| DOE Hydrogen and Fuel Cells Program Record | |
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| **Record:** 14005 | **Date:** October 7, 2014 |
| **Title:** Hydrogen Production Status 2006-2013 | |
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| **Approved by:** Sunita Satyapal | **Date:** November 4, 2014 |

## Item

Historic ranges from 2006 to 2013 for the projected high-volume untaxed cost of hydrogen production are presented for several commercial and near-commercial production pathways. Distributed[1] production pathways of PEM Electrolysis, Bio-Derived Liquid Reforming and Natural Gas Reforming; and the central[2] production pathways of Polymer Electrolyte Membrane (PEM) Electrolysis and Biomass Gasification are included. The cost projections for each pathway are based on Hydrogen Analysis Production Model version 3 (H2A v3)[3] case studies; and the projected cost ranges reflect variability in major feedstock pricing as well as a bounded range for capital cost estimates.

Documented analysis of Distributed Natural Gas Reforming[4] indicates that this pathway is able to meet the 2020 DOE cost threshold goal of <$2/kg for untaxed hydrogen production.[5] As seen in the production cost ranges in Table 1, the remaining pathways require additional research and development (R&D) to meet the cost threshold goal. The H2A v3 case studies for the pathways listed in Table 1 are based on the latest technology advancements reviewed by the DOE-EERE Fuel Cell Technologies Office (FCTO) as of 2014.

**Table 1. Current Status of Projected Pathway-Dependent Hydrogen Production Cost Ranges**

| Current $H_2$ Production Cost [6] | LOW $/kg | BASELINE $/kg | HIGH $/kg |
|---|---|---|---|
| **Distributed Pathways** | | | |
| Distributed PEM Electrolysis | 3.40 | 5.10 | 6.60 |
| Distributed Bio-Derived Liquids | 3.20 | 6.60 | 7.90 |
| **Central Pathways** | | | |
| Central PEM Electrolysis | 3.40 | 5.10 | 6.50 |
| Central Biomass | 2.10 | 2.50 | 4.20 |

[1] Distributed pathways produce hydrogen at ≤ 1,500 kg/day with the production site at a fueling station.
[2] Central pathways produce hydrogen at ≥50,000 kg/day and large facilities removed from the point of use.
[3] H2A v3 is a discounted cash-flow model providing transparent reporting of process design assumptions and a consistent cost analysis methodology for $H_2$ production at distributed and central facilities [1, 2]; H2A v3 cost projections are based on an assumption of high volume, and hydrogen costs are reported in $/kg $H_2$ (using $2007 as the cost basis), as described in the *Analytical Basis* section of this Record.
[4] A 2006 independent analysis of distributed hydrogen production from natural gas concluded that existing technologies could be used to produce hydrogen from natural gas at a cost competitive with gasoline [3].
[5] The DOE 2020 cost threshold is <$4/kg for untaxed, dispensed hydrogen [4]; with $2/kg apportioned to hydrogen production [5] and $2/kg apportioned to dispensing.
[6] Projected high-volume hydrogen production costs ($/kg $H_2$ in $2007) rounded to the nearest $0.10 (excluding delivery and on-site compression, storage, and dispensing); The Baseline, Low and High costs represent variability in major feedstock pricing as well as a bounded range for capital cost estimates as detailed in the *Analytical Basis* section of this Record.

## Analytical Basis

Projected hydrogen production costs (un-dispensed and untaxed) from 2005 through 2013 are shown in Figure 1 for several distributed and central hydrogen production pathways, including: Distributed PEM Electrolysis, Bio-derived Liquid Reforming and Natural Gas Reforming; and Central PEM Electrolysis and Biomass Gasification. The analytical basis for the pathway-dependent cost ranges in the figure is the H2A v3 analysis tool[7] which projects the high-volume cost of hydrogen production using capital, feedstock, and operation and maintenance (O&M) cost contributions levelized over the lifetime of the hydrogen production plant. H2A v3 hydrogen production cost projections are reported in 2007 dollars (2007$) for consistency with EERE-wide analyses utilizing data from the *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2009 Report*[8] which uses 2007$ as its standard cost basis.

