Resource Assessment for Hydrogen Production

Hydrogen Production Potential from Fossil and Renewable Energy Resources

M. Melaina, M. Penev, and D. Heimiller
National Renewable Energy Laboratory

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Technical Report
NREL/TP-5400-55626
September 2013

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Acronyms

AEO	Annual Energy Outlook
AER	Annual Energy Report
BAU	business as usual
Btu	British thermal units
CCS	carbon capture and storage
CSP	concentrating solar power
DOE	U.S. Department of Energy
DRB	Demonstrated Reserve Base
EERE	Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
ERR	Estimated Recoverable Reserves
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GW	gigawatt
GWh	gigawatt-hour
GWdt	gigawatt-days thermal
H2A	Hydrogen Analysis
HHV	higher heating value
IAEA	International Atomic Energy Agency
kg	kilogram
kWh	kilowatt-hour
LDV	light-duty vehicle
LHV	lower heating value
MJ	megajoule
MMBtu	million Btu
MMT	million metric tonnes
MTU	metric tonnes uranium
MW	megawatt
NEA	Nuclear Energy Agency
NREL	National Renewable Energy Laboratory
PV	photovoltaic

Quad	quadrillion Btu
RAR	Reasonably Assured Resources
REF	Renewable Energy Futures
RFS	Renewable Fuel Standard
scf	standard cubic feet
TRR	Technically Recoverable Resources
TWh	terawatt-hour
U	uranium
U_3O_8	uranium oxide
USGS	United States Geological Survey

Executive Summary

This study examines the energy resources required to produce 4–10 million metric tonnes of domestic, low-carbon hydrogen in order to fuel approximately 20–50 million fuel cell electric vehicles (FCEVs). These projected energy resource requirements are compared to current consumption levels, projected 2040 business as usual consumption levels, and projected 2040 consumption levels within a carbon-constrained future for the following energy resources: coal (assuming carbon capture and storage), natural gas, nuclear (uranium), biomass, wind (on- and offshore), and solar (photovoltaics and concentrating solar power). The analysis framework builds upon previous analysis results estimating hydrogen production potentials and drawing comparisons with economy-wide resource production projections.

In addition to incorporating updated estimates and projections for fossil and nuclear resources, we develop revised hydrogen production potential estimates for the geographic distribution of three major renewable energy resources: biomass, wind, and solar. Updated hydrogen production potential maps are developed for each of these renewable resources, indicating production potential per county on both a land area and population basis. These production potentials are compared to an estimate of current gasoline demand at the county level to provide insight into spatial production potential availability with respect to anticipated demand centers where FCEVs would be deployed in large volumes. Total hydrogen demand in 2040 is compared to projected reliance on each resource type across all energy sectors, and total economic and technical hydrogen production potential estimates for fossil, nuclear, and renewable resources are compared on a conceptual basis.

Results convey the relative pressure on the absolute availability and the spatial availability of various resources resulting from either modest or widespread FCEV adoption by 2040. Although this analysis does not account for the economics of hydrogen production and delivery, results suggest that ample domestic, low-carbon energy resources are available in terms of technical production potential and the spatial proximity of adequate resources to future demand centers.

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Introduction

An abundant supply of domestic low-carbon energy resources will be required to reduce future economic and environmental impacts due to energy insecurity and climate change. U.S. oil dependence incurs both direct economic costs upon the economy and indirect costs associated with military expenditures (Delucchi and Murphy 2008; Leiby 2012; Greene 2012), and the potential societal costs of climate change impacts are large compared to the projected costs of abatement (Stern 2010). Various studies have examined the potential to deploy low-carbon advanced vehicles and fuels in order to meet long-term greenhouse gas (GHG) reduction goals (McCollum and Yang 2009; Melaina and Webster 2011; NRC 2013). The use of domestic low-carbon hydrogen in fuel cell electric vehicles (FCEVs) is a promising technological option for reducing both GHG emissions and reliance on imported oil.

A successful, long-term strategy for FCEV deployment is to use hydrogen produced from a diverse array of low-carbon domestic energy resources, such as coal (with carbon capture and storage [CCS]), nuclear, biomass, wind, and solar energy. Natural gas is also addressed as a transitional energy feedstock and as a domestic, low-carbon option if converted to hydrogen in a large central plant with CCS. This study builds upon previous estimates made by Milbrandt and Mann for hydrogen production potentials for wind, solar, and biomass (2007) and for coal, natural gas, nuclear, and hydro power (2009). These studies produced maps indicating resource potential location and intensity at a county level. While the geographic location of fossil, nuclear, and hydro power resources has not changed considerably since the Milbrandt and Mann study (2009), updated maps are presented here for biomass, wind, and solar hydrogen production potentials. These renewable resource potentials are based upon an updated and consistent calculation of technical potential, part of the National Renewable Energy Laboratory's (NREL's) ongoing work to compare the technical potential consistently across renewable energy technologies (Lopez et al. 2012). In addition, fossil and uranium resource data are updated and conversion efficiencies from the updated Hydrogen Analysis (H2A) production case studies are incorporated (DOE 2012). This study also includes a more consistent treatment of economic and technical resource estimates, though additional work is needed to provide a unifying framework for energy resource estimates (cf., Mercure and Salas 2012).

The first section of the report reviews energy resource estimates and classification systems for each of the resource types. In most cases, resource data are taken from the Energy Information Administration's (EIA) 2011 Annual Energy Review (AER) report (EIA 2012c). Production efficiencies are incorporated to develop production potentials for each resource type and renewable potentials are examined spatially through a series of maps. The second section of the report examines two hypothetical future demand scenarios, requiring either 4 or 10 million metric tonnes (MMT) of hydrogen to be produced by 2040 to support a fleet of FCEVs. Resource requirements to meet these demand levels are compared to current resource consumption levels, as well as projected consumption levels in 2040, relying upon projections from EIA's Annual Energy Outlook (AEO) 2013 Early Release results. Comparisons are made to both the AEO *Reference Case* and to an AEO side case that tends to switch to lower carbon energy resources in response to a carbon price signal. In addition to exploring economic potential estimates, total technical potential estimates are compared between the "stock" energy resources (fossil and uranium) and the "flow" energy resources (biomass, wind, and solar). These comparisons provide some insight into the potential contribution of different low-carbon energy resources to future demand for hydrogen from FCEVs.

In summary, this hydrogen production resource assessment addresses the following objectives:

- Estimate total technical and economic hydrogen production potentials for multiple low-carbon energy resources
- Determine the geographic availability of renewable hydrogen on a land-area and per-person basis, and compare these results to the spatial distribution of current gasoline consumption on a per-county basis
- Estimate hydrogen production requirements for hypothetical future demand scenarios
- Estimate the quantity of low-carbon energy resources required to meet hypothetical future demand levels, and compare those requirements to the projected future consumption of each resource.

Energy Resources and Hydrogen Production Potentials

Energy resources are quantified according to resource-specific classifications and metrics. The classification schemes used for mineral resources typically take into account the economic feasibility and geologic certainty of a particular resource (McKelvey 1967; United States Geological Survey [USGS] 1980). In general, the term *resource* refers to naturally occurring material that could feasibly be extracted economically, and the terms *reserves* or *proved reserves* are more restrictive, referring to a subset of total resources that can be recovered with reasonable certainty under existing economic and operating conditions (USGS 1980; BP 2012). However, definitions vary significantly. For example, U.S. coal resource estimates are not associated with an economic component and reflect the amount of coal that exists without reference to the economic feasibility of mining. In contrast, uranium resources are defined according to specific production cost thresholds. As discussed by Rogner (2000) and others (WEC 2010; Mercure and Salas 2012), the categorization and estimation of energy resources is based upon a dynamic relationship between technological advances and changing market conditions. Rogner (2000) summarizes the relationship between resources and reserves as being heavily dependent upon technological developments: "technological improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs" (p. 138).

This study draws upon updated resource data to estimate hydrogen production potentials, and compares projections of future hydrogen demand to projected future consumption of the following energy resources:

- Natural gas
- Coal
- Nuclear (uranium)
- Biomass
- Wind
- Solar.

The distinctions between technological and economic resource potentials are particularly important for interpreting estimates of hydrogen production potential. Though hydrogen FCEVs may prove to be competitive under business-as-usual (BAU) policy and economic conditions, some policy support will likely be needed for early market growth, and greater market share will likely be attained under future market conditions where the cost of carbon or criteria emissions are internalized as market signals or regulatory requirements (NRC 2013). Therefore, the same future market conditions that would prove favorable to FCEVs will likely also be favorable for the economic extraction of low-carbon energy resources. Estimating energy resource potentials involves many uncertainties, and resource potential estimates under BAU conditions are generally better understood than those projected under unique economic or policy-driven market conditions.

Technically Recoverable Resources (TRR) for crude oil and natural gas are defined by EIA as resources that are "producible using current technology without reference to the economic viability thereof" (EIA 2013b, Table 4.1). TRR are calculated as the sum of *Proved Reserves* and *Unproved Resources*, where *Proved Reserves* have a higher degree of economic feasibility and are quantified with greater precision due to more reliable technical data. As a reference, proved natural gas reserves are defined as "those volumes of natural gas that geologic and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions" (EIA 2012b) (see Table 1). As indicated in Figure 1, these general categories are adhered to in the present report, to the degree possible, by describing technical and economic potentials for hydrogen production from different energy resources. For economic potentials, we refer to estimates of *Proved Reserves* for natural gas, *Recoverable Reserves at Producing Mines* for coal, *Reasonably Assured Resources* (RAR) recoverable at \$50/pound of uranium oxide (lb U_3O_8) (\$130/kilogram of uranium [kg U]) for uranium, and high demand results from the Renewable Energy Futures study (NREL 2012) for biomass, wind, and solar resources. For technical potentials, we refer to estimates of *Unproved Resources* for natural gas, *Demonstrated Reserve Base* estimates for coal, RAR recoverable at \$100/lb U_3O_8 (\$260/kg U) for uranium, and a consistent set of technical potential estimates for biomass, wind, and solar resources (Lopez et al. 2012).

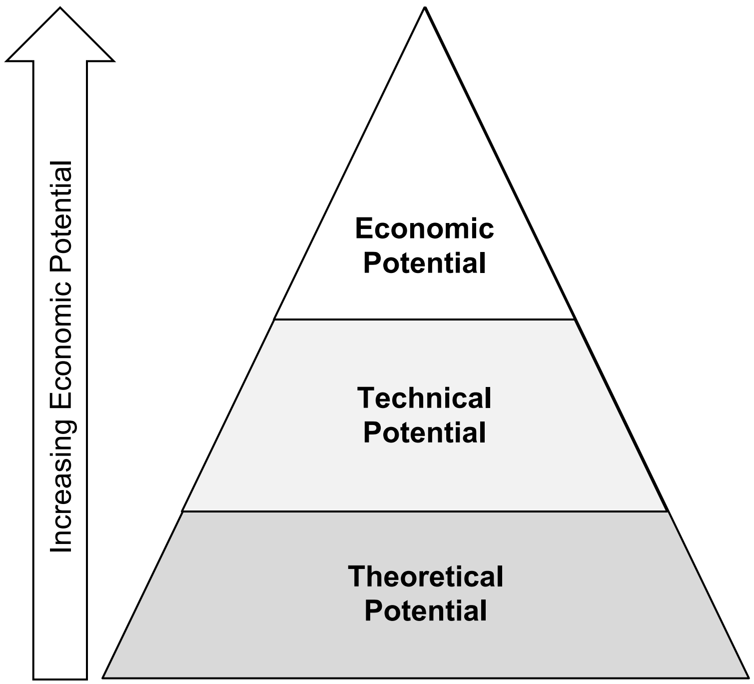
These energy resource classifications are only roughly consistent across the two general categories of technical and economic potential proposed in Figure 1. Each classification category is specific to the unique characteristics, available data, or assessment assumptions of a particular energy resource. For example, classification systems are not necessarily consistent in determining when occurrences of a resource move from the theoretical potential category into the technical potential category, and there are variations and gradations in how different estimates might move from technical into economic potential categories. Figure 1 is a simple, high-level view of multiple resource classification types, and does not include, for example, the dimension of geologic certainty used to classify fossil and nuclear resources. Efforts to develop more consistent analytical representations of economic and technical potentials for multiple resource types are ongoing (cf., Mercure and Sala 2012). An integrated economic assessment of how future market and policy conditions that accelerate the adoption of FCEVs would also change the economic potential of different energy resources is beyond the scope of this study.

The sections below review technical and economic potentials for each resource type, as well as the hydrogen production potentials associated with each resource type. Though the uncertainties associated with the various resource estimates are not discussed in detail, and the inconsistencies between different types of resource estimates and classifications are not resolved, some comparisons are made between technical and economic hydrogen production potential estimates to provide perspective on the total low-carbon hydrogen production potential. These comparisons are made at a high level, and are only intended to provide context and insight into general trends for the overall discussion of hydrogen production potentials. Characterizing the economic or market implications of resource scarcity or availability on future hydrogen production systems or FCEV market dynamics, especially under a given set of policy constraints, would require both a more consistent representation of energy resources and extensive techno-economic and market analyses.

Table 1. Description of Coal, Nuclear, and Natural Gas Reserves

Energy Resource Type	Reserves Description	Source
Coal	Estimated Recoverable Reserves (ERR): "An estimate of coal reserves, based on a demonstrated reserve base, adjusted for assumed accessibility and recovery factors, and does not include any specific economic feasibility criteria." Demonstrated Reserve Base (DRB): "A collective term for the sum of coal in both measured and indicated resource categories of reliability, representing 100 percent of the in-place coal in those categories as of a certain date. Includes beds of bituminous coal and anthracite 28 or more inches thick and beds of subbituminous coal 60 or more inches thick that can occur at depths of as much as 1,000 feet. Includes beds of lignite 60 or more inches thick that can be surface mined. Includes also thinner and/or deeper beds that currently are being mined or for which there is evidence that they could be mined commercially at a given time. Represents that portion of the identified coal resource from which reserves are calculated."	Estimated Recoverable Reserves description from EIA online glossary: http://www.eia.gov/tools/glossary/?id=coal Demonstrated Reserve Base description from AER 2011 Glossary, page 353 (EIA 2012c).
Natural Gas	EIA provides the following description of natural gas *Proven Reserves*: "Those volumes of natural gas that geologic and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions." *Undiscovered Technically Recoverable Resources* are estimated for oil and gas by USGS, which completed the last comprehensive National Assessment of oil and natural gas resources in 1995 and has made updates for high-priority basins since 2000. Recent updates to the classification system since the 1995 assessment are reviewed by Schmoker and Klett (2005), and include three key changes: (1) level of assessment switched from individual plays to a more comprehensive and unifying framework of assessment units, (2) switch from assessing all technically recoverable resources to a more restrictive condition to include technically recoverable resources with the potential to be added to reserves, and (3) change from an unlimited timeline to a 30-year timeframe for when the undiscovered resources might be realized.	Natural Gas Proved Reserves description from EIA (2012b). Undiscovered Technically Recoverable Resources for natural gas are reported through the National Assessment website (USGS 2012)

Energy Resource Type	Reserves Description	Source
Uranium	"RAR: Uranium that occurs in known mineral deposits of such size, grade, and configuration that it could be recovered within the given production cost ranges, with currently proven mining and processing technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Note: RAR corresponds to DOE's uranium reserves category." Uranium reserves are reported with reference to costs below either $50 or $100 per pound of uranium oxide, where EIA's "forward costs" are defined as follows: "Forward costs include the costs for power and fuel, labor, materials, insurance, severance and ad valorem taxes, and applicable administrative costs. Past capital costs are considered 'sunk' costs and mining of the individual deposits may or may not return such costs to investors. Sunk costs for such items as exploration and land acquisition are excluded as are the costs for income taxes, profit, and the cost of money. The forward costs used to estimate U.S. uranium ore reserves are independent of the price at which uranium produced from the estimated reserves might be sold in the commercial market. Reserves values in forward-cost categories are cumulative; that is, the quantity at each level of forward cost includes all reserves at the lower cost in that category."	RAR description is from the AER 2011 Glossary (EIA 2012c). Forward costs description from AER 2011, Table 4.10 (EIA 2012c).



