ENERGY INNOVATION
POLICY & TECHNOLOGY LLC®

INDUSTRIAL TRANSFORMATION TECHNOLOGY AND INVESTMENT MODEL DOCUMENTATION

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ABOUT THE ITTIM

The Industrial Transformation Technology and Investment Model (ITTIM) is a free and open-source tool that maps out transition pathways for regions to achieve non-emitting industrial sectors. It estimates a wide variety of associated outputs, such as industrial energy use, carbon dioxide (CO_2) emissions, energy expenditures, capital investment needs, and more. The model is programmed in Microsoft Excel (with Visual Basic scripting).

As of the writing of this documentation, the ITTIM includes datasets for China, Indonesia, Viet Nam, the Philippines, the United States, and each of the 48 contiguous U.S. states. The number of supported regions may grow in the future.

The model relies on public data from over 125 sources. Full citations are given on the model's "References" tab, and specific data values throughout the model indicate which references they come from.

SYSTEM REQUIREMENTS

The ITTIM uses advanced features of Excel, such as dynamic arrays. Therefore, it requires a version of Excel from Microsoft Office 2021 or later (including Excel from a Microsoft Office 365 subscription). It is compatible with Mac and PC versions of Excel.

QUICKSTART TUTORIAL

DOWNLOADING AND OPENING THE MODEL

The ITTIM is easy to use. Download the Excel file and open it. You will be prompted with a banner that reads :

SECURITY WARNING: Macros have been disabled. Enable Content

The ITTIM uses macros to assist in updating time-series graphs. If you downloaded the ITTIM directly from the website of **Energy Innovation** (www.energyinnovation.org), the **World Bank**, or **Lawrence Berkeley National Laboratory**, it is safe to click "Enable Content." We recommend downloading the model from one of these three organizations to ensure you receive a clean, unmodified copy of the software.

SETTING UP YOUR SCENARIO

Click on the "User Settings" tab. Here, you specify the parameters of your scenario.

First, **select the country or region** you wish to model.

Next, **set the year when a clean industrial sector and the year when a clean electricity sector will be achieved**. In most regions, it is expected that the electricity sector could eliminate its emissions sooner than the industrial sector. The model defaults to achieving a clean industrial sector in 2070 and a clean electric sector in 2060.

Set the **year shown on graphs**. The model is capable of showing how much progress toward clean industry will occur by any specific year of the scenario. For example, if the industry sector is configured to be clean by 2070, and you set the year shown on graphs to 2045, the graphs will show the energy use, emissions, investments, etc. as of 2045, reflecting partial progress toward a clean industrial sector. Usually, it is best to keep the year shown on graphs the same as the year when a clean industrial sector is achieved until you are familiar with the ITTIM.

You **may set a carbon price** (representing a carbon tax or cap-and-trade system). The carbon price alters the cost-effectiveness of different technological interventions (e.g., the shift to clean industry is more cost-effective with a higher price on carbon emissions). It does not alter the choice of technologies used, since the ITTIM is not a cost-driven optimization model. The model defaults to a $50/tonne CO_2 carbon price. The carbon price is ramped in linearly between 2025 and the year you chose for the achievement of a clean industrial sector.

You may choose to **show or hide feedstocks from emissions graphs**. Feedstocks are fossil fuels that are chemically transformed into output products rather than burned for energy. For example, petroleum that is turned into plastic is a feedstock, while petroleum that is burned is not. If emissions from feedstocks are enabled, the ITTIM considers their emissions to be the amount of carbon they contain, converted to CO_2, as if the feedstocks had been combusted. In the real world, some of the carbon in chemical feedstocks gets emitted as process CO_2 from manufacturing facilities, and some ends up in the final output products like urea-based fertilizers and plastics. Some of the carbon in output products is released when the products are used (such as fertilizers and fuel additives). In other cases, the carbon remains trapped for some time, ranging from days to decades or longer, but no chemicals industry product is intended as a long-term storage method of CO_2, and it can be assumed that all the carbon will escape in a human-relevant timescale (centuries). For instance, plastics are often considered resistant to decay, but about a quarter of plastics today are incinerated, that share is projected to rise to half by 2050, and microbes are already evolving metabolic pathways to break down plastics in oceans and soil.