The hydrogen cost ranges shown for each of the pathways in Figure 1 include a Baseline cost projection (represented by a diamond symbol in the plot) along with a cost spread (represented by the vertical bars in the plot indicating Low and High cost values) reflecting variability in major feedstock pricing as well as a bounded range for capital cost estimates included in the H2A v3 analysis. Pathway-specific values for the Baseline, Low and High cost projections shown in Figure 1 are summarized in Tables 2 through 6 along with detailed information on each H2A v3 pathway analysis, including the cost breakdown attributable to capital, feedstock and O&M.

The general methodology used in determining the Baseline, Low and High cost projections for each pathway is summarized as follows:

- The Baseline projections for a given pathway in a given year incorporate documented contemporary assessments of system performance and cost parameters; and use the H2A v3 default treatment of major feedstock costs (e.g., based on lookup tables in the *EIA - AEO 2009 Report* of averaged feedstock costs over the plant lifetime starting in the plant-startup year).
- The pathway-dependent feedstock price ranges used in the analysis of the Low and High cost projections are consistent with documented reports relevant to each pathway major feedstock (as detailed in Tables 2 through 6).
- The Low cost projections use the low-end feedstock price with the Baseline capital cost estimate in the H2A v3 analysis.
- The High cost projections use the high-end feedstock price and the escalated capital cost including a pathway-specific uncertainty factor.
- Based on industry feedback, capital cost uncertainties in H2A v3 are typically modeled as a 30% escalation factor over the Baseline capital cost estimate for most pathways, though a higher percentage is used in specific cases, as indicated case-by-case in Tables 2 through 6.

[7] H2A v3 is a discounted cash-flow model providing transparent reporting of process design assumptions and a consistent cost analysis methodology for $H_2$ production at central and distributed facilities [1]; The high-volume condition in H2A v3 assumes that sufficiently high annual and cumulative volumes have been reached that all economies of scale for capital and unit costs have been achieved.

[8] *Energy Information Administration Annual Energy Outlook 2009 Report*, DOE/EIA-0383(2009), May 2009 [6].

