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Non-hazardous industrial waste in the United States: 100 Million tonnes of recoverable resources

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ABSTRACT

Despite the large volume of non-hazardous industrial waste (NHIW) being generated globally, systematic NHIW reuse policies are lagging, largely owing to piecemeal understanding of generation volumes, locations, chemical constituents, and future trends. Herein, we demonstrate how to estimate the mineral and energy flows embedded in the 200-300 million tonnes of NHIW in the United States using information from process engineering and economic projections. We estimate that the minerals contained in NHIW are on the order of 100 million tonnes and with electricity potential lectricity at 200 billion kWh annually from 1990 to 2016. Both are expected to increase by roughly 50% from 2017 to 2050. The electricity potential and bulk mineral contents (e.g., CaO and SiO_2) are modest compared to the total level of consumption of these resources (<3%), but there are county-level hotspots along the west coast with opporunities possibly large enough to yield significant material benefits at the local scale. Two lower-volume minerals, phosphorus and titanium, are noteworthy from a material substitution standpoint. They are estimated at 0.5-2.0 million tonnes in NHIW annually, which is 10-20% of current consumption and up to 50-80% in hotspot states. Although there are difficulties in cross-national generalization, we anticipate that the workflow steps themselves would be transferrable to other countries to be able to yield the chemical, locational and temporal information needed to inform the design of region-specific NHIW reuse programs and the development of NHIW valorization technologies.

1. Introduction

The growing interest from industrial ecology and other related fields in “closing material loops” has led to careful examination of the potential to recover energy and material resources from waste streams (Herrington, 2013; Li et al., 2019; Stahel, 2016; Tisserant et al., 2017), particularly from agricultural residues and municipal solid wastes (Champagne, 2008; Macias-Corral et al., 2008; Tuck et al., 2012). Non-hazardous industrial waste (NHIW), in contrast, has not received the same level of scrutiny as a potential secondary resource base. NHIW, which includes byproducts generated in manufacturing processes that do not present substantial hazard to human health or the environment (e.g., non-hazardous inorganic chemical wastes, most pulp and paper wastes, or foundry sand), is a significant waste flow by volume (Chertow et al., 2020a; Li et al., 2020). For example, in the US, the volume of NHIW was recently estimated at 0.2-0.3 billion tonnes per year in aggregate (Krones, 2016), which places NHIW on par with the volume of municipal solid wastes generated (0.2 billion tonnes per year) (US EPA, 2017) and 2-3 times the volume of agricultural waste (0.1 billion dry tonnes per year) (Langholtz et al., 2016). Yet, so far, only a few specific types of NHIW, e.g., spent foundry sand (Industry Practices Regarding the Disposal and Beneficial Reuse of Foundry Sand: Results and Analysis, 2007), have been systematically examined for their reuse potential.

In addition to availability in large quantities, NHIW, as shown repeatedly, is a good candidate for virgin material substitution and/or energy valorization given its low toxicity and relative homogeneity in chemical composition for each NHIW type (Chertow and Park, 2019). High levels of virgin material substitution by NHIW globally were consistently found to reduce material footprints, life cycle energy consumption and CO_2 emissions (Chertow and Park, 2019; Eckelman and Chertow, 2009; Laybourn, 2015; Saidan, 2019; Zhu and Chertow, 2016). Energy valorization from NHIW has also been widely successful at

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different scales (Chertow and Park, 2019; Eddine and Salah, 2012; Jourdain and Zwolinski, 2015; Roati et al., 2012; Sheppard and Rahimifard, 2019). Unlike other wastes that are often produced at many smaller locations, the generation of NHIW is typically concentrated in a few larger industrial locations, offering economies of scale for both collection and transportation.

Despite the potential and benefits of reusing NHIW, institutionalizing its reuse in policy has been hampered by three knowledge gaps. First, there is limited understanding of the chemical composition of NHIW. Like many other wastes, NHIW is often reported in broad categories (if reported at all) that are too coarse to infer chemical compositions and inform technology and policy designs (Allen and Behmanesh, 1992; "Guide for Industrial Waste Management, 2003"). Second, there is limited locational information for NHIW generation. As with other waste resources (e.g., waste heat (Gingerich and Mauter, 2015)), the environmental and economic benefits of NHIW reuse are highly sensitive to where the generation occurs owing to the technical, environmental, and economic difficulties of collection, transport and storage (Industry Practices Regarding the Disposal and Beneficial Reuse of Foundry Sand: Results and Analysis, 2007; Liu and Rajagopal, 2019). Finally, there is not yet a reliable projection of future NHIW generation that matches the long time horizon needed for policies and investments to take effect. Policy and adoption lags are well-documented for technology penetration and environmental policies,(Martin et al., 2020; Packey, 1993) and will likely apply to NHIW valorization as well.

In this study, we present the first estimate of the total minerals and energy embedded in NHIW in the US at the compositional, spatial, and temporal resolution necessary to inform NHIW reuse programs and technologies. In prior work, we demonstrated the feasibility of a methodology to examine the historical generation of one NHIW in the US (Li et al., 2020). Here we build of that methodology but significantly expand the scope to include >70% of all NHIWs generated in the US. We also refine the chemical resolution to the substance level and extend the temporal horizon to 1990-2050. Our study aims to provide a comprehensive picture for the availability of NHIW at the national level, and where it matters for business, at the local level. We anticipate that our results will provide a reference point to set realistic circular economy targets at the waste category and substance level, to assess the future waste impacts of national industrial policies (e.g., the Revitalize American Manufacturing and Innovation Act of 2014 (Reed, 2014)), and to inform the development of NHIW valorization technologies.

2. Methods

2.1. Scope of analysis

We cover 22 types of NHIW generated in 24 industrial sectors in this study, which were estimated to be >70% of the total NHIW generated in the US in 2015 (Krones, 2016). Details of the NHIW including the generating industries and their NAICS codes are presented in Table S1. The general methodological framework is provided in Fig. 1.