Energy Resource Type			
Coal	**Natural Gas**	**Uranium**	**Renewable**
Estimated Recoverable Reserves (ERR)	Proved Reserves	RAR Estimates at <$50/lb U_3O_8	Projections of Supply in a High Demand Scenario
Demonstrated Reserve Base (DRB)	Unproved Resources	RAR Estimates at <$100/lb U_3O_8	Current Technical Potential
Other Occurrences	Other Occurrences	Total Undiscovered Resources	Higher Technical Performance

Figure 1. Energy resource potential levels

Source: NREL

Notes: Technical potential for coal is the *Demonstrated Reserve Base* (DRB) minus *Estimated Recoverable Reserves* (ERR). Economic and technical potential estimates for uranium are RAR estimates at two forward-cost thresholds. Total undiscovered uranium resources include prognosticated and speculative resources.

Estimates for Fossil Fuel and Nuclear Resources

Economic and technical potential estimates for coal, natural gas, and uranium are summarized on an equivalent thermal energy basis (quadrillion British thermal units [Btu] [quads], higher heating value [HHV]) in Figure 2. As indicated, proved natural gas reserves have been increasing in recent years, uranium reserves are presented at two distinct cost levels, and both estimated recoverable and total demonstrated coal reserves have been declining slowly over time. Again, these classification systems are not necessarily consistent across resource types, but are used here as general estimates for economic and technical energy resource potentials. Additional information on each of these potentials, and conversions to determine hydrogen production potentials, is provided in the sections below. Descriptions of fossil and uranium reserve and resource categories are summarized in Table 1.

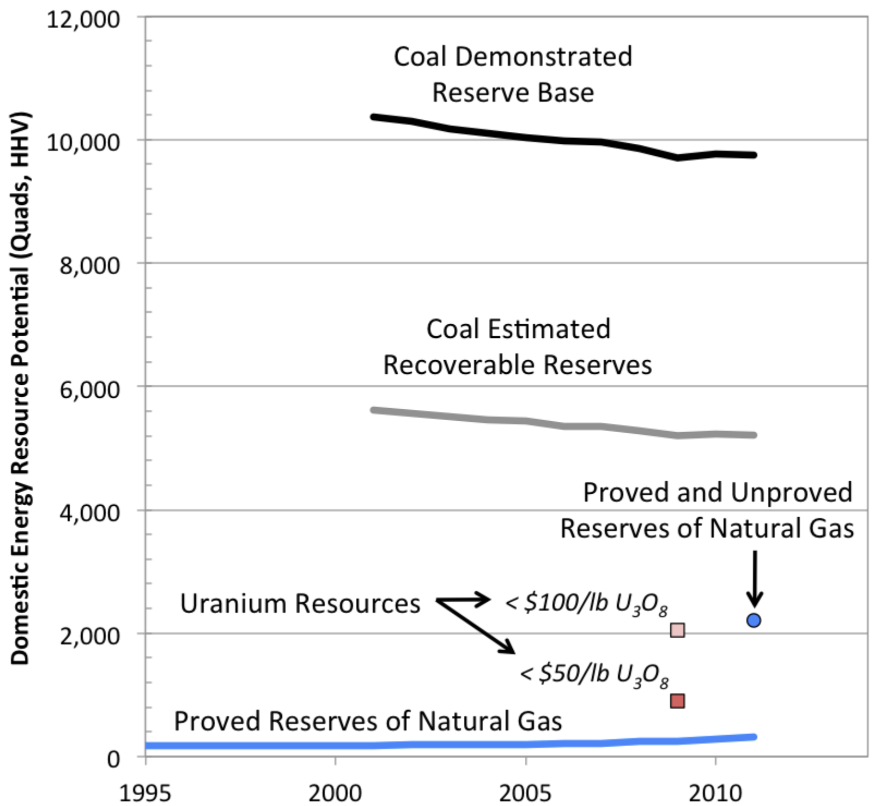


Figure 2. Domestic fossil and uranium energy resource potentials

Sources: EIA 2012c, Table 4.10; EIA 2012d, Table 15; EIA 2012c, Table 4.2.

Coal Resources

EIA reports estimates for the coal *Demonstrated Reserve Base* (DRB), which is "a collective term for the sum of coal in both measured and indicated resource categories of reliability, representing 100 percent of the in-place coal in those categories as of a certain date" (EIA 2013b, p. 353). The annual coal report provides estimates of *Recoverable Reserves at Producing Mines*, the most economic and probable subset of total coal reserves, as well as *Estimated Recoverable Reserves* (ERR) (EIA 2012d). Table 1 provides descriptions of each of these coal resource classifications. Our estimates for hydrogen production potential rely upon the ERR 259 billion short tons for coal's economic potential (Figure 1), following comparisons between coal and natural gas proved reserves presented elsewhere (Rogner 1997; WEC 2010). By comparison, coal resources reported in the DRB are nearly twice as large, at 483 billion short tons (EIA 2012d). The difference of 224 billion short tons is our estimate for coal technical potential (see Figure 1). Wyoming, Montana, and Illinois account for nearly 60% of total coal reported as ERR and in the DRB (EIA 2012d). To convert to thermal energy equivalents, we use EIA's reported HHV of 20.142 million Btu (MMBtu)/short ton for coal produced in 2011 (EIA 2013c). This is similar to the weighted average heating value for the different coal types reported in the DRB (9% lignite, 37% subbituminous, 53% bituminous, and 2% anthracite). The result is a combined technical and economic potential of approximately 9,700 quads for the DRB in 2011 (see Figure 2).

Natural Gas Resources

Proved reserves for dry natural gas are reported by EIA as 304.6 trillion cubic feet in 2010 (EIA 2012c, Table 4.2). The breakdown provided in the previous year, 2009, indicates that reserves of tight gas, shale gas, and coalbed methane accounted for 61% of total proved reserves (EIA 2012c, Table 4.1), with the remainder from conventionally reservoired fields. Figure 2 shows the historical changes in proved natural gas reserve estimates over time. Estimates for natural gas shale reserves have grown rapidly in recent years, increasing by a factor of 4 between 2008 and 2010. Estimates for unproved natural gas, or the "technical potential" category in Figure 1, are reported as 1,930 trillion cubic feet (Tcf) in 2009 (EIA 2012c, Table 4.2). Of this total, 25% is shale gas, 22% is tight gas, 14% is offshore of the lower 48 states, and 14% is on- and offshore in Alaska (EIA 2012a). These EIA estimates depend, in part, on data from the USGS. Oil and natural gas resource classification systems have been modified and updated over time, with recent changes for natural gas summarized by Schmoker and Klett (2005) and described in Table 1.

Adding *Proved Reserves* to *Unproved Reserves*, the estimate for total technical and economic potential for natural gas resources is approximately 2,200 trillion standard cubic feet (scf), or about 2,300 quads on an HHV basis (see Figure 2). To convert to thermal energy equivalent, we use EIA's reported HHV of 1,025 Btu/scf for dry natural gas produced in 2009 (EIA 2012c, Table A4). The geographic distribution of different types of natural gas resources is presented by USGS in a series of maps (USGS 2012). Two of these maps, for conventional and continuous (coalbed gas, shale gas, and tight gas) natural gas resources, are shown in Figure 3 and Figure 4. As indicated, most conventional resources are in the Gulf Coast and Alaska, while most continuous resources are distributed across the Mountain States, throughout the Gulf Region, and in the Appalachian Basin.

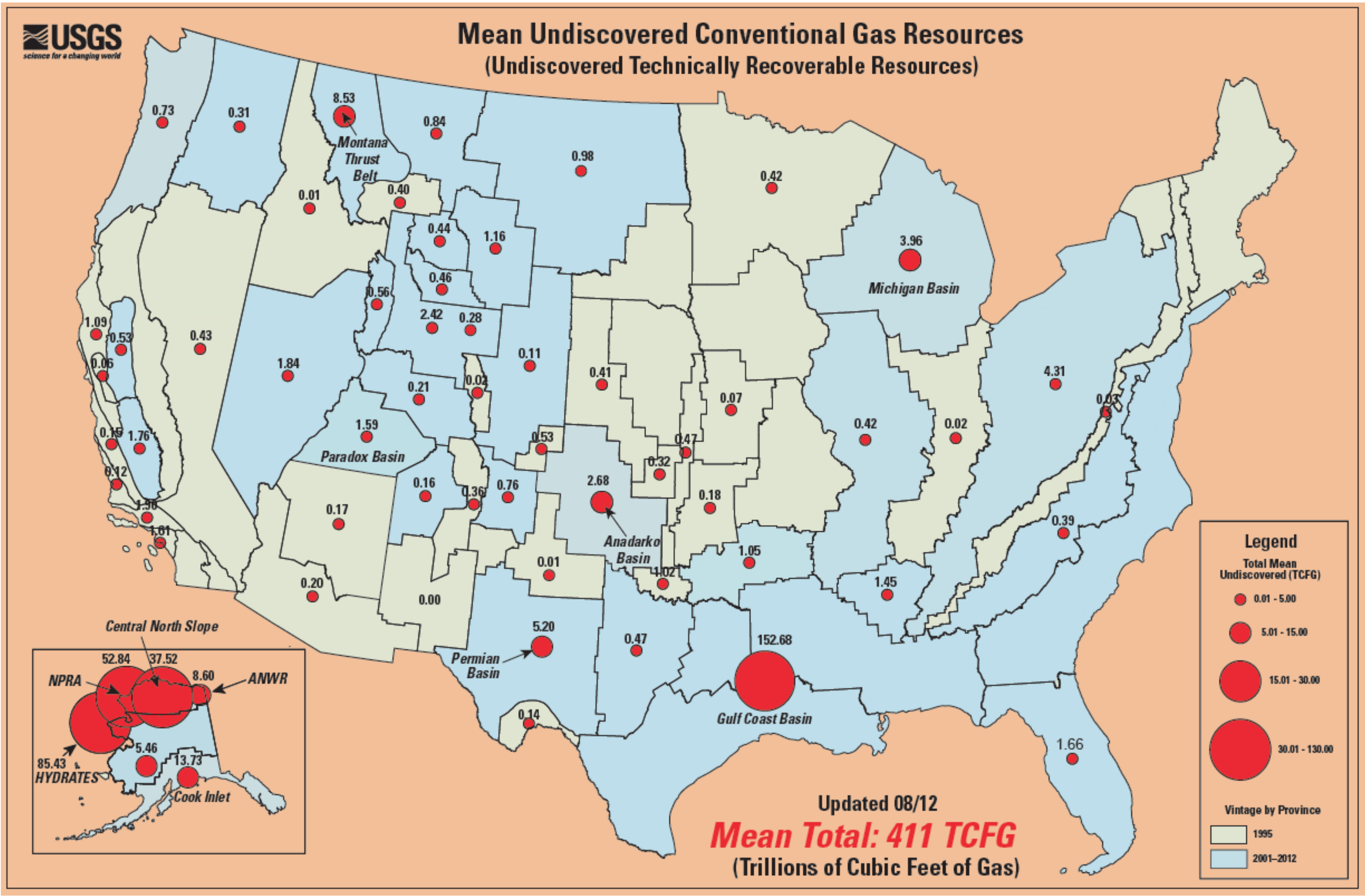


Figure 3. Geographic distribution of conventional natural gas resources

Source: USGS (2012)

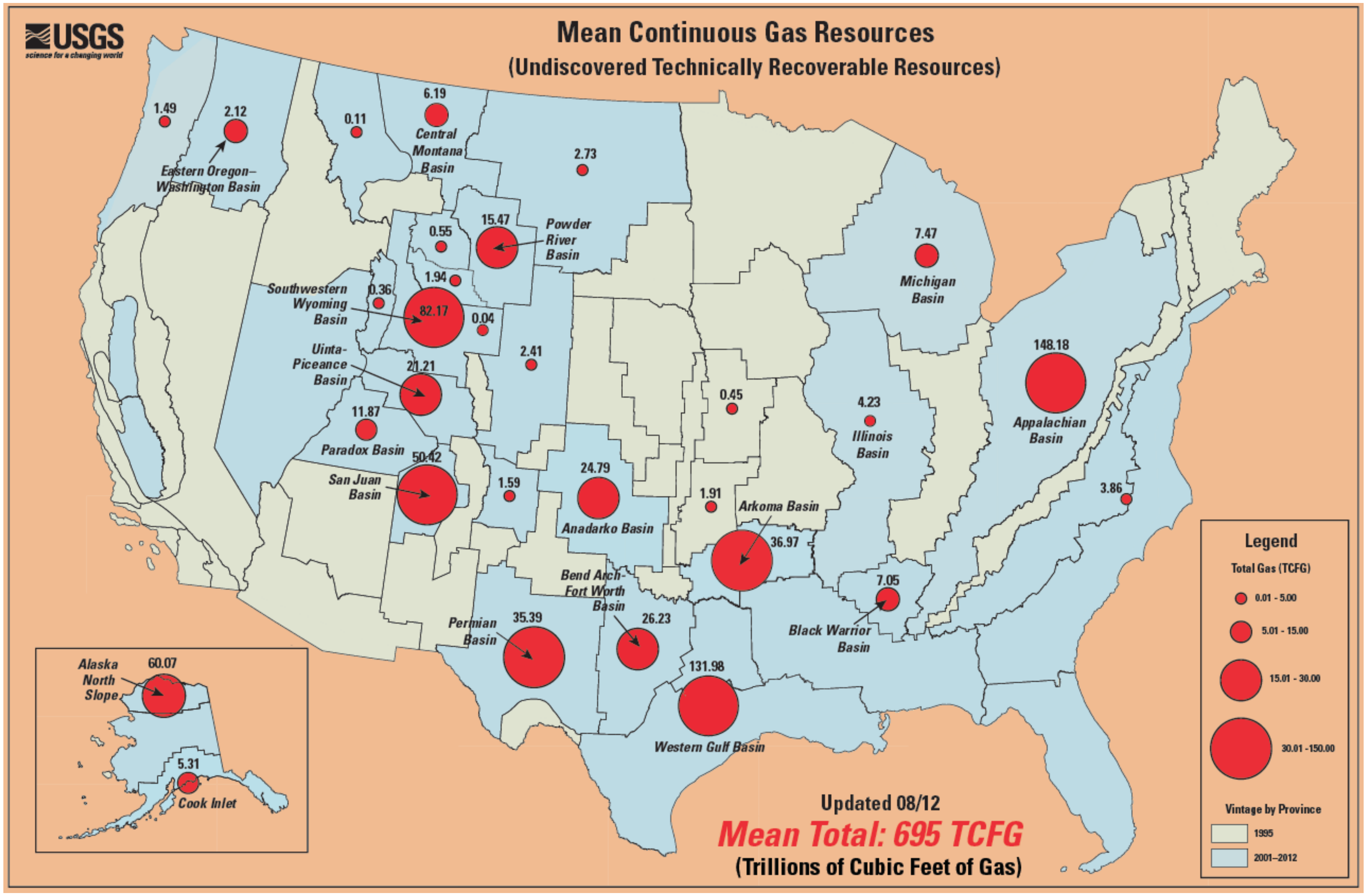


Figure 4. Geographic distribution of continuous natural gas resources

Source: USGS (2012)

