Hydrogen Energy Storage for Renewable-Intensive Electricity Grids:
A WECC Case Study

By

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1. Abstract

Electricity grid operation requires balancing supply and demand for electricity on a continuous basis. The primary option for dealing with the variability in renewable energy generation is to maintain a significant capacity of backup/standby ‘peaker’ generation. Still, off-peak renewable electric production is sometimes curtailed because it cannot be economically used or captured. Low cost, efficient energy storage could enable optimized allocation of intermittent electric generation resources to high-value markets. This research project investigates the feasibility and energy system costs and benefits of hydrogen energy storage (HES) integrated with the electricity grid. This analysis aims to illuminate the impacts of responsive water electrolysis in high-renewable penetration electricity grids to convert renewable electricity into low-carbon hydrogen. This process has the potential to help balance the electric grid while providing an energy carrier that could be used in diverse energy applications.

This research found that round-trip energy arbitrage via H_2 as a storage medium, given a surplus of intermittent renewable generation, is not cost effective. Low round trip efficiencies and high capital cost makes it suboptimal to invest in hydrogen generation infrastructure for arbitrage alone. The sale of H_2 as a transportation fuel has the potential to be a high value stream for otherwise excess generation capacity. Optimal investment in electrolysis and H_2 storage capacity allows for this value to be captured, given an exogenous market for H_2 fuel. Through the utilization of an H_2 generation system, highly renewable systems can: reduce the cost to operate the grid, increase renewable integration into the energy supply, and provide enough hydrogen to fuel millions of fuel cell electric vehicles (FCEVs) at costs that are competitive with gasoline on a cent per mile basis.

2. Introduction

Since the early 2000s, onshore wind and solar photovoltaic (PV) technologies have grown rapidly (SBC Energy Institute, 2014). While these renewably-sourced generation technologies still represent a limited proportion of the global power mix, their share in some electricity markets is significant (Wetstone et al., 2016). Estimations for renewable growth range from an 8 to 18 fold increases over 2014 levels by 2050 (Statoil, 2017). This expanding contribution of renewably sourced generation poses unique challenges to grid operators. The intermittent nature of the production of these technologies makes them largely inflexible, variable, and often in remote locations. The latter point is particularly challenging when renewable rich locations (exceptionally windy or sunny) are not close to high demand centers, requiring long distance transmission. Even if supply-side flexibility could be adequately integrated through dispatch management, better demand-side participation and market connectivity will be a necessity as the overlap between the power sector and the electrified transportation sector grows(Edwards et al., 2008; Ibanez et al., 2016). These complications make the operation of a renewable intensive portfolio particularly difficult, inviting a holistic solution to the systemic inflexibility of the modern grid. Hydrogen energy storage (HES) could offer a solution to this inflexibility and variability through supply and demand-side shaping while concurrently generating an energy storage commodity with multi-sector end uses (Robinius et al., 2017; Steward, 2010).

The research explores the role of energy storage in providing stabilization to a heavily renewable electricity grid. Additionally, sensitivity of HES operation to the magnitude of fuel cell electric vehicle (FCEV) penetration will be analyzed. This is done by developing a dispatch model that incorporates HES into a projected 2050 Western Electricity Coordinating Council

(WECC) electricity grid. This tool allows for the analysis of how operation of this future electricity grid changes when energy storage is employed. Specifically, the following questions will be addressed:

1. How does a highly renewable electricity grid without storage or load flexibility operate?
2. Given a highly renewable electricity grid, how will optimal investments in HES systems impact greenhouse gas emissions, electricity carbon intensity, and grid operation costs?
3. How sensitive is the operation of a highly renewable grid with HES to the expansion of an FCEV market?
4. To what degree can an HES system leverage the rapid growth in renewables to catalyze a transition to low-carbon, low-cost H2 fuel?

3. Background

To model a fundamental shift in the functioning of the energy sector, we take a system-level perspective. Section 3 provides background information on the elements critical to the system-level analysis explained in this paper. Section 3.1 provides geographic and spatial context, 3.2 illuminates the modern political landscape of transportation, energy, and climate policy, 3.3 explains the functioning of the modern electricity grid, section 3.4 speaks to hydrogen generation technologies, section 3.5 elaborates on characteristics of H_2 as an energy carrier, and section 3.6 takes a deep dive on the usage of H_2 as a transportation fuel in the FCEV market. These six factors describe the inputs (seen in Figure 1) for our modeling tool.

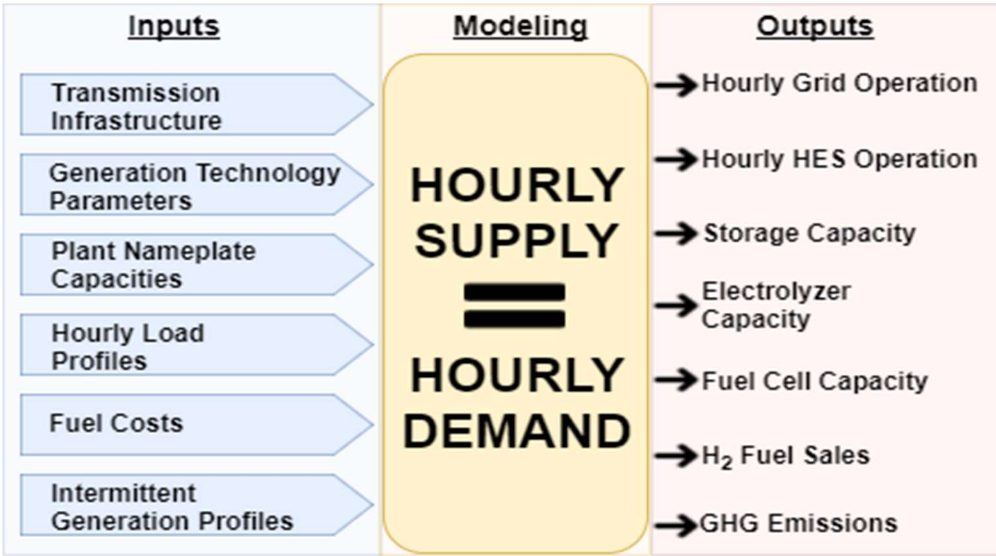

Figure 1. Graphic rendering of dispatch model inputs and outputs

3.1 Western Electricity Coordinating Council

The Western Electricity Coordinating Council (WECC) is the entity that ensures electric system reliability in the Western portion of Northern America as delegated by the North American Electric Reliability Corporation (NERC). The entity, formerly known as the Western Systems Coordinating Council (WSCC), was formed in 1967 with the merger of 40 power system providers. In 2002, the WSCC transitioned to the modern WECC via the merger of three large transmission associations. In 2007 NERC fully appointed the WECC to create, monitor, and enforce reliability standards for all operators within WECC's jurisdiction. Currently, the region under the authority of the WECC includes: two Canadian provinces (British Columbia and Alberta), the Northern portion of Baja California (Mexico), and all or portions of the fourteen Western US states between. This region (see Figure 2) functions as an independent electricity market, where generation is bought, sold, and transmitted within.

Figure 2. *Western Electricity Coordinating Council* (Goodwill, 2017)

3.2 California Energy and Environmental Policy

The California Legislature has enacted numerous policies to reduce the environmental impact of the state's transportation and energy system in 2050. Legislation emphasizes the expansion of the use of alternative fuels in powering transportation and the use of renewable resources in generating electricity. Policies primarily impacting transportation include the Light-duty GHG standard (Pavley), Zero Emission Vehicle Mandate (Brown, 2016), the Low Carbon Fuels Standard (Clegern, 2015), the alternative fuel and vehicle technologies funding program (AB-8) (Loveday, 2013; Perea, 2015), and the Clean Vehicle Rebate Project (California Air Resources Board, 2017b). Policies primarily impacting electricity include the Renewables Portfolio Standard (de Leon, 2016) and the Emissions Performance Standard (Collord, 2006). Further, an as-yet unknown suite of sector-specific policies to be developed as a result of Senate Bill 32 (Pavley, 2016) are likely to have a significant, if indirect, effect on both transportation and energy. We describe each of these policies in greater detail below. Collectively, these policies are expected to stimulate substantial adoption of alternative fuel vehicles and a reduction in use of conventional fuels for electricity generation prior to 2050. It is reasonable to assume that they (or comparable successor policies) may be in effect until 2050. Due to California's role as an economic and political leader in the WECC, it is assumed that CA legislation can serve as a proxy to inform the future policies of other WECC entities. For this reason, it is relevant to examine pertinent Californian policies impacting energy, air quality, and transportation.