2.2. Estimation of NHIW generation

The amount of NHIW generated each year (V_{NHIW}) is estimated based on the value output in the generating sector (V_S) and the sector's NHIW generation intensity factor (I_{NHIW}):

$$V_{NHIW} = V_S \times I_{NHIW} \tag{1}$$

I_{NHIW} (kg/USD) is based on previous studies (Chertow et al., 2020b; Krones, 2016). V_S is the sector output at the four-digit NAICS level in 2009 constant price (Table S2). For 1990-2016, V_S is the sum of the "total value of shipments" of the corresponding six-digit NAICS (Table S2) reported by the National Bureau of Economic Research in the NBER-CES Manufacturing Industry Database (in constant 2009 USD) ("NBER-CES Manufacturing Industry Database, n.d.")

Projections of V_S in 2017-2050 (in constant 2009 USD) for each industrial sector are extracted from the U.S. Annual Energy Outlook 2017 (AEO), based on results from the National Energy Modeling System (NEMS). NEMS is the large-scale energy system optimization model developed by the U.S. Energy Information Administration (EIA) to project energy quantities and prices based on different economic and technology scenarios (Nalley, 2018). The Macroeconomic Activity Module (MAM) in NEMS estimates final demand across all industries for that scenario, while an embedded input-output model accounts for the upstream supply chain. The equilibrium value outputs for each industry are extracted for the AEO reference scenario. A mapping between NEMS industrial sectors and those used for this study is created using the NAICS classification system at the 3- and 4-digit level (Table S2). In addition to the reference case which has 2.1% GDP growth rate, we have

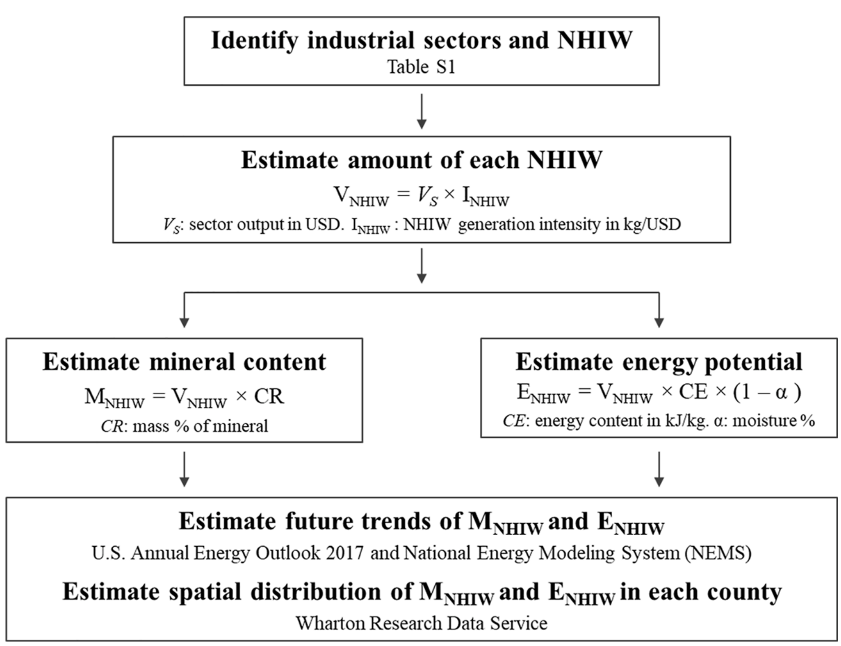

Fig. 1. Diagram of the methodology followed in this study.

also included two AEO side cases, *high-* and *low-economic growth* cases, to provide a range of future industrial development with the GDP growth rates at 1.6% and 2.6%, respectively (Assumptions to the Annual Energy Outlook 2017, 2017a).

2.3. Estimate the minerals content (M_{NHIW}) and energy potential (E_{NHIW})

For each inorganic NHIW, a detailed literature analysis (Table S4) is conducted to identify the key minerals embedded. A total of 11 minerals are thus identified and included in this study. For each NHIW, the minerals included are >90% of the total mass (Table S4). The amount of each mineral is estimated as:

$$M_{NHIW,i} = \sum_{j=1}^{j=15} \left(V_{NHIW,j} \times CR_{i,j} \right) \tag{2}$$

$M_{NHIW,i}$ (million tonnes) is the amount of mineral i ($i \in \{1, 2, \ldots, 12\}$). $V_{NHIW,\ j}$ (million tonnes) is the amount of NHIW j ($j \in \{1, 2, \ldots, 15\}$) estimated using Eq. 1. $CR_{i,j}$ is the concentration of mineral i in NHIW j, (tonne mineral i/tonne NHIW j) based on Table S4.

For each organic NHIW, a similar literature analysis (Table S5) is conducted to identify the energy embedded:

$$E_{NHIW,j} = \sum_{j=1}^{j=7} \left[V_{NHIW,j} \times CE_j \times \left(1 - \alpha_j\right) \right] \tag{3}$$

$$E_{e,j} = E_{NHIW,i} \ \times \ \gamma \tag{4}$$

$E_{NHIW,j}$ (Billion kWh) is the energy potential of in NHIW j ($j \in \{1, 2, \ldots, 7\}$). CE_j is the energy content of the corresponding NHIW. For each CE_j, at least five data sources are used (Table S5). α_j is the moisture content percentage of each NHIW. The energy content is converted to usable electricity potential ($E_{e,j}$) using Eq. 4, in which γ is the electric efficiency by conventional incineration technology (20%).(Galeno et al., 2011)

2.4. Spatial distribution of E_{NHIW} and M_{NHIW}

The mapping of county-level NHIW is done using county-level business data from the InfoGroup database retrieved through Wharton Research Data Service.("NBER-CES Manufacturing Industry Database, n. d."; Services, n.d.) The "location", "sales volume" and "NAICS" reported for each business are used to calculate the distribution of the minerals and energy potential using Eqs. 1–4. The results are aggregated for each county in the US for year 1997, 2007 and 2017. The "sales volume" numbers are also converted to 2009 constant USD.