You may **limit decarbonization to specific subindustries**. Excluded subindustries still exist in the model and its outputs, but no decarbonization technologies are applied to the excluded subindustries. You can exclude subindustries that are not of interest to you, are not within the purview of a regulator or agency you are working with, etc. Conversely, you might choose to include only one subindustry to isolate the costs and benefits of decarbonizing that specific subindustry.

You may make a variety of **adjustments to end-year energy costs, equipment costs, energy use, and discount rate**. These are useful for performing sensitivity analysis or testing the impact of policy interventions that change the costs of specific energy sources or industrial equipment. Energy source cost adjustments can be applied to coal, petroleum, natural gas, bioenergy, or electricity and range from +100% (double cost) to -100% (making that energy type free). The cost of clean hydrogen is instead set by choosing one of three price scenarios: High Improvement, Low Improvement, or Present Day hydrogen prices. The prices used in these scenarios vary by region and are based on cited sources listed in the ITTIM.

You may **limit which technical decarbonization approaches** the model may use. This allows you to visualize the effects of a specific approach or any set of approaches in combination. If efficiency approaches (or direct use of geothermal heat) are disabled, the model will still achieve clean industry, though this involves shifting more fossil fuel use to clean energy and attendant higher costs. If electrification approaches are disabled, subindustries that are able to use CCS and/or hydrogen will attempt to those tools to meet the energy demand that otherwise would have been met by electrification, while other subindustries will fall back on fossil fuels. If CCS, hydrogen, and/or clean feedstocks are disabled, any energy that would have been addressed by the disabled approach(es) will fall back on fossil fuels.

REVIEWING GRAPHS

Once you have chosen your scenario settings, you may browse the graphs, which appear on the light blue-colored tabs. Many graphs show results in eight categories: historical values, a Future BAU (business-as-usual) Projection (that is, what the future would look like without a transition to clean industry), and six tiers of clean industrial technologies. A detailed description of each tier and what it includes appears in the "Technology Tiers" section of this software documentation. Note that the tiers are cumulative. For example, the data shown on the "Tier 3" row include the effects of all earlier tiers, as well as the industrial output changes in the Future BAU Projection.

The following tabs include output graphs:

Energy Use Graphs includes graphs that depict the industrial sector's energy consumption. This includes breakouts by energy type, by subindustry, and a dedicated graph illustrating feedstocks by type.

CO_2 Emissions Graphs shows emissions from the industrial sector by fuel type. It also includes emissions from "cement calcination" (CO_2 released by the breakdown of limestone to form cement). Also included is "fugitive methane" (methane leaked from coal mines, oil and gas fields, pipelines, and equipment) in CO_2e. Note that the fugitive methane is the total amount of escaped methane associated with the production of the fuels consumed by the industrial sector, not the amount of methane leaked from industrial sector facilities. (Most methane leakage happens at the sites of mining and drilling, not from transport pipelines or industrial equipment.) Finally, the CO_2 graphs include emissions associated with the production of electricity purchased by the industrial sector. These indirect emissions are divided into emissions to be expected even if the electricity sector decarbonizes according to the schedule you set – "Electricity (on-target)" – and what the emissions would be if the electricity sector retains the same emissions intensity per unit electricity output as it has today – "Electricity (off-target)."

Financial Expenditures Graphs include a range of financial metrics. These include annual energy expenditures by energy type and expenditures on capital equipment by technology tier (see below). To compare energy and capital costs on the same graph, certain graphs depict capital costs annualized over the lifetime of the industrial equipment, discounted using the discount rate you set on the "User Settings" tab (default of 7%). There are also two graphs that show cost effectiveness – i.e., expenditures per unit of abatement. One shows only capital investment need per unit of abatement, and the other shows holistic cost (annualized capital plus incremental annual energy expenditures) per unit of abatement. Note that capital investment requirements calculated in ITTIM include only the cost of industrial equipment, not land, buildings, or installation, nor the cost of equipment outside the industrial sector (such as new electric power plants or transmission lines, in the electricity sector).

