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## Light Water Reactor Sustainability Program

# Clean Energy Credits for the Production of Low Carbon Hydrogen, Steel and Ammonia using Nuclear Energy

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U.S. Department of Energy

Office of Nuclear Energy

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# Clean Energy Credits for the Production of Low Carbon Hydrogen, Steel and Ammonia using Nuclear Energy

**L. Todd Knighton, Idaho National Laboratory**
**Richard Boardman, Idaho National Laboratory**
**Amgad Elgowainy, Argonne National Laboratory**

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**Office of Nuclear Energy**

# EXECUTIVE SUMMARY

Renewable energy costs of manufacturing and installation have been continuously decreasing due to the ever-increasing volume of installations and the accompanying advances in technology and manufacturing processes, supply chain efficiency, etc. Renewable energy additions to the grid bring the benefits of increasing the diversity of the generation mix and decarbonizing the electric grid. However, renewable energy also creates increased variability and instability on the grid due to the diurnal and seasonal variations in output power inherent with renewable energy power generation.

Nuclear energy is increasingly being recognized for being a large capacity and reliable low-carbon, low-emissions energy source that can help communities, states, and the nation achieve increasingly aggressive decarbonization targets, while enabling further renewable energy grid penetration[1].

Light Water Reactor (LWR) NPPs in the United States, like other sources of electricity generation, are facing increasing market competition from natural-gas combined-cycle (NGCC) power plants due to historically low-priced natural-gas (NG) associated with the U.S. shale gas boom. Some NPPs have been shut down, mainly due to economic considerations. When NPPs close, they have typically been replaced by NG power plants which add carbon to the grid. Future closures of other nuclear plants have been announced and appear imminent unless the status quo operating environment for nuclear energy changes. Therefore, the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program is addressing flexible plant operations that can diversify the revenue of NPPs and provide a framework of options that incentivize nuclear power plant operations by providing credits for the **low-carbon grid power and non-electric products that may be produced from nuclear power**, similar to renewable energy credits (REC). More generally these credits can be termed zero-emissions credits (ZEC), including renewables and nuclear energy. For example, electricity, hydrogen, and products produced from hydrogen such as steel and ammonia could create ZECs or "low-carbon" green energy credits that can be used by obligated industry entities needing to reduce their carbon footprint. Green steel produced from hydrogen using nuclear energy could qualify for very large (~$150/tonne) carbon credits in the European export markets. Other reports completed by the DOE LWRS program have highlighted the vast and diverse markets for non-electric products that can be produced using nuclear energy.[2,3,4] This current work will focus on 1) highlighting the status quo of the Environmental Protection Agency (EPA) Renewable Fuel Standard (RFS), carbon tax/credit systems, low-carbon standards of California, the new green hydrogen standard in New York as well as 2) taking a look at other possible

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[1] https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

[2] Knighton, L. Todd et al., "Scale and Regionality of Nonelectric Markets for U.S. Nuclear Light Water Reactors" (March 2020). Idaho National Laboratory, INL/EXT-20-57885, https://www.osti.gov/biblio/1615670

[3] Hu, Hongqiang et al., "Technoeconomic Analysis on an Electrochemical Nonoxidative Deprotonation Process for Ethylene Production from Ethane" (December 2019). Idaho National Laboratory, INL/EXT-19-56936, https://lwrs.inl.gov/Flexible%20Plant%20Operation%20and%20Generation/Technoeconomic_Analysis_on_an_Electrochemical_Nonoxidative_Deprotonation_Process.pdf

[4] Frick, K. et al., "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest." (September 2019). Idaho National Laboratory, INL/EXT-19-55395, OSTI1569271. DOI: 10.2172/1569271

future frameworks that may incentivize nuclear energy operators and downstream industry employing low-carbon electricity and non-electric products.

Important points to consider related to any possible future renewable hydrogen credit legislation, especially those related to nuclear power and hydrogen production, and their applications:

- The retention of nuclear power generation is critical to achieving federal and states' decarbonization goals across multiple energy sectors.
- Producing hydrogen from nuclear power, especially at low demand periods, increases the capacity utilization factor of nuclear power plants, which can improve the economics of their operation.
- Similar to wind-power, nuclear power can produce near zero-carbon hydrogen to further decarbonize energy use in transportation.
- Producing hydrogen via low temperature electrolysis (LTE) from nuclear power can achieve higher energy conversion efficiency compared to producing hydrogen via LTE from wind energy. Research on high-temperature steam electrolysis (HTSE) technology shows the potential to be much more efficient than LTE given the inherent efficiency gain of the higher reaction temperature as well as the ability to use nuclear heat energy to provide process heat to HTSE.
- Producing hydrogen from nuclear power can be achieved at larger scale compared to hydrogen produced from wind-power, and over longer periods, thus improving the viability of producing zero-carbon hydrogen.
- The contribution of nuclear power to zero-carbon power markets can be extended further to serve other energy sectors such as transportation, as well as building and industrial heat demand, thus contributing to the goals of decarbonization across multiple energy sectors.
- Zero-carbon hydrogen can enable faster deployment of zero-emission hydrogen fuel cell vehicles in all zero-emissions vehicle (ZEV) states (including California and New York), thus reducing the time to achieve ZEV goals in these states, and significantly reduce air pollution created by the transportation sector.

Recommendations include that the EPA, U.S., and state regulators should consider:

1) low-carbon fuel standards not exclusive to transportation fuels and inclusive of nuclear energy and uses other than transportation and electricity (i.e., hydrogen to produce green steel through the Direct Reduced Iron (DRI) process, green ammonia, synthetic fuels etc.)

2) low-carbon fuel standards inclusive of nuclear energy as a total solution to continued decarbonization while supporting the expansion of renewables on the grid and resilient and reliable grid electricity.

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## ACRONYMS

| | |
|---|---|
| ANL | Argonne National Laboratory |
| BOP | balance of plant |
| BWR | boiling water reactor |
| CI | carbon intensity |
| DF | dark fermentation |
| DOE | Department of Energy |
| DRI | direct reduction of iron |
| EDF | Electricite de France |
| ENDP | electrolytic non-oxidative deprotonation of ethane to form ethylene and hydrogen |
| EPA | Environmental Protection Agency |
| FCEV | fuel cell electric vehicles |
| FCTO | fuel cell technology office |
| GHG | greenhouse gases |
| HTE | high-temperature electrolysis also termed HTSE |
| HTSE | high-temperature steam electrolysis also termed HTE |
| IES | integrated energy systems |
| IGCC | Integrated Gasification Combined-Cycle |
| INL | Idaho National Laboratory |
| LCFS | low-carbon fuel standard |
| LTE | low temperature electrolysis |
| LWR | light-water reactor |
| LWRS | Light Water Reactor Sustainability |
| MED | multi effect distillation |
| NG | natural-gas |
| NGCC | natural-gas combined-cycle |
| NHES | nuclear-renewable hybrid energy system |
| NICE | Nuclear Innovation Clean Energy Future |
| NRC | Nuclear Regulatory Commission |
| NREL | National Renewable Energy Laboratory |
| OCF | operating capacity factor |
| PE | polyethylene |
| PEM | polymer-electrolyte membrane |
| PFD | process-flow diagram |
| PP | polypropylene |

| | |
|---|---|
| PV | photovoltaic |
| PWR | pressurized water reactor |
| RIN | renewable identification number |
| RO | reverse osmosis |
| RVO | renewable volume obligation |
| SOEC | solid-oxide electrolysis cell |
| Syngas | synthesis gas ($H_2$ + CO) |
| TBV | turbine bypass valve |
| TCV | turbine control valve |
| tpd | tonnes per day |
| TRL | technology readiness level |
| UI | University of Idaho |
| WGS | water gas shift |
| WSC | Western Services Corporation |
| WTW | well-to-wheels |
| ZEC | zero-emissions credits |
| ZEV | zero-emissions vehicle |

# Clean Energy Credits for the Production of Low Carbon Hydrogen, Steel and Ammonia Using Nuclear Energy

## 1. INTRODUCTION

Renewable energy costs of manufacturing and installation have been continuously decreasing due to the ever-increasing volume of installations and the accompanying advances in technology and manufacturing processes, supply chain efficiency, etc. Renewable energy additions to the grid bring the benefits of increasing the diversity of the generation mix and decarbonizing the electric grid. However, renewable energy also creates increased variability and instability on the grid due to the diurnal and seasonal variations in output power inherent with renewable energy power generation. To enable renewable energy generation capacity to continue to increase, baseload capacity (in the form of natural-gas (NG) power plants or nuclear power plants) and large amounts of energy storage is needed in order to smooth the variability of renewable power generation. Energy storage in many forms is the topic of constant research and development in many areas such as thermal, electrochemical, chemical storage, and other innovative approaches.[5] Currently, in most regions where pumped hydro is geographically not possible, battery technology is the leading method of energy storage with sales of lithium ion batteries growing by 50% per year[5]. However, even with massive gains in the areas of cost reduction and the increases in lifetime and in capacity of batteries over the past two decades, battery technology is far from being cost competitive to provide around the clock storage to allow 100% renewables without baseload powerplants. There also may be material and supply constraints related to battery technology.