2.5. Sensitivity analysis and uncertainties in the spatial allocation

We include potential uncertainties from four sources. The first one is the sector resolution, which is the NAICS included in *Vs* (Eq. 1). For example, for the three organic NHIWs, namely the used bark and wood waste from the wood product industry (NAICS321), the sludge from the petroleum and coal products industry (NAICS 324) and Air Pollution Control (APC) dust from the petroleum and coal products industry (NAICS 324), generation was reported at the three-digit NAICS level. Thus we design a high estimate that uses the *Vs* from all of the six-digit NAICS sectors under the three-digit NAICS sector, as well as a low estimate that only includes the *Vs* from the largest six-digit NAICS sector that generates this NHIW. The details are provided in Table S1-2. The second uncertainty assessed is each sector's NHIW generation intensity factor ($I_{N\ HIW}$ in Eq. 1). We have selected a low, a mid, and a high estimate for $I_{N\ HIW}$ for each sector and each NHIW based on the previous study.("Assumptions to the Annual Energy Outlook 2017, 2017b"; Krones, 2016) The third one is CE_j (Eq. 2) and $CR_{i,j}$ (Eq. 3). We have also included a low, a mid, and a high estimate based on the average and the standard variation of each CE_j and $CR_{i,j}$ reported in the literature (detailed in Table S4-5). Finally, we have included the three growth scenarios from MAM as explained earlier.

We have taken a boundary-case approach for evaluating these uncertainties, with the aim of assessing changes in the estimations if all the parameters assume the high or low values. For example, we have combined the 3-digit NAICS sector (the highest possible output) with high $I_{N\ HIW}$ and high CE_j as the high estimate, and the 6-digit NAICS sector (the lowest possible output) with low $I_{N\ HIW}$ and low CE_j as the low estimate.

The largest uncertainties in the spatial allocation of NHIW (Fig. 3–4) are the discrepancies between the data reported by the Wharton Research Data Service (used in spatial mapping) and the National Bureau of Economic Research (used in estimating the total contents). The value outputs in the Wharton Research Data Service are survey-based, and are typically only 10%-20% of the numbers reported by the National Bureau of Economic Research (detailed in Fig S5). As such, the spatial characterization of NHIW in Figs. 3–4 is likely a substantial under-estimate. This discrepancy will need to be refined when better data becomes available.

3. Results

We estimate that the total available minerals in NHIW from 1990 to 2016 are 80-105 million tonnes in the US (Fig. 2A). The total availability appears to be decreasing since 2007 (at a rate of 2% annually), primarily owing to the shrinkage of the relevant industrial sectors (Fig. 2A). Lime (CaO), salt (NaCl), and silica (SiO_2) are the bulk minerals embedded in NHIW, which together account for 67% of the total mineral content in NHIW. These are versatile minerals potentially reusable by the metallurgical, construction and environmental industries, which, in turn, would reduce the material footprints of the users through substitution (Bhardwaj and Kumar, 2017; Wang et al., 2018).

The sources of the key minerals in NHIW are provided in Fig. 2 and Fig S2. They are contained in a variety of NHIWs but often concentratd in a few sectors. For example, CaO, the most abundant mineral estimated at ~20 million tonnes annually, is contained in a number of NHIWs, from phosphogypsum, cement kiln dust, to combustion ashes (Fig S2), and 90% of it is generated by four sectors: agricultural chemicals (NAICS 3253), cement & concrete manufacturing (NAICS 3273), iron & steel (NAICS 3311-3312), and inorganic chemicals (NAICS 3251) (Fig. 2B).

There are also lower-volume, scarce minerals embedded in NHIW, e. g., phosphorus and titanium, which are estimated at 0.5-2.0 million tonnes annually (Fig. 2A). They are often concentrated in 1-2 NHIWs generated by 1-2 key sectors. For instance, over 55% of the TiO_2 is embedded in the red and brown muds produced in the processing of alumina (Fig S2).

The total electricity potential of NHIW is estimated at 45-70 billion kWh per year (Fig. 2C). Over 70% of the electricity potential comes from the wood waste generated by the wood products industry (NAICS 321), followed by wastes generated by the fruit and vegetable manufacturing industry (NAICS 3114), which contributes ~9% of the total potential (Fig. 2D). This energy potential is modest compared to other waste categories. It is roughly only 10-15% of the total energy potential of agricultural residues in the US and 15-20% of municipal solid wastes as estimated by a previous study (Rajagopal and Liu, 2020).

We project a consistent increase in the mineral contents in NHIW in the next three decades (Fig. 3). Two types of uncertainties have been considered in the projections. The first one is uncertainties in the waste generation rates and mineral contents. The low-, mid-, and high-estimates will reach 100, 150, and 400 million tonnes in 2050 respectively (Fig. 3A). This variability is primarily attributable to variability in the generation rate of lime and limestone particulates in the inorganic chemicals industry (NAICS 3251) and the CaO content in lime and limestone particulates (Figs. 2 and 3B-D). In the high-estimate, the embedded CaO is 91 million tonnes (Fig. 3B), whereas this number is only 7 million tonnes in the low-estimate (Fig. 3D). Future work could refine the generation rates of lime and limestone particulates by