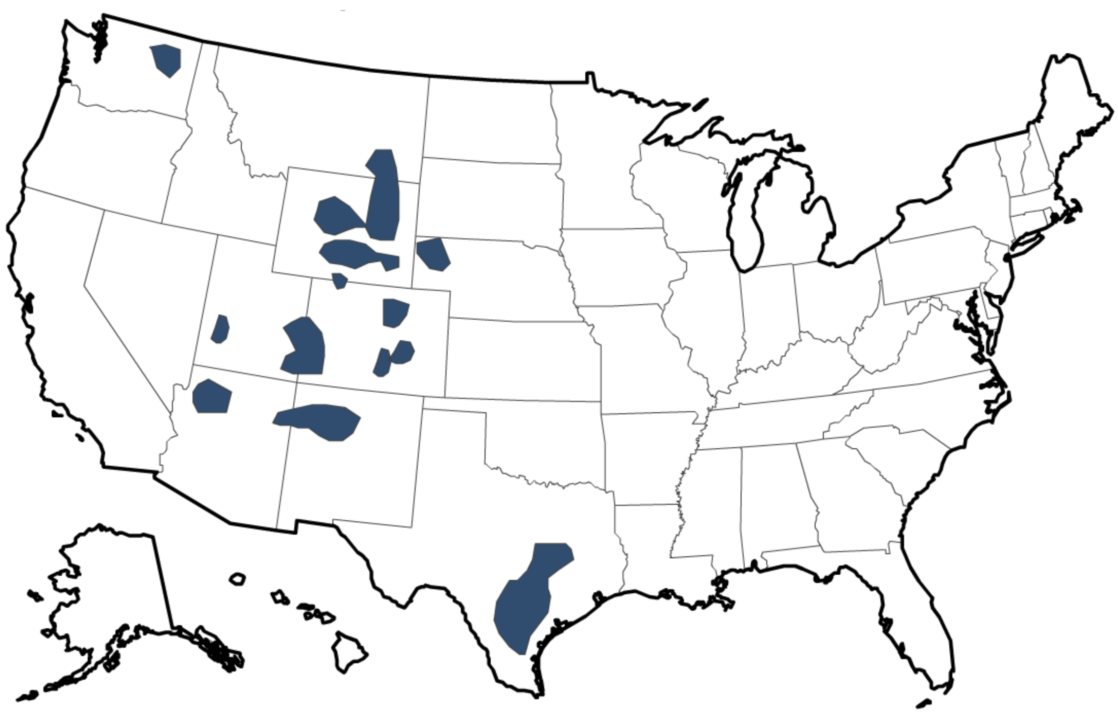
Uranium Resources

EIA reports uranium reserves in units of millions of pounds of uranium oxide, and uses a conversion of 0.848 kg U per 1 kg U_3O_8. The uranium reserve quantities reported by EIA are equivalent to the international categorization for RAR, which is described in Table 1. The two prominent types of uranium reserves reported by EIA are expressed in terms of forward-costs for production, with cost thresholds of less than \$50/lb U_3O_8 and less than \$100 /lb U_3O_8. Components of these forward-costs are described in Table 1. The 2008 uranium reserve estimate from EIA is distinct from reserve estimates in previous years, and reports 539 million pounds of U_3O_8 at less than \$50/lb, and 1,227 million pounds U_3O_8 at less than \$100/lb (EIA 2013b, Table 4.10). The international "Red Book" report also reports inferred reserves (lower geologic certainty) according to RAR cost categories, but not for the United States (Nuclear Energy Agency and International Atomic Energy Agency [NEA-IAEA] 2010). In recent years, the price of uranium has approached and exceeded \$50/lb U_3O_8 (EIA 2012c, Table 9.3), but given the global market for uranium resources, we assume that the \$100/lb cost category is a reasonable estimate for uranium technical potential. There are major uncertainties associated with U.S. uranium resource estimates, and a thorough evaluation of the U.S. uranium resource base has not been conducted for some time. Details on how the RAR classification systems have changed over time, and implications for domestic U.S. and international resource estimates, are discussed elsewhere (NEA-IAEA 2012; WEC 2010). For an estimate of the theoretical potential, we refer to the 6,793 million lb of undiscovered uranium reported by NEA-IAEA (2012, Table 1.14). However, these estimates are also highly uncertain, and future assessment updates may result in significant changes (cf., Hall 2013). With the RAR estimates for each cost level noted above, the uranium economic potential is about 540 million lb U_3O_8, and the combined economic and technical potential is about 1,200 million lb U_3O_8.

Given that uranium imports have been increasing since 1990, restricting our resource calculations to only U.S. uranium resources does not fully capture actual supply or market constraints associated with future demand growth. However, for the sake of simplicity, we restrict our analysis to domestic resources to mirror estimates made for the other resource types. As a reference for a total global technical potential estimate, the results of the recent USGS critical analysis of world uranium resources are relevant. Hall and Coleman (2012) report an estimated 2.1 MMT of recoverable uranium globally. This estimate is comparable in terms of resource type, but more conservative than the "2011 Red Book" RAR estimate from the Organisation for Economic Co-operation and Development NEA-IAEA, reporting 3.45 million metric tonnes of uranium (tU) globally at less than \$130/kg U. Including inferred resources along with RAR increases, the Red Book global estimate is 5.33 million tU at less than \$130/kg U. Of this total, the U.S. contains some 4% of total RAR reserves, or 0.21 million tU (NEA-IAEA 2012). Combined with the established trend of importing uranium, this global distribution of uranium resources highlights a limitation of the present report in attempting to compare only domestic low-carbon energy resources.

EIA reports that the U.S. uranium reserves contained within six states—Wyoming, New Mexico, Arizona, Colorado, Utah, and Texas—together contain approximately 87%–90% of U.S. uranium reserves (EIA 2013b, Table 4.10). An EIA map depicting the general location of reserves is shown in Figure 5. More detailed spatial uranium and other resource data are available from the USGS National Uranium Resource Evaluation website (USGS 2013). NEA-IAEA provides a map of global resources by country (NEA-IAEA 2012, p. 17).

To determine uranium resource consumption for future electricity generation, a nominal burnup rate of 45 gigawatt-days thermal per metric tonne of uranium (GWdt/MTU) is assumed based upon historical data from EIA (2004). A heat rate of 10,458 Btu/kWh (32.6% thermal efficiency) is assumed based upon the average heat rates reported from 1995 to 2011 (EIA 2012c, Table A6). The result is approximately 352,366 kWh of electricity generated per kg of U_3O_8. We assume this approximate rate of uranium use for heat and electricity generation continues into the future in determining hydrogen production potentials. However, future trends in uranium resource management are highly uncertain and contingent upon multiple technological and policy factors (Kazimi, Moniz, and Forsberg 2011). Therefore, projected resource demands are expressed in terms of nuclear electricity generation from the 2013 AEO (EIA 2013a), rather than assuming a conversion rate of uranium to electricity by 2040 (see Table 5).



Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO). National Uranium Resources evaluation. Interim report (June 1979) Figure 3.2; and GJPO data files.

Figure 5. Major U.S. uranium reserves

Source: EIA (2010)

Estimates for Renewable Resources

We use data from the county-level spatial analysis conducted by Lopez et al. (2012) to estimate the technical potential for producing hydrogen from three renewable energy resources: biomass, wind, and solar. A brief description of the resource analysis is provided in the sections below for each technology used to harness these renewable energy resources. Detailed information about system-specific power densities (or equivalent), capacity factors, and land-use constraints is provided in Lopez et al. (2012, Appendix A). The following are general descriptions of the renewable technical potential estimates:

> "These are technology-specific estimates of energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, environmental, and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed."
>
> (Lopez et al. 2012, p. iv)

> "Note that as a technical potential, rather than economic or market potential, these estimates do not consider availability of transmission infrastructure, costs, reliability or time-of-dispatch, current or future electricity loads, or relevant policies. Further, as this analysis does not allocate land for use by a particular technology, the same land area may be the basis for estimates of multiple technologies (i.e., non-excluded land is assumed to be available to support development of more than one technology). Finally, since technical potential estimates are based in part on technology system performance, as these technologies evolve, their technical potential may also change."
>
> (Lopez et al. 2012, p. 2)

For economic potentials, we reference projections to 2050 for renewable electricity production from the Renewable Energy Futures (REF) study (NREL 2012). The REF study explores a range of scenarios in which renewable energy sources provide large percentages of total U.S. electricity, focusing on various scenarios in which 80% of generation is from renewables by 2050. The High-Demand scenario involves assumptions resulting in an annual demand of 5,100 terawatt-hours (TWh) by 2050, with approximately 12% from biomass, 3% from geothermal, 10% from hydropower, 6% from concentrating solar power (CSP), 12.5% from solar photovoltaics (PV), 26.5% from onshore wind, and 10% from offshore wind (NREL 2012, Figure 3-14). The REF study examines costs and barriers to market growth, and therefore constitutes a techno-economic feasibility study that explores the long-term economic potential of renewable energy resources. The study is limited in only addressing electricity, but otherwise provides a consistent and technically integrated projection of relative contributions of each renewable resource.

Another reference relied upon to estimate renewable energy economic potential is the market outcome result from the 2013 AEO *Greenhouse Gas $25* scenario (EIA 2013a). In this side case, a price of $25 per metric ton carbon dioxide is assumed beginning in 2014, and the price increases at 5% per year through 2040. The results of this side case are relevant to estimating economic potentials and are used as a reference for projections of future hydrogen production requirements in the future demand scenarios discussed below.

Assuming the REF high electricity demand results above for 2050 and the approximate percentages of supply by resource type, we estimate an economic potential of 1,000 TWh for solar and 2,000 TWh for wind (see Table 5). For biomass economic potential, we assume that the plateau in supply at approximately 6 quads (350 million tons) between 2020 and 2032 in the 2013 AEO *Greenhouse Gas $25* side case is a robust market outcome that would not conflict with the approximately 550 million tons estimated for biopower in the REF study.[1] The result is an estimated biomass economic potential of approximately 900 million tons. This result is unique to this study, and represents an economic potential corresponding to a future with high demand for low-carbon resources and a relatively high degree of technological development. Additional analysis is required to better understand competition for biomass resources between the transportation fuel and electricity sectors (cf. Ruth et al. 2013).

Biomass Resources

Estimates of biomass resource potential vary significantly. For this study, we assume that the technical potential for biomass resources falls between currently available resources characterized by Lopez et al. (2012) and baseline projections to 2030 from the Billion Ton Study Update (DOE 2011b). The current biomass technical potential reported by Lopez et al. (2012) includes 363.4 million bone-dry tonnes (BDT) of solid biomass and 18.8 million tons of methane as biogas. An HHV of 8,500 Btu/lb is applied for solid biomass, and an HHV of 24,250 Btu/lb is applied for biogas (Lopez et al. 2012). Details on this technical potential for biomass resources are provided in Lopez et al. (2012), a brief summary is provided in Table 2, and updates are available on the NREL Biomass Research Data and Resources website (NREL 2013). Converting these solid and gaseous biomass resources to hydrogen using the conversion efficiencies indicated in Table 3 results in approximately 31 MMT hydrogen per year. The geographic distribution of biomass hydrogen production potential based upon currently available solid and gaseous biomass resources is indicated in Figures 6 and 7. The baseline scenario in the U.S. Billion Ton Update study, at $60 or less per dry ton, projects 1,094 million dry tons by 2030, which is equivalent to approximately 76 MMT hydrogen per year. This upper range for technical potential would only be realized over time and under favorable market, policy, and land use conditions (DOE 2011b).

An appropriate reference for the economic potential is assumed to be biomass supply in the 2013 AEO *Greenhouse Gas $25* scenario (EIA 2013a). Total biomass consumption by 2040 is equivalent to about 8.0 quads (HHV), or approximately 453 million short tons of biomass on an energy equivalent basis, converting to approximately 31.5 MMT hydrogen per year. This is slightly higher than the hydrogen production potential from current biomass resources from Lopez et al. (2012) and significantly lower than the potential from the U.S. Billion Ton Update base case at $60 per dry ton. Within the *Greenhouse Gas $25* scenario, the biomass consumption within the transportation sector is only 15% higher than consumption in the AEO *Reference*

[1] 550 million BDT results from approximately 600 TWh of biopower and 1.1 megawatt-hours per BDT. Note that the biomass supply in the *GHG $25* side case increases rapidly after 2032 as a result of success with cellulosic drop-in fuels (EIA 2013a, Figure 100).

Case.[2] This is probably due to the carbon price signal having little effect on the transportation sector overall. Given that the *Reference Case* does not meet the Renewable Fuel Standard (RFS) requirement of 36 billion ethanol-equivalent gallons by 2022 (Sieminski 2013), we estimate that the *Greenhouse Gas $25* scenario may also fall short by approximately 7 billion gallons of ethanol-equivalent gallons. If additional low-carbon policies were in place to increase biofuels use in this scenario, such that the RFS requirements were met and maintained out to 2040, another approximately 1.7 quads of biomass resources may be required.

Wind Resources

The total technical potential for wind resources is estimated by Lopez et al. (2012) to be 49.8 million GWh of generation, with 66% from onshore wind resources and 34% from offshore wind resources. Assuming a hydrogen production power requirement of 46 kWh per kg of hydrogen for water electrolysis (see Table 3), translates to a technical hydrogen production potential of 1,100 MMT hydrogen per year. The geographic distribution of onshore and offshore wind resources is indicated in Figures 8 and 9. This offshore wind estimate is probably an overestimate, as it does not include an exhaustive set of exclusions. On the other hand, data are not available for some coastal areas that do not have wind data, as indicated. Additional maps and updated wind resource data are provided through the NREL Wind Maps website.[3] Wind generation in the 2013 AEO *Greenhouse Gas $25* scenario is 0.616 million GWh, which results in an economic hydrogen production potential of about 13 MMT hydrogen per year (see Table 3). The *Greenhouse Gas $25* scenario does not project any growth in the market for offshore wind.

Solar Resources

The total technical potential for solar resources estimated by Lopez et al. (2012) includes 2.2 million GWh from urban utility-scale PV systems, 280.6 million GWh from rural utility-scale PV systems, 0.8 million GWh from rooftop PV systems, and 116.1 GWh from CSP systems. The total technical potential is 400 million GWh, with 70% of the total from rural utility-scale PV systems. This translates to 8,700 MMT of hydrogen technical production potential (see Table 6). A summary of the key elements of this assessment is provided in Table 2, and a more detailed description can be found in Lopez at al. (2012). The geographic distribution of this solar potential is indicated in Figure 10, and additional information and updates can be found on the NREL Solar Maps website.[4] By comparison, solar generation in the *Greenhouse Gas $25* scenario is 313 billion kWh, with CSP contributing less than 1%, translating to an economic hydrogen production potential of 6.8 MMT hydrogen per year.

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[2] At the time this report was prepared, only limited results had been made available from the 2013 AEO Early Release (EIA 2013a). A more detailed breakdown of biomass use within different transportation fuel types could not be discerned for the *Greenhouse Gas $25* scenario.

[3] "Dynamic Maps, GIS Data, & Analysis Tools—Wind Maps." (2012). National Renewable Energy Laboratory: http://www.nrel.gov/gis/wind.html.

[4] "Dynamic Maps, GIS Data, & Analysis Tools—Solar Maps." (2012). National Renewable Energy Laboratory: http://www.nrel.gov/gis/solar.html.