With historically low NG prices, NG power plants are being built in many markets which have increasing renewable generation capacity, so that the NG plants can provide baseload capacity and grid stabilization. Existing Light Water Reactor (LWR) Nuclear Power Plants (NPPs) also provide critical baseload capacity and grid stabilization in the surrounding regions near their respective locations. The existing U.S. LWR NPP fleet further provides the grid with all-weather season-long baseload capacity that is important to grid reliability and resiliency. Most of the U.S. LWRs have fully depreciated and retired their capital expenditures, giving them opportunity to integrate with innovative ventures without carrying the burden of past NPP capital spending into the cost-to-benefit analyses. Nuclear energy is increasingly being recognized for being a large capacity and reliable low-carbon, low-emissions energy source that can help communities, states, and the nation achieve increasingly aggressive decarbonization targets, while enabling further renewable energy grid penetration[6]. Currently, nuclear power provides about 20% of the country's electricity and approximately 50% of the low-carbon emissions power. Various organizations are trying to publicize the environmental advantages of nuclear energy. Nuclear Innovation Clean Energy Future (NICE) is an initiative of the Clean Energy Ministerial led by the United States, Canada, and Japan that seeks to provide a forum for public discussion highlighting the environmental benefits of nuclear energy as a primary source of emissions free low-carbon clean energy.[7,8,9,10] Participant countries include Argentina, Poland, Romania, Russia, the United Arab Emirates, and the United Kingdom.

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5 https://itif.org/publications/2018/11/28/making-beyond-lithium-reality-fostering-innovation-long-duration-grid

6 https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

7 https://www.energy.gov/ne/initiatives/nuclear-innovation-clean-energy-future

8 http://cleanenergyministerial.org/about-clean-energy-ministerial

9 https://www.nice-future.org/

10 http://energyforhumanity.org/wp-content/uploads/2019/05/FNC_8p_brochure_PRINT-FINAL.pdf

LWR NPPs in the United States, like other sources of electricity generation, are facing increasing market competition from natural-gas combined-cycle (NGCC) power plants due to historically low-priced NG associated with the U.S. shale gas boom. Some NPPs have been shut down, mainly due to economic considerations. When NPPs close, they have typically been replaced by NG power plants which add carbon to the grid. Future closures of other nuclear plants have been announced and appear imminent unless the status quo operating environment for nuclear energy changes. Therefore, the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program is addressing flexible plant operations that can diversify the revenue of NPPs and provide a framework of options that incentivize nuclear power plant operations by providing credits for the **low-carbon grid power and non-electric products that may be produced from nuclear power**, similar to renewable energy credits (REC). More generally these credits can be termed zero-emissions credits (ZEC), including renewables and nuclear energy. For example, electricity, hydrogen, and products produced from hydrogen such as steel and ammonia could create ZECs or "low-carbon" green energy credits that can be used by obligated industry entities needing to reduce their carbon footprint. Green steel produced from hydrogen using nuclear energy could qualify for very large (~$150/tonne) carbon credits in the European export markets. Other reports completed by the DOE LWRS Program have highlighted the vast and diverse markets for non-electric products that can be produced using nuclear energy.[11,12,13] This current work will focus on 1) highlighting the status quo of the Environmental Protection Agency (EPA) Renewable Fuel Standard (RFS), carbon tax/credit systems, low-carbon standards of California, the new green hydrogen standard in New York as well as 2) taking a look at other possible future frameworks that may incentivize nuclear energy operators and downstream industry employing low-carbon electricity and non-electric products.

# 2. PRODUCTION OF HYDROGEN USING NUCLEAR ENERGY – BEGINNING THE HYDROGEN ECONOMY

Continued decarbonization of the economy can be aided by increasing hydrogen production and use. Hydrogen can be used in industries such as petroleum refining of transportation fuels, industries requiring process heat, and as a transportation fuel for heavy-duty vehicles which require long range and short refueling times. A beginning in the transition to a hydrogen economy will require that hydrogen be immediately available and that it be competitively priced on location where the hydrogen demand exists. To achieve this objective, the following subobjectives are key 1) Cost Effective Hydrogen Production at Scale, 2) Cost Effective Hydrogen Storage, Transportation, Delivery. Nuclear energy can accelerate and enable the accomplishment of these objectives. First, at 1 GW average power capacity for each of 97 U.S. LWRs spread throughout the country, there is enormous low-carbon generating capacity in these existing LWRs, most of which have fully retired capital expenditures associated with their construction, to produce hydrogen via electrolysis (low temperature electrolysis – LTE or developing technology of high-temperature steam electrolysis – HTSE). Second, in most cases, there exists significant potential hydrogen demand in proximity to these LWRs. Techno-economic studies completed around several U.S. LWRs highlight this technical feasibility to produce hydrogen by coupling electrolysis plant to NPPs and the demand potential.[7,8,9] Producing hydrogen to serve demand near LWRs could be an important beginning to establishing hydrogen production and distribution infrastructure. Hydrogen pipeline technology is an existing art. Many of the hydrogen pipelines in the U.S. are located on the gulf coast where there are both large naturally occurring salt domes used for hydrogen storage as well as a large presence of petroleum

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[11] Knighton, L. Todd et al., "Scale and Regionality of Nonelectric Markets for U.S. Nuclear Light Water Reactors" (March 2020). Idaho National Laboratory, INL/EXT-20-57885, https://www.osti.gov/biblio/1615670

[12] Hu, Hongqiang et al., "Technoeconomic Analysis on an Electrochemical Nonoxidative Deprotonation Process for Ethylene Production from Ethane" (December 2019). Idaho National Laboratory, INL/EXT-19-56936, https://lwrs.inl.gov/Flexible%20Plant%20Operation%20and%20Generation/Technoeconomic_Analysis_on_an_Electrochemical_Nonoxidative_Deprotonation_Process.pdf

[13] Frick, K. et al., "Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest." (September 2019). Idaho National Laboratory, INL/EXT-19-55395, OSTI1569271. DOI: 10.2172/1569271

refining and chemical plants. If new hydrogen pipelines can be justified for large hydrogen production volume from LWRs to regional hydrogen demand locations, then the cost of storage and transportation of hydrogen can be reduced.

As with renewable and battery technology, electrolysis technologies have made important advances and cost reductions in the past decade. Electrolysis technology has been able to take advantage of the developments in fuel cell technology since electrolysis is essentially the reverse of the fuel cell process. More advances will come as production volume and experience increases across the industry. Even with these advances, there is still a long way to go towards long-term profitability of electrolysis at scale. This is where low-carbon credits come in for the electricity and non-electric products (such as hydrogen) generated from nuclear energy. Ensuring that low-carbon credits are technology agnostic and apply equally to renewable and nuclear energy on their merits of producing low-carbon energy is key to having a meaningful impact on decarbonization.