Transportation Policies

The Zero Emission Vehicle (ZEV) Mandate, a regulatory program developed by the California Air Resources Board (CARB) in 1990, requires vehicle manufacturers to meet a minimum proportion of vehicle sales with zero emission vehicles, or to purchase credits from manufacturers who exceed their minimum requirements. While multiple compliance pathways exist, the most recent ZEV Action Plan promotes the ZEV Mandate and related policies as a pathway to 1.5 million alternative fueled vehicles on California roadways by 2025, representing 15% of new sales in that year (Brown, 2016).

The Clean Vehicle Rebate Project (CRVP) is a state financial incentive available to purchasers of specified zero emission vehicles. In 2016, CVRP provided over $101 million in incentives, with 71.1% of funds received by battery electric vehicles(California Air Resources Board, 2017b). The CVRP, in conjunction with the ZEV mandate and other incentives, is intended to improve alternative vehicle fuel sales.

In 2013, AB-8 provided a boost to Californian alternative fuel vehicle market outlooks. This bill appropriated over 2 billion USD to funding California's hallmark clean vehicle incentive programs, including: CVRP, the Air Quality Improvement Program, the Enhanced Fleet Modernization Program, and the Zero Emissions Truck and Bus Voucher Program. This money ensures that the state will extend it's clean fuel and vehicle programs through 2023 signifying the single largest financial commitment by the state to furthering the penetration of clean vehicles and fuels (Campbell, 2013).

Energy Policies

The Renewables Portfolio Standard (RPS) is a California state law requiring 50% of all retail sales of electricity to be served by eligible renewable resources by 2030 (de Leon, 2016). The RPS, in effect in various forms since 2002, has supported a significant expansion of renewable energy capacity in California and other WECC states. Annual renewable energy production and procurement by California utilities has more than doubled from approximately 30 million megawatt-hours (MWh) prior to 2002 to almost 70 million megawatt-hours in 2016, with most recent capacity expansion coming in the form of wind and solar photovoltaic facilities. Of new capacity expected to become operational in 2017, 85% of projects (by nameplate capacity in megawatts) are expected to be solar photovoltaic (California Energy Commission, 2015). In parallel with the development of renewable resources, the Emissions Performance Standard, established by California Senate Bill 1368 in 2005, resulted in the closure of numerous coal-powered electrical generating facilities in California and is contributing to the shutdown of coal facilities in other states which were owned or contracted by California utilities (California Energy Commission, 2016). Figure 3 shows the evolution of energy generation by resource type, both in-state and out-of-state (California Energy Commission, 2015).

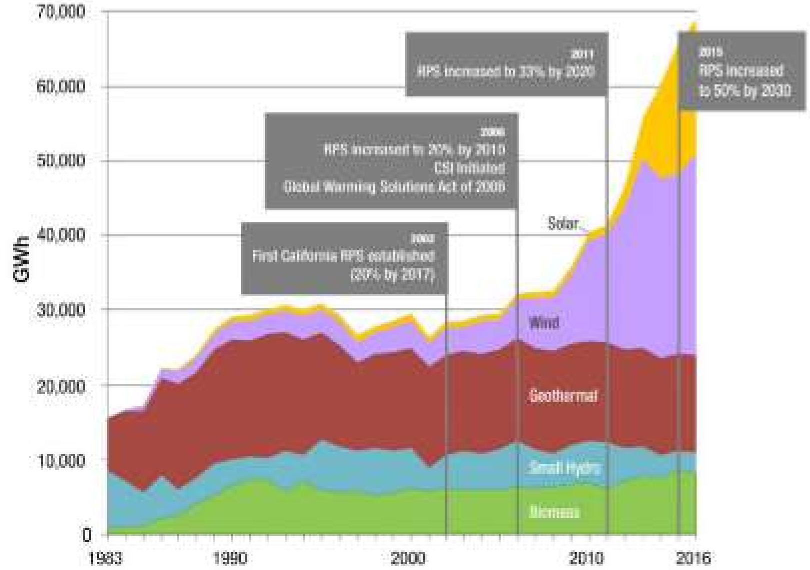

Figure 3. California Energy Generation by Resource Type

Greenhouse Gas Emissions Policies

California Senate Bill 32 (California Air Resources Board, 2017a; Collantes, 2012; Pavley, 2016) established a 2030 target for reducing greenhouse gas emissions to 40% below 1990 levels, a continuation and expansion of previous legislation requiring specified emissions reductions by 2020. At the time of this report, it remains unclear as to whether the Air Resources Board will retain or modify existing regulatory programs overseen such as the Low Carbon Fuel Standard and Cap and Trade or utilize alternative methods for achieving reductions. Regardless, it is reasonable to assume that Senate Bill 32 and its resulting regulatory policies will accelerate the transition to alternative vehicles and renewable energy generation (California Air Resources Board, 2017c).

3.3 Grid Operation

The electric grid is a complex system of power plants, transmission and distribution infrastructure, and electricity end-users, all of which interact through simultaneous electricity markets. Due to the instantaneous nature of electricity and limited opportunities for large-scale electrical storage, electricity supply must be balanced constantly with electricity demand across the system. This section will expound upon three topics critical to the operation of the electricity grid to balance electricity supply and demand: marginal cost dispatch, generation variability, and transmission resources.

In general, grid operators within a balancing area dispatch power plants in ascending order of the price that generators bid into the system to operate (economic dispatch). This bid price is typically represented as the marginal cost of power, in other words the cost of each additional unit of generation not including fixed cost. The fixed costs include land purchases, licensing and permits, and capital expenditures. The marginal cost of power generation is largely derived from the cost of fuel, labor, and maintenance. All else equal, plants with lower marginal costs are brought onto the grid first, with higher marginal cost plants being dispatch sequentially as demand increases. Intermittent renewable power generators have very low marginal costs, due largely to little or no required fuel input (Lazard, 2014). Thus, economic dispatch generally results in renewable power plants being dispatched before more emissions-intensive power plants (Callaway, Fowlie, & Mccormick, 2015). If some fraction of electrical loads are flexible in their timing, such as grid-integrated hydrogen generation through electrolysis, these loads can be directed to periods with sufficient idle capacity among renewables or efficient power plants, mitigating cost and emissions impacts (SBC Energy Institute, 2014). This is known as demand-side management (DSM). DSM can take many forms: load limiters, load-switching, smart-metering, and time-of-use pricing. Each of these techniques varies in practice but has a core similarity in function. These techniques modify consumers demand for energy with the goal of altering the shape the system load and reducing the cost of purchasing electricity. Methods to achieve this can include financial incentives, caps on consumption, smart-appliances shifting active hours, or consumer education (Strbac, 2014; Torriti, 2012).

Power plants that operate with very low fuel costs, such as renewable resources, generally operate at their full feasible availability. Demand from fossil generators is reduced as California and other states develop additional renewable resources, though this reduction has tremendous temporal heterogeneity between hours, days, seasons, and years. Currently, this variability in generation is balanced via the dispatch of highly inefficient natural gas peaker-plants. These facilities have the capacity to ramp-up generation quickly enough to counter-balance a commensurate decrease in generation from an intermittent renewable facility or spike in load. However, these generators are both costly and inefficient, consuming large amount of natural gas at a very low heat rate as well as requiring a large capital investment with a low capacity factor (Lindley, 2010).

The transmission system is a network of high-voltage electrical lines that transfer electricity over long distances from power plants to areas where electricity is used. Transmission capacity is constrained by the power capacity of specific transmission lines, limiting the trading capacity between regions. Further, the transmission and distribution of electricity results in energy losses, which increase with the distance of transmission, resulting in increased costs when serving electricity demand in one location with generation from a distant location.

3.4 Hydrogen Production

There are numerous ways to make hydrogen including from hydrocarbon resources or electricity. Producing H2 from a primarily fossil-based feedstock has little interaction with the electricity and thus the capacity to positively impact operation of the electricity grid is limited (Carmo, Fritz, Mergel, & Stolten, 2013). This section describes the primary means of making H2.