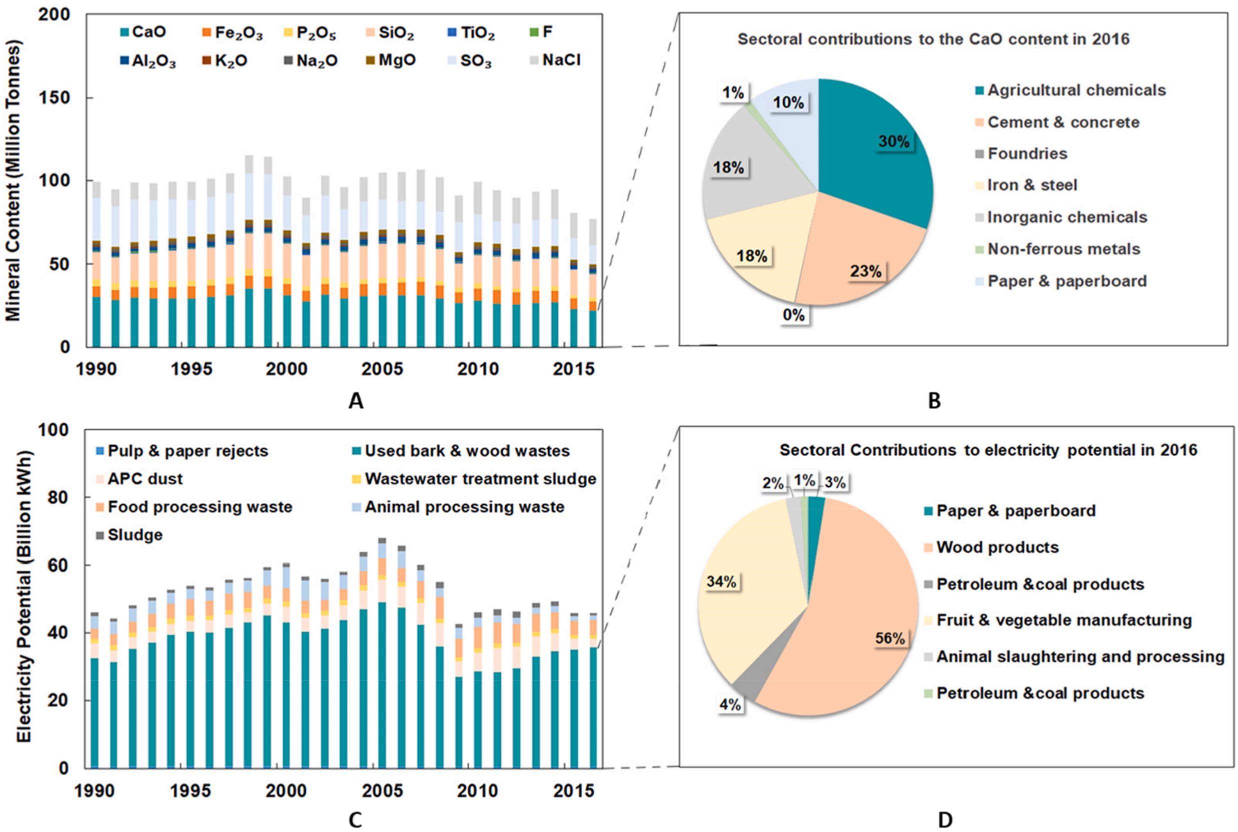

Fig. 2. Total minerals content (A) and electricity potential (C) in NHIW in the US in 1990-2016 and sectoral contributions to CaO (B) and electricity potential (D) in 2016.

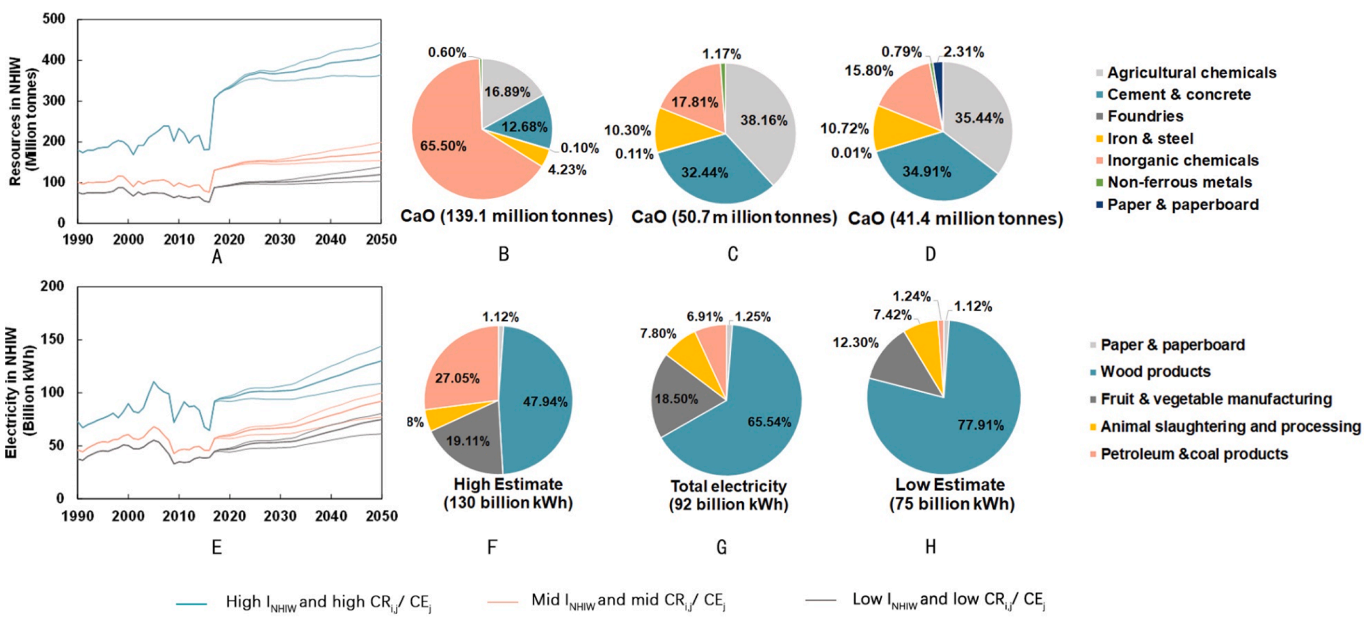

Fig. 3. Future trends of mineral contents (A) and electricity potential (E) in NHIW in the US until 2050, and sectoral contributions to the CaO and electricity potential in 2016 under high-, mid-, and low-estimate (B-D and F-H) respectively. The green, orange, and grey lines in A and E represent high-, mid-, and low-estimate respectively. Each estimate also includes high-, mid-, and low-economic growth projections for 2017-2050 as described in the U.S. Annual Energy Outlook 2017 (Section 2 in "Methods").

technology and location.