The discussion around nuclear energy's role in clean energy credits is an important one to show that nuclear energy can be key in meeting environmental goals for reductions in emissions. Recently the European Union European Commission recently created a Technical Expert Group to define which activities should be included within an EU Sustainable Finance Taxonomy

[14]. The purpose of this taxonomy was to highlight sustainable industries as an easy access list for investors looking to invest in sustainable energy. Nuclear energy was not included in this taxonomy. In the Sustainable Nuclear Assessment report of 2019 commissioned by LucidCatalyst Ltd. and the non-profit think tank Think Atom and funded by Electricite de France (EDF), the authors provided comment to the taxonomy arguing that "the world's scientific consensus concludes that maintaining and expanding nuclear energy is necessary to achieve sustainability objectives, such as climate change mitigation." They also point out that a significant number of European Union member states have climate and sustainability policies which include a future role for nuclear energy, including: France, Finland, Sweden, Poland, Bulgaria, Lithuania, Romania, the United Kingdom, Slovenia, Slovakia, Hungary and the Czech Republic. [15]

# 3. EXISTING CLEAN ENERGY AND LOW-CARBON INCENTIVES AND OBLIGATIONS

## 3.1 EPA Renewable Fuel Standard (RFS)

EPA developed the RFS as mandated by Congress in the Energy Policy Act of 2005 ($RFS_1$) and further amended in the Energy Independence and Security Act of 2007 ($RFS_2$). The RFS program seeks to "move the United States toward greater energy independence and security" and "increase the production of clean renewable fuels."16 The EPA administers the $RFS_2$ and regulates volume requirements for several categories of renewable fuels. In particular, the EPA created the four renewable fuel categories shown in Table 1, with different Renewable Identification Number (RIN) codes for compliance and trading of credits. A RIN is a serial number code assigned to each batch of produced renewable fuel to enable the tracking of its production, use, and trading. Once a RIN number is assigned to a fuel batch, it becomes a renewable energy [fuel] credit (REC). Table 1 shows the four fuel categories, as well as their estimated 2022 volumes and minimum required greenhouse gases (GHG) emissions reductions (compared to their petroleum counterpart), and the RIN codes for each fuel category. The original $RFS_2$ volume mandates required 16 billion gallons to be cellulosic biofuels (e.g., ethanol, naphtha, and diesel).

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14 https://ec.europa.eu/info/sites/info/files/business_economy_euro/banking_and_finance/documents/200309-sustainable-finance-teg-final-report-taxonomy_en.pdf

15 http://energyforhumanity.org/en/resources/reports-en/sustainable-nuclear-assessment-sustainability-nuclear-power-eu-taxonomy-consultation-2019/

16 Energy Independence and Security Act of 2007, Pub. L. No. 110-140, 121 Stat. 1492 (2007) ("EISA")

The RIN category D3 generates the most credits per unit volume of the renewable fuel. The RIN credits encourage investment in renewable fuel production for the transportation sector. The RIN credits can be traded, and thus their prices can fluctuate subject to their supply and demand markets. In general, the RIN generator is responsible for fulfilling all reporting requirements, keeping all records for each step in the pathway from extraction to end-use. Each year, the EPA decides and announces the mandated fuel production volume for each of the RIN categories.

The renewable biofuel categories include ethanol, as well as gasoline and diesel blendstocks such as naphtha or diesel hydrocarbons. While current gasoline blends incorporate 10% ethanol by volume (E10), mainly from corn-ethanol, ethanol demand may decline in the future given projected decreases in gasoline demand. In such a scenario, most of the 16 billion gallons per year of cellulosic biofuels would likely be diesel blendstocks.

Table 1. EPA RFS Fuel Types, GHG emissions reduction requirements, and accompanying approximate blend Volume Requirements.

| **Fuel Type** | **Volume Requirement by 2022 ($10^9$ Gallons)** | **GHG Emissions Reduction** | **RIN Code** | **Fuel Examples** |
|---|---|---|---|---|
| Renewable Fuel | 15 | 20% | D6 | Corn-ethanol |
| Advanced Biofuels | 21 | 50% | D5 | Sugarcane ethanol |
| Biomass-Based Diesel | | 50% | D4 | Biodiesel; renewable diesel |
| Cellulosic Biofuels | | 60% | D3/D7 | Cellulosic-based ethanol, naphtha, or diesel; biogas-based fuels |

Obligated parties must generate or acquire RIN credits to fulfill their renewable volume obligation (RVO) under $RFS_2$. Obligated parties are gasoline and diesel refineries or importers. The information required to generate RINs include the following:

- Fuel type (RIN category), production process, end-use as a transportation fuel.
- Type and quantity of feedstock used for fuel production.
- Renewable fuel volume.
- Originating facility and fuel production date.

The process of generating RINs, includes the following steps:

- Developing a pathway for a renewable fuel from one of the $RFS_2$ approved feedstock types, through its end-use as a transportation fuel.
- Submit the detailed pathway information for each process involved to EPA for evaluation, review and approval.
- The pathway information is supplied to an EPA approved third-party auditor or quality assurance plan provider to conduct and verify that RINs have been properly generated and are valid for compliance purposes[17].
- Once RINs are approved and generated, they are entered in EPA Moderated Transaction System to allow companies to report and track transactions for RINS following $RFS_2$ regulations[18].

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[17] https://www.epa.gov/renewable-fuel-standard-program/quality-assurance-plans-under-renewable-fuel-standard-program

[18] https://www.epa.gov/fuels-registration-reporting-and-compliance-help/how-use-emts-report-transactions-fuel-programs

Figure 1 below shows an example of the lifecycle of RINs from creation to retirement.

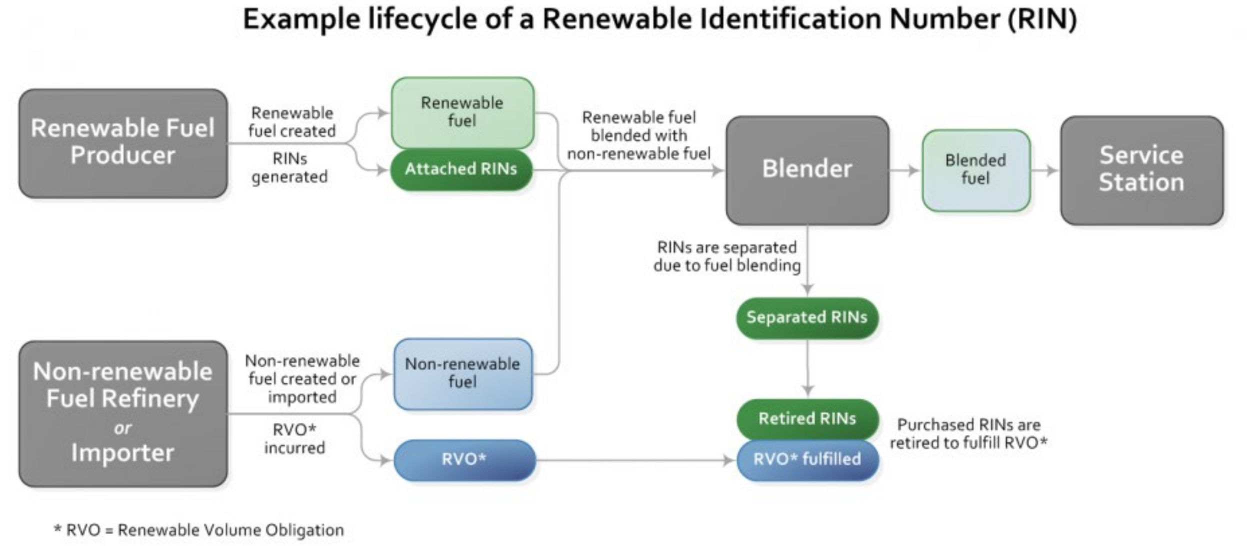

Figure 1. Example Lifecycle of a Renewable Identification Number (RIN)[19]

Biogas pathways were not in the original RFS$_2$, which were introduced in 2014. Biogas pathways belong to the high-credit RIN category (D3). The biogas sources qualified under this RIN category are landfills, municipal wastewater treatment facility digesters, agricultural digesters, and separated municipal solid waste digesters; and biogas from the cellulosic components of biomass processed in waste digesters. The renewable fuels produced from the biogas pathways could be renewable NG for compressed or liquefied NG (CNG or LNG), renewable electricity for charging battery electric vehicles, or hydrogen for FCEVs. However, as of today, the RFS$_2$ does not consider nuclear power pathways in any of the "renewable" or low-carbon categories. Petitioning EPA to consider nuclear power for fuel production (e.g., hydrogen for fuel cells, electricity for battery electric vehicle recharging, or for electro-fuel production) can open the RFS credit scheme to nuclear power generators for the generation of electricity and the production of low-carbon hydrogen from nuclear energy. Note that the California low carbon fuel standard (LCFS) and EPA RFS provide GHG emissions credits that are restricted to fuels used exclusively for transportation. The possible future amendment of these rules to include credits for the broader uses of fuels such as hydrogen (i.e., hydrogen for DRI and metals production, ammonia production, etc.) represents further opportunities to reward low-carbon generation of electricity and hydrogen.