Steam Methane Reforming

To date, hydrogen has been primarily produced via steam reforming of natural gas or other carbonaceous fuels. This system uses high temperature water vapor in the presence of a metal-based catalyst to produce H_2 and carbon dioxide. Typically, this process produces low-purity hydrogen along with a large emissions-footprint, although additional technologies can be employed to purify the hydrogen (pressure swing absorption purification). Additionally, steam reforming of natural gas does not relieve dependencies on fossil fuels. SMR has served as an intermediate pathway for H_2 production, allowing the generation of hydrogen for numerous purposes, including as a transportation fuel. Moving towards a hydrogen fuel that is concurrently low-carbon and whose generation can serve as a grid stabilization tool will require new technological pathways. For this effort, high-quality hydrogen can be produced with an input of only water and electricity following a process known as electrolysis.

Polymer Electrolyte Membrane Electrolysis

Electrolyzers leverage well-developed technology that uses electricity to separate water into hydrogen and oxygen (Grigoriev, Porembsky, & Fateev, 2006). The major types of electrolyzers being produced and developed include polymer electrolyte membrane (PEM), alkaline with liquid electrolyte, alkaline with solid electrolyte, and solid oxide electrolyzer (SOEC). For our research, we assume that PEM electrolyzers are the primary technology for H_2

generation. Their operational flexibility and variety of potential system configurations makes them an ideal candidate as a load follower and grid service provider. Research conducted at the National Renewable Energy Lab by Eichman et al. explains that electrolyzers can effectively support the electric sector by quickly modulating their electricity consumption profile. This responsive behavior can provide value to the system operator in the form of ancillary services (ramping, frequency regulation, spinning reserve, non-spinning reserve, and transmission & distribution support) while simultaneously providing hydrogen for use in vehicles (Eichman, Harrison, & Peters, 2014; Eichman & Townsend, 2016). Furthermore, PEM electrolysis is considered to have a considerable potential for cost reduction from economies of scale and a reduction in the amount of noble metal catalyst used in manufacturing similar to that of PEM fuel cells in automotive applications (Barbir, 2005; James & Moton, 2014; Millet, Ngameni, Grigoriev, & Fateev, 2011; Tsuchiya & Kobayashi, 2004).

3.5 Hydrogen as an Energy Carrier

Despite not being naturally occurring in its molecular form, hydrogen possesses unique characteristics that make it a potentially promising energy carrier. These traits include: an exceptional energy-to-mass ratio, transportation and storage possibilities, a synergy between H_2 generation and intermittent renewable energy generation, no on-site emissions when converted to energy with a fuel cell, raw materials for its production are abundant, safety advantages, and a host of multisector end-use applications (Balat, 2008; Beach, 2005; Mazloomi & Gomes, 2012).

In relation to the consumption of fossil fuels, H_2 has long-term viability and practicality. Hydrogen can be produced from a large number of potential feedstocks (water, energy, hydrocarbons, or ammonia). Additionally, hydrogen has an energy per mass content of 143MJ/kg, an amount up to three times greater on a fuel-only basis (not considering weight of fuel tanks) than prevalent liquid hydrocarbon-based fuels (Ahluwalia & Peng, 2009). This yields H_2, a very flexible energy source with many end-uses such as turbines, combustion engines, and fuel cells (Mazloomi & Gomes, 2012; Weeda, Wilde, Schaap, & Wallmark, 2014).

Hydrogen can be stored in a gaseous form in both tanks or salt caverns, as a cooled liquid, in a metalloid framework, or as a hydrogen-rich substance like anhydrous ammonia (Evans, Strezov, & Evans, 2012; Lindley, 2010; Renewable & Wolf, 2011; Rowsell & Yaghi, 2015; Schlapbach & Züttel, 2001). This host of storage options allows for a tailoring to specific applications. Concurrently, pipelines used for transmission and distribution, if packed with H_2, would serve effectively as additional product storage. This capacity for wide-scale long-term storage makes hydrogen a promising energy carrier to service consumers previously utilizing liquid or gaseous hydrocarbon-based fuels.

There are some difficulties with large-scale generation, storage, transportation, and consumption of hydrogen as an energy carrier. The round-trip efficiency for energy storage (electricity-hydrogen-electricity) of most mainstream conversion technologies is low in comparison to other energy storage technologies. Additional problems exist with the transmission and distribution of hydrogen. Chemical properties of the molecule make it extremely prone to both leakage and embrittlement of metallic pipeline, although specialty polymer pipes are currently in production that are resistant to leakage and embrittlement. Low energy-to-volume ratio in its gaseous state makes it expensive to transport by truck and unrealistic by ship. Finally, a lack of maturity in the hydrogen sector results in a scant force of people qualified to work with H_2 relevant technologies.

3.6 FCEV market projections

The fuel cell electric vehicle (FCEV) market provides a stable high value demand stream for H_2. Having stability in demand imparts confidence to investors to build infrastructure (both refueling and generation), it also improves the return on investment outlook for car manufacturers looking to expand into the alternative vehicle market. For these reasons, it is important to consider the various magnitudes of FCEV penetration into the vehicle market through 2050. This section will elaborate on FCEV technologies and market projections.

Fuel cell electric vehicles are electric-drive vehicles that operate a fuel cell in conjunction with an on-board store of hydrogen to produce power. The fuel cell leverages the thermodynamics of an electrolyzer to produce electricity on demand from hydrogen and oxygen with only water and heat as byproducts. For this reason, FCEVs have no tailpipe emissions. Full fuel cycle emissions can be generated from the production of hydrogen as well as energy used for compression, transportation, and dispensing if zero-carbon energy is not used. Coupled with zero-carbon hydrogen that utilized zero-carbon energy for compression, transport, and dispensing, an FCEV can be operated without producing any upstream emissions as well. Fuel cells have no moving parts and are produced modularly, so they have the potential for high reliability and low manufacturing cost. Furthermore, because of the technological similarities of the electrical powertrain to both hybrid vehicles and battery electric vehicles, some elements of FCEV manufacturing have the potential to leap-frog higher along the learning curve than a typical inceptive technology (Tsuchiya & Kobayashi, 2004).

A 25% market share of FCEVs in the light-duty sector has the capacity to account for over 10% of the cumulative emissions reductions necessary to mitigate climate change to two degrees Celsius (International Energy Agency, 2014). For this reason, many countries have incorporated FCEV adoption into their emissions-reduction plans. The US, Japan, South Korea, and the European Union have made a combined commitment to having over 520,000 FCEVs on the road with over 830 fueling stations by 2020 (Weeda et al., 2014). Following similar commitments, the International Energy Agency projects that FCEVs could account for as much as 30% of all new vehicle sales globally, or approximately 60 million vehicles sold annually by 2050 (Department of Energy, 2016; International Energy Agency, 2014).

FCEVs can also be utilized in other transportation sectors. Fuel cell powered buses are being demonstrated globally, while research and development is being done to assess the viability of medium- and heavy-duty trucks, trains, and ships run on hydrogen.

4. Modeling and Methods

4.1 Economic Dispatch Models

Grid dispatch models attempt to represent the operations of complex electrical systems using modern optimization techniques. In general, grid dispatch models identify the lowest-cost resource mix to meet a specific level of demand across multiple zones, with representation of physical and economic characteristics of both generation and transmission within the system boundary. This modeling technique has been used in the past to represent a variety of systems with two main approaches: long-term system planning models and short-term hourly models.

Long-term models are typically run at system level over long periods of time with a low level of temporal granularity. They generally minimize system cost of investing in and operating the electricity grid by optimizing the mix of generation units and their dispatch and technological developments to adhere to a set of exogenous constraints (Johnston, Mileva, Nelson, & Kammen, 2013; Loulou, Goldstein, Remme, Lehitla, & Kanudia, 2016; Nelson, 2013; Wei et al., 2014; Yang, Yeh, Zakerinia, Ramea, & Mccollum, 2015). Short-term time series models take hourly historical data of electricity supply-capacity and demand to assess a system's capability to match supply with demand. These models typically operate on an hourly level without incorporating electricity generation capacity expansion. Examples of these models include work done to assess the implication of integrating intermittent renewables, EV charging strategies, energy storage infrastructure, and policy analysis (Eyer, 2010; Gnanadass, Prasad, & Manivannan, 2004; Palanichamy & Babu, 2008; Richardson, 2013; Soares & Almeida, 2009; Yalcinoz, 2007).