Table 2. Data Information and Sources for Renewable Energy Resource Estimates

Resource Type	Resource Data Information	Sources
Solid Biomass and Biogas	Biomass and biogas data from Lopez et al. (2012) are updates to the 2005 report by Milbrandt. Biomass data and updates are available online (http://www.nrel.gov/gis/data_biomass.html). Key aspects of the biomass data are summarized below: • Secondary mill residues, and urban wood waste, updated in 2012 • "The data from Milbrandt (2005, updated in 2008) illustrate the biomass resources currently available in the United States. Subsequent revisions of this analysis could evaluate projected U.S. resource potential, including dedicated energy crops such as those provided by the recent DOE update (DOE 2011b) of the billion-ton biomass study (Perlack et al. 2005)." (Lopez et al. 2012, p. 6) • It is assumed that all biomass resources are available. Competition between different markets (e.g., biopower, biofuels, hydrogen) has not been taken into account • Estimates for gaseous biomass (methane emissions) are currently being updated. See the NREL Biomass Maps website for updates and access to data or maps: http://www.nrel.gov/gis/biomass.html.	Lopez et al. (2012) Data are available online: http://www.nrel.gov/gis/re_potential.html
Onshore Wind	• Defined at 80 m above ground • Annual average gross capacity factor of 30% (net capacity factor of 25.5%) • The analysis assumed "typical utility-scale wind turbine power curves," and excluded environmental and conflicting land-use areas or areas with slopes greater than 20% • "AWS Truepower modeled the wind resource data using its Mesomap process to produce estimates at a 200-m horizontal spatial resolution. These resource estimates were processed to eliminate areas unlikely to be developed, such as urban areas, federally protected lands, and onshore water features…We estimate annual generation by assuming a power density of 5 MW/km^2 (DOE EERE 2008) and 15% energy losses to calculate net capacity factor" (Lopez et al. 2012, p. 5).	Lopez et al. (2012) Data are available online: http://www.nrel.gov/gis/re_potential.html
Offshore Wind	• Defined at 90 m above ground • Florida and Alaska data not available at time of publication (omitted from totals) • Exclusions: shipping lanes, marine sanctuaries, and others • Generation estimates assume a power density of 5 MW/km^2, and develop capacity factors as a function of local or regional conditions	Lopez et al. (2012) Data are available online: http://www.nrel.gov/gis/re_potential.html

Resource Type	Resource Data Information	Sources
	• Other land exclusions and technical assumptions are detailed in Lopez et al. (2012).	
Urban and Rural Solar PV	• Urban PV systems are assumed to be located on suitable land areas within urban area boundaries, and rural PV systems are assumed to be located on suitable land areas outside of urban area boundaries • Urban areas smaller than 18,000 m^2 are excluded • Areas with slopes greater than 3% are excluded • Annual capacity factors are taken from the National Solar Radiation Database • Other land exclusions and technical assumptions are detailed in Lopez et al. (2012).	Lopez et al. (2012) Data are available online: http://www.nrel.gov/gis/re_potential.html

Table 3. Amount of Renewable and Non-renewable Resources Required to Produce 1 kg of Hydrogen and Production Efficiencies

Resource	Conversion Pathway	Amount to Produce 1 kg Hydrogen [a]		Production Efficiency [b] (E_{out}/E_{in}, LHV)
Natural gas	Steam methane reforming	167.5 scf	165 MJ	73.1%
Coal	Coal gasification with CCS	9.8 kg	271 MJ	44.3%
Nuclear (uranium)	High-temperature electrolysis	6.72×10^{-5} kg U	260 MJ	46.0%
Nuclear (uranium)	Thermochemical	7.03×10^{-5} kg U	273 MJ	44.0%
Biomass	Biomass gasification	13.0 kg bone dry biomass	242 MJ	48.3%
Wind power	Electrolysis	46 kWh	166 MJ	72.6%
Solar power	Electrolysis	46 kWh	166 MJ	72.6%

MJ = megajoule

[a] Values are derived from H2A Future Central Case Studies for each resource type and from the central electrolysis case study for wind and solar. Efficiencies indicated are for "hydrogen energy out" divided by "resource energy in," and do not account for any additional input feedstock consumption or electricity byproduct credits. Efficiency definitions are distinct in that resource "energy in" is in different forms, as noted in the column indicating MJ of resource required. The 167.5 scf per kg for steam methane reforming is derived from the future central steam methane reforming case study, 9.8 kg of coal is from the future central coal gasification case study (coal use is equivalent between the with and without CCS case studies), and 13.0 kg bone dry biomass is from the future central biomass gasification case study. Heat content of coal is 27.685 MJ/kg coal, and it is associated with natural gas with an LHV of 930 Btu/scf. Uranium consumption for the nuclear high-temperature electrolysis and thermochemical production pathways are described above. The H2A case studies are available from the DOE H2A website: http://www.hydrogen.energy.gov/h2a_prod_studies.html.

[b] Production efficiency is defined as the energy of the hydrogen out of the production process (on a LHV basis) divided by the sum of the energy into the process from the feedstock. Production efficiencies indicated for wind and solar are based on electrical energy input (46 kWh) and nuclear efficiencies are on a heat input basis.

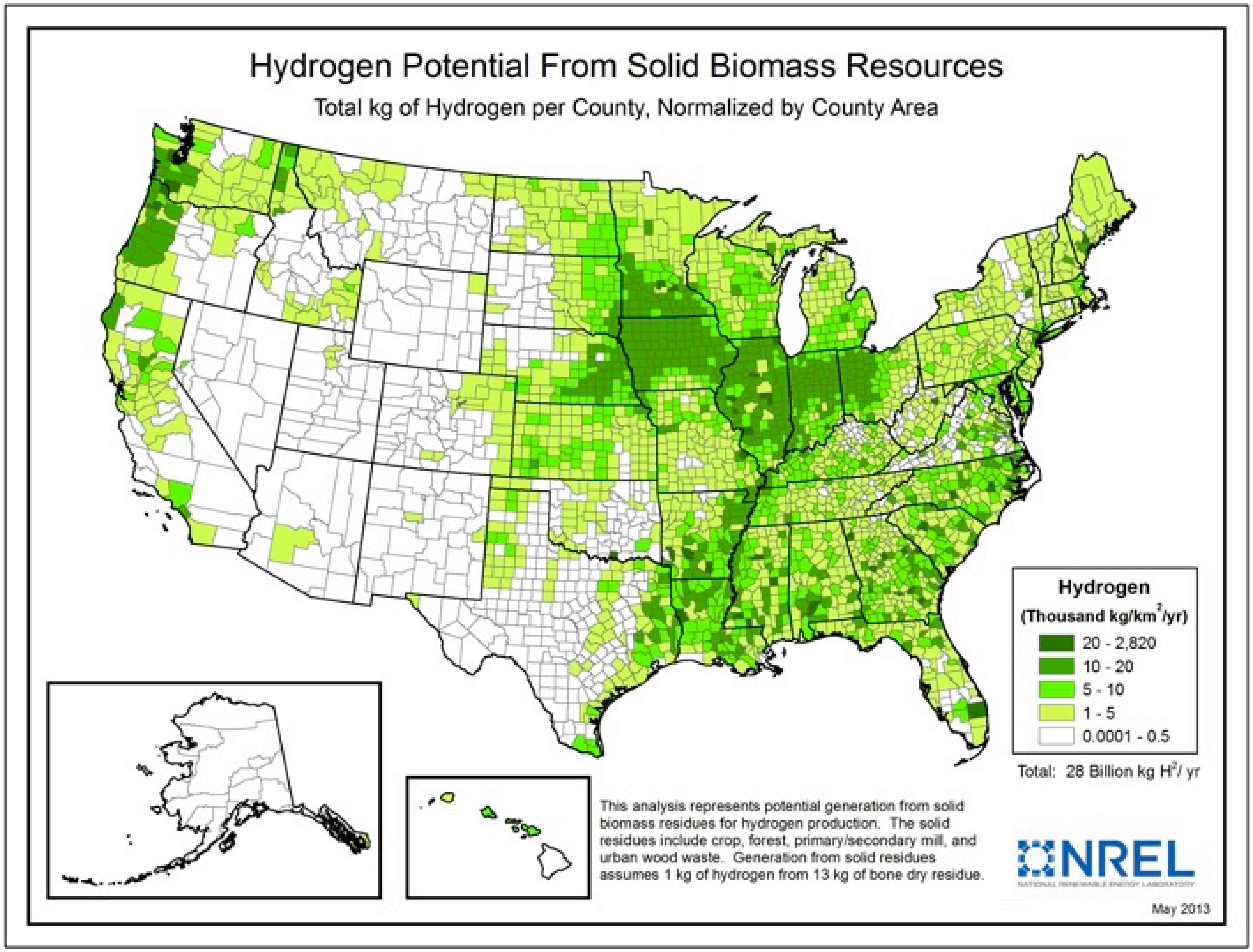

Figure 6. Hydrogen production potential from solid biomass resources, by county land area

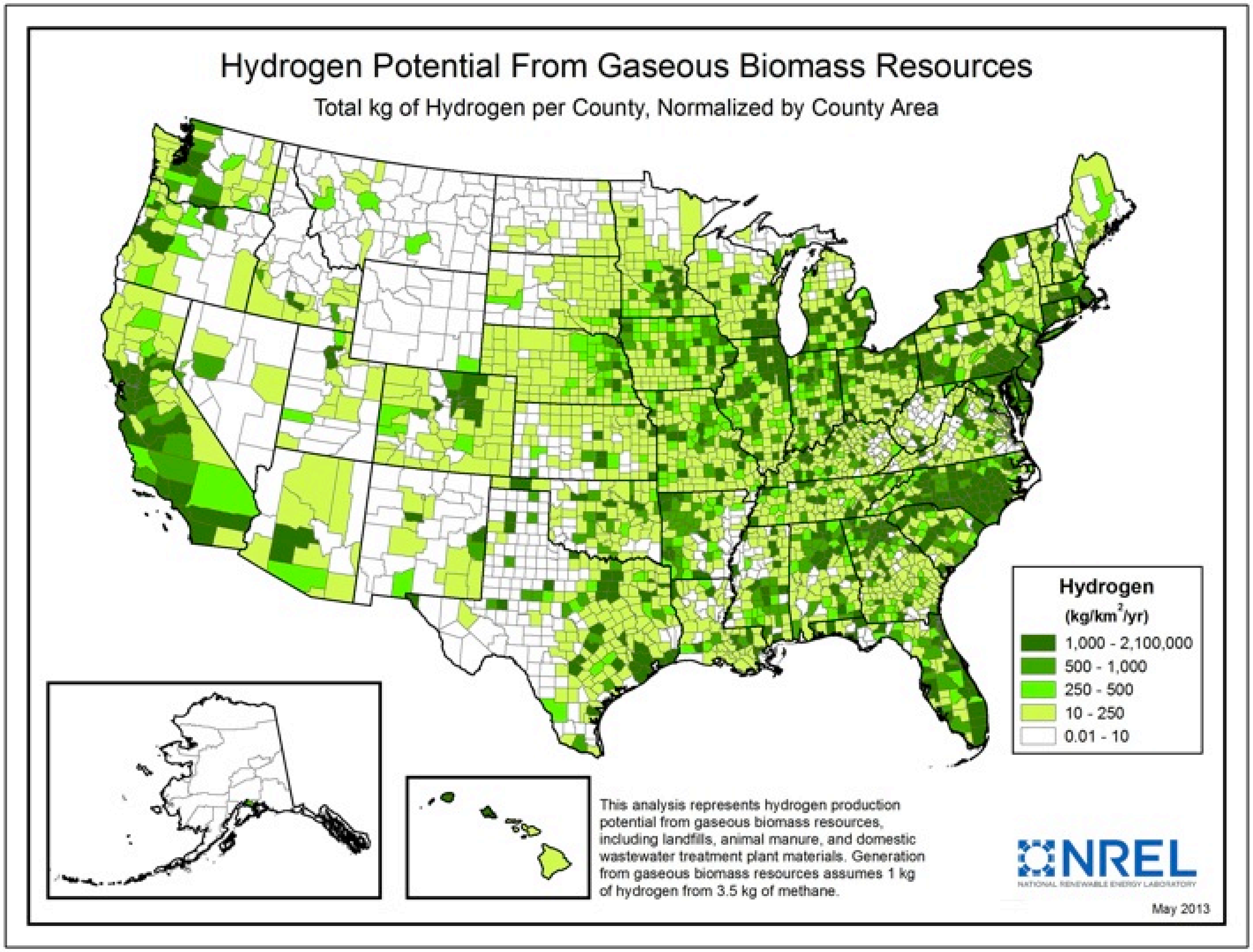

Figure 7. Hydrogen production potential from gaseous biomass resources, by county land area

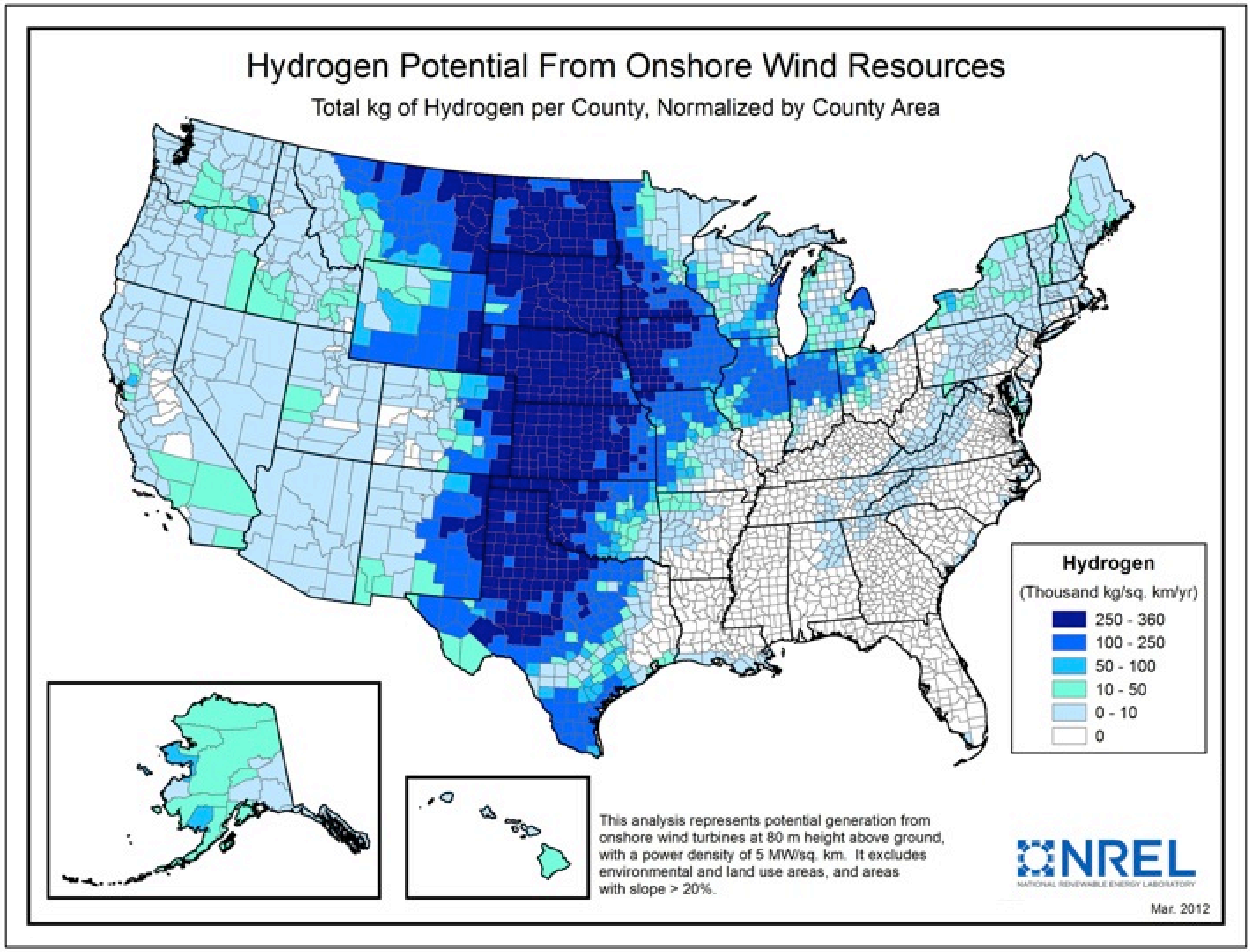

Figure 8. Hydrogen production potential from onshore wind resources, by county land area