Later in this report, hydrogen produced from nuclear energy for use in FCEVs or subsequent conversion to synthetic transportation fuels are discussed as low-carbon fuels that can use nuclear power as the feedstock source. These fuels should qualify for credits under California LCFS, but do not qualify for credits under the EPA RFS regulation as it is currently written.

## 3.2 California State Low-Carbon Fuel Standard (LCFS)

The state of California developed zero-emissions vehicle (ZEV) mandates to curb air pollution emissions from vehicle tailpipes. This spurred the deployment of both battery electric vehicles (EVs) and hydrogen fuel cell electric vehicles (FCEV). California also developed its low-carbon fuel standard (LCFS) to regulate carbon intensity (CI) of fuels produced, purchased, and used within the state. The CI is calculated based on the life cycle GHG emissions of the used fuel, or well-to-wheels (WTW) analysis,

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[19] https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-numbers-rins-under-renewable-fuel-standard

accounting for all steps involved in producing, transporting, and consuming the fuel. The LCFS uses ANL's gas, Regulated Emissions, and Energy use in Technologies (GREET) model[20] for the WTW analysis to calculate the CI of alternative transportation fuels, including hydrogen pathways for use in fuel cell vehicles.

California Air Resources Board developed the LCFS regulation to reduce the CI of transportation fuel used in California by at least 10 percent by 2020 and 20% by 2030 from a 2010 baseline. LCFS sets CI standards (the LCFS standards decrease over time) in grams of carbon dioxide equivalent per megajoule (grams $CO_{2e}$ /MJ) of fuel produced for gasoline, diesel, and the alternative fuels that replace them. The LCFS lets the market determine which mix of fuels will be used to reach the program targets by allowing the trade of carbon dioxide ($CO_2$) credits between credit generators and obligated parties. Compliance with LCFS is achieved when an obligated party uses credits to match its deficits (i.e., when CI is higher than annual benchmark set by LCFS). Credits are retired when used to cover deficits in annual compliance. The objectives of the LCFS include reducing GHG emissions, diversifying fuel supply, reducing petroleum dependency and emissions of air pollutants[21]. In April 2020, more than 4 million metric tons of $CO_{2e}$ were traded in the California LCFS market, with the price of $CO_2$ credits near $200/ton at times.[22] LCFS credits do not expire but can only be held by obligated parties under LCFS.[23] Other jurisdictions, such as the Pacific Coast Collaborative, a regional agreement between California, Oregon, Washington, and British Columbia, align policies with California to reduce GHG emissions within their states.

For high efficiency vehicles, such as hydrogen FCEVs and battery EVs, the CI of the fuel is adjusted by dividing it with the vehicle's energy economy ratio (EER) which is the efficiency of the FCEV relative to the baseline internal combustion engine vehicle (ICEV)[24]. The EER is 2.5 for hydrogen fuel cell vehicles and 3.4 for battery EVs[25]. However, California requires that 40% of the hydrogen produced and used for fuel cell vehicles in the state should come from "renewable" sources. Similarly, at least 40% of the electricity used to recharge battery EVs should come from renewable sources. If California regulations were to consider nuclear power as near zero-carbon, i.e., like "renewables", this would open the LCFS credits to the nuclear power generators for electricity and hydrogen production.

## 3.3 New York State Renewable and Curtailed Hydrogen Credits

The New York State Assembly is currently establishing the "renewable hydrogen credit".[26] The state of New York is also establishing another "curtailed hydrogen credit" that is worth 1.5 times the "renewable hydrogen credit". The obligated parties will be gas utilities. The size of the credit and the obligation amount are to be decided by the New York State Energy Research and Development Authority. This is currently the only credit scheme in the U.S. that will be specifically established for hydrogen and not restricted to transportation fuels like the California LCFS and EPA RFS. Note that the nuclear power capacity in New York State is over 5 GW and contributed over 37% of total electricity generated in the state in 2019.27 Furthermore, nuclear power generation in New York State represents 58% of its zero-carbon electricity generation. The 5 GW of nuclear electricity has the capacity to produce over 2000 metric tons of hydrogen each day (0.8 million metric tons of hydrogen annually), capable of powering over 4 million zero-emission fuel cell vehicles in the state. The following are important points to consider

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20 https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/lut-doc.pdf

21 https://ww3.arb.ca.gov/fuels/lcfs/background/basics-notes.pdf

22 https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

23 https://stillwaterassociates.com/lcfs-101-a-beginners-guide/?cn-reloaded=1

24 https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

25 https://ww3.arb.ca.gov/fuels/lcfs/cleanfinalregorder112612.pdf

26 https://www.rff.org/publications/issue-briefs/investment-tax-credits-hydrogen-storage/

27 https://www.eia.gov/state/data.php?sid=NY#SupplyDistribution

related to New York's and any other possible future renewable hydrogen credit legislation, especially those related to nuclear power and hydrogen production, and their applications:

- The retention of nuclear power generation is critical to achieving federal and states' decarbonization goals across multiple energy sectors.
- Producing hydrogen from nuclear power, especially at low demand periods, increases the capacity utilization factor of NPPs, which can improve the economics of their operation.
- Similar to wind-power, nuclear power can produce near zero-carbon hydrogen to further decarbonize energy use in transportation.
- Producing hydrogen via LTE from nuclear power can achieve higher energy conversion efficiency compared to producing hydrogen via LTE from energy. Research on HTSE technology shows the potential to be much more efficient than LTE given the inherent efficiency gain of the higher reaction temperature as well as the ability to use nuclear heat energy to provide process heat to HTSE.
- Producing hydrogen from nuclear power can be achieved at larger scale compared to hydrogen produced from wind-power, and over longer periods, thus improving the viability of producing zero-carbon hydrogen.
- The contribution of nuclear power to zero-carbon power markets can be extended further to serve other energy sectors such as transportation, as well as building and industrial heat demand, thus contributing to the goals of decarbonization across multiple energy sectors.
- Zero-carbon hydrogen can enable faster deployment of zero-emission hydrogen fuel cell vehicles in all ZEV States (including CA and NY), thus reducing the time to achieve ZEV goals in these states, and significantly reduce air pollution created by transportation the sector.

Once the New York credit market is established, and if nuclear-hydrogen is granted the same credits as renewable hydrogen, non-fuel applications such as direct reduction of iron (DRI) and ammonia production can potentially benefit from these $CO_2$ credits. Later in this report the potential GHG emission reduction impacts of using hydrogen produced from nuclear energy in metals production using the DRI process as well as in ammonia production is discussed.

## 3.4 Zero-Emissions Credits for Nuclear Power in Illinois and New York

The State of Illinois has implemented a ZEC system that applies to electricity generated from nuclear energy.[28,29] This system was modeled after a similar system already employed in the state of New York. In Governor Andrew Cuomo's 2015 letter directing the Department of Public Service to develop a Clean Energy Standard, he said that the closure of nuclear facilities "would eviscerate the emission reductions achieved through the state's renewable energy programs, diminish fuel diversity, increase price volatility, and financially harm host communities."

ZECs are awarded to nuclear generators on a $/MWh basis pegged to the calculated social cost of carbon (SCC)[30]. ZECs compensate electricity generators for producing zero-emissions electricity and are modeled after similar REC programs for renewable energy. The ZEC price can fluctuate depending on the market electricity price and capacity market.[31]

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28 https://www2.illinois.gov/sites/ipa/Documents/2018ProcurementPlan/Zero-Emission-Standard-Procurement-Plan-Approved.PDF

29 https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/zero-emission-credits-201804.pdf

30 https://costofcarbon.org/about

31 https://statepowerproject.org/illinois/

# 4. ENVIRONMENTAL LIFE CYCLE ANALYSIS OF NUCLEAR POWER GENERATION COMPARED TO RENEWABLE ENERGY

## 4.1 Life Cycle Analysis Methodology

Life cycle analysis (LCA) evaluates the environmental impacts of any product by tracking energy use and emissions throughout all phases of its life cycle, including primary material recovery, processing, transportation, conversion, end-use, and end of life (i.e., disposal or recycling). Argonne National Laboratory's (ANL) Greenhouse GREET®)32 model is a globally recognized and widely used (over 40,000 users worldwide) tool to evaluate and quantify the environmental impacts of producing and using hundreds of energy types and products from a life cycle perspective. Specific to nuclear power generation, GREET evaluates its life cycle impacts from uranium mining, through fuel transportation, enrichment, and use in power plants for electricity generation, and transmission and consumption of electricity by end users. GREET also evaluates the environmental impacts of building power plants and spreads the burden over the energy output of the power plant throughout its entire life. GREET covers all power generation technologies, including nuclear, coal-boiler, NG boiler, gas turbine and combined-cycle, biomass power, integrated gasification combined-cycle, concentrated solar, solar photovoltaic (PV), wind, hydro, geothermal, etc. Because of the capability of handling all generation technologies in the GREET model, accurate reference comparisons can be made between these technologies. ANL has performed many LCAs of various power generation technologies using the GREET model. For nuclear power, both pressurized water reactors (PWR) and boiling water reactors (BWR) are modeled in GREET.