Subindustry Breakout Graphs contains a variety of output metrics disaggregated by industrial subsector. This includes energy use by energy type, CO2 emissions by emissions source, annual energy expenditures by energy type, capital investment by technology tier, and anticipated change in output (product demand), all broken out by subsector. There are controls on this sheet to customize the graphs' content. First, select a graph scope at the top of the sheet (Historical, Future BAU, or after one of the technology tiers), and the first several graphs will all be updated to show the corresponding results. The graph of capital investment requirements can also be customized to show or hide investments in specific technology tiers. For example, if you want to see only capital investment needs for direct electrification (Tiers 2a and 2b), you can disable all other tiers.

Time Series Graphs includes a few graphs with a time axis. Since one model run is a snapshot in time, these graphs are constructed by performing multiple model runs with different settings for the "Year Displayed on Graphs" control and logging the data. A Visual Basic macro automates the model runs and copying of data, and the "Time Series Graphs" sheet can detect if the graphs are outdated (do not show data corresponding to the settings you chose on the "User Settings" tab). If the top of the sheet shows any messages indicating an update is needed, click the "Update Time-Series Graphs" button. Then, if needed, update the "Max year to show on graphs" setting as indicated on the sheet. Once the graphs are updated, you can scroll down to see industrial electricity demand, CO_2 emissions by energy source, and annual energy expenditures over time.

Tier 1, 2a, 2b Composition Graphs shows pie charts that illustrate the degree to which different technologies within these tiers are contributing to the energy or fossil fuel use reduction achieved by each tier. For more details, see the tier explanations below.

Asian Country Comparison Graphs provide some static comparisons of historical values for China, Indonesia, Viet Nam, and the Philippines. Since these graphs only depict historical data, they are not affected by any user settings.

TECHNOLOGY TIERS

The ITTIM divides technologies and other changes to industrial processes into six tiers, the first of which represents the highest priority interventions and the last of which represents the lowest priority interventions, with the priority level of each tier determined by the costs, technological maturity, emissions impacts, and practicality of the interventions it includes. Each tier represents a non-overlapping set of measures, and the six tiers cumulatively mitigate 97% to 99% of industrial energy-related and cement calcination emissions in each region.

Below, we explain which interventions are included in each tier, and why.

TIER 1: MATERIAL EFFICIENCY, PRODUCT LONGEVITY, AND ENERGY EFFICIENCY

The first tier encompasses the lowest-hanging fruit among industrial decarbonization solutions: those that reduce industrial energy use or material intensity without reducing product quality. These interventions, which span energy efficiency, material efficiency, and product longevity, often save firms money by reducing input costs.

Energy efficiency encompasses improving thermal and electrical efficiency via equipment-level interventions (e.g., selecting efficient equipment models and adjusting their speed, pressure, or other operating parameters) and facility-level interventions (e.g., aligning the size of equipment with material flows or designing pipes to move fluid efficiently).

Material efficiency strategies minimize the amount of new material used to create the same product, mainly by altering either product designs (e.g., material substitution, new configurations) or industrial processes (e.g., automation, additive manufacturing).

Product longevity strategies keep materials, products, and physical infrastructure (e.g., buildings) in use for as long as possible, reducing both material waste and demand for newly manufactured materials. Example strategies include using durable and long-lasting materials in manufacturing and construction, designing products for easy repair and remanufacture, and “adaptive reuse” strategies that find new uses for intact materials, products, and infrastructure.

TIER 2A: ELECTRIFICATION OF NON-THERMAL, LOW-TEMPERATURE, AND SOME STEELMAKING PROCESSES

The next tier represents the most cost-effective options for electrification of processes that currently rely on fossil fuel combustion, thereby increasing their efficiency and reducing their emissions impact if powered by clean electricity. Tier 2a electrifies all non-thermal processes and low-temperature thermal processes (below 150 °C). It also shifts some primary steelmaking to secondary (recycled) steelmaking.