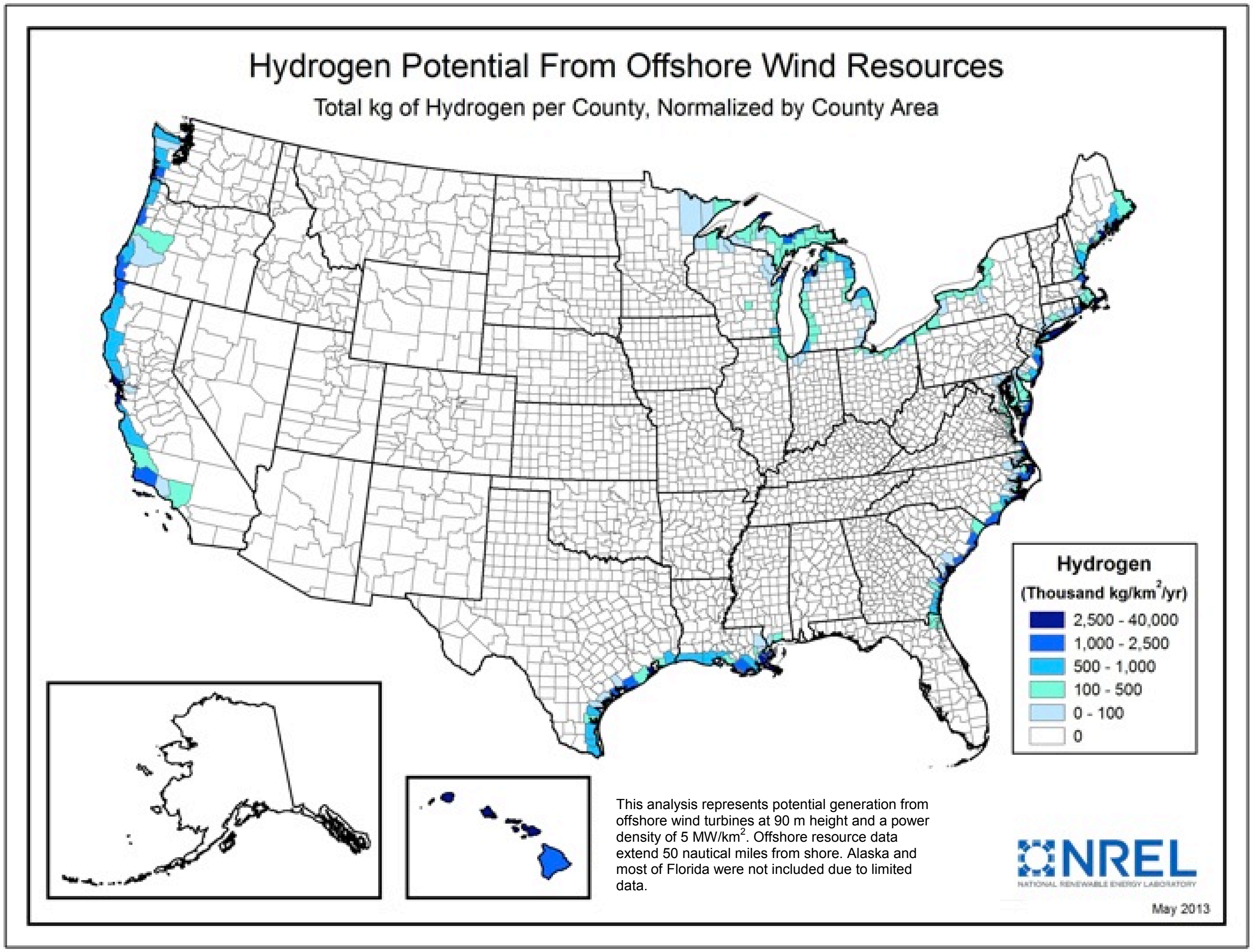

Figure 9. Hydrogen production potential from offshore wind resources, by county land area

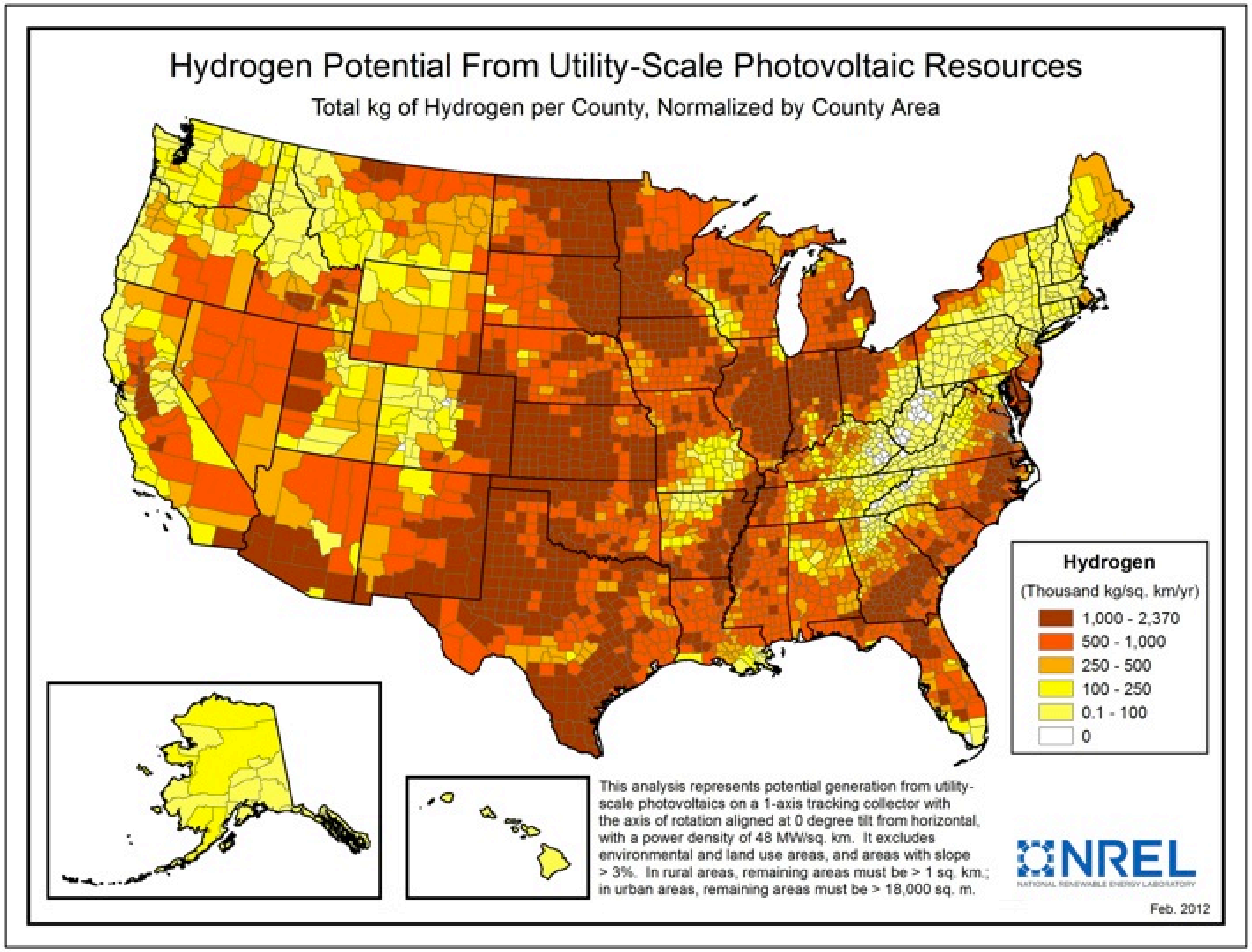

Figure 10. Hydrogen production potential from utility-scale PV resources, by county land area

Combined Renewable Hydrogen Production Potential

The renewable hydrogen production potential from biomass, wind, and solar is depicted in terms of total kg per county, normalized by county area, in Figure 11. When compared to Figure 10, the potential intensity patterns reveal that solar potential tends to dominate over biomass and wind. Figure 12 provides the same data and indicates color coding for the dominant renewable potential in each county. Only a small handful of counties are not dominated by solar, with biomass dominating in parts of Appalachia, and either wind or biomass dominating a small number of counties scattered across Midwestern, Mountain, and Northwestern regions.

Total renewable production potential can also be examined with respect to the spatial distribution of population and gasoline consumption. The 2010 population by county is indicated in Figure 13. Gasoline demand data at the state level are allocated by population, and shown in terms of total gallons per county in 2010 in Figure 14. This distribution is nearly identical to the relative distribution of population, but it proves insightful when used as the basis for renewable hydrogen production potential. The energy basis ratio of renewable hydrogen production potential and gasoline consumption is indicated by county in Figure 15. Higher ratios are indicated in low population counties, and counties where gasoline use exceeds the hydrogen production potential are prevalent across Appalachia and near major urban areas. Most major urban areas are relatively close to counties where the renewable hydrogen production potential is 1–5 times greater than gasoline consumption.

Water Resource Restrictions

As discussed in Milbrandt and Mann (2009), regional water availability may prove to be a limiting factor for the hydrogen production potential from fossil, nuclear, or renewable energy resources. As indicated in Figure 11, significant renewable hydrogen production potential exists in the northern and southern Midwest states, but these regions, especially the southern states, have significant drought and water availability issues. The potential influence of new transportation fuels on water resources is complex, and has been examined in a number of recent studies (Harto et al. 2010; King et al. 2010). Future insights will be attained from assessments that adopt a life-cycle framework, account for overall impacts on water resource stress rather than just withdrawals, and include tradeoffs among multiple transportation fuel options (cf. Scown et al. 2011). Water use for the electricity sector will also change in a low-carbon future supportive of alternative transportation fuels (Clemmer at al. 2013). A useful and integrated assessment of the impacts of future alternative fuel systems on water resources would need to take into account a wide range of uncertain and interrelated factors, and would need to explicitly account for various decision-making processes related to water resource management.

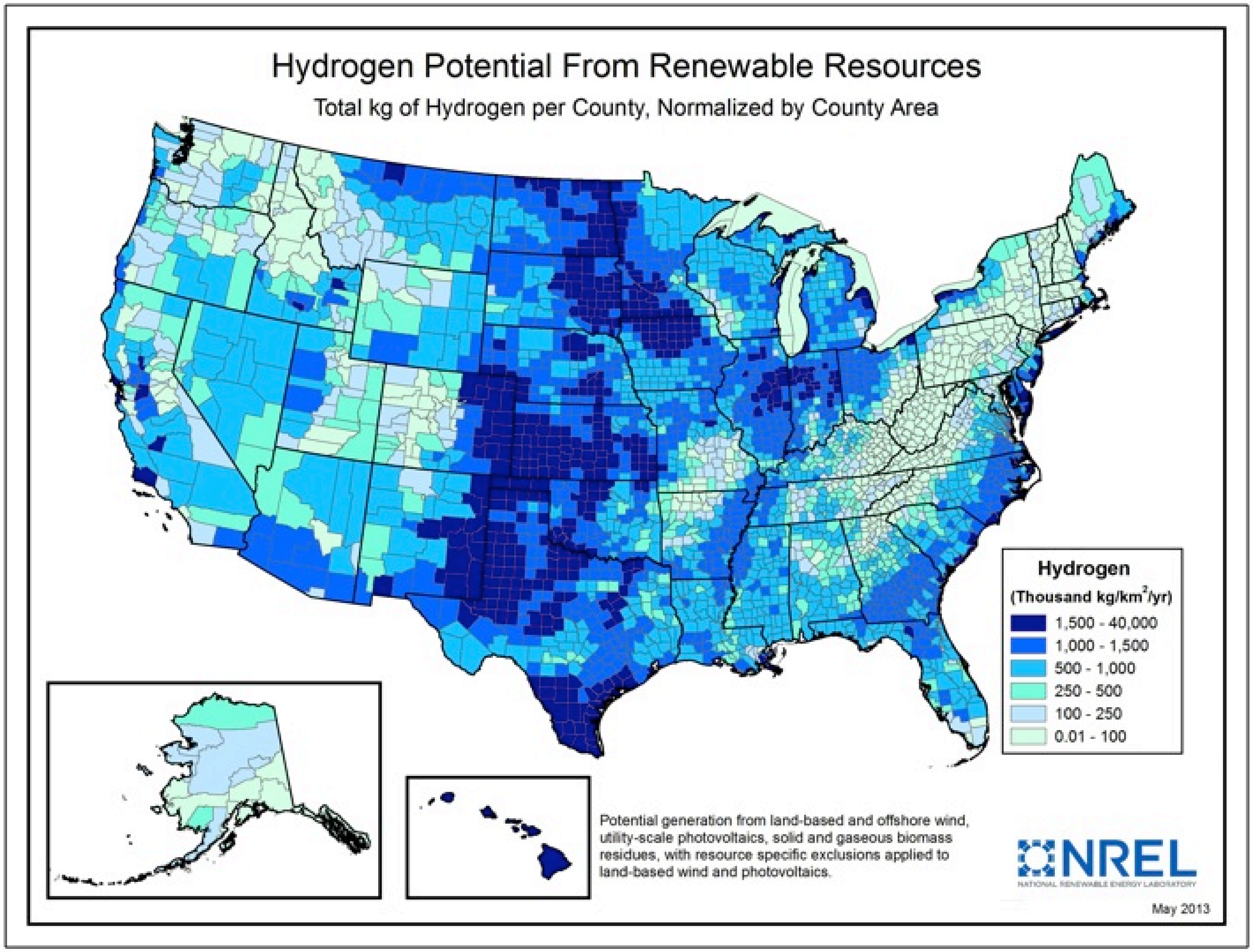

Figure 11. Hydrogen production potential from renewable resources, by county land area

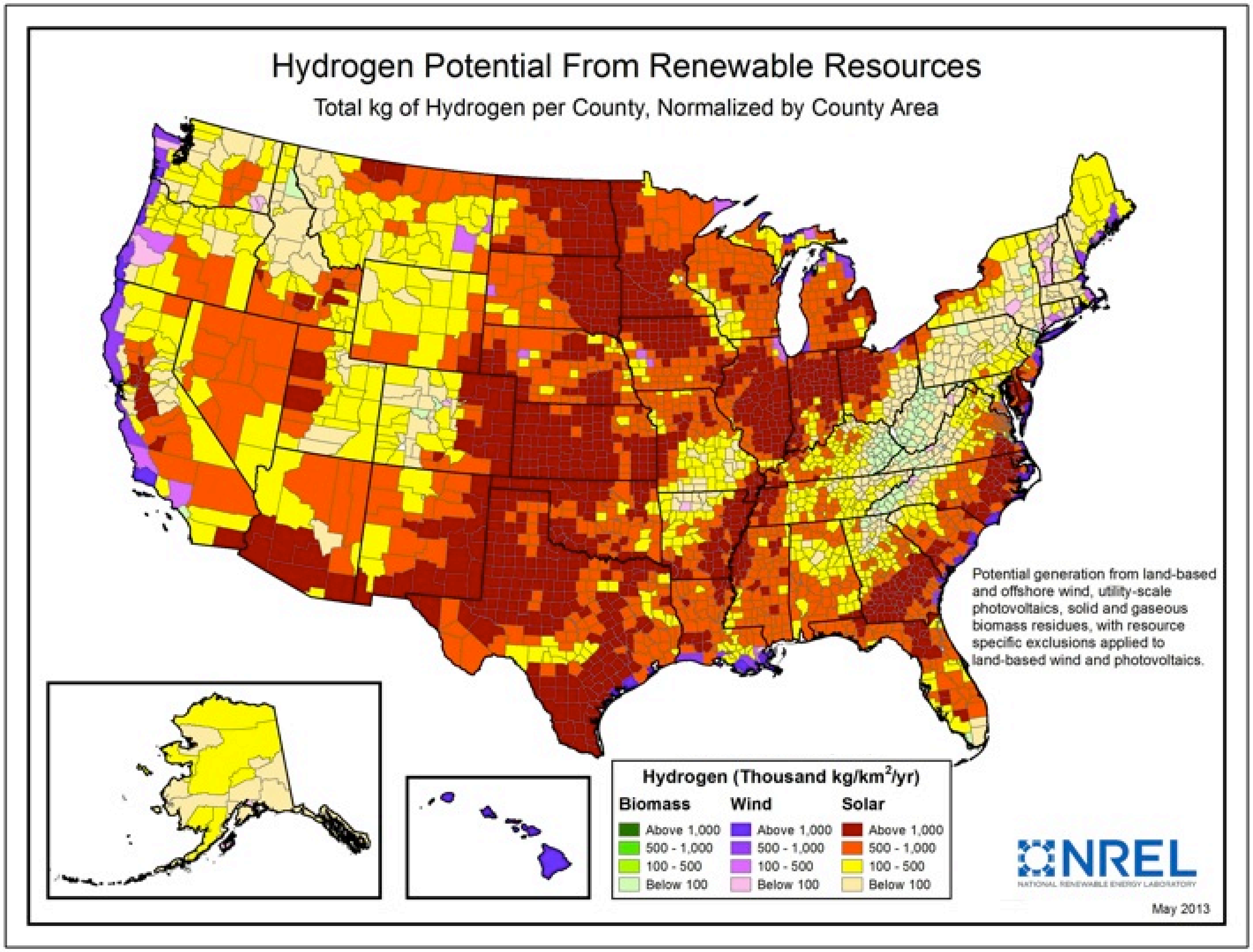

Figure 12. Hydrogen production potential from dominant renewable resources, by county land area