Historically, dispatch models incorporated electrical load profiles as exogenous inputs, commensurate with the limited real-world capabilities of grid operators to flexibly manage loads. Recent studies (Mccarthy & Yang, 2009; Sohnen, Fan, Ogden, & Yang, 2015) have explored incorporating some component of electrical demand as a decision variable within the optimization model. This has a variety of research and operational applications, including managing electric vehicle loads, production of alternative fuels such as hydrogen, optimizing industrial processes, and utilizing large-scale battery storage.

4.2 Model overview

Optimized **D**ispatch of **E**nergy **S**ystems and **S**torage (ODESS) is a grid dispatch model which analyzes system parameters to determine the cost-minimizing resource output across a time horizon, given specific electrical loads and policy constraints. ODESS was programmed by the authors in GAMS (General Algebraic Modeling System) utilizing the CPLEX solver. The novelty of this tool is that it simultaneously optimizes energy generation, energy storage system capacity investment, and the operation of a hydrogen energy storage system with multiple end uses for the energy carrier. This modeling tool yields a rich data output of cost-minimized grid operations meeting a projected electricity load subject to predetermined constraints.

Model Parameters

Model parameters consist of exogenous data that serves to establish boundaries and thresholds on the system. These parameters include various demands, costs, efficiency scalars, and policy limits. Model parameters are in **Table 1**.

Table 1. ODESS Parameters, Scalars, and Multiples	
$genCost_{g,r}$	The cost in USD/MWh to dispatch generator *g* in region *r*. Fossil fuel prices for electric power generation originate from the reference case of the Energy Information Agency's Annual Energy Outlook (Energy Information Administration, 2015). The fuel price for each load area is matched to the NERC subregion with the greatest overlap with the associated region *r*. Uranium prices were taken from the California Energy Commission's Cost of Generation Model (Klein, 2007). These parameters were compiled by the SWITCH team and are discussed more fully in the cited literature (Wei et al., 2014).
$demandLoad_{t,r}$	The hourly demand for electricity in time step *t* and region *r*. Each hourly demand corresponds to an observed load on one historical hour from the year 2006. These hourly loads were then shaped using hourly load profiles for energy efficiency, electrification of heating, and electrification of the transportation sector. The magnitude of the load is dictated by electricity load projections. This work was completed by Max Wei et al. and is discussed more fully in the cited literature (Wei et al., 2014).
$maxGen_{r,g,t}$	Represents the maximum power that can be created by generator *g* in region *r* in time step *t*. Baseline 2015 data was geolocated into regions *r* from the Energy Information Agency's Annual Electric Generator Report (Energy Information Agency, 2007). Canadian and Mexican generation facilities were included using data in the WECC Transmission Expansion Planning Policy Committee database (Western Electricity Coordinating Council, 2009). No plant was permitted to operate past its designated decommission data. Using this data, the SWITCH Team projected cost-minimizing system conditions constrained by various policy targets to achieve a likely 2050 generation portfolio for the WECC. The process of data compilation and modeling is discussed more fully in the cited literature (Wei et al., 2014). To reduce model complexity, generation facilities were aggregated by primary driver, fuel, region, and heatrate.
$transCap_{r,o}$	The maximum power that can be transmitted between two regions *r* and *o* along a transmission corridor in MW. Data compiled by the SWITCH

Table 1. ODESS Parameters, Scalars, and Multiples	
	team utilizing data on thermal limits of power lines from the Federal Energy Regulatory Commission (Wei et al., 2014).
$H2FuelDemand_{r,w}$	Demand for hydrogen in the ancillary market in region *r* and week *w*. Week *w* corresponds to a rolling set of 168 study hours. This demand corresponds to the maximum amount of H_2 (MWh) that can be sold into the ancillary market in the associated week. This parameter was determined using weekly automotive fuel demand profiles scaled to the magnitude needed to fuel the number of FCEVs being considered in a given scenario. Week long demand periods were used to capture the inherent storage capacity in hydrogen refuel stations and other infrastructure.
$hydroMax_{r,t}$	The maximum power that can be dispatched from hydroelectric plants aggregated to region *r* and in time step *t*. This parameter is a function of the nameplate capacity of the facilities in region *r* and the historic average inflow of water to the associated reservoir.
$hydroMin_{r,d}$	The minimum power that can be dispatched from hydroelectric plants aggregated to region *r* and in day *d*. Day *d* corresponds to a rolling set of 24 study hours. This figure is a function of the nameplate capacity of the facilities in region *r* and the established minimum flowrate through the facility required to maintain downstream ecological norms.
fuelPrice	The price a consumer pays for H_2 in the ancillary market in USD/MWh H_2
transLoss	The efficiency associated with transmission between any two regions.
inEff	The efficiency losses associated with conversion of electricity into storage.
outEff	The efficiency losses associated with conversion of the storage medium back into electricity.
PEMeleclyzer	The cost of one additional unit of electrolyzer capacity (USD/MW)
FC	The cost of one additional unit of fuel cell capacity (USD/MW)
storageTank	The cost of one additional unit of storage capacity (USD/MWh)

Capacity Investment Decision Variables

These decision variables include a set of choices made a single time during the optimization. Investments made in each region dictate the stringency of constraints on various dispatch decisions. Capacity investment decision variables are in **Table 2**.

Table 2. Capacity Investment Decision Variables

$PEMCap_r$	The amount of PEM electrolyzer (electricity-to-hydrogen conversion) capacity (in MW) to invest in, in each region
$FCCap_r$	The amount of fuel cell (hydrogen-to-electricity conversion) capacity (in MW) to invest in, in each region
$storCap_r$	The amount of hydrogen storage capacity (in MWh) to invest in, in each region

Investment into hydrogen transmission and distribution infrastructure is directly determined by the model but is assumed to be made on a per kg basis. Additionally, no investment is made into refueling stations that sell the hydrogen or any related infrastructure. To address these 'per kg' costs, a scalar of 1.31 USD/kg is added to the cost to purchase hydrogen in the auxiliary market.

Dispatch Decision Variables

These decision variables include choices made in every study hour about how to dispatch generation from power plants, transmission, energy conversion, storage, and auxiliary market sales such that an exogenous demand profile is satisfied in each region for each time step. Dispatch decision variables are in **Table 3**.

Table 3. Dispatch Decision Variables

$gen_{r,g,t}$	Amount of power (MW) to generate (and dispatch) from each powerplant generator category in each region in each time step
$stor_{t,r}$	The amount of energy (MWh) in storage in each time step in each region
$storIn_{t,r}$	The amount of energy (MWh) being fed into storage in each time step in each region
$storOut_{t,r}$	The amount of energy (MWh) to discharge from storage in each time step in each region
$trans_{o,t,r}$	Amount of electricity (MWh) to transfer along each transmission corridor in each time step

Table 3. Dispatch Decision Variables	
fuelH2$_{t,r}$	The amount of hydrogen (MWh) sold to the FCEV fuel market in each time step in each region

Objective Equation

The objective of the model is to minimize the cost of dispatch of generation. The three main parts of the objective equation are outlined in **Table 4**. The model minimizes the sum of these elements.

Table 4. System cost to operate the grid		
Generation	$\sum_{t,r,g} gen_{r,g,t} * genCost_{g,r}$	The sum across each time step, region, and generator of the amount of generation dispatched multiplied by the marginal cost to generate in each region where *genCost* equals cost in USD/MW to dispatch generator *g* in region *r*.
Investment	$+\sum_{r} storCap_r * storageTank$ $+\sum_{r} PEMCap_r * PEMeleclyzer$ $+\sum_{r} FCCap_r * FC$	The sum across each region of the magnitude of capacity to be installed multiplied by the associated per unit cost to install where: *storageTank* equals the cost in USD/MWh of storage capacity, *PEMeleclyzer* equals the cost in USD/MW of electrolyzer capacity, and *FC* equals the cost in USD/MW of fuel cell capacity.
Ancillary	$-\sum_{t,r} fuelH2_{t,r} * fuelPrice$	The sum across each time step and region of the hydrogen sold to the ancillary market multiplied by the revenue from selling a unit of H_2 where *fuelPrice* equals the amount a consumer pays per unit of H_2 purchased in USD/MWh H_2

Model Constraints

The ODESS model also contains a series of algebraic constraints (used to represent operation of the system) that must be satisfied. These equations serve two primary purposes. One grouping of the model constraints serves to require the model to operate in a way that is consistent (or largely so) with the real-world operations. Constraints include: electricity demand must be satisfied, capacity limitations, and limits on hydroelectric dispatch and flow. A second category of constraints serve a 'book-keeping' role. Examples functions of these constraints include: summing transmission along corridors, conservation of energy and mass, and totaling ancillary H_2 sales across the week. Model Constraints can be found in Table 6.

