Elsevier Editorial System(tm) for Energy Policy

Manuscript Draft

Manuscript Number:

Title: H2POWER: DEVELOPMENT OF A METHODOLOGY TO CALCULATE LIFE CYCLE COST OF SMALL AND MEDIUM-SCALE HYDROGEN SYSTEMS

Article Type: Full Length Article

Section/Category:

Keywords: hydrogen; refueling; life cycle

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Manuscript Region of Origin:

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# H2POWER: DEVELOPMENT OF A METHODOLOGY TO CALCULATE LIFE CYCLE COST OF SMALL AND MEDIUM-SCALE HYDROGEN SYSTEMS

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## Abstract:

At this time, hydrogen-based power plants and large hydrogen production facilities are capital intensive and unable to compete financially against hydrocarbon-based energy production facilities. An option to overcome this problem and foster the introduction of hydrogen technology, is to introduce small and medium-scale applications such as residential and community hydrogen refueling units. Such units could potentially be used to generate both electricity and heat for the home, as well as hydrogen fuel for the automobile. Cost modeling for the integration of these three forms of energy presents several methodological challenges. This is particularly true since the technology is still in the development phase and both the financial and the environmental cost must be calculated using mainly secondary sources. In order to address these issues and aid in the design of small and medium-scale hydrogen refueling, this study presents a computer model to calculate financial and environmental costs of this technology using different hydrogen pathways. The model can design and compare hydrogen refueling units against hydrocarbon-based technologies, including the "gap" between financial and economic costs. Using the methodology, various penalties and incentives that can foster the introduction of hydrogen-based technologies can be added to the analysis to study their impact on financial cost.

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## Introduction:

Hydrogen is an energy carrier that can be used to generate electricity and heat with little or no emissions and can be produced from a variety of domestic feedstock. In the future, hydrogen could replace gasoline and diesel to power vehicles, thus considerably reducing the amount of pollutants generated from the tailpipes of automobiles. At this time, however, hydrogen production is expensive; at its current cost it can not compete against gasoline as an automobile fuel (EERE 2003), nor against existing residential heating or electric power systems.

At present, there is no infrastructure to produce, transport and deliver hydrogen throughout the country. Several pathways and technologies are being studied to provide affordable hydrogen to power homes, factories, automobiles and other equipment that run on electricity. In the meantime, transitional strategies are needed to introduce hydrogen to the public and test the technology (EERE 2004). One of these strategies is the use of small to medium hydrogen production systems that can be used to provide energy for the home. When hydrogen-fueled vehicles become available, these home hydrogen systems could also be used to supply fuel for the automobile. A modular design of the system could allow scaling up hydrogen production if this becomes necessary.

This paper will describe a methodology used to build a computer-based model (called H2POWER) to design small and medium hydrogen fuel refueling systems and estimate their associated financial and environmental costs. These systems provide electricity and heat to meet the energy demands of either 1) a home and automobile or 2) a cluster of homes and a number of automobiles. The approach also compares the results against a Baseline of conventional energy sources for the home and the automobile. The resulting costs are given for two different perspectives: homeowner and developer.

## Definitions

Hydrogen Refueling Unit (HRU): A system that can generate hydrogen through a steam methane reformer or electrolyzer and send it to a fuel cell to obtain electricity for a single home or a small cluster of homes (e.g., 1-6 homes + 2 automobiles). The system is capable of recovering waste heat from the fuel cell to obtain space and/or water heating. Additionally, the system can produce hydrogen to refuel at least one automobile. Typical power generation for an HRU in the analysis is 6,000 kWh/year of electricity, 17,000 kWh/year of space heat and 5,000 kWh/year of water heat and 400 kg $H_2$/year.

Neighborhood Refueling Unit (NRU): A system with the same technical specifications and functions as the HRU, but scaled up to provide heat, electricity and transportation fuel for a co-located neighborhood or community. The system comprises a dedicated hydrogen auto fuel dispensing station, a dedicated facility with support personnel and power distribution infrastructure. Due to their large capacities, the cost of the components of the NRU differ from those in the HRU in that they are built of different materials and specifications, have different economies of scales and efficiencies, and therefore, are modeled based on different data.

Baseline: Homes meet their electricity demand using the existing utility grid, which generates most of its output using fossil fuels such as coal and natural gas. Residential space heat is generated with a furnace that feeds on a hydrocarbon-based fuel and water heat is obtained from a boiler that also consumes a hydrocarbon-based fuel. Automobiles are refueled with gasoline, diesel or natural gas.

Life Cycle Costing: This is a discounted cash flow methodology to calculate all monetary inflows and outflows that occur during the life of a system, from the initial capital cost of the system to operation to equipment disposal. In H2POWER, the life cycle cost analysis is an evaluation of both financial and monetized environmental costs incurred during the life cycle of an HRU, and NRU and a Baseline.

Environmental Externalities: An externality is an unintended side-effect generated by an economic activity. Externalities can be positive or negative, and are not internalized in the price that the consumer pays for the product generated by the economic activity. Environmental externalities such as air pollution from tailpipes and factory stacks have mainly negative effects, as they can harm human health and the environment (Owen, Anthony D. 2004).

Externality Adders: This is simply the monetary unit in which externalities are measured. Once the effects of an externality have been established and their monetary value has been measured, a dollar per unit of product must be assigned to the externality in order to be able to compare it against other externalities. For instance, the externalities generated by carbon dioxide ($CO_2$) emitted from a gasoline vehicle can be measured in dollars per gallon of gasoline, dollars per kilometer (depending on the fuel efficiency of the vehicle) and dollars per kilogram of $CO_2$ emitted (Owen, Anthony D. 2004).

## Model description

When a new run is started in H2POWER, the model prompts the user to define the Baseline by providing information about the hourly and monthly energy loads of the average home of the current project, type of fuel and technology used for space and water heating, type of vehicle and type of vehicle fuel. The user can also specify the utility grid mix or use the average US grid mix as defined by the Energy Information Administration (EIA).

After defining Baseline conditions, the user must define technologies, pathways and feedstock for the HRU and/or NRU. If the user decides to power the hydrogen system with renewable energy, the user will also have to define whether a wind turbine or PV array will be used, and indicate backup power and storage assumptions. In this case, the user should define the wind and/or sunlight conditions of the project.

The user can specify the characteristics of the components of the HRU and NRU or use the “default values” from the model. A graphic representation of the technologies that must be specified for the HRU and NRU is shown in Figure 1.