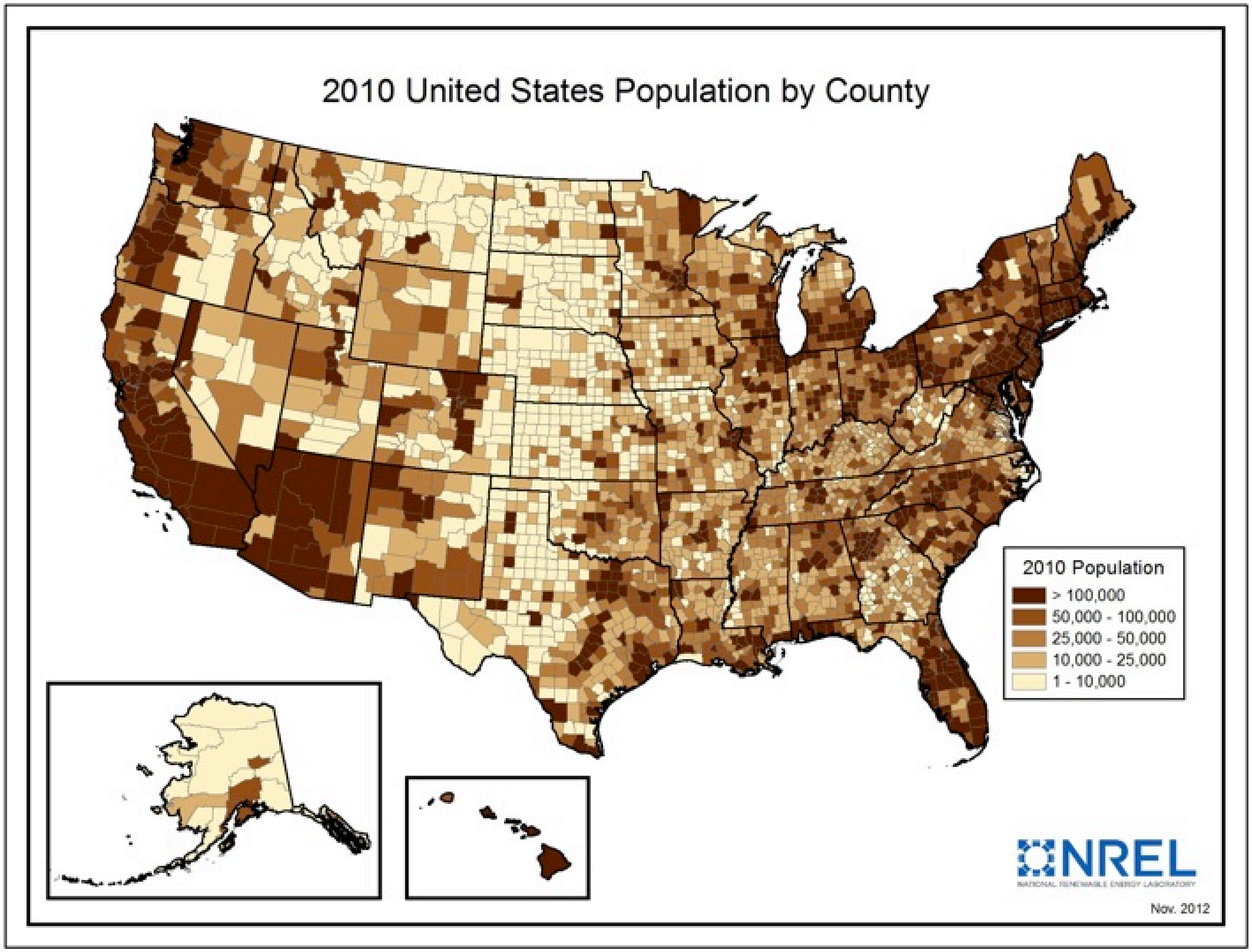

Figure 13. Population of the United States, by county

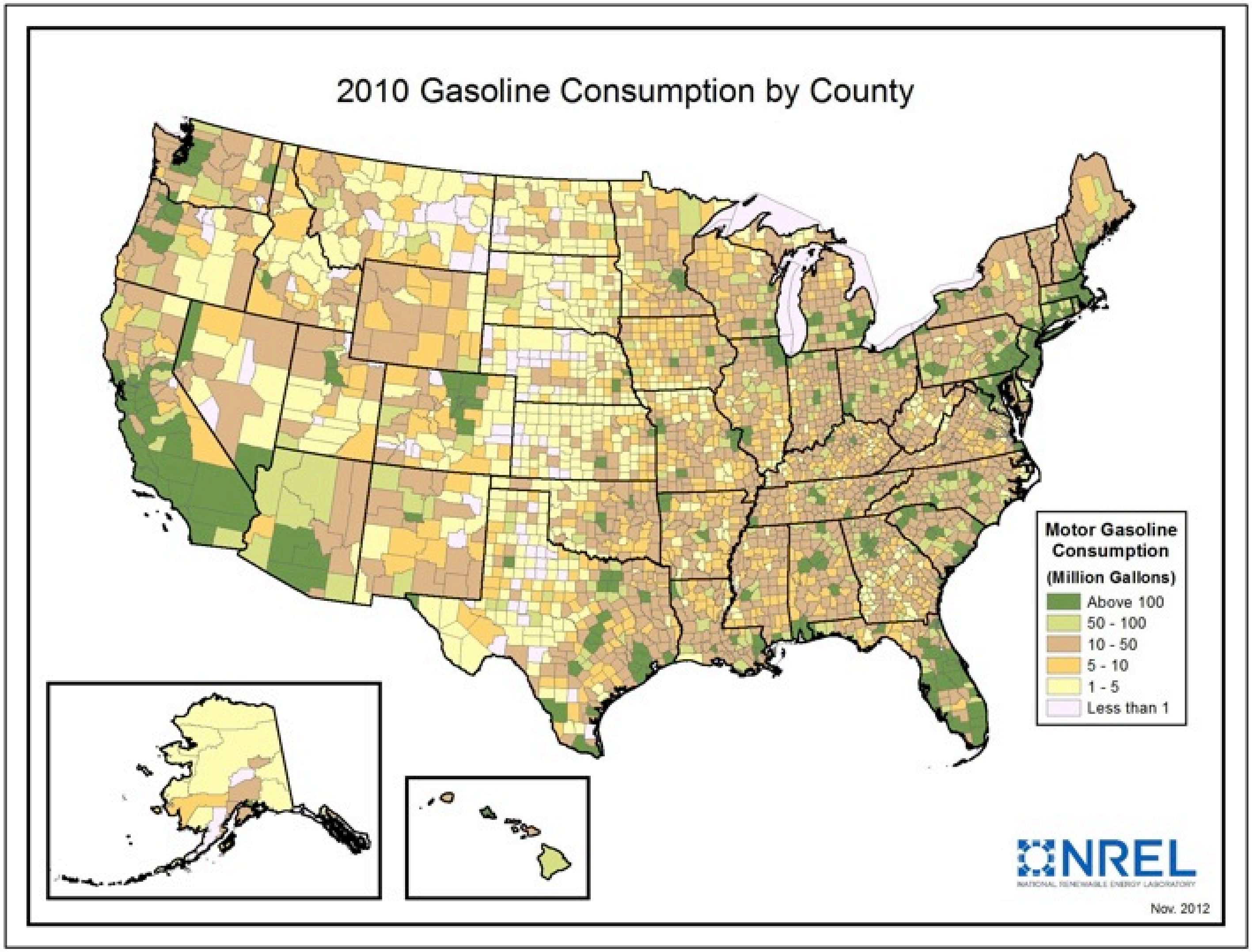

Figure 14. U.S. gasoline consumption by county, 2010

Gasoline consumption data at the state level are from EIA's State Energy Data System (SEDS) and are allocated to counties on a population basis.

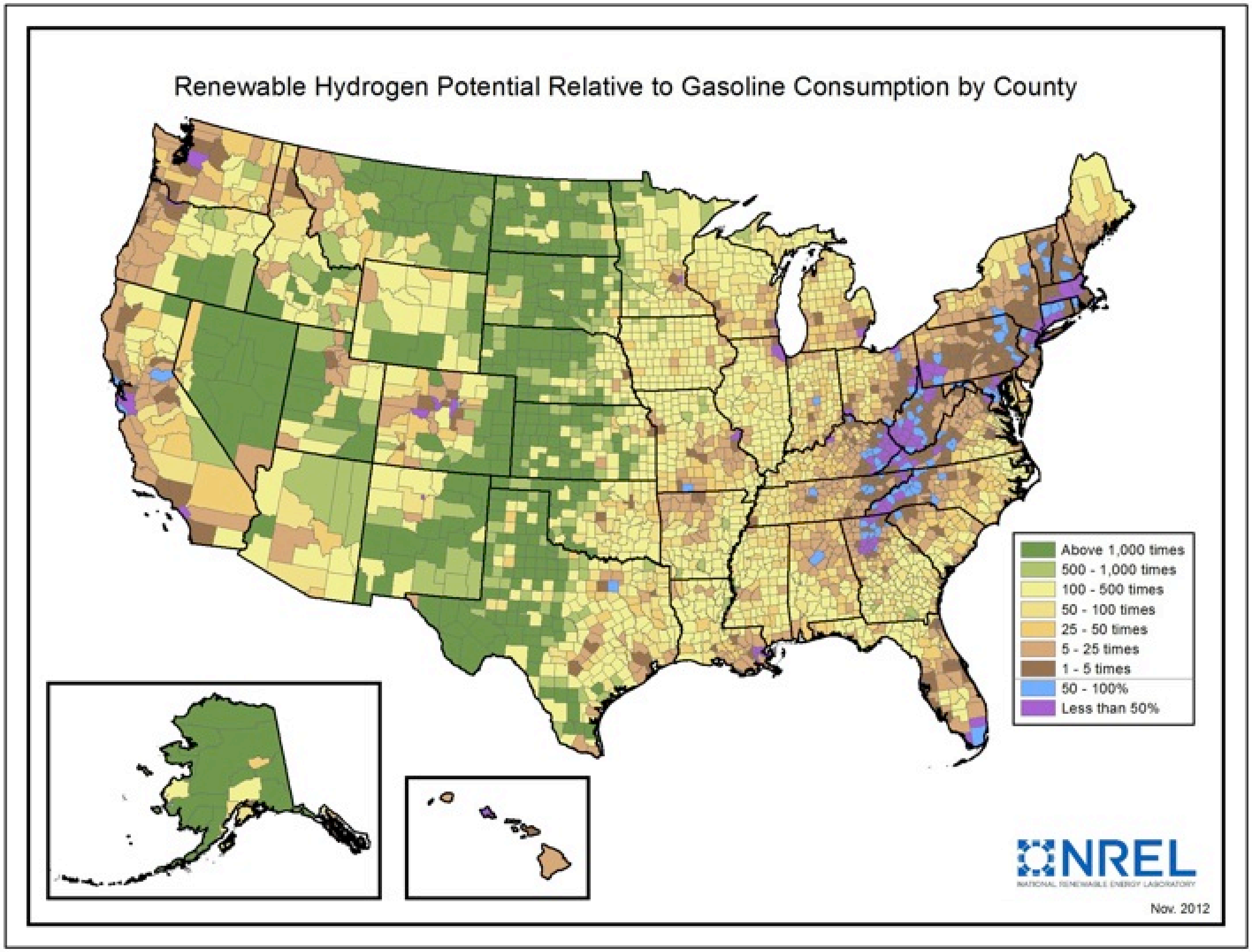

Figure 15. Renewable hydrogen production potential relative to gasoline consumption, by county

Gasoline demand at the state level is allocated to counties on a population basis.

Hydrogen Production Potential Summary

Table 3 summarizes energy inputs required to produce 1 kg of hydrogen from each resource. Conversion pathways and production efficiencies, on a lower heating value (LHV) basis, are shown for each resource and are taken from the H2A future case studies (DOE 2012). Key conversion factors are indicated in Table 4. Natural gas is converted through central steam methane reforming, the most prevalent pathway for producing hydrogen at petroleum refineries today, and coal and biomass are converted by way of gasification. The coal gasification pathway assumes CCS, though this pathway has essentially the same coal consumption per kilogram hydrogen produced as the non-CCS pathway. Additional energy feedstock consumption and byproduct electricity credits are not included in the energy efficiencies indicated in Table 3. Nuclear production efficiencies are described above. Wind and solar resources are shown as producing hydrogen by way of central electrolysis, with the efficiency of 46 kWh per kg hydrogen from the future H2A case study. Researchers are currently investigating more direct means of converting solar energy into hydrogen (Turner et al. 2008), but these pathways are in the relatively early phases of development and projected performance for future central electrolysis systems is an appropriate baseline for the present analysis. Ramsden et al. (2009) have reviewed hydrogen production costs and conversion efficiencies for multiple pathways using the H2A production model.

Hydrogen production potential estimates for the two nuclear pathways, high temperature electrolysis and thermochemical, include assumptions about uranium use that are not included in the H2A case studies. For high-temperature electrolysis, we assume the same nominal burnup rate of 45 GWdt/MTU, as well as the estimate from O'Brien et al. (2010) that a 600 MW-thermal plant can produce 78×10^{6} scf/day of hydrogen, and therefore has a conversion efficiency of 46% for heat to hydrogen (LHV). This assumes a very high temperature reactor, with helium coolant exiting the reactor and entering a Brayton power cycle at about 900°C. These assumptions result in a nominal use rate of 6.72×10^{-5} kg U/ kg hydrogen. This value is used to determine uranium resource requirements for the high-temperature electrolysis production pathway.

For the future thermochemical production pathway, we again assume a nominal burnup rate of 45 GWdt/MTU, and rely upon the estimate from Brown et al. (2003) that a high temperature nuclear reactor (~950°C outlet temperature) powering a sulfur-iodine (S-I) thermochemical cycle could achieve a 44% thermal efficiency (LHV) in producing hydrogen. This efficiency and burnup rate result in a uranium use rate of 7.03×10^{-5} kg U/ kg hydrogen.

Table 4. Conversion Assumptions

Metric	Value	Units	Source
Biomass			
Required biomass	13.0	kg biomass/kg hydrogen	H2A Future Case Study
Biomass energy content	18.61	MJ/kg biomass (LHV)	H2A Conversion Factor, (Biomass MYPP Feedstock)
Coal			
Required coal (future coal with CCS)	12.383	kg coal/kg hydrogen	H2A Future Case Study (adapted to coal heat content indicated below)
Coal required for 50% by 2040	98.0	MMT	Calculated
Coal energy content	20.75	MMBtu per metric tonne (LHV) Comparable to EIA HHV of 19.85 MMBtu/tonne)	2013 AEO (EIA 2013a)
Natural gas			
Required natural gas	156,000	Btu natural gas/kg hydrogen	H2A Future Case Study
Gas Btu content	1,024	Btu per scf (HHV)	2013 AEO (EIA 2013a)
Wind Power			
Required wind electrolysis electricity	46.0	kWh/kg hydrogen	H2A Future Case Study
Solar Power			
Required solar electrolysis electricity	46.0	kWh/kg hydrogen	H2A Future Case Study
Nuclear Power			
High temperature electrolysis	46.2%	Thermal conversion	H2A Future Case Study
Thermochemical	44.0%	Thermal conversion	Brown et al. (2003)
Uranium use (high temperature electrolysis)	$6.72*10^{-5}$	kg uranium per kg hydrogen	O'Brien et al. (2009)
Uranium use (thermochemical, 950°C)	$7.03*10^{-5}$	kg uranium per kg hydrogen	Brown et al. (2003)

Note: heating values or conversions unique to a particular publication were used for some calculations.