## 4.2 Nuclear Electricity LCA Comparisons

The greenhouse gas (GHG) emission or CI of nuclear electricity is less than solar PV and comparable to renewable wind electricity (in grams of $CO_2$ per kWh of generated electricity), if we include the construction phase of each power generator, as shown in Figure 2.[33] Similarly, the CI of hydrogen generated from nuclear electricity (nuclear-$H_2$) by electrolysis is comparable to hydrogen generated from renewable wind energy (wind-$H_2$) by electrolysis for FCEV applications (in grams of $CO_2$ per equivalent service unit) as shown in Figure 3.[34, 35] Note that the use of fuel does not release any emissions in nuclear, hydro, wind, and solar for obvious reasons.

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[32] https://greet.es.anl.gov/

[33] https://greet.es.anl.gov/publication-lca-goethermal-III

[34] https://www.hydrogen.energy.gov/pdfs/progress16/ix_5_elgowainy_2016.pdf

[35] https://www.hydrogen.energy.gov/pdfs/review16/sa057_elgowainy_2016_o.pdf

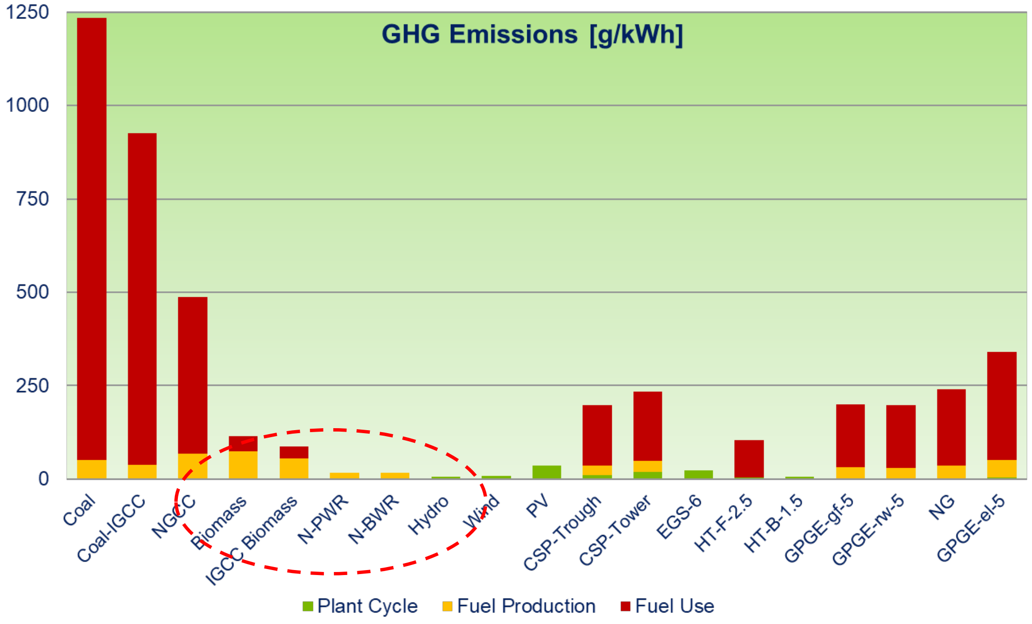

Figure 2. GHG Carbon Intensity LCA Comparison for various electricity generation technologies using the GREET Model. Acronyms: IGCC: Integrated Gasification Combined-Cycle, NGCC: Natural-Gas Combined-Cycle, CSP: Concentrated Solar Power, EGS: Enhanced Geothermal System, HT: Geothermal Hydrothermal Flash, GPGE: Geopressured Gas and Electric

Figure 3 shows a comparison of life cycle or WTW greenhouse gas (GHG) emissions of various hydrogen pathways, including the comparison of hydrogen produced using nuclear vs. wind energy. It shows that nuclear-$H_2$ (SOEC-HTRG, third bar from left) is equivalent to last bar (wind-$H_2$), with the only significant contribution to emissions stemming from the hydrogen compression and precooling at the fueling station (blue portion of the bar).

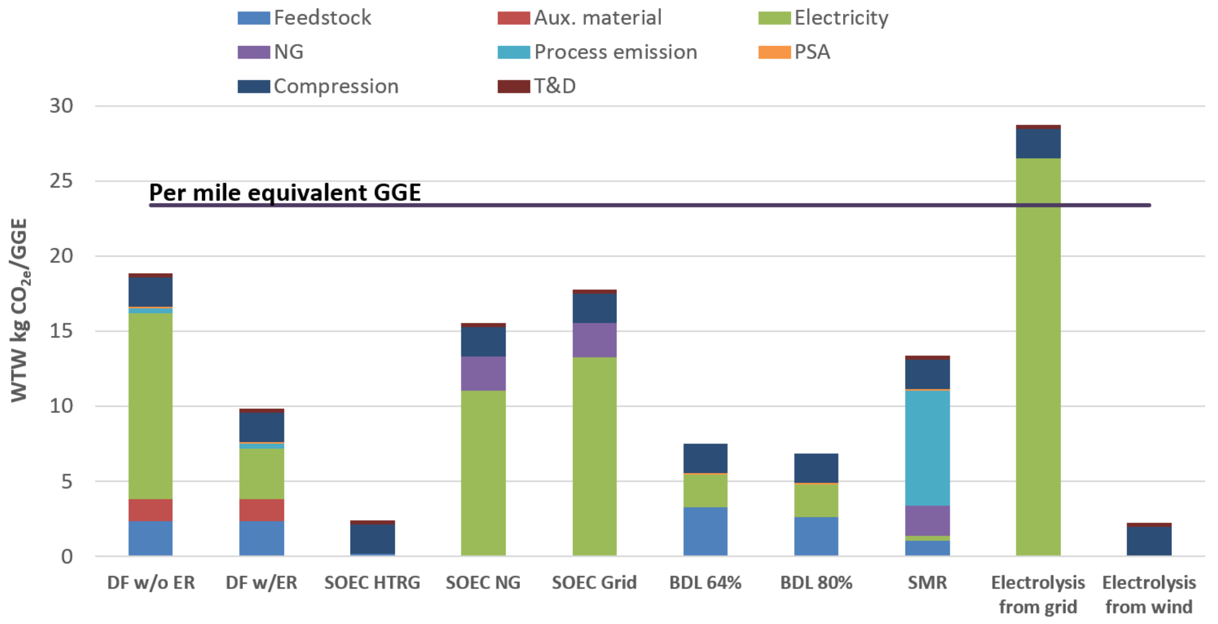

Figure 3. WTW GHG emissions or CI comparison of various hydrogen fuel cell electric vehicle (FCEV) pathways compared to gasoline internal combustion electric vehicle (ICEV). Acronyms: DF: Dark Fermentation, ER: Energy Recovery, SOEC: Solid-Oxide Electrolysis Cell, HTRG: High-Temperature Gas Reactor, NG: Natural-Gas, BDL: Biomass Derived Liquid, SMR: Steam Methane Reforming.