The user interface prompts the user to define the characteristics of the following components of an HRU and an NRU (some of the inputs are optional):

- Hydrogen storage: the user must specify type of storage tank, pressure and additional storage capacity
- Hydrogen production: the user must select between a steam methane reformer and an electrolyzer. If desired, the user can also specify efficiency, power demand, maintenance cost and physical life or accept the default inputs.
- Fuel Cell: a fuel cell is an electrochemical device that separates the positive ions (protons) of the hydrogen molecule from the negative (electrons), and sends the electrons to an electric circuit to produce electricity; the byproducts of this device are heat and water. Besides the type of fuel cell, the user can specify maintenance cost, physical life and general characteristics used to calculate the price of the fuel cell.
- Compressor: the compressor increases the pressure of the hydrogen gas so that it flows more quickly to the storage tanks. The user also has the possibility to specify power demand, O&M cost and physical life.
- Auto Fuel Dispenser: the dispenser is a machine that can provide hydrogen to a hydrogen-powered automobile by injecting it in the storage tank of the vehicle using a special hose. Additional characteristics that the user can

input include electricity demand, O&M cost, physical life, average dispensing time, discharge limit of battery and voltage. In the case of the NRU, the user must specify the number of dispensers that will be installed to refuel the vehicles in the neighborhood.

For each of the above pieces of equipment, unit cost is calculated based on a user assumption about the production volume for commercial manufacturing and related cost data based on available industry studies.

- <u>Supplemental electricity:</u> certain components of the NRU and the HRU require electricity to operate. This external electricity to feed the system components contributes to the total socioeconomic cost of the system. When the electricity is supplied by the existing utility grid, most of the electricity would typically be produced using non-renewable resources such as coal, which generate environmental externalities, whereas when the electricity is supplied by a renewable resource such as wind or sunlight, the production of electricity has few environmental externalities. When the user chooses to install either a wind turbine or a photovoltaic system (PV), H2POWER will interpret this as a hybrid system, in which most of the electricity will be provided by the turbine or the PV and peak loading demand will be covered by the hydrogen system.
    - <u>Existing utility grid:</u> the user must specify the electricity mix used by the utility company and the pollution control strategies installed at the power generation stations. Most of the electricity generated by utility companies in the U.S. comes from non-renewable fuels such as coal and natural gas, and a smaller part is

    generated using renewable sources such as geothermal and nuclear power.

  - Wind turbine: although it is not worth it to install a wind turbine to power an HRU that serves only one home, it might be worth it to use it when a small group of houses is connected. In order to size the turbine, the user must specify its height, wind speed, percentage of total power supplied by the turbine and whether batteries will be installed. Other non-default specifications such as O&M cost and physical life are optional.
  - Photovoltaics (PV): the user must specify the characteristics of the place where the PV cells will be installed, including orientation factor, annual kWh produced per 1 kW of DC array, percentage of panels on rooftop, cost of land (if any of the panels will be installed on land) and whether or not the system will include batteries. Optional specifications include cost of installation, O&M cost, and specifications of the batteries.

As well as technical specifications and direct cost data, the interface allows the user to input penalties and incentives that can be implemented to make HRUs and NRUs more attractive for homeowners and developers. These include penalizing pollution generation and/or fuel consumption, raising the price of fuel at the pump, providing low sales tax, low interest loans, net metering and others.

After H2POWER performs all calculations, the results are displayed in ten different worksheets in a new spreadsheet file that opens automatically. The results are displayed in tables and charts.

## Methodology

Among other uses, the model was developed to determine the "gap" that exists between the monetized environmental benefits that would accrue to the nation from the development of local-scale hydrogen production facilities and the financial costs that face prospective homeowners and developers who might pursue such technologies, and to identify and evaluate incentives that are needed to encourage acquisition of such technologies despite the "gap." After capacity requirements are determined for each of the alternatives, the computer-based model (H2POWER) uses engineering economics to calculate the net present cost of those financial and monetized environmental cash flows associated with small and medium hydrogen technologies, as well as the Baseline, throughout a pre-defined study period. This provides a basis for comparing the afore-mentioned "gap".

Once the cash flows are calculated, the model computes the net present cost of the financial and environmental costs of each technology and compares them. Given the average energy loads of a home, H2POWER can calculate the capacity of each of the components of a Home Refueling Unit (HRU) and a Neighborhood Refueling Unit (NRU) and compare them to a Baseline (conventional energy).

## Model Construction

H2POWER was built on Microsoft Excel and Visual Basic and features an optional computational aid for Monte Carlo Simulation (@RISK, a Palisade Software). The applications of these statistical tools and the description of the methodology used in the H2POWER will be explained in this section.

### *Financial Analysis*

H2POWER contains data from the technical literature and when available, manufacturer specifications about each of the components of the HRU, NRU and Baseline. The data include: capital cost, operation and maintenance cost, installation cost, cost-volume escalation rates, efficiency, electric demand, and physical life.

To calculate the cost of a component, the cost variable is taken as the dependent variable (Y) and the cost-affecting variables (i.e. component size, volume of manufacturing production, efficiency, physical life) as the independent variables ($X_i$=$X_1$, $X_2$, $X_3$…). A multivariate statistical analysis is then conducted in order to construct a formula that can estimate the best value of Y for different values of $X_i$.

Since most costs vary with time, the model automatically brings costs up to date and estimates future costs using different price indices. Component costs in the Baseline (such as furnaces and boilers) are assumed to vary according to the consumer price index (CPI); therefore, the CPI is used to update the cost of all replacement components of the Baseline as required for subsequent years in the cash flow. Cost of components in HRU and NRU are normalized using the chemical engineering price index, and replacement costs calculated accordingly at the end of their useful lives.

Fuel and electricity costs are key factors in the total cost of the life cycle of each technology. For this reason, H2POWER gives the user the opportunity to decide what cost and cost escalation rate will be used to estimate the cost of fuel and electricity throughout the life cycle of the technology. The user can decide to use estimates from the Energy Information Administration (EIA) or use her/his own costs and escalation rates.

All costs in the cash flows are calculated in actual dollars. Cost normalization of other items such as maintenance, set up fees, taxes, installation and others is done using the CPI.

When all the costs have been estimated and normalized, they are compiled in a cash flow table that calculates the financial Net Present Cost (NPC) for the pathways and conditions selected by the user.

### *Environmental analysis*

The model contains two databases that contribute to the calculation of environmental costs: emissions rates and externality adders.