## Hydrogen Production Cost Projection Plots

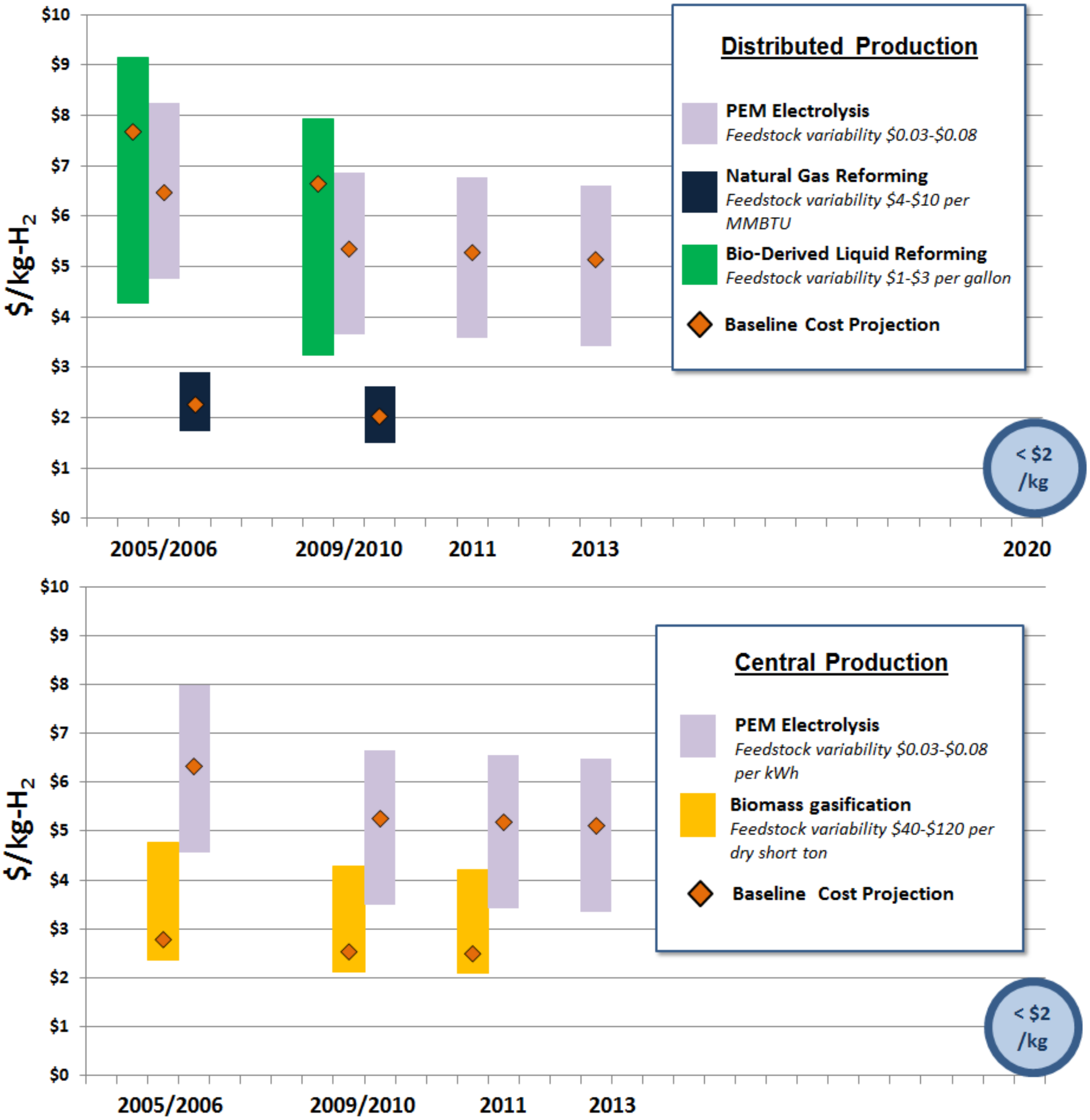


**Figure 1. Hydrogen production cost ranges (un-dispensed and untaxed, reported in $2007) for distributed and central pathways, including feedstock and capital cost variability. Bars for different years in each pathway reflect documented technology improvements for the pathway in the corresponding time period.[9]**

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[9] The documented references for each pathway and each time period are included in Tables 2 through 6.

## Pathway-Specific H2A v3 Analysis Summaries

The following tables provide additional information detailing the assumptions and calculations used in the H2A v3 analysis of cost ranges for each of the production pathways represented in Figure 1.

### Table 2. Distributed Natural Gas Reforming

| Year | Capital [a] | O&M [b] | Feedstock [c] | Other [d] | Production Total |
|---|---|---|---|---|---|
| | **Low-End Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $0.74 | $0.25 | $0.62 | $0.13 | $1.74 |
| **2009/2010** | $0.56 | $0.19 | $0.62 | $0.13 | $1.50 |
| | **Baseline Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $0.76 | $0.25 | $1.14 | $0.12 | $2.27 |
| **2009/2010** | $0.58 | $0.19 | $1.14 | $0.12 | $2.03 |
| | **High-End Cost Contributions [e] ($/kg in 2007$)** | | | | |
| **2005/2006** | $0.95 | $0.28 | $1.56 | $0.12 | $2.91 |
| **2009/2010** | $0.72 | $0.21 | $1.56 | $0.12 | $2.61 |

[a] Based on H2A v3 modeling of a 1,500 kg/day distributed production plant with a 20 year plant lifetime: The baseline capital cost input was $2,031,647 for the 2005/2006 case using capital cost assumptions from the 2006 Distributed Natural Gas Independent Assessment Report [3]; and $1,530,446 for the 2009/2010 case, based on the Current Forecourt Production Case Study for Distributed Natural Gas [18].