## 4.3 Nuclear-Hydrogen for Fuel Cell Electric Vehicles (FCEVs)

The GHG emissions associated with the hydrogen production and delivery/dispensing pathway can be estimated using a WTW analysis with NL'sar GREET® 2019 model. The WTW analysis can be further broken down into well-to-pump (WTP) and pump-to-wheels (PTW) stages. The WTP stage includes fuel production from the primary source of energy (feedstock) to its delivery to the vehicle's energy storage system (fuel tank). The PTW stage includes fuel consumption during the operation phase of the vehicle to power the vehicle's wheels. The results from WTP and PTW analyses are combined to give the WTW GHG emissions associated with various vehicle-fuel technologies. WTW analysis was carried out using the GREET® 2019 model for light-duty vehicles (LDVs) including, FCEVs, using various hydrogen production and delivery pathways, and baseline gasoline ICEVs. Fuel economy of 26 miles per gallon (mpg) was assumed for gasoline ICEV and 55 mpgge (miles per gallon gasoline equivalent) for hydrogen ($H_2$) FCEV. Conventional ICEs (Internal Combustion Engines) using gasoline were compared to FCEV's using hydrogen produced from NG steam methane reforming (SMR) and nuclear electricity.

The WTW $CO_{2e}$ emissions per mile for LDVs comparing ICEV using gasoline, FCEV using $H_2$ from SMR, and FCEV using Nuclear-$H_2$ are shown in Figure 4. The ICE using gasoline produces over 400 g $CO_{2e}$/mile, while FCEV using $H_2$ from gaseous SMR produces 250 g $CO_{2e}$/mile, and FCEV using $H_2$ from nuclear electricity produces slightly above 50 g $CO_{2e}$/mile, on a WTW basis, with 86% reduction in CI compared to baseline gasoline ICEV (Figure 3).

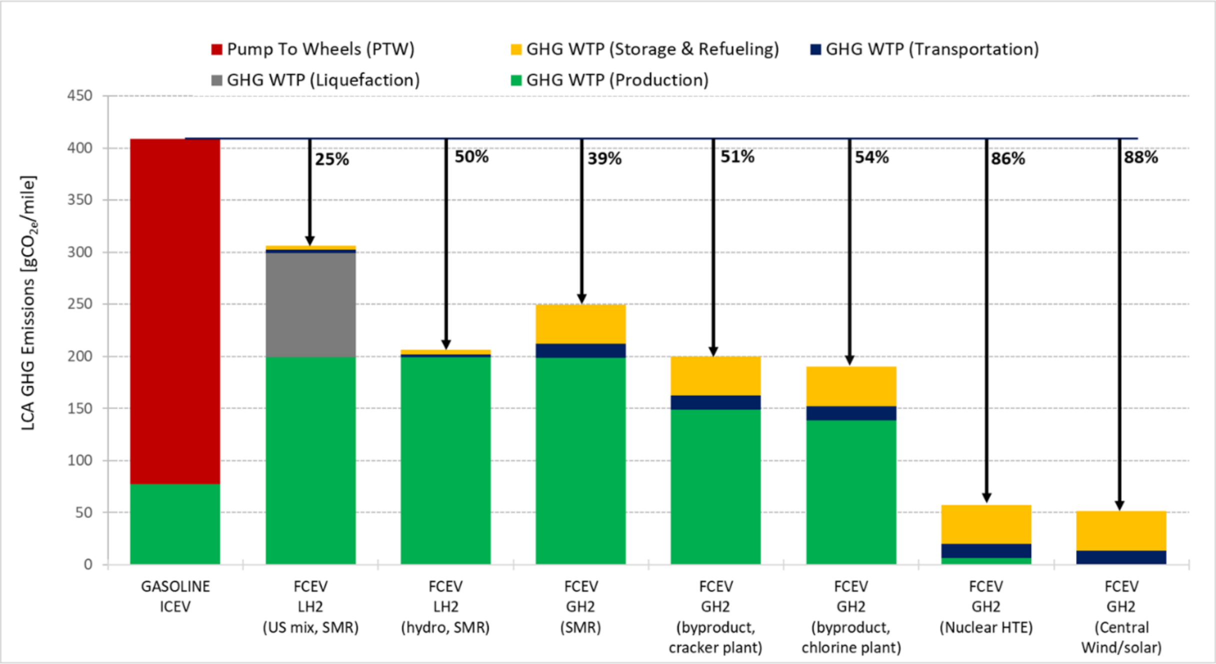

Figure 4. Life cycle or WTW GHG emissions associated with light-duty FCEVs using alternative hydrogen production pathways.

ANL techno-economic analysis of hydrogen infrastructure pathways[36], show that liquid hydrogen (LH$_2$) pathways provide economic advantage over gaseous hydrogen (GH2) pathways due to higher energy density of LH$_2$. However, from Figure 4, we note that GHG emissions associated with the liquefaction process (second bar from left) add approximately 100 gCO$_{2e}$/mi, when considering CI of average U.S. electricity grid mix. However, when hydropower is used for the liquefaction process (third bar from left), its impact on CI of hydrogen is eliminated. Similar CI results can be expected if liquefaction process sources nuclear power instead of hydropower. We note here that electricity use to liquefy a kg of hydrogen ranges between 11-17 kWh/kg, depending on production scale and supplied hydrogen pressure, which is approximately 0.2 – 0.33 of the electricity demand by electrolyzers to produce the same amount of hydrogen. Thus, collocating liquefaction plants next to electrolyzers can provide better utilization of nuclear power while reducing the CI of LH$_2$ and benefiting from attractive economics of transportation and delivery to end-use applications.

The WTW CO$_{2e}$ emissions per mile associated with moving a ton of goods using heavy-duty vehicles (HDVs) are also compared. The conventional short-haul HDV using ICE diesel in compression-ignition direct-injection engine produces 103 g CO$_{2e}$/ton-mile, while the fuel cell HDV using H$_2$ from SMR produces 73 g CO$_{2e}$/ton-mile and the fuel cell HDV using nuclear-H$_2$ produces only 10 g CO$_{2e}$/ton-mile as shown Figure 5. The WTW GHG emission reduction by nuclear-hydrogen compared to baseline gasoline and diesel fuels for LDVs and HDVs can be translated into GHG emission credits under California LCFS using the CO$_2$ credit price as traded in that market. The CO$_2$ credit price was recently traded near $200/tonne in the LCFS market[37].

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[36] https://hdsam.es.anl.gov/index.php?content=hdsam

[37] http://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

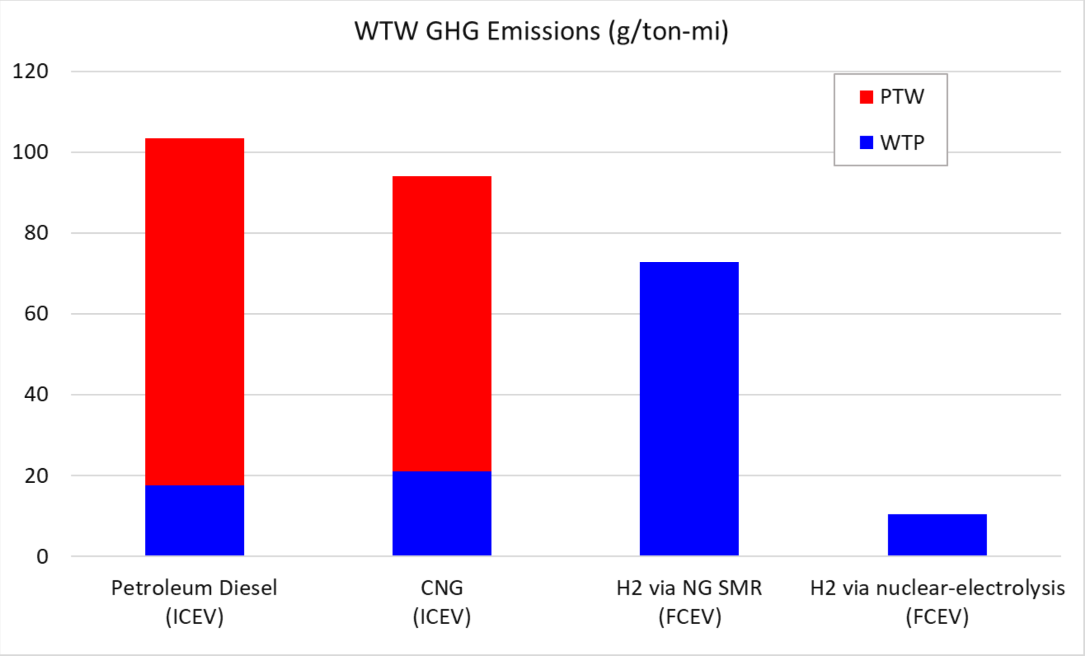

Figure 5. WTW GHG emissions associated with heavy-duty drayage trucks using alternative vehicle/fuel pathways.