Additionally, in regions with geothermal potential, Tier 2a includes some use of direct geothermal heat for industrial processes (i.e., not geothermal power generation). Although this is not electrification, the cost is similar, making it a natural fit in Tier 2a.

Non-thermal processes such as material grinding, compression, and conveyance activities that are powered by diesel engines can easily be electrified using commercial technologies like electric motors. Switching diesel engines for electric motors can reduce operating expenses because electric motors are more efficient than combustion engines and because diesel fuel is a comparatively expensive fossil fuel.

Electrifying thermal processes is more challenging given the high costs of electricity relative to fossil fuels, which makes most electric heating equipment more expensive to operate than conventional equipment. Industrial heat pumps, which are commercially available and can supply heat up to 150-200 °C, are an exception to this rule. Heat pumps move heat from a source to a sink, increasing its temperature by manipulating its pressure. Because they use electricity to move heat rather than convert electricity to heat, they can deliver much more energy than they take in, partially or fully overcoming the higher operating costs of electrification.

Secondary steelmaking involves the use of electric arc furnaces (EAFs) to turn scrap steel into recycled steel. EAFs are widely commercially available and account for 29% of global steelmaking today. The maximum potential of secondary steel is limited by scrap availability and quality, but there is potential to scale it up in many countries or regions where scrap collection can be improved.

TIER 2B: ELECTRIFICATION OF MEDIUM- AND HIGH-TEMPERATURE PROCESSES

After the first two tiers are implemented, the remaining fossil fuel use represents medium- and high-temperature industrial process heat, which is more challenging to decarbonize. Tier 2b directly electrifies most of this remaining heat. Existing electric technologies can provide process heat at all temperatures used in industry today, although much of the relevant equipment is not yet commercial and is more expensive to operate than conventional heating equipment. Still, direct electrification has advantages over alternatives such as clean hydrogen or carbon capture and storage, which are featured in later tiers.

Today, medium-temperature industrial heat (150 to 500 °C) is often provided by fossil-fuel-fired boilers, for which commercially available electric boilers are a one-to-one substitute. High-temperature heat (above 500 °C) is concentrated in a few energy-intensive industries: iron and steel, chemicals, non-metallic minerals, and non-ferrous metals. A variety of electric technologies reach the highest temperatures used in industry and are suitable for bulk heating applications, including electric resistance heating, induction heating, and electric arcs. However, equipment that uses these technologies to electrify certain industrial processes is still being researched and piloted.

Thermal batteries—effectively electric resistance heaters with built-in thermal energy storage—are capable of reducing the energy cost of electrified heat by enabling industrial facilities to rely on cheap off-grid renewables or to buy grid electricity only in the cheapest hours of the day. Commercialized thermal batteries can reach 300 to 500 °C, and those that can reach 1500 to 1700 °C are being developed. The ITTIM does not assume the use of thermal batteries when making energy cost estimates (meaning, the model assesses electricity costs at the typical rate for industrial buyers of grid electricity) because thermal batteries are not sufficiently mature and widespread, and because they require either off-grid deployment or special electricity tariff arrangements with utilities, conditions that cannot be assumed to be widely available across the modeled regions.

TIER 3: CARBON CAPTURE AND USE OR STORAGE

Certain high-temperature industrial processes may lack commercial electrification options for multiple decades. For example, plasma torches that can heat cement kilns and electrolytic technologies that can replace fuel-fired primary steelmaking are still at the laboratory stage. Carbon capture and use or storage (CCUS) is an option for decarbonizing these processes. Not only is retrofitting fossil fuel combustion with CCUS less expensive in the ITTIM than burning green hydrogen, but it also demands no additional electricity from the grid (though it increases the fossil fuel consumption of the process it is applied to). Moreover, CCUS can play a dual role in the cement industry, addressing both energy-related emissions and process CO_2 emissions until alternative cement chemistries and/or electrified cement kilns and precalciners are commercialized.