[b] Operations and maintenance (O&M) costs including related fixed costs.

[c] Feedstock costs for natural gas in the baseline case are obtained from the 2009 Annual Energy Outlook (AEO) reference [2], which includes yearly natural gas price fluctuations over the plant lifetime. Feedstock costs for the Low- and High-end cases are based on natural gas prices of $4.00 and $10.00/MMBTU, respectively, fixed over the plant lifetime; this price range is consistent with ranges in the AEO reference.

[d] "Other" costs include decommissioning costs, and other variable costs, including utilities.

[e] The high-end cases include a capital cost escalation factor of 1.3 to account for uncertainty in the baseline capital cost estimates.

**Table 3. Distributed PEM Electrolysis**

| Year | Low-End Cost Contributions ($/kg in 2007$) | | | | |
|---|---|---|---|---|---|
| | Capital [a] | O&M [b] | Feedstock [c] | Other [d] | **Production Total** |
| **2005/2006** | $2.36 | $0.72 | $1.64 | $0.04 | $4.76 |
| **2009/2010** | $1.51 | $0.47 | $1.64 | $0.03 | $3.65 |
| **2011** | $1.46 | $0.45 | $1.64 | $0.03 | $3.58 |
| **2013** | $1.35 | $0.42 | $1.64 | $0.02 | $3.43 |
| | **Baseline Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $2.36 | $0.72 | $3.34 | $0.05 | $6.47 |
| **2009/2010** | $1.51 | $0.47 | $3.34 | $0.03 | $5.35 |
| **2011** | $1.46 | $0.45 | $3.34 | $0.03 | $5.28 |
| **2013** | $1.35 | $0.42 | $3.34 | $0.03 | $5.14 |
| | **High-End Cost Contributions [e] ($/kg in 2007$)** | | | | |
| **2005/2006** | $3.02 | $0.82 | $4.37 | $0.05 | $8.26 |
| **2009/2010** | $1.94 | $0.53 | $4.37 | $0.03 | $6.87 |
| **2011** | $1.87 | $0.51 | $4.37 | $0.03 | $6.78 |
| **2013** | $1.73 | $0.47 | $4.37 | $0.03 | $6.60 |

[a] Based on H2A v3 modeling of a 1,500 kg/day distributed production plant with a 20 year plant lifetime: The baseline capital costs include uninstalled stack capital costs of $1,100, $500, $463, and $381 per kW in years 2005/2006, 2009/2010, 2011, and 2013, respectively. These inputs result in total capital cost inputs of $7,688,106, $4,926,306, $4,755,995, and $4,398,802, respectively. See references [7], [8], [9], and [10].

[b] Operations and maintenance (O&M) costs including related fixed costs.

[c] Feedstock costs for industrial electricity in the baseline case are obtained from the 2009 Annual Energy Outlook (AEO) reference [2], which includes yearly electricity price fluctuations over the plant lifetime. Feedstock costs for the Low- and High-end cases are based on industrial electricity prices of $0.03 and 0.08/kWh, respectively, fixed over the plant lifetime; this range is consistent with findings in the *2009 Independent Panel Review on Water Electrolysis* [11].

[d] "Other" costs include decommissioning costs, and other variable costs, including utilities.

[e] The high-end cases include a capital cost escalation factor of 1.3 to account for uncertainty in the baseline capital cost estimates.