Table 5. ODESS Model Constraints

constraint1

$$\forall(r,t), \quad \sum_{g} gen_{r,g,t} + \sum_{o} trans_{o,t,r} * transLoss - \sum_{p} trans_{r,t,p} - storIn_{t,r} - demandLoad_{t,r} + storOut_{t,r} * outEff = 0$$

For all regions across each time step, dispatched generation must equal demand load with accounting for operation of transmission and storage

constraint2

$$\forall(r,g,t), \quad gen_{r,g,t} - maxGen_{r,g,t} \leq 0$$

For all generators in each region across each time step, dispatched generation cannot exceed maximum generator capacity, *maxGen*

constraint3

$$\forall(r,t), \quad stor_{t,r} + fuelH2_{t,r} - storCap_{r} \leq 0$$

For all regions across each time step, stored hydrogen and that hydrogen being sold into the ancillary market must be less than the storage capacity in that region

constraint4

$$\forall(r,o,t), \quad trans_{o,t,r} - transCap_{o,r} \leq 0$$

For all transmission corridors between each combination of regions across each time step, the amount of energy transmitted cannot exceed the capacity for transmission along that corridor

constraint5

$$\forall(t,r), \quad stor_{t,r} - stor_{t-1,r} - storIn_{t,r} * inEff + storOut_{t,r} + fuelH2_{t,r} = 0$$

For each region across each time step energy and mass are conserved with accounting for efficiency losses and energy sold to the ancillary market

constraint6

$$\forall(r,w), \quad (\sum_{w} fuelH2_{w,r}) - H2FuelDemand_{r,w} \leq 0$$

For each region across a rolling grouping of 168 time steps, the summation of energy sales to the ancillary market in week *w* cannot exceed demand for energy in the ancillary market for that week *w* in that region *r*

Table 5. ODESS Model Constraints

constraint7

$$\forall(r,t), \qquad storIn_{t,r} - PEMCap_r \leq 0$$

For each region across each time step, the amount of electricity converted into stored energy cannot exceed the capacity of the electricity-to-storage conversation technology

constraint8

$$\forall(r,t), \qquad storOut_{t,r} - FCCap_r \leq 0$$

For each region across each time step, the amount of stored energy converted into electricity cannot exceed the capacity of the storage-to-electricity conversation technology

constraint9

$$\forall(r,t,hydro), \qquad (\sum_{hydro} gen_{r,hydro,t}) - hydroMax_{r,t}$$

For each region and generator in a subset *hydro* across each time step, the summation of dispatch of *hydro* cannot exceed the maximum dispatchable capacity of *hydro*

constraint10

$$\forall(r,d,hydro), \qquad hydroMin_{r,d} - (\sum_{d} gen_{r,hydro,d}) \leq 0$$

For each region across a rolling grouping of 24 time steps and each generator in subset *hydro*, summation of *hydro* dispatch across day *d* cannot fall below the minimum performance level of that generator

4.3 Model Assumptions and Parameter Values

Model parameters (discussed in section 4.2) are assigned values based on literature review of relevant work in the sector. **Table 6** outlines values assumed for each parameter for each modeling scenario. The value for *fuelPrice* reflects the price paid by consumers of H_2 in the ancillary market. For this project, the ancillary market represents only H_2 purchased as a transportation fuel. 4.31 USD/kg H_2 represents an 'at the pump' threshold value at which hydrogen is projected to be competitive with gasoline on a fuel cost per mile basis (taking into account the relative efficiency of FCEVs relative to gasoline vehicles). This value represents the willingness to pay of the consumer for the product, not the cost to generate and distribute the product. If H_2 is generated, the cost to do so will be, at a maximum, equal to 4.31USD/kg H_2. It is assumed that production of H_2 above this cost would not be competitive with gasoline and would not be purchased by consumers. Lifetime of both the PEM electrolyzer and fuel cell are assumed to be calendar hours, as opposed to hours of usage. This assumption was made to maintain linearity of the model and reduce model complexity. Cost to install storage capacity (*storageTank*) represents a mix of carbon wrapped tanks and advanced geologic storage techniques. Greater detail regarding the methodology used to arrive at these values can be found in the cited literature in table 7.

Table 6. ODESS Parameter Values

Parameter	Value	Source
fuelPrice	4.31USD/kg H_2	(Ruth & Joseck, 2011)
transLoss	.953	(Energy Information Administration, 2011)
inEff	.86	(International Energy Agency, 2014)
outEff	.57	
PEMeleclyzer	640USD/kW	
FC	660USD/kW	
storageTank	1USD/kWh	
PEM lifetime	75,000 hrs	
FC lifetime	80,000 hrs	

Economic assumptions surrounding the modeling effort include population growth trends, transportation shares, and policy goals. It is assumed that population growth rates continue in line with those made by the California Department of Finance and U.S. Census Bureau (CADOF, 2007; United States Census Bureau, 2014). Most macroeconomic drivers and sensitivities were adopted from the SWITCH study which in turn reported this data from a related PIER study. More can be read in the associated reports (Masanet et al., 2009; Wei et al., 2014).

It was assumed for modeling purposes that all California policy goals were achieved. Concurrently, it was assumed that all the other states and regions in the WECC achieved identical policy goals 10 years after California. This assumption is in place to mimic the leadership of the California legislation in crafting and implementing aggressive climate legislation and the trend for other state entities to follow. These policies can be read about specifically in section 3.2. In aggregate, these policies enforce a radical overhaul in the way that energy is supplied and utilized, culminating in a target of an 80% reduction in GHG emissions below 1990 levels by 2050 in California. This is achieved via aggressive energy efficiency, electrification, decarbonization of generation, and decarbonization of transportation through electrifications and utilization of alternative fuels. Greater detail regarding the development of the base scenario can be found in section 4.3.

4.4 Scenarios

Technological developments and deployments were modeled by the SWITCH team in order to project a base case scenario of what the 2050 WECC grid could resemble. The base case scenario proposed by the SWITCH team in the cited research was used as a benchmark to study the impacts of HES (Wei et al., 2014). This section will outline the base case scenario, key elements of the system, and the factors changed to model and analyze HES scenarios.

Base Case Scenario

Besides economic and technical developments, the system characterized in this study as the *base case scenario* (BC) possesses three fundamental shifts in operation from the current grid of 2016. These elements are:

- Aggressive energy efficiency across all sectors
- Extensive decarbonization of energy generation
- Large-scale electrification of heating and transportation

These three changes in structure and operation play a huge role in drastically reducing the overall carbon emissions of the region. Energy efficiency measures are implemented across all sectors and are both economically practical and effective at reducing overall demand. The measures in the BC scenario max out at their projected technical potential in CA in 2050 and with a ten-year lag in the rest of WECC

Extensive decarbonation of the energy generation sector also serves a dual purpose. In addition to the initial carbon abatement associated with decarbonization, a low carbon intensity of electricity allows for electrification in other sectors to serve as a carbon abatement measure. Decarbonization of the power sector is technologically very feasible with a suit of technologies available to serve this goal (photovoltaics, nuclear, wind, tidal, concentrated solar, geothermal, carbon capture and sequestration, hydroelectric, and biofuels). We use the basecase assumptions of the SWITCH team (Wei et al., 2014) with some adaptations. For the purpose of this study, storage capacity projected by the SWITCH team was removed from the 2050 BC scenario. To compensate for this reduction in supply flexibility, small additions to some nameplate capacities for dispatchable fossil generation sources were added on an as-needed basis. Final nameplate capacities can be seen in *Figure* 4.