The emissions rates database is built from two sources: The first source is the AP-42 document from the Environmental Protection Agency (EPA 2005), which contains information about pollutants released to the atmosphere from mobile and stationary sources. The second source is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, which calculates energy requirements and emissions of different vehicle technologies throughout their life cycles.

The database of externality adders contains information selected from peer reviewed journals, the US government and the European Community. The pollutants for which externality adders were obtained include: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous dioxide ($N_2O$), volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), sulfur oxides (SOx) and lead (Pb). Since different studies report externality adders in different currencies and base years, values were converted to actual dollars using the CPI for all items. This database is used to build a probability distribution function for every pollutant and calculate externality adders for the project. The user can choose to calculate deterministic mean externality adders using a simple spreadsheet built-in formula or optionally utilize Monte Carlo simulation with @RISK.

Using both databases, the annual cash flow per pollutant is calculated using the formula shown in Figure 2.

Once the annual externality cost of each pollutant in the project has been calculated, the model proceeds to estimate future externality values throughout the life cycle of the components. Finally, H2POWER compiles all externalities in a cash flow table and calculates the environmental NPC for the pathways and conditions selected by the user.

## Case Study

Input assumptions and model outputs are provided for one case study. Energy loads are assumed for a prototypical home or "neighborhood" unit in the Washington, DC area (see TIAX 2002). Other "default values" for this example, such as electricity mix and fuel cost use national averages.

Inputs:

*General inputs:*

- Hourly and monthly energy loads
- First year of the project: 2006.
- Study period: 15 years.
- Nominal discount rate used to calculate net present costs: 4.6%[1].
- Inflation rate for environmental analysis: 1.9% (EERE 2005).
- Home description: 130 $m^2$, 3 bathrooms, 3 bedrooms
- Fuel costs will be calculated using EIA's estimations

*Baseline (conventional fossil fuels and utility grid for a given location):*

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[1] Based on 10 year minimal interest rate on treasury bonds.

- Electricity mix: US national average (see Figure 3) according to EIA (EIA 2005). Technology and efficiencies were selected based on the "AP-42" document of the EIA (EIA 2003)
- The pollution control strategies for the electric utility grid (see Figure 4) were selected based on the "AP-42" document (EIA 2003)
- Fuel for space heating: 100% Natural gas
- Vehicle type: Passenger car
- Fuel type: Conventional gasoline
- Number of vehicles per home: 2

*Hydrogen Refueling Unit (HRU)*:

- Number of homes: 6
- Source of hydrogen: Steam Methane Reformer (SMR)
- Volume of manufacturing production of SMRs: 100 units per year[2]
- Power source for hydrogen production: General grid
- Use same source to power components? Yes
- Fuel cell type: Polymer Electrolyte Membrane Fuel Cell (PEMFC)
- Volume of manufacturing production of fuel cells: 100 units per year
- Over design of fuel cell (overcapacity): 0%
- Hydrogen storage tank type: Composite
- Volume of manufacturing production of storage tanks: 1000 units per year
- Initial pressure: 0.12 MPa
- Storage pressure: 41.3 MPa
- Volume of manufacturing production of compressor: 100 units per year

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[2] The volume of manufacturing production of the components is used to calculate component cost.

- Number of vehicles per home: 2
- Vehicle's hydrogen storage capacity: 5 kg
- Vehicle's tank storage pressure: 40 MPa
- System's configuration: The system will produce electricity and water heating for the home and hydrogen for the automobile (configuration no. 3)
- Volume of manufacturing production of dispenser: 100 per year
- Vehicle's hydrogen storage capacity: 5 kg
- Vehicle's tank storage pressure: 40 MPa

*Neighborhood Refueling Unit (NRU, same as HRU, except for the following)*:

- Number of homes: 400
- Storage pressure: 24 MPa (booster compressor will be used to reach vehicle's storage pressure)
- Number of dispensers per station: 6
- Volume of manufacturing production of dispenser: 1,000 per year

Note also that modeling differences for the NRU include the cost calculation of a service station for hydrogen refueling, power transmission infrastructure and O&M personnel, as well as the use of different data, multivariate analyses and equations to calculate cash flows.

The rest of the inputs were be automatically defined by H2POWER using default values. H2POWER calculates how different penalties and incentives affect the results of the project. However, no penalties or incentives were used in this example.

## Results:

Some of the results generated after H2POWER completed all calculations are described below:

For every alternative (Baseline, HRU and NRU), H2POWER calculates the net present cost for the system and for each of the components. Figure 5 shows a breakdown of the net present cost of an HRU at the financial level. Based on the inputs given to this particular example, the most expensive item for the Baseline system is the heat generation component, and for the HRU and the NRU, the most expensive item is the cost of fuel. This means that natural gas has great influence on the net present cost of the three alternatives.

In order to calculate the life cycle of the Baseline, HRU and NRU, H2POWER designs the system components by calculating their capacities using an iterative process. The HRU component design for this example is shown in Table 1.

H2POWER can also calculate the "gap" between financial and environmental net present costs. The financial NPC to the homeowner is presented given three different options: Baseline, HRU and NRU. As seen in Table 2, the results indicate that the aggregated NPC per home of the NRU is higher than the NPC per home of the other two options. However, the NRU has the lowest environmental cost. The minimum incentive needed by the homeowner to make HRUs competitive compared to conventional technology is $23,463, which is considerably lower than the maximum incentive that the government should offer to avoid externalities associated with conventional energy sources. This is the financial "gap" between financial and environmental cost. Given the inputs of the current project, the NPC per home of the NRU is greater than the NPC of the HRU, but it offers greater socioeconomic savings. Therefore, it is worth it to provide incentives to bridge the "gap" for the pathways selected for the HRU and the NRU.

H2POWER also calculates the present cost of each of the alternatives from a developer's perspective. For the developer, the financial cost of the technology does not include operation and maintenance. Therefore, the incentives needed by the developer to use hydrogen technology are lower than the incentive needed by the homeowner.

H2POWER calculates net present cost of environmental externalities for the three options (Baseline, HRU and NRU) and breaks it down to show how the externalities are generated. Figure 6 shows the breakdown of the net present cost of the externalities for an HRU (environmental analysis). In this case, heat generation was the item that generated the most externalities. When the three options are compared, it is apparent that the hydrogen-based alternatives generate four to five times less externalities than the Baseline (see Table 2).