### Table 4. Distributed Bio-Derived Liquids Reforming

| Year | Capital [a] | O&M [b] | Feedstock [c] | Other [d] | Production Total |
|---|---|---|---|---|---|
| | **Low-End Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $1.47 | $0.53 | $2.19 | $0.09 | $4.28 |
| **2009/2010** | $0.74 | $0.24 | $2.19 | $0.07 | $3.24 |
| | **Baseline Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $1.56 | $0.53 | $5.50 | $0.09 | $7.68 |
| **2009/2010** | $0.82 | $0.24 | $5.50 | $0.08 | $6.64 |
| | **High-End Cost Contributions [e] ($/kg in 2007$)** | | | | |
| **2005/2006** | $1.92 | $0.58 | $6.57 | $0.09 | $9.16 |
| **2009/2010** | $1.02 | $0.26 | $6.57 | $0.08 | $7.93 |

[a] Based on H2A v3 modeling of a 1,500 kg/day distributed production plant with a 20 year plant lifetime: The baseline capital cost input was $3,821,087 for the 2005/2006 case using capital cost assumptions from the 2003 Multi-Year Research, Development and Demonstration Plan [16]; and $1,906,631 for the 2009/2010 case, based on the *Current Forecourt Production Case Study for Distributed Bio-Derived Liquids* [17].

[b] Operations and maintenance (O&M) costs including related fixed costs.

[c] Feedstock costs for bio-derived liquids (e.g., ethanol) in the baseline case are obtained from the 2009 Annual Energy Outlook (AEO) reference [2], which includes yearly feedstock price fluctuations over the plant lifetime. Feedstock costs for the Low- and High-end cases are $1.00 and $3.00/gallon of ethanol, respectively, fixed over the plant lifetime; this price range is consistent with ranges in the AEO reference.

[d] “Other” costs include decommissioning costs, and other variable costs, including utilities.

[e] The high-end cases include a capital cost escalation factor of 1.3 to account for uncertainty in the baseline capital cost estimates.

### Table 5. Central PEM Electrolysis

| Year | Capital [a] | O&M [b] | Feedstock [c] | Other [d] | Production Total |
|---|---|---|---|---|---|
| | Low End Cost Contributions ($/kg in 2007$) | | | | |
| 2005/2006 | $2.27 | $0.65 | $1.63 | $0.01 | $4.56 |
| 2009/2010 | $1.41 | $0.43 | $1.63 | $0.01 | $3.48 |
| 2011 | $1.36 | $0.42 | $1.63 | $0.00 | $3.41 |
| 2013 | $1.31 | $0.40 | $1.63 | $0.01 | $3.35 |
| | Baseline Cost Contributions ($/kg in 2007$) | | | | |
| 2005/2006 | $2.28 | $0.65 | $3.38 | $0.02 | $6.33 |
| 2009/2010 | $1.43 | $0.43 | $3.38 | $0.01 | $5.25 |
| 2011 | $1.37 | $0.42 | $3.38 | $0.01 | $5.18 |
| 2013 | $1.33 | $0.40 | $3.38 | $0.01 | $5.12 |
| | High End Cost Contributions [e] ($/kg in 2007$) | | | | |
| 2005/2006 | $2.88 | $0.74 | $4.34 | $0.02 | $7.98 |
| 2009/2010 | $1.80 | $0.48 | $4.34 | $0.02 | $6.64 |
| 2011 | $1.74 | $0.47 | $4.34 | $0.01 | $6.56 |
| 2013 | $1.67 | $0.45 | $4.34 | $0.02 | $6.48 |

[a] Based on H2A v3 modeling of a 50,000 kg/day central production plant with a 40 year plant lifetime: The baseline capital costs include uninstalled stack capital costs of $1,100, $500, $463, and $381 per kW in years 2005/2006, 2009/2010, 2011, and 2013, respectively. These inputs result in total capital cost inputs of $251,930,601, $156,169,777, $150,264,527, and $143,880,472, respectively. See references [7], [8], [9], and [10].

[b] Operations and maintenance (O&M) costs including related fixed costs.

[c] Feedstock costs for industrial electricity in the baseline case are obtained from the 2009 Annual Energy Outlook (AEO) reference [2], which includes yearly electricity price fluctuations over the plant lifetime. Feedstock costs for the Low- and High-end cases are based on industrial electricity prices of $0.03 and 0.08/kWh, respectively, fixed over the plant lifetime; this range is consistent with findings in the *2009 Independent Panel Review on Water Electrolysis* [11].