In our model, Tier 3 applies CCUS to a portion of the fossil fuel use remaining after Tier 2b in the non-metallic minerals and iron and steel industries. Although CCUS is commercially deployed today on high-purity CO_2 streams (e.g., from ethanol and ammonia production), Tier 3 does not apply CCUS to those activities because our model does not disaggregate the chemicals subindustry down to the level of specific products.

Today's post-combustion CCUS systems capture less than 100% of the CO_2 in the exhaust gas stream. In our model, CCUS captures 90% of the CO_2 generated by a CCUS-equipped facility. Additionally, since CCUS increases fossil fuel use, it increases upstream methane leakage associated with fossil fuel production. The use of CCUS is the reason that the clean industrial scenarios modeled in the ITTIM only reduce emissions by 97-99% rather than 100%.

TIER 4A: GREEN HYDROGEN COMBUSTION

Tier 4a replaces all fossil fuels remaining after Tier 3 with green hydrogen, excluding fossil fuel feedstocks for the chemicals industry. This encompasses the remaining process heat in the chemicals, refining, iron and steel, non-ferrous metals, and non-metallic minerals industries. While the creation of green hydrogen can be too energy-intensive to be cost-effective for many applications, it may make economic sense in industries with high temperature needs where electrification is not yet technologically mature and hydrogen is already used in process streams (e.g., chemicals, refining), and in other industries that still have remaining emissions to address even after earlier tier strategies are deployed (e.g., primary iron and steel). In the iron and steel industry, green hydrogen can simultaneously serve as a chemical reducing agent and source of high-temperature heat when used in direct reduced iron furnaces (H_2-DRI). In these specific circumstances, the utilization of green hydrogen for process heat can be a sensible strategy to reach net zero.

Today, nearly all of the world's hydrogen is produced from fossil fuels, around three quarters from steam methane reforming (SMR) of natural gas and around a quarter from the gasification of coal. This process releases large volumes of CO_2. CCUS can be retrofitted to this process to create low carbon "blue hydrogen." However, the most promising zero-carbon hydrogen production pathway involves the use of renewable electricity in electrolyzers to split water into hydrogen and oxygen, creating what is commonly known as "green hydrogen." All three forms of hydrogen are molecularly identical—only their production pathways vary.

Hydrogen can be burned instead of natural gas in industrial equipment, but the equipment must be upgraded to accommodate hydrogen's lower volumetric energy density and manage safety risks like leakage and flammability. Hydrogen also has a higher flame temperature than natural gas, leading to higher nitrogen oxide (NO_x) emissions unless safeguards are implemented. Finally, hydrogen requires substantial enabling infrastructure, including electrolyzers to produce hydrogen, renewable energy to power electrolyzers, and dedicated pipelines that are designed to prevent small hydrogen molecules from leaking.

TIER 4B: CLEAN CHEMICAL FEEDSTOCKS

One of the last and most technically challenging aspects of industrial decarbonization is shifting from fossil-based to clean chemical feedstocks, used to make ammonia, methanol, olefins, aromatics, and downstream products like plastics and fertilizers. This does not address energy-related emissions from the facility, but it can address upstream (scope 3) emissions from fossil fuel production and processing, as well as downstream (scope 3) emissions from the use and end-of-life of products. It can also reduce process CO_2 emissions, which arise because only some of the carbon in feedstocks ends up in chemical output products. However, zero-carbon feedstocks are only used at small scale today (and some pathways, like conversion to BTX aromatics, are still being researched and demonstrated), so it may take multiple decades before they reach meaningful scale.

Tier 4b shifts all fossil fuel feedstocks to low-carbon feedstocks. By default, 30% of feedstock demand is met with bioenergy, 40% with green hydrogen, and 30% with blue hydrogen. These proportions roughly account for the available supplies of sustainable biomass for feedstocks and clean electricity to produce green hydrogen. The production of blue hydrogen is not emissions-free, but it may be a good option for decarbonizing steam methane reforming equipment before it is ready for replacement and where clean electricity for green hydrogen production is unavailable. Another potential fit is for petroleum refineries. Today, they burn byproducts of the crude oil they refine—refinery fuel gas (RFG) and petcoke. These substances could be converted to blue hydrogen, which is used in refinery processes like hydrocracking and desulfurization.