The second type of uncertainties explored is the different economic growth rates under the same waste generation rates and mineral contents. This typically leads to a ±10% difference from the baseline estimate (Fig. 3A). For example, the total mineral count in 2050 in the high-estimate based on high economic growth is 450 million tonnes, which is ~30 and ~80 million tonnes higher than the estimates based on regular and low economic growth, respectively (Fig. 3A).

The total electricity potential of NHIW follows a similar growth trend as the minerals. The total electricity from NHIW will reach 74, 92, and 130 billion kWh in 2050 in the low-, mid-, and high-estimates respectively (Fig. 3E). In all three estimates, wastes (e.g., bark and wood chips) generated by the wood products sector (NAICS 321) are the main sources of NHIW, contributing 48%, 66%, and 78% of the total electricity potential in the low-, mid-, and high-estimates for 2050 respectively (Fig. 3F-H). The largest uncertainty is the electricity potential of NHIW produced by the petroleum & coal products industry (NAICS 324), which could contribute up to 27% of the total potential in the high-estimate (Fig. 3F), but only 1.2% in the low-estimate (Fig. 3H).

The minerals in NHIW are mainly located in California, the Great Lakes, and along the east coast, with little change seen in the spatial distribution between 1997 and 2017 (Fig. 4A-C). In general, most counties saw an increase in 2007 and a slight decrease in 2017. The increase in Nevada, Utah, North Dakota and Kentucky was particularly significant in 2007 (Fig. 4B), whereas the decrease in 2017 was most significant in Nevada (Fig. 4C). The change in 2007 was mainly caused by the relocation of the non-ferrous metals industry (NAICS 3314) out of those regions, whereas the decrease in 2017 was caused by the shrinkage of the inorganic chemicals (NAICS 3251) and cement & concrete (NAICS 3273) industries. The key constituents, i.e., CaO, SiO_2, and Fe_2O_3, follow similar trends in 1997-2017, which are presented in the SI (Fig S3).

The electricity potential of NHIW was originally concentrated in the Pacific Northwest, California, and the New England regions (Fig. 4 D-F), but shifted from the coasts to the Midwest in 1997-2017 (Fig. 4D-F). In 2007 in particular, there was a substantial increase in the electricity potential in the Midwest States such as Montana, Wyoming and Colorado (Fig. 4E). The shift continued through 2017, although an overall decrease in the electricity potential was seen during this time, as evidenced by a decrease in the number of counties with high electricity potential (100 million kWh or higher) throughout the US in 2017 (Fig. 4F). The main driver for the change was the output of the wood products industry (NAICS 321), which, for example, decreased from 1.16 to 0.67 billion USD in California from 1997-2007 but increased from 0.09 to 0.19 billion USD in Colorado during the same time (Fig S3).

The availability of bulk minerals and electricity potential in NHIW is typically <3% of current consumption (Fig. 5 and Table S3). For example, SiO_2, the second most abundant mineral in NHIW, is typically available at 5-10 kg/cap/year in the top 10 states (e.g., Nebraska, Missouri, and Iowa), whereas the US average per capita consumption is ~300 kg/cap/year (Fig. 5A). The per capita electricity potential is 30-120 kWh/cap/year in the top 10 states, with Connecticut and South Dakota standing out with a per capita electricity potential of >100 kWh/cap/year (Fig. 5D). However, this potential is merely ~0.2% of the per capita consumption in those states (Fig. 5D).

In contrast, the availability of low-volume constituents, primarily TiO_2 and P_2O_5, are much more significant relative to consumption (Fig. 2 & Table S3). The availability of TiO_2 is well over 20% of the current consumption in the top states (e.g., Nebraska, Louisiana and Maine) on a per capita basis (Fig. 5B). The availability of P_2O_5 can be as high as 50-80% of current consumption in top states such as Nebraska, South Dakota, Idaho and Kansas (Fig. 5C).

4. Discussion

Overall, our estimate suggests that NHIW reuse policies in the US should focus on recovering minerals rather than energy, as the electricity potential of NHIW (Fig. 3E) is modest compared to the other waste streams (e.g., agricultural residues and municipal solid waste). We also project that the availability of these minerals in NHIW will steadily increase until 2050, well beyond the time horizon needed to economically justify the implementation of relevant policies and investments.

In terms of mineral recovery, the low-hanging fruit with low technological barriers is likely the high-volume constituents such as SiO_2 and CaO. These can potentially be reused by the construction industry relatively easily (e.g., in concrete and mortar), and their availability is conveniently concentrated around population centers (e.g., California) where the demand by the construction industry is the highest. While the total availability is modest compared to consumption on the national level (Fig. 5), the scale and benefits may be non-trivial at the local level. For example, the combined total availability of these minerals can be over one million tonnes per year in a few adjacent counties in California (Fig. 4), where the total cement consumption was ~8.5 million tonnes in 2016 state-wide (van Oss, n.d.). There are, however, large uncertainties around the generation rates of CaO as indicated in our estimate. A careful assessment of generation rates near these supply hotspots is still needed in future work.