Hydrogen Production Requirements for Future Demand Scenarios

Two hypothetical future demand scenarios have been developed to examine a range of energy resource requirements in 2040. The *Hydrogen Success* scenario requires 20 MMT of hydrogen per year by 2040, representing the amount of hydrogen needed to fuel approximately 100 million light-duty FCEVs. Figure 16 indicates an S-shaped ramp-up in demand from 2010 to 2040 as FCEV market share grows and eventually saturates. A *Niche Market* demand scenario is also shown, requiring 4 MMT of hydrogen per year by 2040, representing the amount of hydrogen needed to fuel approximately 20 million FCEVs. Both demand scenarios are a simplified representation of light-duty vehicle (LDV) market growth and vehicle stock growth dynamics, with both assuming that the average FCEV on the road in 2040 travels 12,000 miles per year and has an average on-road fuel efficiency of 60 miles per kg of hydrogen. Other market growth patterns could result in similar levels of demand by 2040.[5] With the 2013 AEO *Reference Case* projection of 284 million LDVs by 2040 (EIA 2013a), 100 million and 20 million FCEVs would be 35% and 7% of total LDVs, respectively. More fully developed scenarios, with comparable FCEV market share growth as the *Hydrogen Success* scenario and unique estimates of energy resource requirements, are described elsewhere (Greene et al. 2008; NRC 2008; Ogden, Yang, and Parker 2011; O'Brien 2012; NRC 2013).

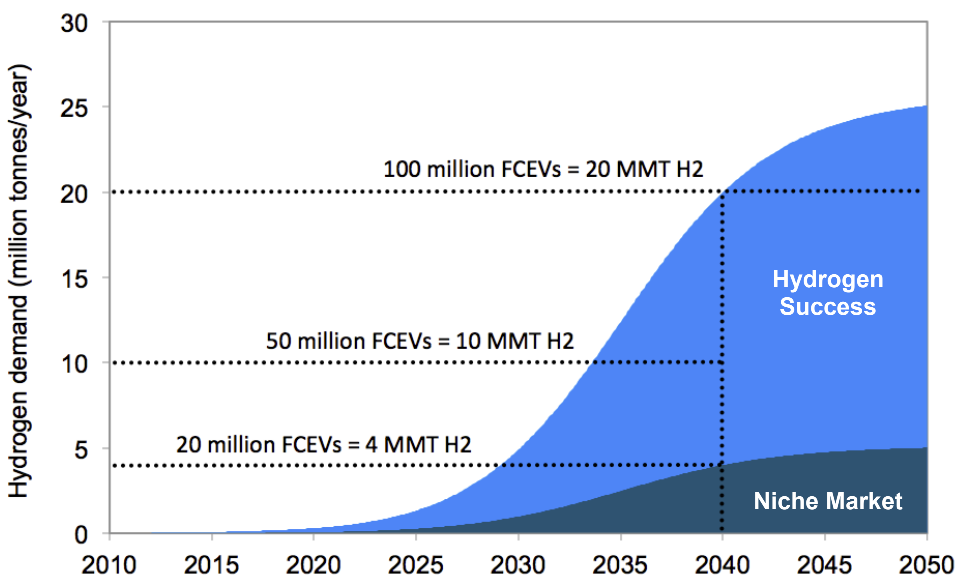

Figure 16. Adoption curve indicating the ramp-up to a hydrogen demand resulting from 100 or 20 million FCEVs deployed by 2040

Given these two demand scenarios, we estimate how much of any single low-carbon energy resource would be required by 2040 to supply 50% of the total hydrogen demand projected in the *Hydrogen Success* scenario (10 MMT, as shown in Figure 16), or 100% of total demand in the *Niche Market* scenario (4 MMT). The *Niche Market* scenario is referenced only occasionally

[5] Analytically consistent estimates of LDV fleet dynamics and future fuel demand can be generated using vehicle stock models that account for market share, vehicle vintaging, and reduction in vehicle miles traveled per year for older vehicles. Examples include the Scenario Evaluation and Regionalization Analysis (SERA) stock sub-model (OpenEI 2012), which is based on the VISION model (Ward 2008).

below, while most of the focus is on resource consumption for the *Hydrogen Success* scenario. We do not attempt to estimate a mix of production sources in 2040. Instead, we estimate requirements for any single resource to provide these two demand levels. The resulting estimates provide a context for discussing the potential implications of future FCEV fuel demand for resource constraints or market dynamics.

Natural gas is more carbon intensive than the other five resource types assessed, but it is considered here as an important transition energy resource to support growing markets as a low-carbon hydrogen infrastructure develops over time. Central natural gas production with CCS is also a technological option. This analysis is limited to plant-gate hydrogen production potential only, so storage and delivery pathway efficiencies are not taken into account. The efficiencies of delivery pathways will vary regionally and between resource types, but these are best analyzed within a spatially detailed and dynamic cost-optimization framework and are not considered in this study.

Table 5 shows fossil and nuclear resource availability, consumption in 2012, consumption by 2040 under BAU and carbon-constrained market conditions, and the amount of resource needed to produce 4 or 10 MMT of hydrogen. Table 6 shows the same metrics for biomass, wind, and solar energy resources. In both tables, resource availability is shown as the economic potential and as the total TRR. Values are indicated for both the 2013 AEO *Reference Case* and the *Greenhouse Gas $25* scenarios (EIA 2013a), where the latter involves imposition of a $25/ton carbon tax. Resource requirements to produce 10 MMT hydrogen for 50 million FCEVs and 4 MMT for 20 million FCEVs are also indicated. Values in the final four rows of each table are the percent increase in projected 2040 resource consumption as a result of producing 4 or 10 MMT of hydrogen for both the *Reference Case* and *Greenhouse Gas $25* scenarios, calculated using the following equation:

(Projected consumption + Requirement for FCEV demand) / Projected consumption

These results build upon previous estimates reported in Appendix B of the U.S. DOE Hydrogen and Fuel Cells Program Plan (DOE 2011a). Significant differences include resource availability estimates being reported as both economic potential and TRR (sum of economic and technical potentials), a comparison with projections to 2040 from both a BAU and carbon-constrained scenario (2013 AEO *Reference Case* and *Greenhouse Gas $25* scenario), and projected consumption to produce hydrogen reported for two demand levels (4 and 10 MMT hydrogen). In addition, wind and solar potentials are based upon more consistent estimates: economic potential values are based upon REF Study estimates for total electricity generation (NREL 2012) under favorable economic and technological progress conditions, and TRR estimates are from the more consistent assessment conducted for multiple renewable resources by Lopez et al. (2012). The estimates reported in this study are therefore updates to estimates reported in the Program Plan (DOE 2011a) and are developed with a more consistent basis for both technical and economic potentials. For example, the solar and wind technical resource potentials in Lopez et al. (2012) are characterized with significant technical detail and consistently across resource types, while the resource availability estimates for solar and wind in the Program Plan are best described as estimates of economic potential as defined in the present report.

Table 5. Availability, Current Consumption, and Projected Consumption for Fossil and Nuclear Resources

Resource Metric		Fossil and Nuclear Pathways [a]			
		Natural gas [b]	**Coal** [c] (with CCS)	**Nuclear** [d] (high temp. electrolysis)	**Nuclear** [d] (thermo-chemical)
Resource Availability					
Economic Resource Potential		305 Tcf	259 B tons	809 M lb U_3O_8	
Technically Recoverable Resource		2,200 Tcf	483 B tons	1,841 M lb U_3O_8	
Resource Consumption (without hydrogen for FCEVs) [e]					
Current [2012]		25.5 Tcf	891 M tons	770 TWh	
Reference Case: 2040		29.5 Tcf	1,071 M tons	903 TWh	
GHG $25 Case: 2040		26.9 Tcf	132 M tons	1,788 TWh	
Resource to Produce Hydrogen for 20 & 50 million FCEVs [f]					
50 M FCEVs		1.7 Tcf	137 M tons	278 TWh	292 TWh
20 M FCEVs		0.7 Tcf	55 M tons	111 TWh	117 TWh
Percent Increase in 2040 Resource Consumption for 20 & 50 million FCEVs					
Reference Case	20 M FCEVs	2%	6%	12%	13%
	50 M FCEVS	6%	13%	31%	32%
GHG $25 Case	20 M FCEVs	2%	41%	6%	7%
	50 M FCEVS	5%	103%	16%	16%

B = billion; GHG $25 = 2013 AEO *Greenhouse Gas $25;* M = million;
Technically Recoverable Resource = sum of economic and technical potentials

[a] Calculations were made to determine the hydrogen quantity required. Some systems require input energy such as electricity or produce useful byproducts such as heat or electricity.

[b] Natural gas economic potential from 2010 *Proved Reserves* (Annual Energy Review 2011, Table 4.2 [EIA 2012c]) and technical potential from 2009 Total Technically Recoverable Resources (Annual Energy Review 2011, Table 4.1).

[c] Coal economic potential from 2011 Estimated Recoverable Reserves and technical potential from Demonstrated Reserve Base from the 2011 Annual Coal Report (EIA 2012d). Resource availability values are from EIA's 2010 *Annual Energy Review* (EIA 2011), available at http://www.eia.gov/totalenergy/data/annual.

[d] The two nuclear production pathways are for High Temperature Electrolysis and Thermochemical, as described above. Uranium resource economic potential is from 2008 uranium reserves at a forward-cost category of up to $50/lb U_3O_8, and technical potential is at a forward-cost category of up to $100/lb U_3O_8 (Annual Energy Review 2011, Table 4.10).

[e] Current consumption values from EIA online data tables for natural gas (http://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm), the Quarterly Coal Report (http://www.eia.gov/coal/production/quarterly/pdf/tes1p01p1.pdf) and the *Electricity Supply, Disposition, Prices and Emissions* table for nuclear (http://www.eia.gov/oiaf/aeo/tablebrowser/). Projected resource consumption values in 2040 are from the *Reference Case* and *Greenhouse Gas $25* scenario from the 2013 Annual Energy Outlook (EIA 2013a).

[f] See Figure 16 and related discussion. Fifty and 20 million FCEVs consume 10 and 4 MMT hydrogen per year, respectively, assuming 12,000 miles per year per vehicle and 60 miles per kg hydrogen. Resources required are determined from the H2A case study production efficiencies summarized in Table 3.

Table 6. Availability, Current Consumption, and Projected Consumption for Biomass, Wind and Solar Resources

Resource Metric		Renewable Pathways		
		Biomass [a]	Wind [b] (on/offshore)	Solar [c] (PV & CSP)
Resource Availability				
Economic Resource Potential		900 M tons	2,000 TWh	1,000 TWh
Technically Recoverable Resource		417–1,094 M tons	50,000 TWh	400,000 TWh
Resource Consumption (without hydrogen for FCEVs) [d]				
Current [2012]		245 M tons	137 TWh	3.5 TWh
Reference Case: 2040		433 M tons	252 TWh	59 TWh
GHG $25 Case: 2040		474 M tons	616 TWh	313 TWh
Resource to Produce Hydrogen for 20 & 50 million FCEVs [e]				
50 M FCEVs		130 M tons	460 TWh	460 TWh
20 M FCEVs		52 M tons	184 TWh	184 TWh
Percent Increase in 2040 Resource Consumption for 20 & 50 million FCEVs				
Reference Case	20 M FCEVs	13%	73%	161%
	50 M FCEVS	33%	183%	401%
GHG $25 Case	20 M FCEVs	12%	30%	47%
	50 M FCEVS	30%	75%	116%

Technically Recoverable Resource = sum of economic and technical potentials (see note a below for biomass); PV = photovoltaic; *GHG $25* = 2013 AEO *Greenhouse Gas $25*

[a] Biomass economic potential is the sum of 350 M tons of (plateaued) supply projected between 2020 and 2032 in the 2013 AEO Early Release *Greenhouse Gas $25* scenario (EIA 2013a) and 550 M tons for biopower by 2050 in the high demand REF Study scenario (NREL 2012). This result is unique to this study and represents an economic potential corresponding to a future with high demand for low-carbon resources and a relatively high degree of technological development. The technical potential range includes a low value for current resources from Lopez et al. (2012) and a high value from the Billion Ton Study update baseline scenario in 2030, with a price of $60 per dry ton (DOE 2011b). Biomass consumption is not sufficient to meet RFS requirements and would require an additional ~100 M tons (~1.7 quads) to meet RFS requirements.

[b] Wind resource economic potential is assumed to be equal to the projected 2050 production projection from the REF Study (NREL 2012).

[c] Solar resource economic potential is assumed to be equal to the projected 2050 production projection from the REF Study (NREL 2012).

[d] Resource consumption values are from the *Reference Case (Ref)* and *Greenhouse Gas $25 (GHG$25)* scenario from Annual Energy Outlook: 2013. Wind and Solar electricity values are from the *Renewable Energy Generating Capacity and Generation* table (http://www.eia.gov/oiaf/aeo/tablebrowser/). Biomass consumption is from multiple sources in the *Renewable Energy Consumption by Sector and Source* table, with quads converted to million short tons assuming 8,500 Btu/lb (HHV) (Lopez et al. 2012). Biomass consumption projections do not meet RSF biofuel requirements and could involve an additional ~100 M tons if those requirements are met.

[e] See Figure 16 and related discussion. Fifty and 20 million FCEVs consume 10 and 4 MMT hydrogen per year, respectively, assuming 12,000 miles per year per vehicle and 60 miles per kg hydrogen. Resources required are determined from the H2A case study production efficiencies summarized in Table 3.

Unlike the other *Resource Availability* estimates indicated, the biomass TRR potential is a range bounding the economic potential estimate. This reflects the high degree of variability among estimates and estimation methodologies for future biomass resources. In addition, the projected biomass consumption values in 2040 for the *Reference Case* and *Greenhouse Gas $25* scenarios fall short of the RFS biofuel requirements by approximately 10 billion ethanol-equivalent gallons (EIA 2013a). With market and policy conditions sufficient to actually meet the RFS requirements, these scenarios could involve an additional consumption of ~100 M tons (~1.7 quads) biomass (assuming 50% thermal conversion).

The additional resource consumption for producing 10 MMT hydrogen is also indicated graphically in Figure 17a for the BAU 2013 AEO *Reference Case* scenario (EIA 2013a). To allow for comparison, all resource values have been converted to quads from the values in Tables 5 and 6. The white bars indicate current consumption in 2012, and the blue crosshatched bars represent projected consumption in 2040 under BAU conditions. The stacked solid blue bars indicate the additional resource consumption due to FCEVs. The degree to which consumption increases due to FCEV adoption varies by resource. The percent increases in projected consumption are indicated, as factor increases, along the horizontal axis for each resource. With respect to projected consumption in the *Reference Case*, these increases are 6% for natural gas, 13% for coal, 31% for nuclear, 33% for biomass, 183% for wind, and 780% for solar. These factor increases are based on market outcome results from the 2013 AEO *Reference Case* (EIA 2013a), and account for increases over consumption levels across all energy sectors, including buildings, electricity, industry and transportation. These results suggest that hydrogen demand from future market success with FCEVs would not place excessive strain on resources or production capacity for natural gas or coal, would comprise a significant portion of total demand for nuclear and biomass, and would significantly exceed expected demand for wind and solar.

Any future scenario in which hydrogen vehicles attain strong market share by 2040 might involve policies or market forces not present in a BAU scenario, and these factors are likely to change demand for low-carbon resources in other sectors. For example, in a carbon-constrained future, there might be increased demand for wind and solar, which would lower the factor increases for those resources by increasing total projected consumption without market success with FCEVs. For this reason, projections from the 2013 AEO *Greenhouse Gas $25 s*cenario are also included in Tables 5 and 6, and indicated visually in Figure 17b. As shown, the relative consumption increases are distinct from those shown in Figure 17a. Percent increases due hydrogen production for low-carbon resources are less because overall use of these resources has increased, and the percent increase for coal is significantly higher, 104% compared to 13%, because projected demand for coal has declined. Percent increases for each of the other resources are as follows: 6% for natural gas, 16% for nuclear, 30% for biomass, 75% for wind, and 147% for solar. These results suggest less relative strain on nuclear, wind, and solar resources compared to the *Reference Case*.