MODEL SCOPE

In addition to the technology coverage detailed above, the ITTIM's scope can be defined along several dimensions: covered regions, subindustries, energy sources, pollutants, timeframe, and costs.

REGIONS

As of the writing of this documentation, the ITTIM includes datasets for China, Indonesia, Viet Nam, the Philippines, the United States, and each of the 48 contiguous U.S. states. The number of supported regions may grow in the future.

When combined, these five countries accounted for over 55% of total energy-related CO_2 emissions from the industrial sector worldwide in 2019. While reported energy consumption and cost figures are specific to the modeled regions, the ITTIM's broader findings (e.g., on viable technological pathways, costs, etc.) can be generalized to other regions with ambitions for industrial development.

SUBINDUSTRIES

The analysis covers manufacturing activities, which include fabricating raw materials (such as steel, cement, and chemicals), refining or processing fuels, cooking and packaging food, and producing finished products such as vehicles and machinery. Non-manufacturing activities such as mining and quarrying, oil and gas drilling, agriculture, and construction are excluded. The covered subindustries are:

Food, beverage, & tobacco	Chemicals	Machinery
Textiles, leather, & apparel	Plastic & rubber products	Vehicles & transport equip

Wood & furniture	Non-metallic minerals	Electronics
Pulp, paper, & printing	Iron & steel	Other metal products
Refining & fuel processing	Nonferrous metals	Other manufacturing

ENERGY SOURCES

The ITTIM considers all energy sources purchased by these subindustries, including fossil fuels, bioenergy, electricity, and heat/steam (e.g., district heating). Intermediate energy carriers (such as refinery fuel gas produced and consumed within a refinery, or electricity produced by a captive power plant) are not explicitly tracked, but the inputs used to create those intermediate energy carriers are included. The analysis focuses on pathways by which industry can transition away from fossil fuel use. To achieve emissions benefits, it is necessary for the electricity sector to similarly transition to non-emitting sources. Though the electricity sector is not modeled in detail in this study, industrial electricity demand and the emissions associated with purchased electricity are included in the ITTIM. It is also important to ensure bioenergy and district heat are produced sustainably, but bioenergy and district heat supply are not covered in the model. Feedstocks (fuels that are transformed to become part of the output products, such as petroleum that goes into making plastics) are included in the study and shown separately from non-feedstock fuels in graphs.

POLLUTANTS

This study assesses CO_2 emissions from industrial fossil fuel use and from the calcination of minerals to form cement (scope 1 emissions). It also considers upstream CO_2 emissions from purchased electricity under multiple assumptions about progress toward electricity sector decarbonization (scope 2 emissions). It also includes methane (CH_4) emissions attributable to the fossil fuels purchased by manufacturers – i.e., leakage from oil and gas extraction operations and coal mine methane, in units of CO_2-equivalent. However, the study does not include all greenhouse gas emissions caused by industrial activity; it excludes industrial emissions of nitrous oxide (N_2O), a byproduct of nitric and adipic acid manufacturing, and emissions of fluorinated gases (F-gases), chemical products often used as refrigerants and propellants.

TIMEFRAME

The ITTIM reports outputs in 2022 (the most recent year for which data are available for all modeled regions) and in five-year increments from 2025 through an end year specified by the model user, which can be as far away as 2100. However, projected future demand for industrial energy use (in the future BAU case) are based on projections for the year 2050, as demand levels farther in the future are highly uncertain, as they depend not only on countries' growth trajectories and populations, but also on BAU energy efficiency improvements and on the structure of regions' economies (such as if a region's economy shifts to contain a lower proportion of heavy industry and a higher proportion of services). Therefore, the choice of year when clean industry is achieved predominantly affects the rate at which new capital equipment must be deployed, not the total quantity of equipment that must be deployed.