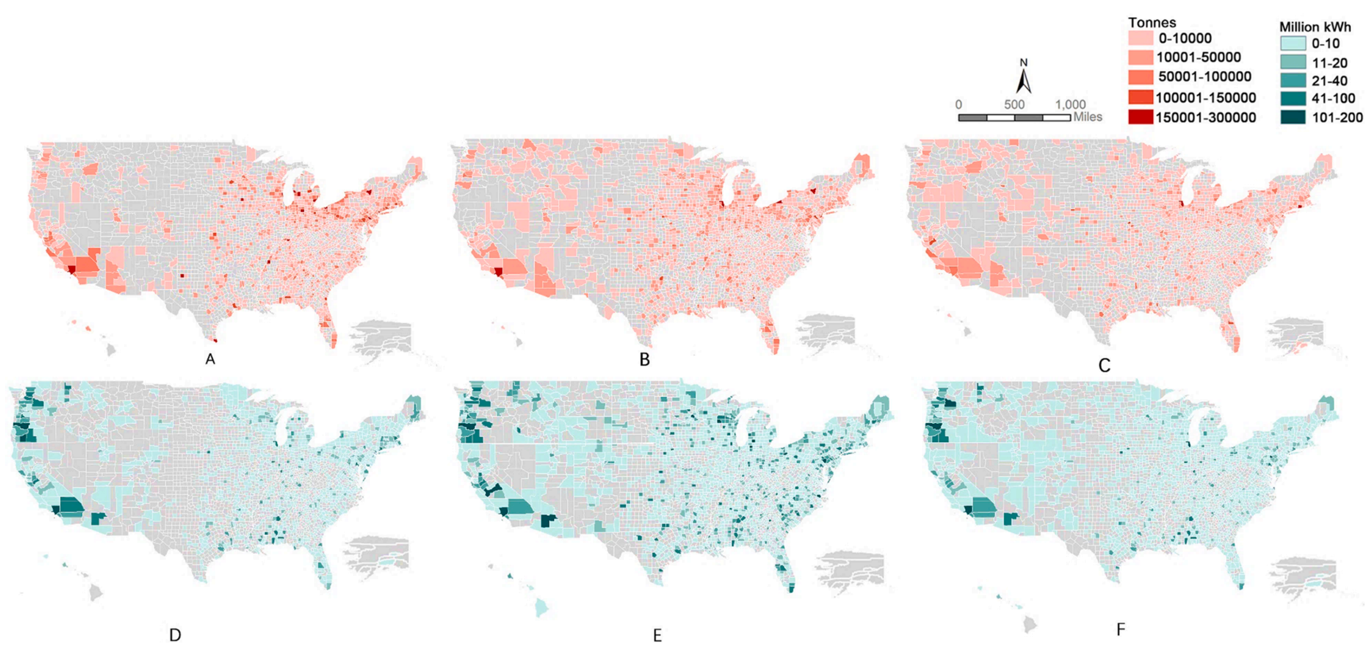

Fig. 4. County-level distribution of the total mineral content (1997: A, 2007: B, and 2017: C) and the total electricity potential (1997: D, 2007: E, and 2017: F) in NHIW in the US.

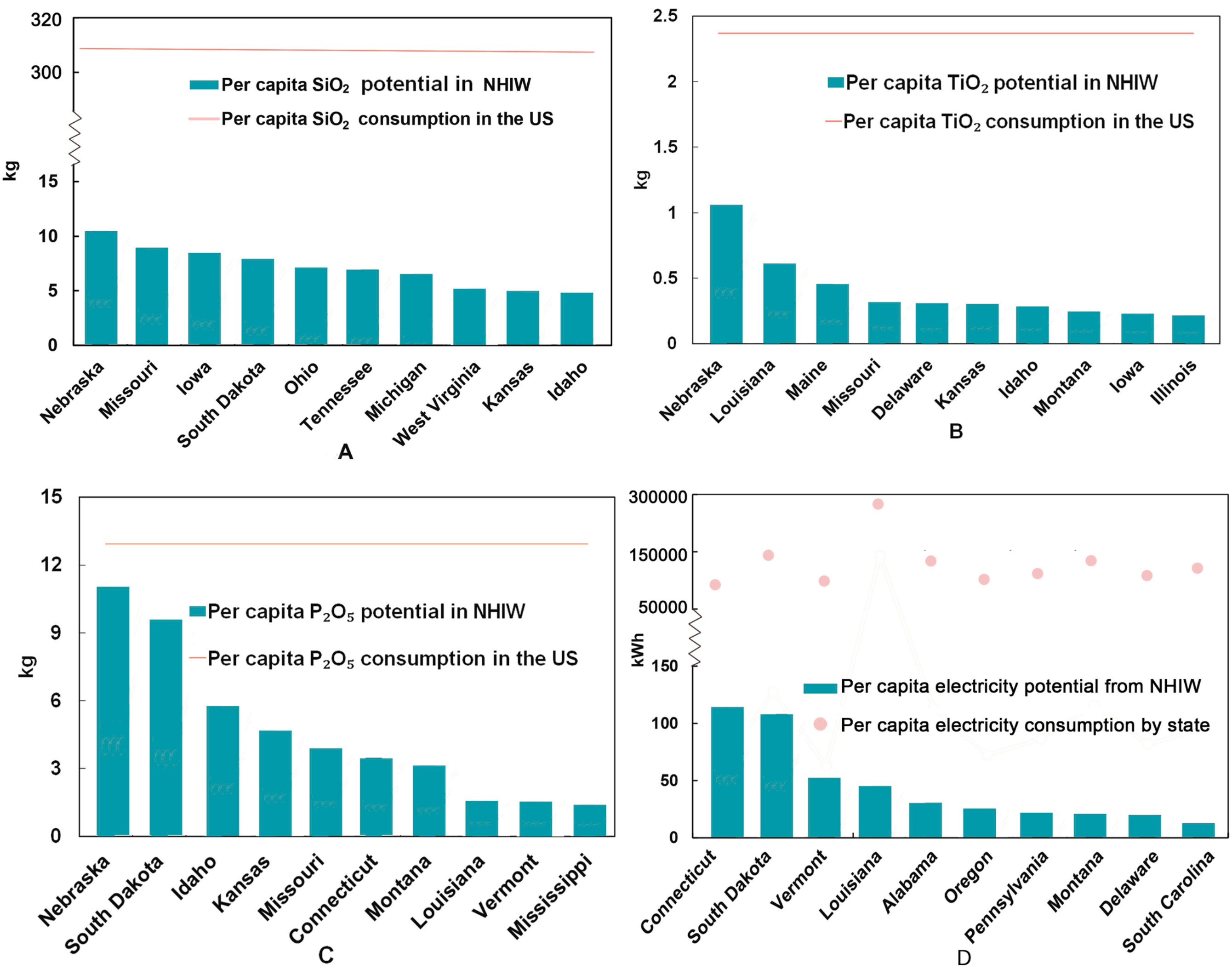

Fig. 5. Per capita recovery potential of SiO_2 (A), TiO_2 (B), P_2O_5 (C) and electricity (D) in the top 10 states in comparison to consumption in 2017. The data sources for per capita consumption are provided in the SI (Table S3).