Each of the values indicated for coal in Figure 17 is based on different heating values. For the current consumption values, taken from the Quarterly Coal Report, the 2013 AEO consumption heating value for 2012 of 19.77 MMBtu per short ton is used. For projected consumption values, EIA reports 19.261 MMBtu per short ton in the *Reference Case* and 20.668 MMBtu per short ton in the *Greenhouse Gas $25* case. The results expressed in quads in Figure 17 are therefore more consistent than the million short ton values reported in Table 5. The wind and solar values shown in quads have been converted to thermal equivalents assuming 9,760 Btu/kWh.

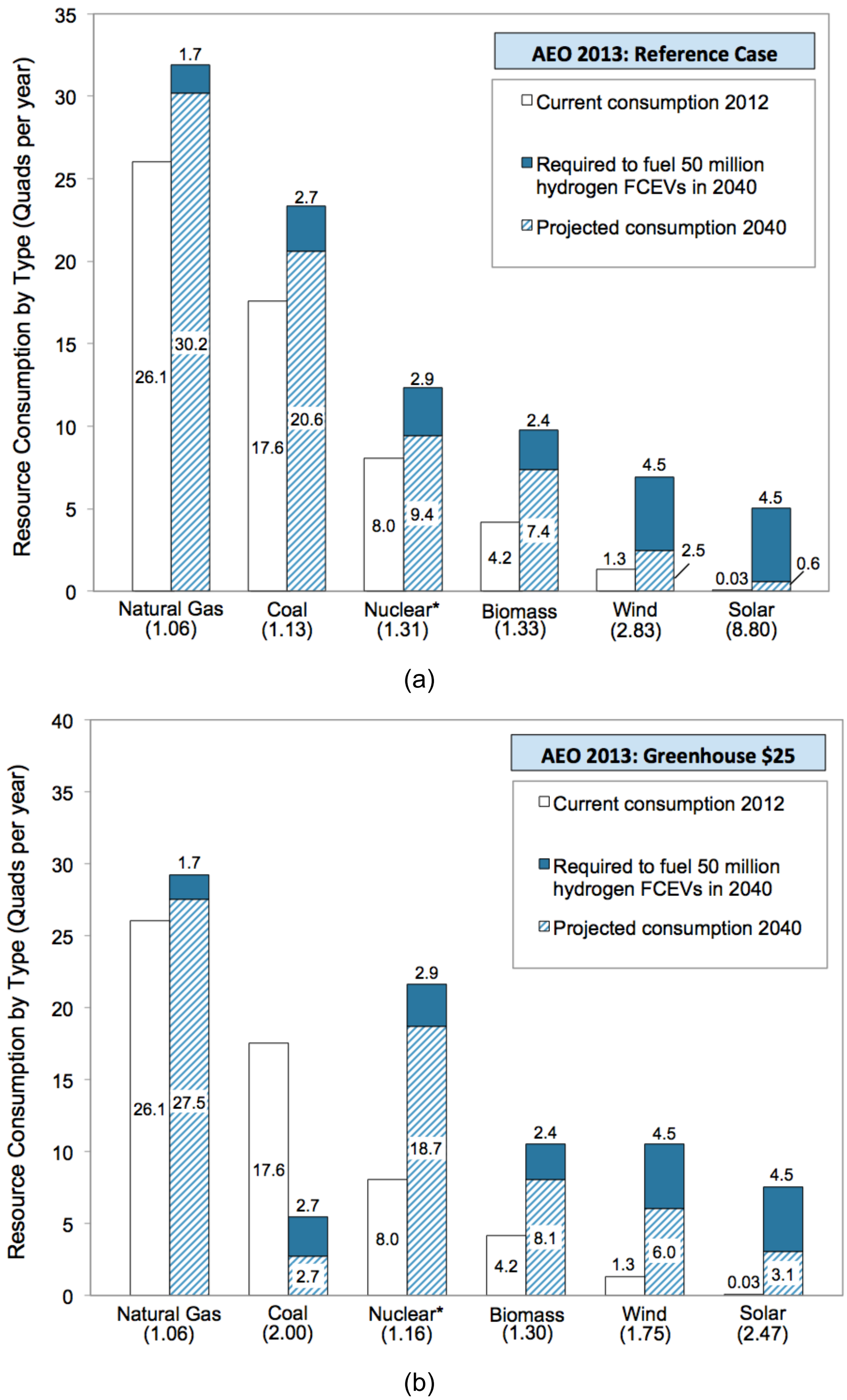

Figure 17. Current and projected *Reference Case* (a) and *Greenhouse Gas $25* scenario (b) energy consumption across all energy sectors by resource type, with requirements for 50 million FCEVs

Hydrogen required to meet 50% of FCEV demand in 2040 (or the hydrogen requirement for 50 million FCEVs) is shown as a stacked bar on top of the 2040 AEO 2013 *Reference Case* consumption values (a) and *Greenhouse Gas*

$25 scenario values (b). The factor increase for each resource is shown in parentheses. Values are equivalent to those shown in Tables 5 and 6. Biomass consumption is not sufficient to meet RFS requirements and would require an addition ~1.7 quads to meet RFS requirements.
* Nuclear values are for high temperature electrolysis. Thermochemical nuclear consumption results (not shown) are 3.1 quads for FCEVs, representing factor increases of 1.32 (*Reference Case*) and 1.16 (*Greenhouse Gas $25*).

Conceptual Comparison of Fixed and Flow Energy Potential Estimates

Conceptual comparisons of the economic and technical hydrogen production potentials for fossil, nuclear, and renewable energy resources are relevant in the context of long-term energy system dynamics. Over the long term, considerable technological advances or major shifts in market conditions are feasible and could significantly influence how economic and technical potential estimates are determined. Within this context, it is relevant to compare current resource estimates on a more conceptual basis that resolves the inherent "fixed" nature of fossil and uranium resources and the "flow" nature of renewable resources. High-level results for economic and technical potential estimates (summed as TRR estimates) and corresponding hydrogen production potentials are summarized in Table 7. These estimates are highly uncertain and speculative and are therefore indicated with limited significant figures. Estimates are shown in both physical resource units and as total hydrogen production potential in million metric tonnes of hydrogen (MMT) and quads. Renewable potentials are shown on an annual basis. As indicated, renewable hydrogen production potentials are distinct from fossil and nuclear potentials in that the economic hydrogen production potential for biomass falls within the uncertain range for TRR (as discussed above), the wind TRR is greater than the economic potential by a factor of 25, and the solar TRR is greater than the economic potential by a factor of 400. By comparison, fossil and nuclear TRR estimates for hydrogen production are greater than the corresponding economic potentials by factors ranging from 2 to 7.

Table 7. Technical Resource Potential for Finite and Renewable Resources

Resource	Resource Potential			Hydrogen Production Potential		
Fossil and Nuclear	**Physical Resource**		**Quads**	**Hydrogen Potential**		**Quads H2**
Natural Gas (EP)	300	Trillion cubic feet	310	1,800	MMT H2	240
Natural Gas (TRR)	2,200	Trillion cubic feet	2,300	13,100	MMT H2	1,800
Coal (EP)	260	Billion short tons	5,200	18,900	MMT H2	2,600
Coal (TRR)	480	Billion short tons	9,700	35,400	MMT H2	4,800
Uranium (EP)	500	Million lbs U_3O_8	900	3,100	MMT H2	400
Uranium (TRR)	1,200	Million lbs U_3O_8	2,100	7,000	MMT H2	900
Renewable	**Physical Resource**		**Quads/yr**	**Hydrogen Potential**		**Quads H2/yr**
Biomass (EP)	900	Million tons eq.	15	60	MMT H2/yr	8
Biomass (moderate)	400	Million tons eq.	7	30	MMT H2/yr	4
Biomass (high)	1,100	Million tons eq.	19	80	MMT H2/yr	10
Wind (EP)	2,000	TWh electricity	20	40	MMT H2/yr	6
Wind (TRR)	50,000	TWh electricity	500	1,100	MMT H2/yr	150
Solar (EP)	1,000	TWh electricity	10	20	MMT H2/yr	3
Solar (TRR)	400,000	TWh electricity	3,900	8,700	MMT H2/yr	1,200

Notes: EP = Economic Potential, TRR = Technically Recoverable Resource. Biomass TRR is shown as a moderate to high range. Conversions to quads are on a higher heating basis; EIA thermal equivalent of 9760 Btu/kWh is used for wind and solar. Sums are rounded.

Figure 18 places the “fixed” resource estimates for natural gas, coal, and uranium (indicated in quads) on a conceptually consistent temporal basis at the “flow” resource estimates for biomass, wind, and solar resources (quads per year). This comparison provides a general “ballpark” perspective on how renewable resource potentials compare to the “in the ground” estimates for fossil and uranium resources. Though nuclear, coal, and natural gas resource estimates will certainly change within an actual timeframe of 40 years, in response to changing consumption rates, economic conditions, and technological factors, they are indicated as conceptual fixed values based upon recent estimates of economic potential (low range) and TRR (high range). Figure 18 provides a visual depiction of the relative magnitudes of each resource type in terms of conceptual years: the solar TRR exceeds all fossil and uranium hydrogen production potential estimates within several years, and the wind TRR is comparable to domestic uranium, natural gas, and coal hydrogen production potentials on conceptual timeframes of approximately 5, 10 and 30 years, respectively. In contrast, the biomass TRR range approaches the economic hydrogen production potentials for natural gas and uranium on a conceptual timeframe of approximately 30–40 years. As suggested by the figure inset, the TRR range for biomass is comparable to the cumulative economic hydrogen production potential estimates for solar, wind and biomass, ranging from 3–8 quads per year.

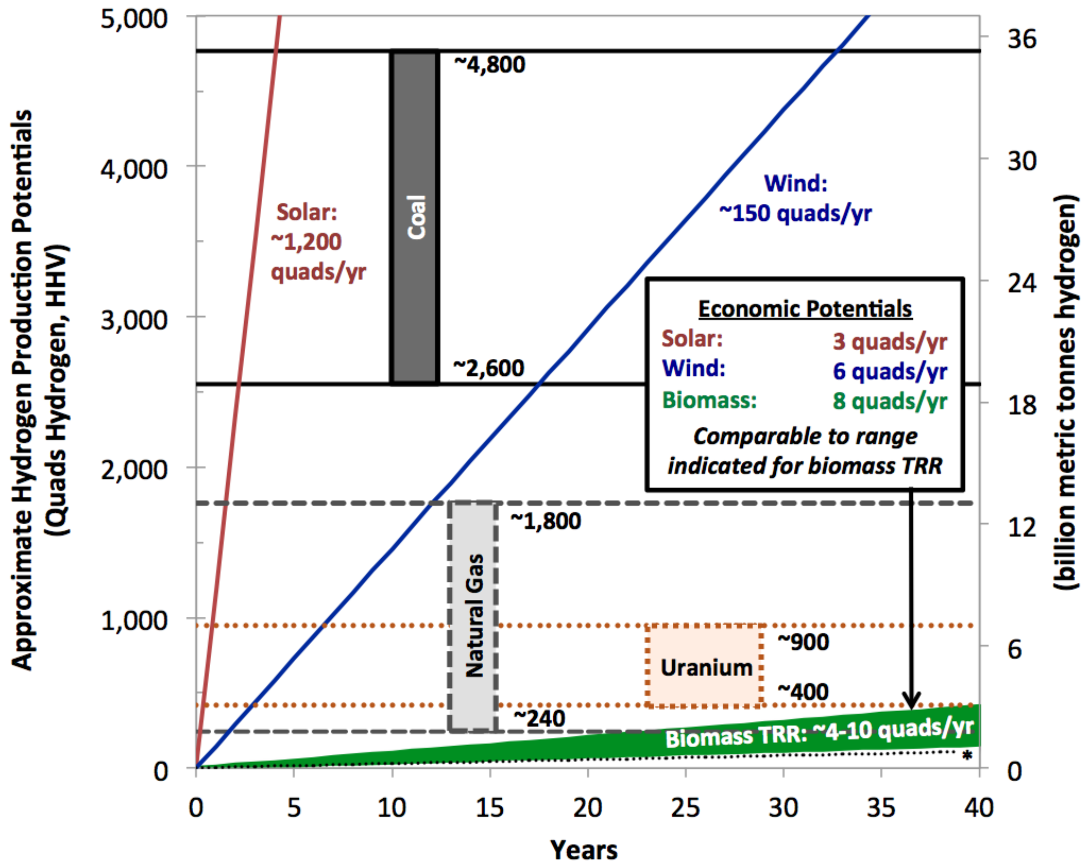

Figure 18. Approximate hydrogen production potentials for each resource

Technical hydrogen production potentials from solar, wind, and biomass resources are quantified as flows (quads hydrogen per year) and shown accumulating linearly across a conceptual time scale. Though nuclear, coal, and natural gas resource estimates do change with time, in response to changing economic and technological factors, they are indicated as fixed values based upon recent estimates of economic potential (low range) and TRR (high range; the sum of economic and technical potentials). The dotted line and asterisk at the bottom of the figure (*) represent cumulative production of 20 MMT hydrogen per year over 40 years. All values are highly uncertain approximations. Resource categories are not necessarily consistent on an economic or technical basis across all resource types or categories. Values are consistent with those shown in Table 7 and discussed in earlier sections of the report.

The secondary vertical axis indicates the resource production estimates in physical units, with the scale of 37 billion metric tonnes of hydrogen being equivalent to ~5,000 quads on an HHV basis. For reference, the annual demand of 20 MMT hydrogen in 2040 from Figure 16 is indicated as increasing cumulatively over time in the dashed line and asterisk at the bottom of the figure, summing to a total of 0.82 billion metric tonnes over 40 years. This comparison reinforces the conclusion above that ample domestic, low-carbon energy resources are available (as measured in terms of technical potential for all resources and economic potential for fossil and nuclear resources) for high hydrogen demand scenarios requiring on the order of 10 MMT of hydrogen per year from any particular resource type.

Conclusions

The use of domestic low-carbon hydrogen in FCEVs is a promising option for reducing U.S. oil imports and GHG emissions. This study assesses energy resource requirements to produce 10 MMT of hydrogen in a future Hydrogen Success scenario with 100 million FCEVs deployed by 2040. We estimate the energy resources required to supply this level of hydrogen demand, illustrating how domestic resources could be relied on to produce large volumes of low-carbon hydrogen. We do not attempt to estimate the mix of production sources in 2040. Instead, we estimate what would be needed for any single resource to satisfy 50% (10 MMT) of the total 2040 hydrogen demand level (20 MMT for 100 million FCEVs). These estimates build upon previous hydrogen production resource assessments by Milbrandt and Mann (2007, 2009), and extend previous comparisons to future hydrogen consumption levels (DOE 2011a) by drawing distinctions between economic and technical resource potentials.

The spatial distribution of renewable hydrogen production potential is explored through a series of maps and is compared to the distribution of both population and gasoline consumption levels. For projected levels of resource consumption, a percent increase in projected nationwide consumption due to FCEV hydrogen demand is estimated for a BAU scenario (2013 AEO *Reference Case*), as well as a carbon-constrained scenario in which low-carbon resources are relied upon to a greater degree (2013 AEO *Greenhouse Gas $25* case). The results of this assessment suggest that ample low-carbon and domestic energy resources are available to supply hydrogen to future FCEV markets.

Future work may consist of the following:

- Compare resource use across multiple fuel types
- Examine regional variations in resource potential and availability
- Incorporate additional constraints on resource potential, such as water resource limitations or barriers to developing delivery systems
- Contribute to resource-constrained scenarios of transportation energy use
- Include comparisons for non-LDV transportation demands (e.g., shipping, heavy-duty vehicles, air transport)
- Contribute to supply curve calculations for low-carbon scenario studies.

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