H2POWER can also calculate the upstream and downstream emissions of each option throughout its life cycle. The upstream emissions represent all the pollutants generated before the generation of electricity (i.e. during extraction and transportation), while the downstream emissions show the amount of pollutants that are generated during electricity production. For this example,

Figure 7 shows the comparison between pollutants emitted by an HRU and an NRU and the Baseline. H2POWER calculated that the Baseline configuration will generate 111,230 kg of pollutants throughout its life (15 years), while the HRU will generate 15,495 kg and the NRU 14,065 kg.

The results file generated by the H2POWER spreadsheet displays a sensitivity analysis of the financial and environmental costs given different combinations of configuration type (electricity +/- space heat +/- water heat +/- automobile fuel) and number of houses. The net present costs for the HRU and NRU can only be fairly compared when the same pathway is selected for both alternatives (like in this example). The results show that for every configuration of the HRU, the financial cost per home decreases when the number of houses connected increases, and appears to remain constant after 8 houses. As expected, for the NRU, the cost per home decreases as more capacity is added, which is due to the economies of scale; as capacity increases, the cost of production per unit of capacity decreases.

The costs of fuel and electricity have a strong influence over the NPC of the Baseline, HRU and NRU because in this example, all three alternatives are connected to the existing utility grid and all three alternatives utilize natural gas. The results demonstrate that the NPC of the Baseline is highly sensitive to the cost of natural gas and gasoline and slightly less sensitive to the cost of electricity. The charts also demonstrate that for the selected pathway, the sensitivity of the HRU and the NRU NPCs to the cost of fuel and electricity is lower relative to the sensitivity of the Baseline NPC.

## Additional Simulations:

In order to compare the results of different combinations of inputs, five additional cases were tested in H2POWER. Table 3 displays the inputs and Table 4, Figure 8 and Figure 9 the outputs.

## Conclusions:

H2POWER facilitates the easy analysis of financial and environmental life cycle costs of small and medium hydrogen-based refueling systems. The methodology built in the software is an attempt to forecast and evaluate the financial viability of interconnection between hydrogen production and end use. H2POWER establishes a comprehensive basis for both cost analysis of alternative system design configurations and policy analysis for financial incentives to encourage the utilization of cleaner technologies.

H2POWER is not intended to find the exact capital and net present cost of a pathway. The model should be used for relative comparisons among options to select an alternative over another, aid in system design and specification of components and to test the relative magnitude of various penalties and incentives.

One of the greatest strengths of the methodology is that it provides great flexibility, which allows the user to input and test a large number of scenarios including different energy loads, fuel types, vehicle types, electricity mixes, technologies and equipment.

The methodology presented in this study is only one attempt to model small to medium-scale renewable energy systems. Other methodologies powered by different, more powerful computational aids should be used to allow a greater array of pathways, technologies and processes.

Because of the lack of publicly available cost information, much of the data used in H2POWER to calculate financial costs of hydrogen technologies were obtained from secondary sources. The cost database in the model will need to be updated as these technologies transition to the commercialization phase and cost information becomes available.

**References:**

US DOE Energy Efficiency and Renewable Energy (EERE). 2003 *Hydrogen Basics*. http://www.eere.energy.gov/RE/hydrogen_basics.html (accessed October 2005).

US DOE Energy Efficiency and Renewable Energy (EERE). 2004. *Hydrogen Posture Plan*. Washington, DC

US DOE. Energy Efficiency and Renewable Energy (EERE). 2005. Hydrogen, Fuel Cells and Infrastructure Technologies Program: DOE H2A Analysis Group http://www.eere.energy.gov/hydrogenandfuelcells/analysis/analysis_group (accessed March 2005).

Energy Information Administration (EIA). 2003. Technology Transfer Network Clearinghouse for Inventories & Emission Factors. Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources." http://www.epa.gov/ttn/chief/ap42/index.html (accessed August 2004).

Energy Information Administration (EIA). 2005. Annual Energy Outlook 2005 with projections to 2025 http://www.eia.doe.gov/oiaf/aeo/download.html (accessed June 2005).

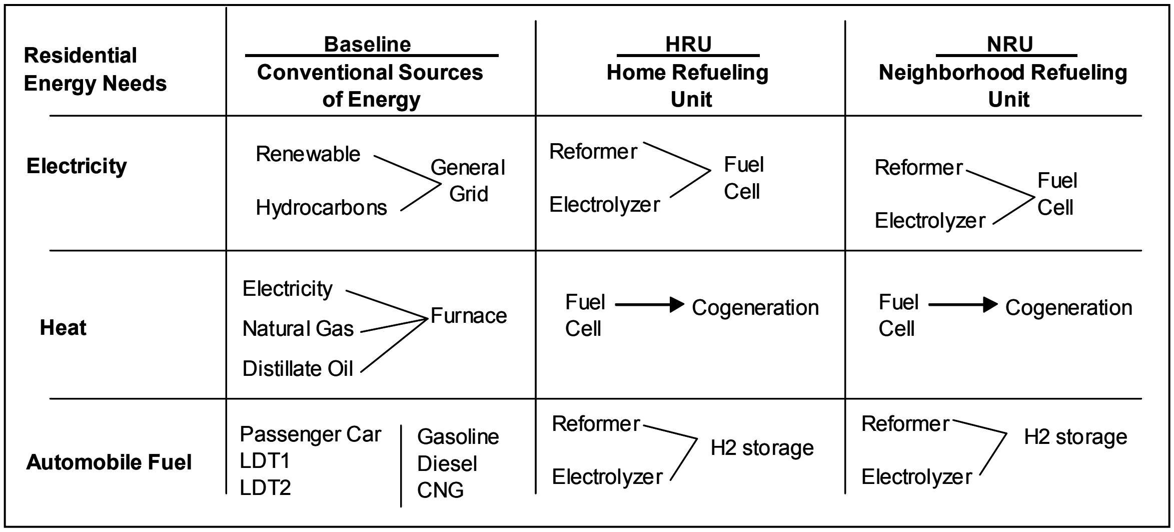
Environmental Protection Agency (EPA). 2005. Emissions Factors & AP 42 http://www.epa.gov/ttn/chief/ap42/ (accessed January 2006)

Owen, Anthony D. 2004. *Environmental Externalities, Market Distortions and the Economics of Renewable Energy Technologies*. The Energy Journal 25, (3): 127-156.