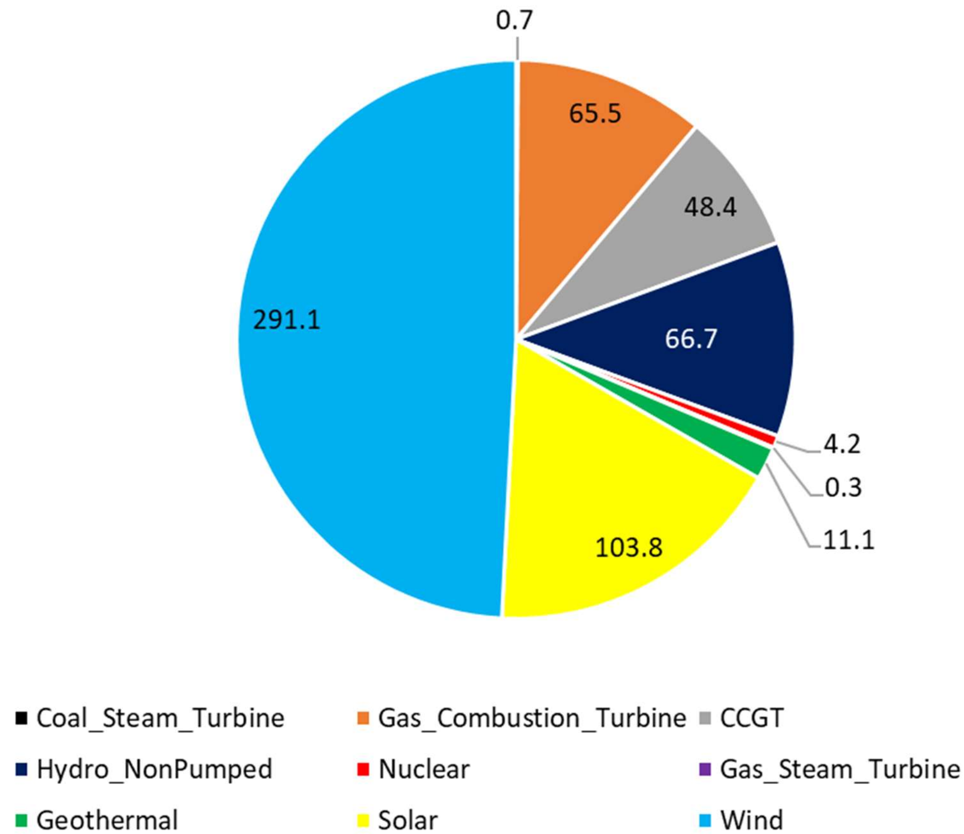

Figure 4. 2050 WECC Nameplate Capacities (GW)

With the power sector decarbonized, electrification can be used to replace on-site combustion of fossil fuels with the utilization of zero-carbon electricity. Primary targets of such electrification include natural gas water heaters, natural gas space heaters, and internal combustion engine vehicles. Although electrification (when coupled with a decarbonized power sector) can be very effective at carbon abatement, it increases power demand and in turn increases required installed capacity. Within the BC scenario, electrification of heating and transportation increases overall electricity demand by 7% over the counterfactual, even with extensive efficiency measures being implemented. Greater detail on the extent of electrification can be found in Table 7.

Hydrogen Energy Storage Scenarios

Modeling operation of the base case scenario using ODESS allows for an analysis of the optimal operation of the electricity system. In order to compare, hydrogen energy storage (HES) scenarios were developed under the same methodology. Besides having the capacity to invest in HES systems, and in some case additional demand for H_2 on the ancillary market, all things between the HES scenarios and BC scenario are held static. The generation portfolio, vehicle and heating electrification rates, and demand profiles are all held constant across scenarios.

Table 7. Comparison of modeling scenarios

<table>
<tr><th>Scenario</th><th>HES System</th><th>Price of H_2</th><th>VMT by FCEV</th></tr>
<tr><td>Base Case</td><td>No</td><td rowspan="2">-</td><td>0%</td></tr>
<tr><td>No Market</td><td rowspan="3">Yes</td><td>0%</td></tr>
<tr><td>Moderate FCEV</td><td rowspan="2">4.31 USD/kg</td><td>10%</td></tr>
<tr><td>High FCEV</td><td>55%</td></tr>
</table>

Table 7 shows the differences between the base case scenario (BC), HES No Market scenario (No Market), Moderate FCEV scenario (Mod FCEV), and High FCEV (High FCEV) scenario. H_2 has a litany of potential end uses that could be considered within the ancillary market. For this project, the only avenue of sales outside of energy arbitrage is H_2 as a transportation fuel. This is the use of hydrogen as an on-board fuel for fuel cell electric vehicles. To better understand the sensitivity of grid operations to the magnitude of transportation fuel demands, this project considers three HES-compatible scenarios: No Market, Moderate FCEV and High FCEV. In simple terms, these scenarios analyze the economics of a 2050 grid's ability to service a demand for transportation fuel given a consumer's willingness to pay for fuel. Hydrogen fuel is supplied to refueling stations on a rolling weekly basis. Annual demand assumptions for fuel are based on scenario-specific stock of FCEVs, average VMT, and vehicle efficiency. Results of these calculations can be found in **Table 8**.

Table 8. Hydrogen Fuel Demand Characteristics in 2050

Scenario	Stock (mil veh)	% of PLDVs	annual H_2 consumption (TWh)
No Market	0	0%	0
Moderate FCEV	6.8	10%	24.9
High FCEV	37.5	55%	137.8

Annual demand is disaggregated into weekly consumption using trends in gasoline consumption from the Energy Information Administration (Energy Information Administration, 2017). These consumption trends are applied to the magnitude of annual consumption to arrive at the weekly demand for H_2 fuel.

5. Results

5.1 Base Case Scenario Results

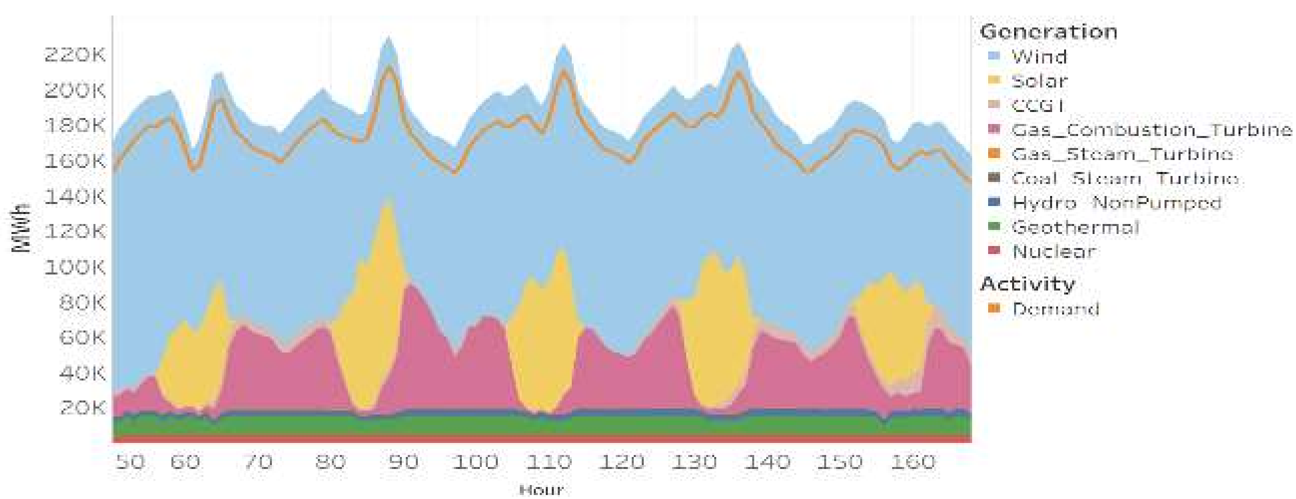

Figure 5. Dispatched generation across 120 study hours without HES disaggregated by generation technology, not including curtailed generation

Figure 5 shows a sample 5 day period (120 time steps) of generation dispatch for the entire Western Interconnection in the BC scenario. The orange line labeled *Demand* shows the entire system demand for power at each observed time step. The summation of all dispatched generation is bound to the demand, with just a small surplus to account for transmission inefficiencies. shows the results for the operation of the grid in the base case scenario. Carbon intensity (CI) of electricity in the BC scenario is 45.4kg CO2/MWh, very low in comparison to 2016 levels at approximately 345kg CO_2/MWh (Environmental Protection Agency, 2016) This is an expected result considering the extensive decarbonization of the power sector. With approximately 80% of generation capacity being zero-carbon, emissions rates from the power sector drops dramatically. Additionally, wind and solar generation serviced over 75% of power demand across the year. This is due almost entirely to the sheer magnitude of intermittent nameplate capacity in portfolio, accounting for nearly 66% of capacity. Despite this, 32% of all wind and solar generation was curtailed. This totals over 553 TWh of curtailment of zero carbon intermittent resources. Concurrently, coal steam turbine, CCGT, nuclear, and geothermal plants all operated at a relatively high capacity factors in relation to other generation sources (58.4%, 38.0%, 98.6%, and 87.5% respectively), and yet serviced a much smaller portion of demand (.24%, 10.4%, 2.3%, and 5.5% respectively). Hydroelectric generation has a zero-marginal cost, and so would be prioritized over other dispatchable sources of generation with a non-zero marginal cost, however operated at a capacity factor of only 9.8%. This is due to both constraints on transmission capacity limiting widespread use of a geographically constrained resource, and ecological limits on the maximum flowrate of water out of a reservoir. Overall the generation mix of the BC scenario led to total annual emissions of 70.1 Mt COs and a wholesale system cost of 7.5 billion USD.