[d] “Other” costs include decommissioning costs, and other variable costs, including utilities.

[e] The high-end cases include a capital cost escalation factor of 1.3 to account for uncertainty in the baseline capital cost estimates.

### Table 6. Central Biomass Gasification

| Year | Capital [a] | O&M [b] | Feedstock [c] | Other [d] | Production Total |
|---|---|---|---|---|---|
| | **Low End Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $1.09 | $0.29 | $0.61 | $0.38 | $2.37 |
| **2009/2010** | $0.86 | $0.26 | $0.61 | $0.39 | $2.12 |
| **2011** | $0.83 | $0.26 | $0.61 | $0.38 | $2.08 |
| | **Baseline Cost Contributions ($/kg in 2007$)** | | | | |
| **2005/2006** | $1.10 | $0.29 | $1.01 | $0.38 | $2.78 |
| **2009/2010** | $0.87 | $0.26 | $1.01 | $0.39 | $2.53 |
| **2011** | $0.84 | $0.26 | $1.01 | $0.38 | $2.49 |
| | **High End Cost Contributions [e] ($/kg in 2007$)** | | | | |
| **2005/2006** | $2.13 | $0.43 | $1.83 | $0.38 | $4.77 |
| **2009/2010** | $1.69 | $0.36 | $1.83 | $0.39 | $4.27 |
| **2011** | $1.63 | $0.36 | $1.83 | $0.38 | $4.20 |

[a] Based on H2A v3 modeling of a 50,000 kg/day central production plant with a 40 year plant lifetime: The baseline cost includes total direct capital cost of 225, 177, and 170 million dollars ($2007) in years 2005/2006, 2009/2010, and 2011, respectively. These inputs result in total capital cost inputs of $321,890,212, $253,730,212, and $243,790,212, respectively. See references [12], [13], and [14].

[b] Operations and maintenance (O&M) costs including related fixed costs.

[c] Feedstock costs for biomass (e.g., woody biomass) reflect the H2A default, with biomass prices and heating value derived from the Bioenergy Technologies Office (BETO) 2011 Multi-Year Program Plan [19] (Table B-4, and B-7, respectively). Feedstock costs for the Low- and High-end cases are based on feedstock costs of $40 and $120 per dry short ton for woody biomass, respectively, fixed over the plant lifetime; this range is consistent with findings in the independent report *The Hydrogen Production Cost Estimate Using Biomass Gasification* [15].

[d] "Other" costs include decommissioning costs, and other variable costs, including utilities.

[e] Findings of *The Hydrogen Production Cost Estimate Using Biomass Gasification* [15] show capital costs approximately 2x those reported in references [12], [13], and [14]. To reflect this level of uncertainty in the baseline cases, a capital cost escalation factor of 2 was used in the high-end cases.

**Note:** This record is a revision of record #12002 with updated H2A version 3 analyses of all reported production pathways. In addition to input from technology-specific developers, this record has been peer-reviewed by Brian James (Strategic Analysis, Inc.), Todd Ramsden (National Renewable Energy Laboratory), Fred Joseck (DOE FCTO), and Tien Nguyen (DOE FCTO).

## References


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[15] *Hydrogen Production Cost Estimate Using Biomass Gasification,* NREL (2011), NREL/BK-6A10-51726, http://1.usa.gov/1qqECOy

[16] *Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan: Planned program activities for 2003-2010*, U.S. Department of Energy (2003), p. 3-11, http://1.usa.gov/VGXT6d

[17] *Current Forecourt Hydrogen Production from Ethanol 1500 kg per day version 3.0*, B. James, et. al., March 2012, http://1.usa.gov/1pVahev

[18] *Current Forecourt Hydrogen Production from Natural Gas 1500 kg per day version 3.0*, B. James, et. al., March 2012, http://1.usa.gov/1pVahev

[19] *Biomass Multi-Year Program Plan*, U.S. Department of Energy (2011), Table B-4 and B-7. http://1.usa.gov/1lKpvUe