TIAX LLC. 2002. Grid-independent Residential Fuel-Cell Conceptual Design and Cost Estimate" http://www.netl.doe.gov/coal/Distributed%20Generation/publications/gridindependentresidentialfuelcellconcept.pdf (accessed March 2004).

The White House. 1992. Circular No. A-94. Revised (Transmittal Memo No. 64). MEMORANDUM FOR HEADS OF EXECUTIVE DEPARTMENTS AND ESTABLISHMENTS SUBJECT: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. http://www.whitehouse.gov/omb/circulars/a094/a094.html (accessed June 2004).

# Figures and Tables



| Residential Energy Needs | Baseline<br>Conventional Sources of Energy | | HRU<br>Home Refueling Unit | NRU<br>Neighborhood Refueling Unit |
|---|---|---|---|---|
| Electricity | Renewable<br>Hydrocarbons → General Grid | | Reformer<br>Electrolyzer → Fuel Cell | Reformer<br>Electrolyzer → Fuel Cell |
| Heat | Electricity<br>Natural Gas<br>Distillate Oil → Furnace | | Fuel Cell → Cogeneration | Fuel Cell → Cogeneration |
| Automobile Fuel | Passenger Car<br>LDT1<br>LDT2 | Gasoline<br>Diesel<br>CNG | Reformer<br>Electrolyzer → H2 storage | Reformer<br>Electrolyzer → H2 storage |

NOTE: Passenger Car: <6000 lbs, Light Duty Truck 1 (LDT1): <6000 lbs and LDT2 (LDT2): 6000 – 8000 lbs.

**Figure 1.** General description of energy pathways for every alternative.

(kg pollutant/ kg fuel)*(USD/kg pollutant)*(kg fuel/year)= USD/year

Emissions rates database: pollutants generated by each component throughout their life cycle:

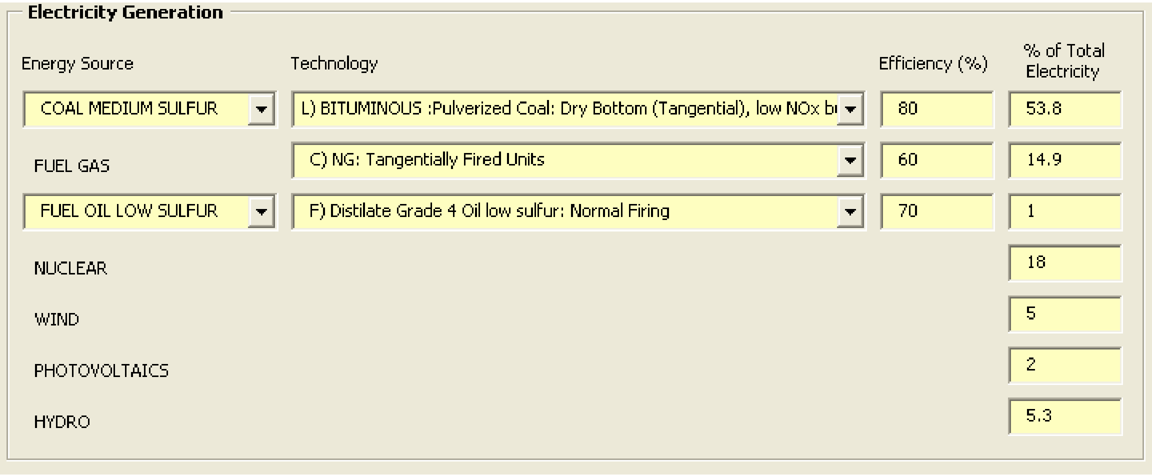
- Extraction
- Refining
- Distribution
- Consumption

Externality adders database:
Two options:
1) @RISK calculates best probability distribution and mean
2) Excel calculates simple mean

Calculated with average US data or user input

Annual externality cost of pollutant

**Figure 2.-** Description of Formula Used to Calculate Monetary Environmental Cash Flows



**Electricity Generation**

| Energy Source | Technology | Efficiency (%) | % of Total Electricity |
|---|---|---|---|
| COAL MEDIUM SULFUR | L) BITUMINOUS :Pulverized Coal: Dry Bottom (Tangential), low NOx b | 80 | 53.8 |
| FUEL GAS | C) NG: Tangentially Fired Units | 60 | 14.9 |
| FUEL OIL LOW SULFUR | F) Distilate Grade 4 Oil low sulfur: Normal Firing | 70 | 1 |
| NUCLEAR | | | 18 |
| WIND | | | 5 |
| PHOTOVOLTAICS | | | 2 |
| HYDRO | | | 5.3 |

**Figure 3.-** Electricity mix using sources, technologies, efficiencies and electricity mix chosen as inputs for the current example.

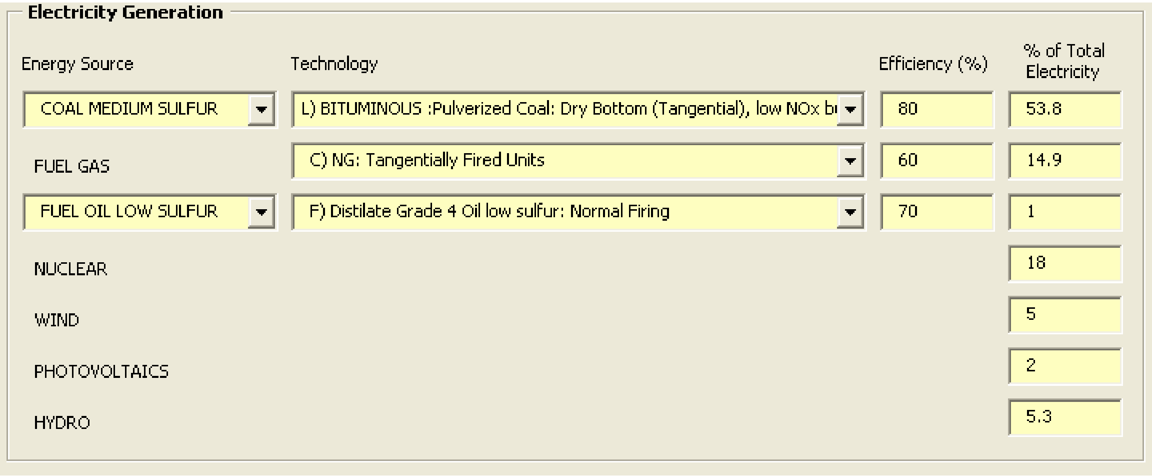


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**Figure 4.-** Electricity mix using sources, technologies, efficiencies and electricity mix chosen as inputs for the current example.