5.2 No Ancillary Market Scenario Results

The No Ancillary Market Scenario (No Market) resulted in annual grid operation identical to that of the BC. Optimal operation resulted in zero installed storage and H_2

conversion capacity. Power was generated and dispatched identically to the BC scenario. This occurred for two primary reasons: 1) the large capital cost to install conversion and storage capacity, and 2) the inefficiency associated with using HES as an electricity storage system, i.e. low efficiency conversion from electricity to H_2 and back. To avoid these two costs, it was preferable to operate the system relying on dispatchable fossil fuel plants rather than HES. Policy measures that price CO_2 emissions or encourage low-CO_2 generation like Cap and Trade, or RPS could be effective at helping to offset the aforementioned costs and inefficiencies. In addition, establishing a market to sell H_2 into, like a transportation fuel market, would allow for a greater capacity factor of the storage and conversion technology.

5.3 Moderate FCEV Scenario Results

The moderate FCEV scenario assumes that 10% of WECC light-duty passenger-VMT is met by FCEVs. This is approximately 6.8 million FCEVs on the road with similar occupancy and travel patterns as ICE vehicles in 2016, requiring approximately 24.25 TWh of hydrogen fuel annually. The model is not constrained to meet 100% of the hydrogen fuel demand each week, but instead is capped at providing a maximum of that week's demand. This is regulated by providing an exogenous *willingness-to-pay* for H_2 fuel (in USD/kg of H_2). The model will optimally generate and sell hydrogen into the ancillary fuel market up until either (1) the maximum demand for fuel is met for that week, or (2) the marginal cost to generate a unit of H_2 is greater than the markets willingness-to-pay for that unit. Subsequently, the model will also invest optimally in necessary infrastructure to generate the H_2. The Moderate FCEV scenario optimization resulted in a capacity of 37.6 GWh of H_2 storage, 5.8 GW of PEM electrolyzer capacity, and zero fuel cell capacity. No fuel cell capacity was installed by the model because the optimal solution did not involve any H_2 production for energy storage and arbitrage purposes.

As mentioned in the No Market scenario, this is the result of the large capital cost of grid level H_2 conversion technology and low round trip efficiencies. The conversion technology and storage capacity that was installed was used to service the high value FCEV fuel market. 100% of demand for H_2 transportation fuel was met by the system.

Operation of the grid in the presence of an HES system and moderately sized ancillary market resulted in an average electricity CI of 47kg CO_2/MWh, a 2.4% increase in CI from the BC scenario. This scenario did not constrain CO_2, and so in some cases fossil fuels were consumed to create H_2 if it could be done profitably. For this reason, annual emissions increased approximately 4.6% to 73.1 Mtonnes CO_2 from the BC scenario. Generation details and capacity factors for the Moderate FCEV scenario can be seen in Table 9.

Demand was serviced nearly identically to the generation profiles of the No Market scenario. As for capacity factor, the largest change proportionately was seen in coal, increasing by 6% from the BC. In magnitude, however, this is a relatively small change due to the small penetration of coal-fired generation in the grid. Intermittent curtailment decreased by only 3% (15 TWh) in Moderate FCEV scenario from the BC (553 TWh in BC to 538 TWh in modFCEV). In summation, introducing a moderately sized FCEV fuel market increased annual zero-carbon generation by 20.7 TWh over BC and increased fossil-fired generation by 7.9 TWh over BC.

The Moderate FCEV scenario produced 728 ktonnes of H_2, servicing 100% of the demand for H_2 at 4.31$/kg. This is enough H_2 to fuel approximately 4.4 million FCEVs with average travel behavior for a year. The hydrogen produced had a CI of 895 gCO_2/kg H_2. Not accounting for the improved chemical-to-mechanical energy conversion efficiency of a fuel cell to an internal combustion engine, this H_2 fuel is approximately 89% cleaner then E10 gasoline.

Large scale production of low-carbon fuel was made possible by the excess capacity of zero-emission generation, and the capability to capture that excess temporally.

5.4 High FCEV Scenario Results

The High FCEV scenario supposes that 55% of all passenger-VMT is serviced by FCEVs, accounting for approximately 37.5 million passenger FCEVs. This provides a demand for hydrogen approximately 5.5 times that of the Moderate FCEV scenario. Generation details and utilization percentages for the High FCEV scenario can be found in Table 9.

Similar to prior scenarios, very little changed with respect to the percentage of total demand that was met by each generation technology with the exception of CCGT, which rose by 3.8% with respect to BC. There was, however, was a nontrivial increase in capacity factors across most technologies. Coal, wind, CCGT, and solar all saw robust upward trends in capacity factor from BC due to their low marginal cost. The additional demand for H_2 relaxed constraints on some regions that were meeting 100% of demand in the Moderate FCEV scenario, allowing for an overall increase in generation. The willingness to pay for H_2 was left unchanged. Because of this, the hierarchy of resources that could be cost-effectively captured to make H_2 profitably did not shift – leaving coal, CCGT, and zero-marginal cost generation sources the primary target for cost minimization. This resulted in an electricity CI of 58 $kgCO_2/MWh$, a 26.8% increase from BC. With a large demand enticing more sizable investments in capacity, there is more of a capability for the system to capture greater amounts of otherwise low capacity factor generation sources. In the High FCEV scenario, curtailed intermittent generation was reduced to 27% of potential generation, down from 32% in the BC (473 TWh curtailed in highFCEV down from 553 TWh in the BC). Enough H_2 was generated in this scenario to service roughly 100% of the demand, or 133 TWh of hydrogen fuel. This is enough hydrogen to fuel approximately 37.5 million FCEVs for one year.

Similarly to the ModFCEV scenario, no investment was made in fuel cell capacity in this scenario. Despite the large investments in PEM electrolyzers (26.2 GW) and H_2 storage (304 GWh), there was not an economic motivation to invest in reconversion technology to allow for energy arbitrage.

5.5 Scenario Comparison

The flexibility to generate H_2 from low cost sources and utilize it as a high value fuel was the driving factor for investment into H_2 generation and storage technology. Having an auxiliary market for H_2 transportation fuel increased overall demand for electricity to serve as a feedstock for electrolysis. *Figure* 6 shows the amount of curtailment of intermittent renewables that occurred as a function of each scenario. As the incentive to invest in H_2 generation increases, the temporal flexibility of the grid also increases. Additionally, greater sums of flexible load increase the magnitude of demand, reducing the sum of curtailed renewables. The ModFCEV and HighFCEV scenarios showed a potential to reduce curtailment by 15 TWh and 79 TWH respectively.

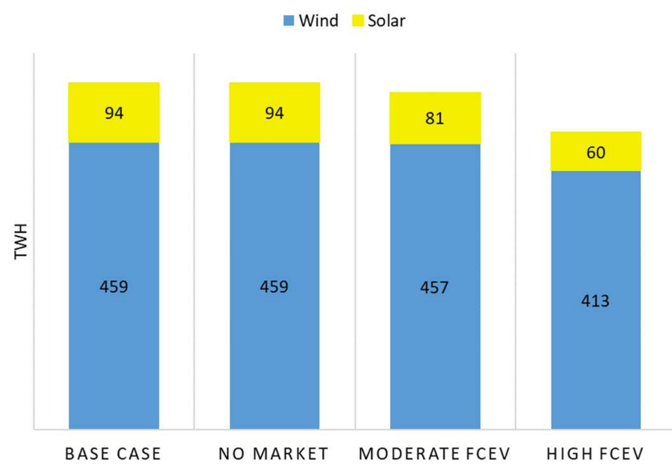

Figure 6. Curtailment of intermittent renewable generation as a function of scenario

For this reason, the High FCEV scenario (largest demand for H_2) has the lowest curtailment rate, although there is still a significant amount of curtailment (>25% of electricity generation). This increased utilization of renewable resource is not the direct product of emissions regulation but is driven by market forces. Greater temporal flexibility in load and a greater magnitude of load enable the model to favor lower cost generation methods. In most cases, zero-carbon generation provides the lowest marginal cost. For this reason, renewable utilization increases most rapidly as load-shaping measures are introduced.