## 4.4 Nuclear-Hydrogen for Synthetic Fuels Production

Significant quantities of high purity $CO_2$ are generated in industrial processes such as ethanol production plants, as well as SMR plants that produce hydrogen from NG for ammonia production and NG processing plants. These high purity $CO_2$ sources present opportunities for the production of synthetic chemicals and fuels such as methanol, Fischer-Tropsch (FT) diesel, and dimethyl ether, while minimizing the cost and energy penalty to capture $CO_2$ relative to other dilute $CO_2$ sources (e.g., from flue gases of coal and NG power plants). The hydrogen demand for synthetic fuel production can be estimated based on the stoichiometric 1:3 mole ratio of $CO_2$ to $H_2$, which is required for the synthesis of FT fuels.

The life cycle environmental benefits associated with synthetic fuel production using near zero-carbon hydrogen from nuclear power, in terms of reduction of greenhouse gas (GHG) emissions, were evaluated for the FT processes producing synthetic fuel blends, such as FT naphtha, jet and diesel fuels. The GREET® 2019 model was used to estimate the GHG emissions assuming captured $CO_2$ and Nuclear-$H_2$ for producing these synthetic fuels. The GHG emissions associated with the synthetic fuels production and dispensing can be estimated using a WTW analysis. Figure 5 compares the GHG emission for the production of conventional fuels, such as petroleum gasoline, jet fuel and diesel, to highlight the benefits of the FT pathways using nuclear $H_2$. The $CO_{2e}$ emission per MJ of gasoline, diesel, E10 and FT fuel from a standalone plant using nuclear-hydrogen are about 94, 92, 91 and 9 g $CO_{2e}$/MJ respectively. Other CIs for low-carbon fuels, such as bio-ethanol, are also shown in Figure 6.

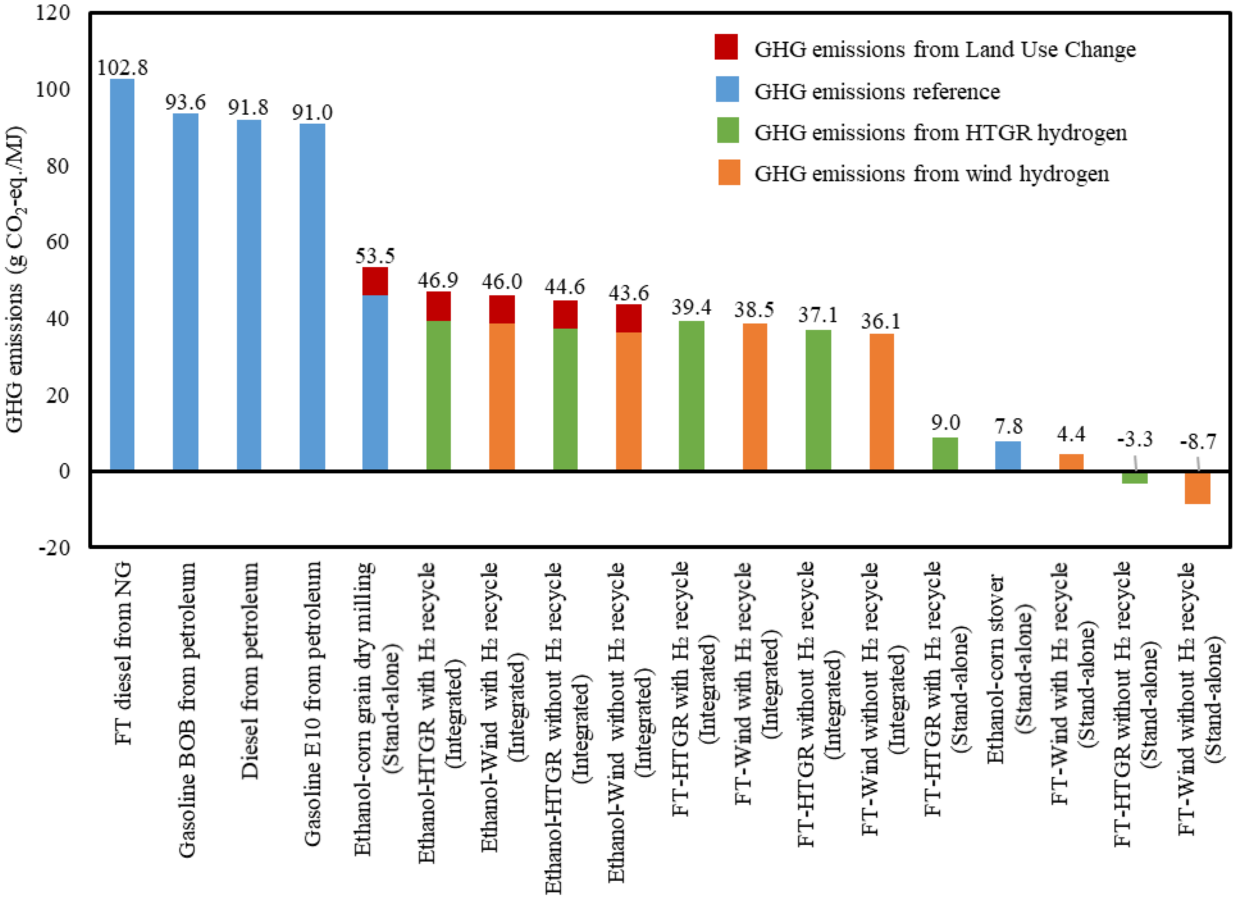

Figure 6. Life cycle or WTW GHG emissions associated with alternative fuel production pathways, including synthetic fuels using nuclear-hydrogen from high-temperature gas reactor (HTGR)

The WTW GHG emission reduction by synthetic FT fuels using nuclear-hydrogen compared to baseline gasoline and diesel fuels for LDVs and HDVs can be translated into GHG emission credits under California LCFS using the $CO_2$ credit price traded in that market.

## 4.5 Direct Reduced Iron (DRI) for Metals Refining & Steel Production

The direct reduction of iron is a process for producing high purity iron (DRI) from ore at temperatures below the melting point of iron by reducing the iron oxide ore and driving off oxygen in a reactor using a reducing agent. The reducing agent can be elemental carbon from NG or coal, hydrogen or a mix of hydrogen and carbon monoxide gas (syngas). In the conventional approach to steel making, iron ore is reduced to “pig” iron using coking coal as the reducing agent in a blast furnace, and the pig iron is then converted to steel in a basic oxygen furnace (BOF). In the U.S., the amount of steel produced by electric arc furnace (EAF) has been increasing and is expected to continue to grow, mainly due to the increased production of scrap, which can be incorporated in the EAF feed, while the amount produced by BOF is expected to remain relatively flat. The DRI process using 100% hydrogen as the reducing agent requires up to 100 kg hydrogen per metric tonne of steel, i.e., a mass ratio of approximately 10%. However, using hydrogen in a blend with NG with up to 30/70 ratio by energy to produce DRI would not require modifications to the original technology developed to work only with NG.[38]

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[38] Chevrier, V., 2018. “Hydrogen Uses in Ironmaking,” presented at the H2@Scale Workshop, Chicago, IL (August 1). https://www.energy.gov/sites/prod/files/2018/08/f54/fcto-h2-scale-kickoff-2018-8-chevrier.pdf

Figure 7 compares the $CO_{2e}$ emissions per metric tonne (MT) of steel produced for four possible process pathways in the steel making process: 1) Blast Furnace / BOF (using coal), 2) EAF (using grid electricity), 3) EAF (using nuclear electricity), and 4) DRI (using nuclear-$H_2$). The GHG emissions from each respectively is: 2.15 MT $CO_{2e}$ / MT steel from blastfFurnace, 0.91 MT $CO_{2e}$ / MT steel from EAF using grid electricity, 0.13 MT $CO_{2e}$ / MT steel from EAF using nuclear electricity, and 0.01 MT $CO_{2e}$ / MT steel from DRI using Nuclear-$H_2$, assuming the reducing agent is 100% hydrogen. The use of near zero-carbon nuclear-hydrogen for the DRI process can potentially be sourced competitively when applying the credit prices offered by New York State, if clean low-carbon hydrogen produced using nuclear energy can qualify for the same credits as renewable hydrogen.