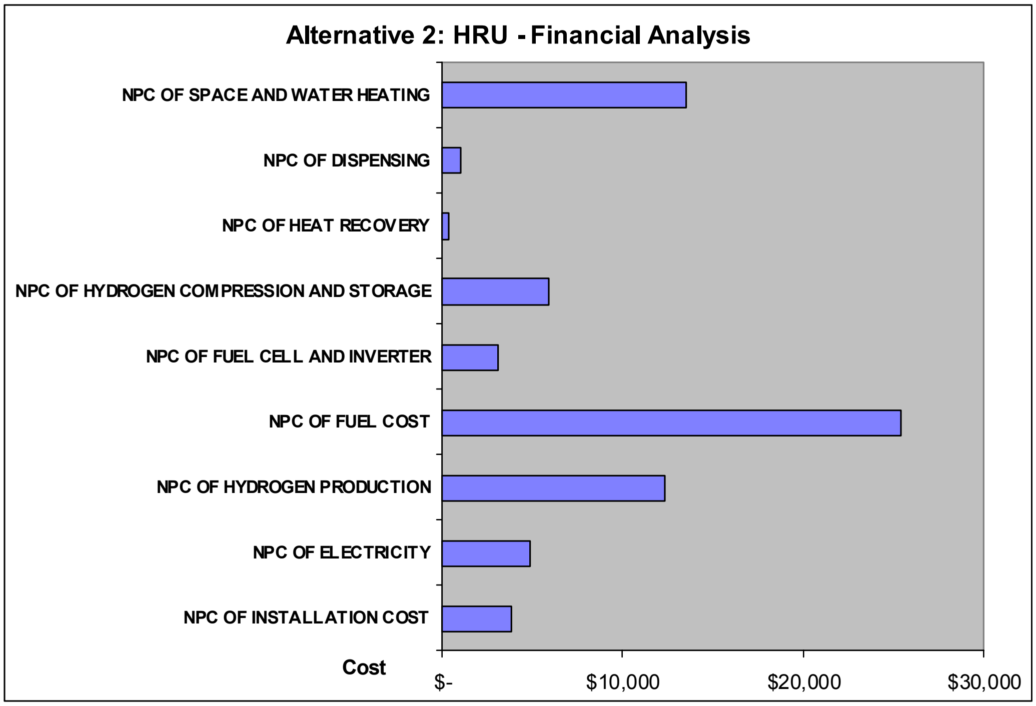

**Figure 5.-** Financial cost breakdown of Home Refueling Unit (HRU)

| Home Refueling Unit | | | | |
|---|---|---|---|---|
| Total | $ 22,450.33 | Number of homes: | | 6 |
| **Components** | **Cost per Home** | **Total Cost** | **Capacity** | **Units** |
| Reformer | $ 8,480.52 | $ 50,883.15 | 30.03 | kgH2/d |
| Electrolizer | $ - | $ - | 30.03 | kgH2/d |
| Wind Turbine | $ - | $ - | - | kWh/y |
| PV system | $ - | $ - | 0 | |
| Fuel Cell | $ 3,064.26 | $ 18,385.58 | 18.90 | kW |
| Compressor | $ 2,703.85 | $ 16,223.09 | 0.96 | kgH2/h |
| Storage Tanks | $ 3,898.74 | $ 23,392.46 | 60 | kg of H2 |
| Heat Recovery | $ 235.01 | $ 1,410.05 | 55% | % heat recovery |
| Auto-Fuel Dispenser | $ 1,028.20 | $ 6,169.18 | Fill 5 kg H2 tank in7 minutes | |
| Boiler | $ 3,039.75 | $ 18,238.48 | 6570 | kWh/y |
| Furnace | $ - | $ - | 0 | kWh/y |

**Table 1.-** Home Refueling Unit: Results of Systems Integration and Component Sizing (H2POWER Results).

| HOMEOWNER AND SOCIETY PERSPECTIVES (15 YEAR LIFE CYCLE) | | | | | |
|---|---|---|---|---|---|
| ALTERNATIVES | NET PRESENT COST OF ENERGY GENERATION (FINANCIAL LEVEL): | NET PRESENT COST OF EXTERNALITIES (ENVIRONMENTAL LEVEL): | MINIMUM INCENTIVE NEEDED BY HOMEOWNER | MAXIMUM INCENTIVE THAT THE GOVERNMENT SHOULD OFFER | COMMENTS |
| BASELINE | $ 46,914 | $ 96,711 | | | |
| HRU | $ 70,221 | $ 41,173 | $ 23,463 | $ 55,538 | GOVERNMENT SHOULD OFFER INCENTIVES |
| NRU | $ 67,736 | $ 44,261 | $ 20,822 | $ 52,450 | GOVERNMENT SHOULD OFFER INCENTIVES |

**Table 2.-** Homeowner and government perspectives for Baseline, HRU and NRU give the inputs for this example (H2POWER results).