COSTS

The ITTIM estimates two types of costs: energy costs and capital equipment costs. Energy-using industrial equipment such as boilers and furnaces often lasts for decades, so energy costs are typically the largest contributor to the total lifetime costs of owning and operating the equipment. Capital cost—the cost of purchasing the equipment, amortized over its lifespan—is the second-largest contributor. The costs of installation, buildings, and land are not included. Other costs (such as operations and maintenance, insurance premiums, etc.) are typically smaller and tend to be similar between clean and emitting variants of a technology – for instance, electric boilers and natural gas boilers may require a similar number of workers to operate and maintain them. Therefore, they are excluded. (Purchased non-energy inputs such as metal purchased by an automobile manufacturer or flour purchased by a food manufacturer represent the largest cost that manufacturers face, but this study does not estimate these costs, as this study is focused on energy and energy-using equipment, and—except in the case of material efficiency technologies—the costs for non-energy inputs are similar between low- and high-emitting production processes.)

Natural gas prices in the United States are based on data published by the U.S. Energy Information Administration (EIA) that reflect the prices charged by local distribution companies (LDCs), such as gas utilities, to industrial gas buyers. However, most industrial firms are "transport customers" that purchase their gas directly from pipelines owned by gas transmission companies, bypassing local utilities. Transport customers pay lower gas prices for two reasons: they buy in bulk, and they do not help cover utilities' expenses for maintaining their gas distribution systems. The EIA indicates that in 2024, only 14% of natural gas sold to industry went through local distribution companies (and this percentage can be considerably lower for certain states, such as 5% in Illinois and under 1% in Pennsylvania). Therefore, the U.S. natural gas prices included in the model are higher than most industrial firms pay. Data on gas rates for transport customers are difficult to find because individual companies may sign contracts with gas suppliers stipulating the terms of the gas sales, and these contracts are not public. Using lower natural gas prices in the model would increase the cost of decarbonization, since the avoided gas use would confer smaller savings.

CARBON PRICING

In addition to the costs noted above, the ITTIM can simulate a carbon price that increases from present-day values to a value specified by the user (any value from $0 to $250 per tonne CO_2 in $25 increments). The carbon price is phased in linearly from 2025 to the user-specified year when clean industry is achieved. The carbon price setting represents the combined effects of direct carbon pricing, such as a carbon credit market or carbon tax, as well as indirect carbon pricing, such as withdrawing existing fossil fuel subsidies. This carbon price impacts the cost-effectiveness of the technological interventions described in "Technology Tiers" above. It does not alter the choice of technologies used, since the ITTIM is not a cost-driven optimization model.

CLEAN HYDROGEN COSTS

The model incorporates three price scenarios for green hydrogen costs, which vary by country. The default ("High Improvement") settings are based on favorable projections for hydrogen cost declines by 2050 and are $1.80/kg in China, $3.50/kg in Indonesia, $2.17/kg in Vietnam, $3.53/kg in the Philippines, and $3.00/kg in the United States. Achieving these prices would require significant progress in reducing renewable electricity generation and transmission costs. The model also supports "Low Improvement" and "Present Day" pricing assumptions as alternate cases. In all three cases, these prices are used as the cost of both green hydrogen and blue hydrogen, since it is assumed these two types of hydrogen will be competing with each other in each modeled region. These hydrogen prices imply a cost of electricity for green hydrogen that is far below the costs of electricity used for direct electrification in the ITTIM. This is because hydrogen production can be preferentially located where lower-cost electricity is available (such as areas with abundant wind, solar, and hydroelectric power), and electrolyzer use can be concentrated in the hours of the day with the lowest electricity prices due to the inherent ability of hydrogen to store energy until it is needed. In contrast, firms employing direct electrification must purchase electricity at the time it is needed (absent other storage technologies such as batteries, which are not included in the ITTIM).

ACKNOWLEDGEMENTS

The ITTIM was developed by Jeffrey Rissman,[1] Hongyou Lu,[2] Sonali Deshpande,[1] Nik Sawe,[1] and Hon Leung Curtis Wong[2].

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