Several of the lower-volume minerals in NHIW are potentially more valuable from a resource recovery standpoint. The key examples in this category are titanium and phosphorus. Their availability in NHIW is significant compared to consumption on the national level (10-20% of total consumption), and particularly in hotspot states (50%-80% of per capita consumption). There are likely technological challenges associated with reusing these minerals (e.g., the radioactivity of phosphogypsum (Rutherford et al., 1994)), but their significance in terms of circularizing the material flows at both the national and state level warrants further investigations into the technical feasibility of their reuse (Kataki et al., 2016; Mayer et al., 2016).

Given the findings, our policy recommendations indicate that areas with high potential of NHIW reuse could consider refining the reporting of NHIW generation and altering the relevant local codes and permits to facilitate reuse. For example, given the high potential of construction reuse, California could consider more granular reporting of relevant NHIW generation processes (or NHIW compositions) and tailored construction permits to facilitate even wider NHIW reuse in the construction sector (CALGreen Construction Waste Management Requirements). Similar approaches can be taken with lower-volume minerals in other key states.

Finally, this study aims to provide a generalizable first step that can facilitate the development of NHIW reuse policies and valorization technologies. In general, the workflow can be adopted by countries where similar economic statistics are available. However, generalizing this workflow will require a careful assessment of the cross-country differences in waste classifications, waste management regulations, and future output of industrial sectors. Other complementary analyses, such as the economics of reusing the minerals in NHIW, will still be needed before implementing any policies or technologies.

5. Conclusions

In this study, we demonstrate a workflow to estimate the mineral content and energy potential of NHIW and apply it to the United States. Our main conclusions are three-fold. First, the mineral content in NHIW is more noteworthy than the energy potential, which is on the order of 100 million tonnes and will increase by roughly 50% from 2017-2050 in the US. Second, some scarce contents of NHIW, e.g., phosphorus and titanium, are significant relative to consumption and should be the focus of further policy and technology studies. Finally, reuse of the bulk mineral contents in NHIW, mainly CaO and SiO_2, should focus on a few hotspots at the county scale, given the modest potential on the national level.

CRediT authorship contribution statement

Jinjin Chen: Investigation, Visualization, Formal analysis, Writing -

original draft. **Xiao Li:** Investigation, Writing - original draft. **Kaixin Huang:** Investigation, Methodology, Writing - original draft. **Matthew J. Eckelman:** Methodology, Writing - review & editing, Funding acquisition. **Marian R. Chertow:** Methodology, Writing - review & editing, Funding acquisition. **Daqian Jiang:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105369.