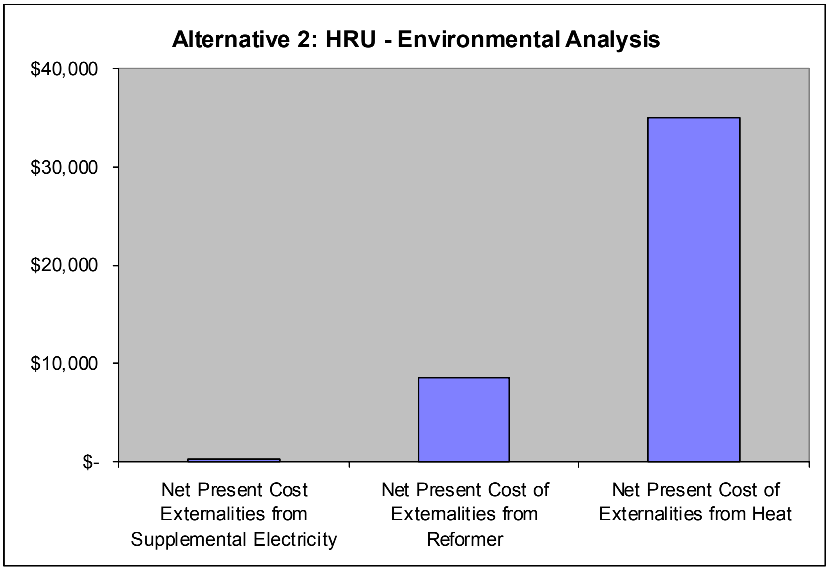

**Figure 6.-** Socioeconomic cost breakdown of Home Refueling Unit (HRU)

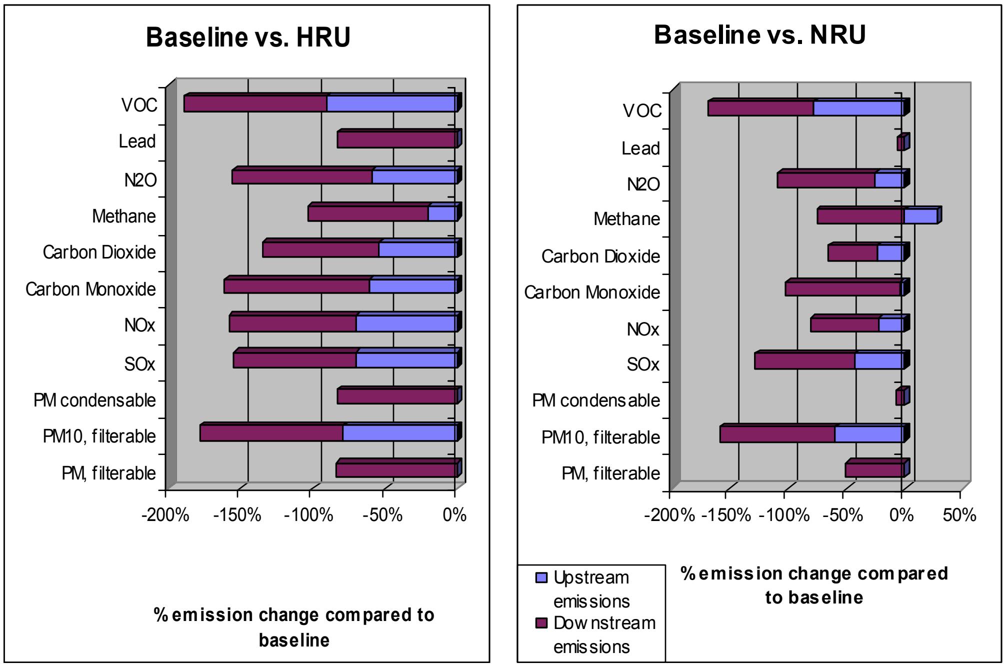

**Figure 7.-** Percentage of pollutants emitted from an HRU and an NRU compared to the Baseline (H2POWER results).

| Table of Inputs | | | | | |
|---|---|---|---|---|---|
| **Simulation** | **$H_2$ Source** | **Electricity Source** | **Number of homes** | **Penalties and Incentives** | **Other** |
| Base Case | SMR | Grid | 6 | - | |
| | SMR | Grid | 400 | - | |
| 1 | Electrolyzer | Grid | 6 | Emission penalties (\$/kg): PM: 0.002, SOx: 0.005, NOx: 0.005, CO: 0.01, $CO_2$: 0.03, $CH_4$: 0.06 , $N_2O$: 0.1, and Pb: 0.5 | Vehicle fuel: natural gas |
| | Electrolyzer | Grid | 400 | | |
| 2 | Electrolyzer | Wind/grid[1] | 8 | Incentives: 0% sales tax on wind turbine, \$0.05/W and 50% net metering[2] at \$0.05/kWh | - |
| | Electrolyzer | Wind/grid | 500 | | - |
| 3 | Electrolyzer | PV[3]/grid | 8 | Incentives: 0% sales tax on PV, \$0.05/W and 80% net metering[2] at \$0.05/kWh | Configuration 1: Electricity, hydrogen for the automobile plus heat recovery for water heating |
| | Electrolyzer | PV/grid | 500 | | |
| 4 | SMR | Wind/grid | 6 | Incentives: 0% sales tax on wind turbine and 50% net metering[4] at \$0.05/kWh | Large volumes of production for HRU and NRU respectively (units/year): SMR: 10,000 and 1,000; fuel cell: 10,000 and 1,000; compressor: 10,000 and 1,000; storage tanks: 100,000 for both; and dispenser: 10,000 and 6,000 |
| | SMR | Wind/grid | 100 | | |
| 5 | SMR | Grid | 8 | Penalties: \$0.03/gallon diesel, \$0.03/kg $CO_2$, \$0.5/kg Pb, \$0.01/kg NOx and \$0.1/kg $N_2O$ | Vehicle: LDT1 (light duty truck < 6,000 lbs or 2721 kg)<br>Vehicle Fuel: Conventional diesel |
| | SMR | Grid | 500 | | |

**Table 3.-** Additional simulations in H2POWER: Table of Inputs.

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[1] Turbine height=40 m, wind speed=8 m/s, percentage of total energy provided by turbine=80%, no batteries.

[2] Percentage of "extra" electricity that is sold to the grid.

[3] Photovoltaics (PV): Orientation factor=0.95, annual kWh produced from a 1-kW DC array=1500 kWh/kWstc, percentage of total energy provided by PV=25%, percentage of panels on rooftop=50%, cost of land (to install the rest of the panels)= \$2000/acre, no batteries.

[4] Percentage of "extra" electricity that is sold to the grid.

**Table of Outputs**

| Simulation | | Financial NPC to homeowner | NPC of environmental externalities | Minimum incentive needed by homeowner | Maximum incentive from government | Developer’s Investment | Minimum incentive for developer |
|---|---|---|---|---|---|---|---|
| **Base Case** | **Baseline** | $ 46,914 | $ 96,711 | | | $4,358 | |
| | **HRU** | $ 70,221 | $ 41,173 | $ 23,463 | $ 79,383 | $25,250 | $20,892 |
| | **NRU** | $ 67,736 | $ 44,261 | $ 20,822 | $ 74,677 | $19,868 | $15,510 |
| **1** | **Baseline** | $76,176 | $90,790 | | | $4,358 | |
| | **HRU** | $138,595 | $41,548 | $62,419 | $49,242 | $25,204 | $20,846 |
| | **NRU** | $120,844 | $44,650 | $44,668 | $46,140 | $14,608 | $10,249 |
| **2** | **Baseline** | $46,914 | $96,711 | | | $4,358 | |
| | **HRU** | $100,142 | $36,188 | $53,228 | $60,523 | $69,175 | $64,817 |
| | **NRU** | $164,982 | $41,179 | $118,069 | $55,532 | $106,225 | $101,866 |
| **3** | **Baseline** | $46,914 | $96,711 | | | $4,358 | |
| | **HRU** | $106,448 | $16,154 | $59,534 | $80,557 | $365,992 | $361,634 |
| | **NRU** | $431,449 | $15,428 | $384,535 | $81,283 | $283,204 | $278,846 |
| **4** | **Baseline** | $46,914 | $96,711 | | | $4,358 | |
| | **HRU** | $49,634 | $40,965 | $2,721 | $55,746 | $20,500 | $16,141 |
| | **NRU** | $47,054 | $39,120 | $140 | $57,591 | $12,322 | $7,964 |
| **5** | **Baseline** | $83,391 | $82,409 | | | $4,358 | |
| | **HRU** | $86,354 | $41,157 | $2,963 | $41,252 | $22,537 | $18,179 |
| | **NRU** | $89,481 | $45,893 | $6,090 | $36,516 | $21,291 | $16,932 |