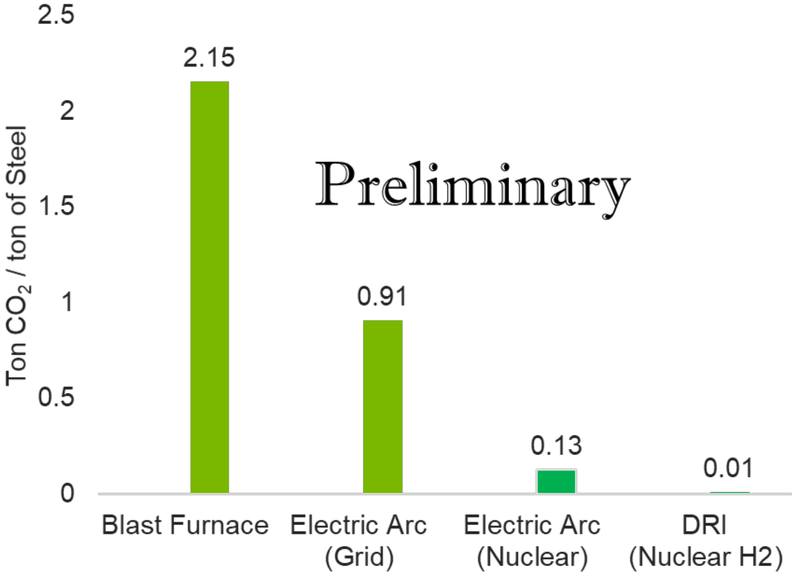

Figure 7. Life cycle $CO_2$ emissions associated with alternative steel production pathways.

## 4.6 Ammonia Production

Ammonia is produced by the Haber-Bosch process which reacts hydrogen, usually produced from NG via the SMR process, with nitrogen separated from the air. The Haber-Bosch process uses hydrogen in a molar ratio of 3 moles $H_2$ to 2 moles of NH3, therefore 0.178 kilograms of hydrogen are required to produce one kilogram of ammonia. As ammonia is the source of nitrogen in other fertilizer products, this can be generalized as 0.216 kilograms hydrogen per kilogram of nitrogen in fertilizer. To evaluate the environmental benefits and trade-offs for using hydrogen produced from nuclear energy (nuclear-$H_2$) for ammonia production, the Haber-Bosch process was considered. The GREET 2019 model was used to conduct the LCA for ammonia production. Various production pathways for hydrogen were considered to understand the $CO_2$e emissions associated with various ammonia feedstock sources and production pathways. Figure 8 below compares the CO2e emissions from the conventional ammonia production process with the nuclear-hydrogen production pathway with and without using nuclear electricity for the air separation unit (ASU). Figure 7 compares the CO2e per tonne of nitrogen (N) in the fertilizer for three ammonia production pathways, a baseline conventional pathway using SMR of NG, another pathway using nuclear-$H_2$ and grid electricity for the ASU, and a third pathway using nuclear power for both $H_2$ production and the ASU. The conventional pathway produces about 2.9 MT $CO_2$ /ton N, while the nuclear-$H_2$ and the nuclear for both $H_2$ and ASU produce 1 and 0.01 MT $CO_2$ /ton N, respectively, on a life cycle basis.

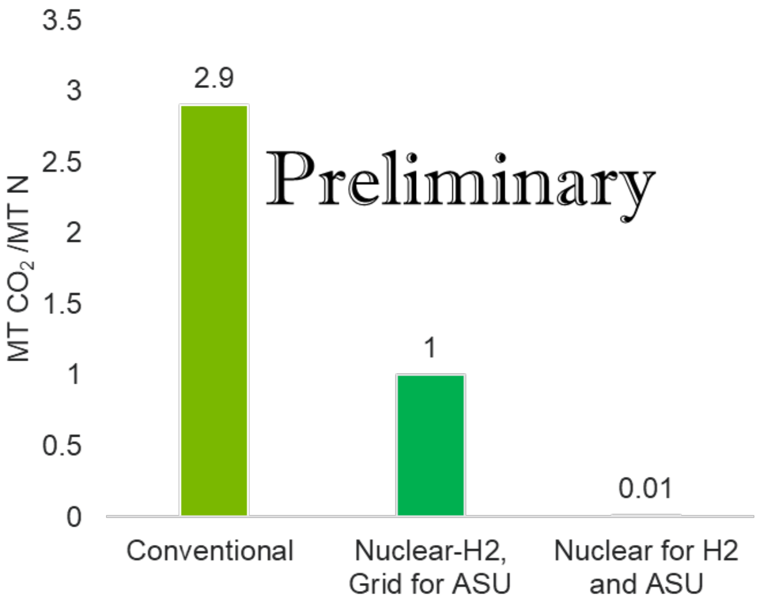

Figure 8. Life cycle $CO_2$ emissions associated with alternative nitrogen (N) fertilizer production pathways.

The use of near zero-carbon nuclear-hydrogen for the ammonia synthesis process can potentially be sourced competitively when applying the credit prices offered by New York State, if nuclear-hydrogen pathways can qualify for the same credits of renewable hydrogen.

# 5. CONCLUSIONS

Nuclear energy is being recognized as a high capacity, resilient, and reliable source of low-carbon energy for use in electricity generation, hydrogen production, and clean energy credit systems exist and are being developed to help ensure this energy source is appropriately compensated to enable it continued contributions to large scale decarbonization. Nuclear energy is a large portion of the low-carbon generation mix in the U.S.

There is precedent for nuclear energy being included in existing and proposed clean energy frameworks and legislation (New York & Illinois Clean Energy Standards for electricity generated from nuclear energy, California LCFS for transportation fuels, and New York curtailed hydrogen credits)

Electricity and hydrogen produced from nuclear energy can be considered low-carbon and comparable to renewable energy such as solar and wind even after the entire life cycle is considered (including uranium mining, fuel manufacture, plant construction, etc.). The production of green hydrogen using nuclear energy could be a beginning of a transition of parts of the energy and manufacturing sectors to hydrogen.

Retiring nuclear plants and not valuing this low-carbon energy with the commensurate credits given to renewable energy may lead to drastic increases in carbon emissions (from substitute baseload plants such as NG combined-cycle) at a time when decreases in carbon emissions are being sought, which is contrary to the goals of decarbonization.

Restated here are important points to consider related to New York's and any other possible future renewable hydrogen credit legislation, especially those related to nuclear power and hydrogen production, and their applications:

- The retention of nuclear power generation is critical to achieving federal and states' decarbonization goals across multiple energy sectors.
- Producing hydrogen from nuclear power, especially at low demand periods, increases the capacity utilization factor of NPPs, which can improve the economics of their operation.
- Similar to wind-power, nuclear power can produce near zero-carbon hydrogen to further decarbonize energy use in transportation.
- Producing hydrogen via LTE from nuclear power can achieve higher energy conversion efficiency compared to producing hydrogen via LTE from energy. Research on HTSE technology shows the potential to be much more efficient than LTE given the inherent efficiency gain of the higher reaction temperature as well as the ability to use nuclear heat energy to provide process heat to HTSE.
- Producing hydrogen from nuclear power can be achieved at larger scale compared to hydrogen produced from wind-power, and over longer periods, thus improving the viability of producing zero-carbon hydrogen.
- The contribution of nuclear power to zero-carbon power markets can be extended further to serve other energy sectors such as transportation, as well as building and industrial heat demand, thus contributing to the goals of decarbonization across multiple energy sectors.
- Zero-carbon hydrogen can enable faster deployment of zero-emission hydrogen fuel cell vehicles in all ZEV States (including CA and NY), thus reducing the time to achieve ZEV goals in these states, and significantly reduce air pollution created by transportation the sector.

Recommendations include that the EPA, U.S., and state regulators should consider:

1. low-carbon fuel standards not exclusive to transportation fuels and inclusive of nuclear energy and uses other than transportation and electricity (i.e., hydrogen to produce green steel through the DRI process, green ammonia, etc.)
2. low-carbon fuel standards inclusive of low-carbon nuclear energy as a total solution to continued decarbonization while supporting the expansion of renewables on the grid and resilient and reliable grid electricity.