References

Allen, D.T., Behmanesh, N., 1992. Non-hazardous waste generation. Hazard. Waste Hazard. Mater. 9, 91–96. https://doi.org/10.1089/hwm.1992.9.91.
Assumptions to the Annual Energy Outlook 2017, 2017a. U.S. Energy Information Administration, Washington, DC 20585.
Assumptions to the Annual Energy Outlook 2017, 2017b. 235.
Bhardwaj, B., Kumar, P., 2017. Waste foundry sand in concrete: a review. Constr. Build. Mater. 156, 661–674. https://doi.org/10.1016/j.conbuildmat.2017.09.010.
Champagne, P., 2008. Bioethanol from agricultural waste residues. Environ. Prog. 27, 51–57. https://doi.org/10.1002/ep.10242.
Chertow, M., Krones, J., Li, X., 2020a. Making up for Lost Time (and Space): Quantifying Non-hazardous Industrial Waste Output and Beneficial Use Opportunities in the US. Draft Report to Environmental Research and Education Foundation.
Chertow, M., Krones, J., Li, X., 2020b. Making up for Lost Time (and Space): Quantifying Non-hazardous Industrial Waste Output and Beneficial Use Opportunities in the US. Draft Report to Environmental Research and Education Foundation.
Chertow, M., Park, J., 2019. Chapter 18 - reusing nonhazardous industrial waste across business clusters. In: Letcher, T.M., Vallero, D.A. (Eds.), Waste, Second Edition. Academic Press, pp. 353–363. https://doi.org/10.1016/B978-0-12-815060-3.00018-9.
Eckelman, M.J., Chertow, M.R., 2009. Quantifying life cycle environmental benefits from the reuse of industrial materials in Pennsylvania. Environ. Sci. Technol. 43, 2550–2556. https://doi.org/10.1021/es802345a.
Eddine, B.T., Salah, M.M., 2012. Solid waste as renewable source of energy: current and future possibility in Algeria. Int. J. Energy Environ. Eng. 3, 17. https://doi.org/10.1186/2251-6832-3-17.
Galeno, G., Minutillo, M., Perna, A., 2011. From waste to electricity through integrated plasma gasification/fuel cell (IPGFC) system. In: Int. J. Hydrog. Energy, The 3rd Annual Korea-USA Joint Symposium on Hydrogen & Fuel Cell Technologies, 36, pp. 1692–1701. https://doi.org/10.1016/j.ijhydene.2010.11.008.
Gingerich, D.B., Mauter, M.S., 2015. Quantity, quality, and availability of waste heat from United States thermal power generation. Environ. Sci. Technol. 49, 8297–8306. https://doi.org/10.1021/es5060989.
Guide for Industrial Waste Management, 2003.
Herrington, R., 2013. Road map to mineral supply. Nat. Geosci. 6, 892–894. https://doi.org/10.1038/ngeo1947.
Industry Practices Regarding the Disposal and Beneficial Reuse of Foundry Sand: Results and Analysis, 2007. The American Foundry Society.
Jourdain, C., Zwolinski, P., 2015. Optimization of a non-hazardous integrated solid waste processing line. In: Procedia CIRP, The 22nd CIRP Conference on Life Cycle Engineering, 29, pp. 674–679. https://doi.org/10.1016/j.procir.2015.02.083.
Kataki, S, West, H, Clarke, M, Baruah, D.C., 2016. Phosphorus recovery as struvite from farm, municipal and industrial waste: Feedstock suitability, methods and pre-treatments. Waste Manag. 437–454. https://doi.org/10.1016/j.wasman.2016.01.003.
Krones, J.S., 2016. Accounting for non-hazardous industrial waste in the United States (Thesis). Massachusetts Institute of Technology.
Langholtz, M.H., Stokes, B.J., Eaton, L.M., 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstock, 2016. Oak Ridge Natl. Lab. Oak Ridge Tenn. Manag. UT-Battelle LLC US Dep. Energy, pp. 1–411.
Laybourn, P., 2015. Industrial Symbiosis Delivering Resource Efficiency and Green Growth.
Li, X., Chertow, M., Guo, S., Johnson, E., Jiang, D., 2020. Estimating non-hazardous industrial waste generation by sector, location, and year in the United States: a methodological framework and case example of spent foundry sand. Waste Manag. 118, 563–572. https://doi.org/10.1016/j.wasman.2020.08.056.
Li, Z., Diaz, L.A., Yang, Z., Jin, H., Lister, T.E., Vahidi, E., Zhao, F., 2019. Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. Resour. Conserv. Recycl. 149, 20–30. https://doi.org/10.1016/j.resconrec.2019.05.025.
Liu, B., Rajagopal, D., 2019. Life-cycle energy and climate benefits of energy recovery from wastes and biomass residues in the United States. Nat. Energy 4, 700–708.
Macias-Corral, M., Samani, Z., Hanson, A., Smith, G., Funk, P., Yu, H., Longworth, J., 2008. Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. Bioresour. Technol. 99, 8288–8293. https://doi.org/10.1016/j.biortech.2008.03.057.
Martin, R., Schlüter, M., Blenckner, T., 2020. The importance of transient social dynamics for restoring ecosystems beyond ecological tipping points. Proc. Natl. Acad. Sci. 117, 2717–2722. https://doi.org/10.1073/pnas.1817154117.
Mayer, B.K., Baker, L.A., Boyer, T.H., Drechesel, P., Gifford, M., Hanjra, M.A., Parameswaran, P., Stoltzfus, J., Westerhoff, P., Rittmann, B.E., 2016. Total Value of Phosphorus Recovery. Environ. Sci. Technol. 6606–6620. https://doi.org/10.1073/pnas.1817154117.
Nalley, S., 2018. The National Energy Modeling System: An Overview 2018, 75.
NBER-CES Manufacturing Industry Database [WWW Document], n.d. URL http://www.nber.org/data/nberces.html (accessed 10.20.19).
Packey, D.J., 1993. Market Penetration of New Energy Technologies (No. NREL-TP-462-4860). National Renewable Energy Laboratory, Golden, Colorado.
Rajagopal, D., Liu, B., 2020. The United States can generate up to 3.2 EJ of energy annually from waste. Nat. Energy 5, 18–19. https://doi.org/10.1038/s41560-019-0532-x.
Reed, T., 2014. In: H.R.2996 - 113th Congress (2013-2014). Revitalize American Manufacturing and Innovation Act of 2014.
Roati, C., Fiore, S., Ruffino, B., Marchese, F., Novarino, D., Zanetti, M.C., 2012. Preliminary evaluation of the potential biogas production of food-processing industrial wastes. Am. J. Environ. Sci. 8, 291.
Rutherford, P.M., Dudas, M.J., Samek, R.A., 1994. Environmental impacts of phosphogypsum. Sci. Total Environ. 149, 1–38. https://doi.org/10.1016/0048-9697(94)90002-7.
Saidan, M.N., 2019. Cross-sectional survey of non-hazardous waste composition and quantities in industrial sector and potential recycling in Jordan. Environ. Nanotechnol. Monit. Manag. 12, 100227 https://doi.org/10.1016/j.enmm.2019.100227.
Services, W.R.D., n.d. Wharton Research Data Services [WWW Document]. WRDS. URL https://wrds-www.wharton.upenn.edu/pages/ (accessed 10.20.19).
Sheppard, P., Rahimifard, S., 2019. Embodied energy in preventable food manufacturing waste in the United Kingdom. Resour. Conserv. Recycl. 146, 549–559. https://doi.org/10.1016/j.resconrec.2019.03.002.
Stahel, W.R., 2016. The circular economy. Nat. News 531, 435. https://doi.org/10.1038/531435a.
Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., Tukker, A., 2017. Solid waste and the circular economy: a global analysis of waste treatment and waste footprints. J. Ind. Ecol. 21, 628–640.
Tuck, C.O., Pérez, E., Horváth, I.T., Sheldon, R.A., Poliakoff, M., 2012. Valorization of biomass: deriving more value from waste. Science 337, 695–699. https://doi.org/10.1126/science.1218930.
US EPA, O., 2017. Guide to the Facts and Figures Report about Materials, Waste and Recycling [WWW Document]. US EPA. URL. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/guide-facts-and-figures-report-about-materials. accessed 11.12.20.
van Oss, H., n.d. Mineral Industry Surveys: Cement- Monthly Publications. United States Geological Survey (USGS).
Wang, D., Shi, C., Farzadnia, N., Shi, Z., Jia, H., Ou, Z., 2018. A review on use of limestone powder in cement-based materials: |mechanism, hydration and microstructures. Constr. Build. Mater. 181, 659–672. https://doi.org/10.1016/j.conbuildmat.2018.06.075.
Zhu, J., Chertow, M.R., 2016. Greening industrial production through waste recovery: "comprehensive utilization of resources" in China. Environ. Sci. Technol.
https://www.calrecycle.ca.gov/lgcentral/library/canddmodel/instruction/newstructures. (Accessed 29 December 2020).