**Table 4.-** Additional simulations in H2POWER: Table of Outputs

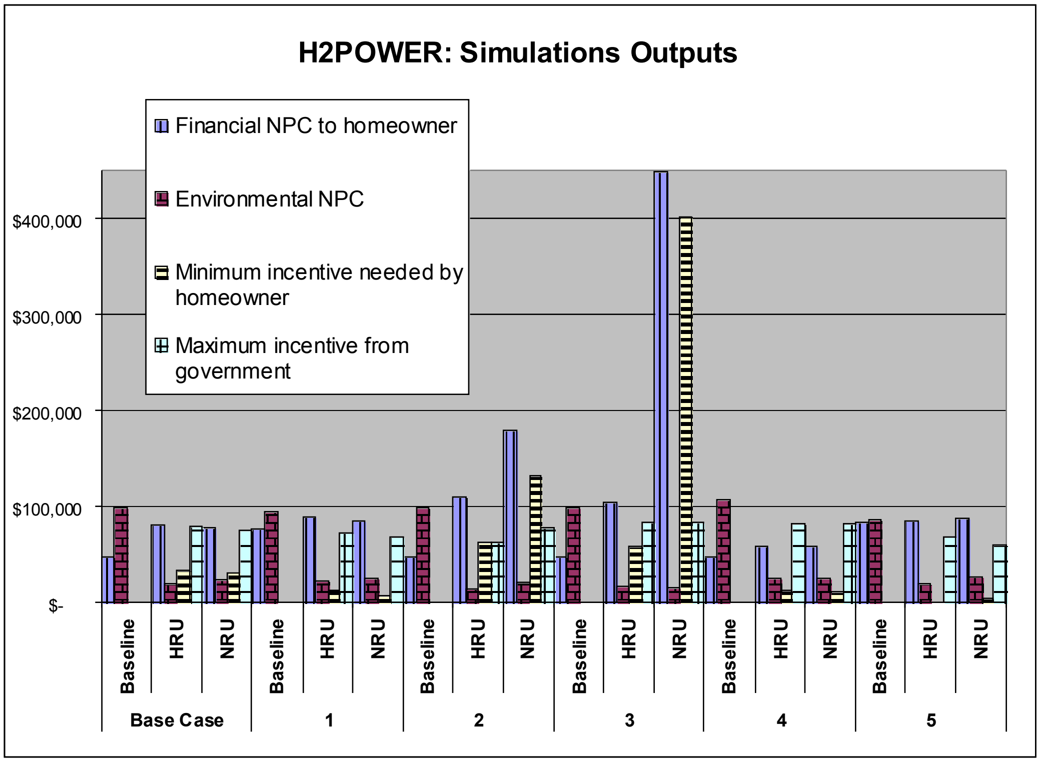

**Figure 8.-** Additional simulations in H2POWER: chart of outputs.

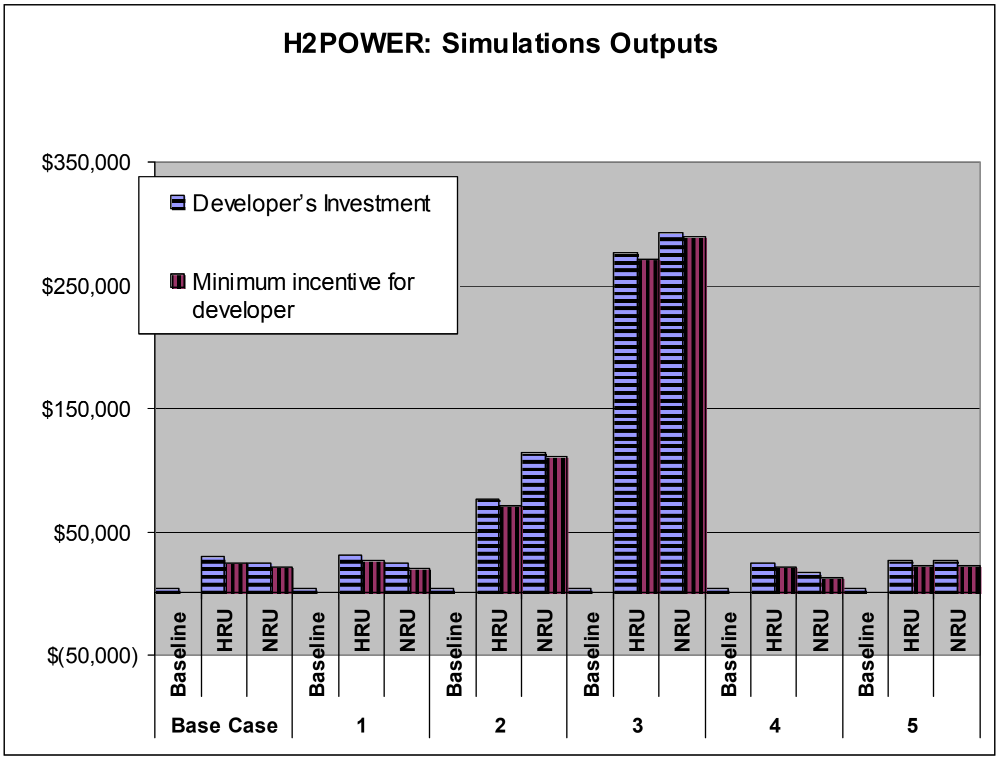

**Figure 9.-** Additional simulations in H2POWER: Developer's perspective, chart of outputs