developed by the U.S. Energy Information Agency (EIA) [3]: the 2016 Annual Energy Outlook (AEO) "reference" scenario with and without the CPP ruling being implemented, referred to hereafter as the "CPP" and "No CPP" scenarios, respectively. The CPP scenario assumes that the EPA's final CPP ruling is implemented according to the proposed timetable and that all states choose to meet their GHG emissions targets using the mass-based option rather than the rate-based approach (i.e., emissions targets are based on absolute annual GHG emissions rather than on the amount of GHGs emitted per unit of electricity generated). The reductions in GHG emissions are to be achieved by improving the thermal efficiencies of existing fossil fuel-fired power plants, employing demand-side energy efficiency measures and, as illustrated in Fig. 1, expanding the use of renewable energy generation technologies including solar PV and wind power [4]. In contrast, the No CPP scenario assumes that the CPP ruling is permanently voided and not replaced by any other GHG emissions controls on the power sector but that other programs (e.g., the Northeast's Regional Greenhouse Gas Initiative and California's Global Warming Solutions Act of 2006) are maintained [5].

Under the CPP scenario, U.S. solar PV generation capacity grows to exceed that of wind power by the year 2032 and that of coal by 2035, while under the No CPP scenario solar PV generation capacity surpasses that of wind power by 2033 but does not surpass that of coal by the end of the scenario in 2040. Importantly, this CPP scenario represents only one possible means of achieving compliance with the CPP ruling under known technological and demographic trends. Indeed, the EIA has published five alternative CPP scenarios that reflect the degree of flexibility in the CPP ruling by varying the type of emissions compliance target that the states choose to implement (mass-based versus rate-based), the degree of interregional GHG emissions allowance trading, the allocation of the GHG emissions allowances (to the electricity generators versus the load-serving entities), and the extent of the emission reductions beyond 2030. A comparison of these different scenarios and their projected solar PV and wind power generation capacity additions are detailed in Appendix A. Also note that the projections provided in the EIA's 2016 AEO assessment are in stark contrast to the projections specified by a previous EIA report on the impact of the CPP [4], which was based on the 2015 AEO reference case scenario and the EPA's CPP draft ruling. In this previous EIA assessment of the CPP, wind power was projected to reach 205 GW of installed generation capacity by 2040, a value that is 50% greater than what is projected for solar PV and virtually the same as what is projected for coal by the same year. The notable inconsistences between assessments are due to differences between the EPA's CPP draft and final rulings, including a delayed compliance start date and updated economic and technological information and assumptions including lower natural gas prices, lower capital costs for renewable energy plants, and extensions of renewable tax credits [5]. What actually gets implemented on the ground will undoubtedly be different from what is projected in any of these scenarios as it will be up to the individual states to decide how best to meet the requirements of the CPP ruling if it is implemented. Nevertheless, the EIA's 2016 AEO reference scenarios provide a reasonable basis for comparison of future U.S. solar PV and wind power generation capacities with and without the CPP being implemented.

Despite the uncertainty regarding these specific projections, it is likely that the United States will continue to grow and perhaps accelerate its transition to renewable energy technologies. From a materials perspective, the expanded use of renewable energy technologies would likely lead to an increased use of a number of minor metals that are utilized by these technologies. Minor metals are typically defined as those that have relatively low production or

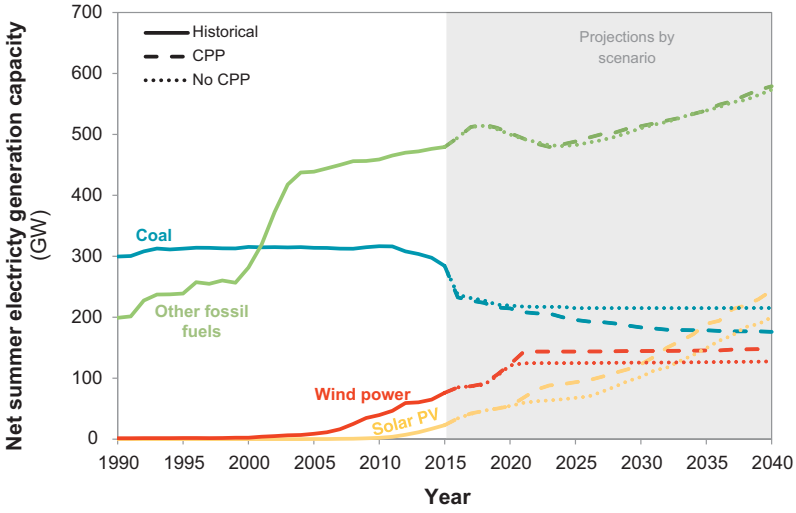

Fig. 1. U.S. net summer electricity generation capacity for coal, other fossil fuels, wind power, and solar PV technologies in units of gigawatts (GW) based on historical data since 1990 and projections up to the year 2040 under the EIA's 2016 AEO "reference case" scenario with and without the CPP. Generation capacities from the electrical power, combined heat and power, and end-use sectors are included. The "other fossil fuels" category includes oil and natural gas steam, combined cycle, combustion turbine/diesel, distributed natural gas, and other gaseous fuels. Electricity generation capacities from other sources are not displayed. Data source: U.S. Energy Information Agency [3].