The ModFCEV and HighFCEV scenarios have the capacity to sell H_2 for a profit, up until a certain demand threshold is met. The price at which the H_2 can be sold at is exogenously at \$4.31/kg H_2. Energy generation must increase to serve as a feedstock in order to generate H_2. Figure 7 shows the cost to operate the system and the revenue from sales of hydrogen in each scenario. The objective function for each scenario would be the difference of these two numbers.

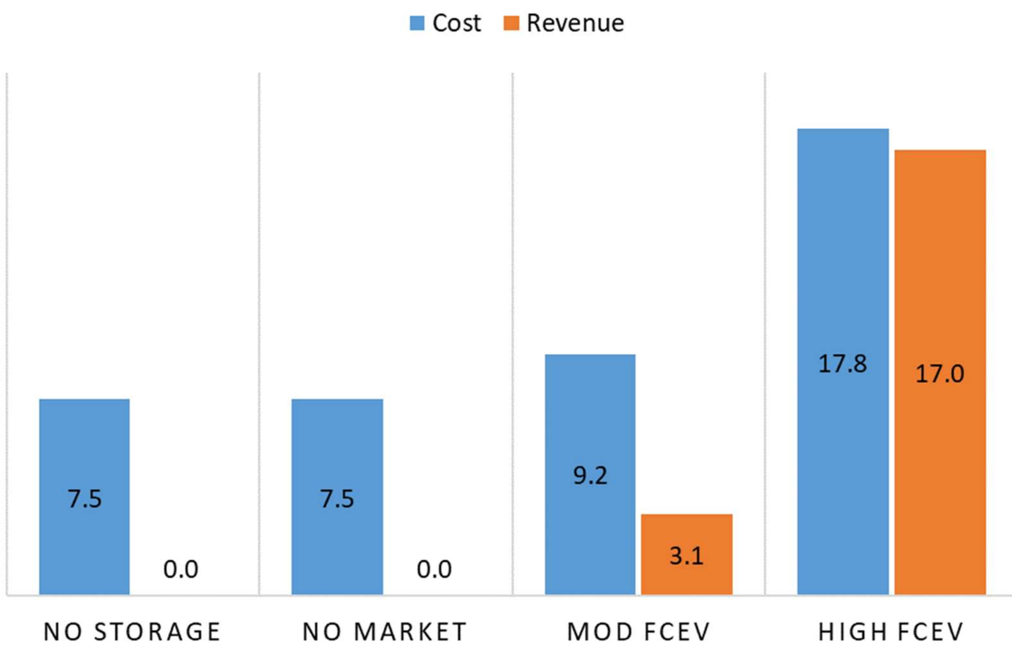

Figure 7. Electricity generation cost and revenue from H_2 sales in billion USD

It is important to understand what the impacts of using H_2 as a transportation fuel are in order to assess the costs and benefits. An important metric is the carbon intensity of the fuel, on an energy basis (kg CO_2/ kg H_2) and on a per mile basis (kg CO_2/vehicle mile). This metric can be calculated using two different approaches, attributionally and consequentially. The attributional allocation of carbon burden onto the H_2 is determined by taking the product of the average hourly emissions rate (kg CO_2/MWh) and the electricity used to generate H_2 (MWh) divided by the total MWh of H_2 produced. This represents attributing the average emissions rate of the grid to the H_2 produced, regardless of the impact additional demand for electricity caused by H_2 generation has on emissions rates. The consequential approach attributes the marginal emissions from increasing demand for electricity as a feedstock to generate H_2 to the H_2 produced. This was calculated by attributing the emissions from electricity generation that is in excess of the BC scenario to H_2 generation and dividing by the total sum of H_2 produced. Figure 8 shows the attributional and consequential CI of H_2 produced in both the ModFCEV scenario and

HighFCEV scenario. The CI of H_2 is shown in a per mile basis so as to be comparable to data available for other passenger light duty vehicles. It is assumed that H_2 is consumed at a rate of 60mi/kg H_2. The consequentially calculated CI is higher than the attributional because the use of dispatchable generation allows for the minimization of electrolyzer capacity. The flexible nature of dispatchable generation allows the model to satisfy all of the H_2 demand with less electrolyzer capacity, and so the model favors using more dispatchable fossil fuels to generate additional H_2. This yields the higher consequential CI because the H_2 is considered 'responsible' for the marginal emissions.

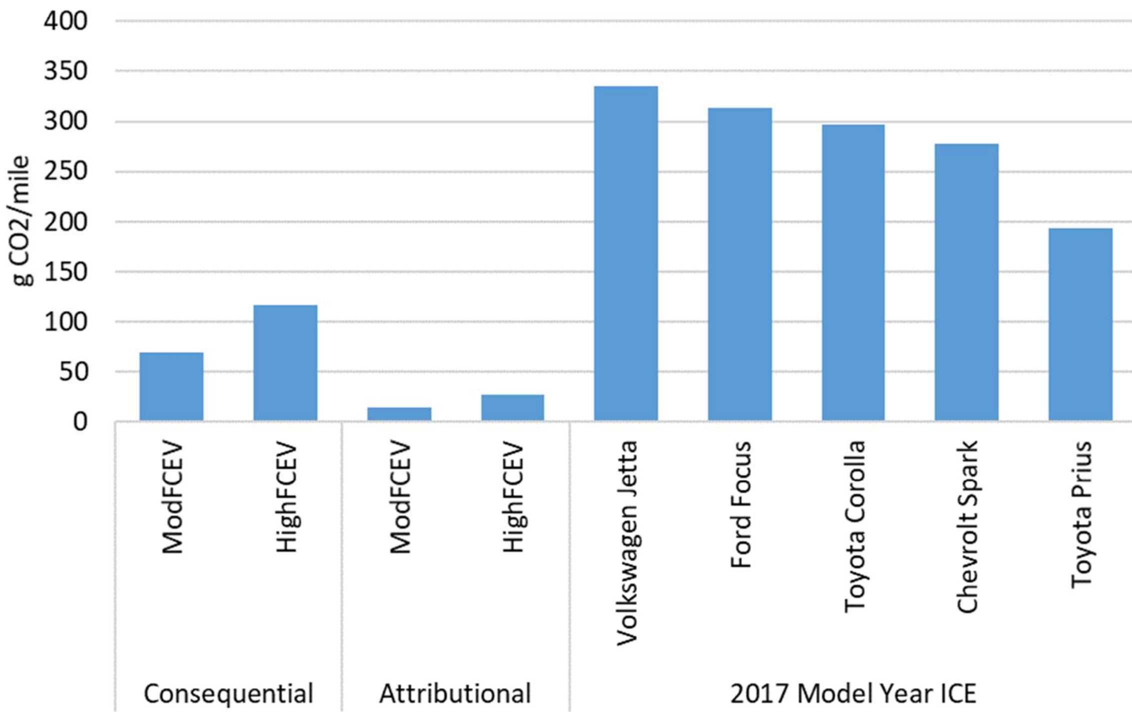

Figure 8. Attributional and consequential carbon intensities of H_2 compared to popular 2017 passenger light duty vehicles (Environmental Protection Agency, 2018)

Table 9 summarizes the outcomes for the various scenarios. The capacity factors stated for solar and wind generation are a percentage of generation that is utilized by the grid to service demand or make H_2 divided by the total energy generation. This is as opposed to a traditional capacity factor metric of generation divided by nameplate capacity.

	Summary Statistics		Unit	Base Case	No Market	Moderate FCEV	High FCEV
	Objective Function		000,000	7503.85	7503.85	6141.48	817.13
Generation	Fossil		TWh	182	182	190	256
Generation	Zero-Carbon		TWh	1362	1362	1382	1449
Generation	Intermittent		TWh	1183	1183	1199	1263
	Curtailed Intermittent Generation		TWh	553	553	538	474
Capacity Factor	Coal Steam Turbine		%	58.4%	58.4%	64.5%	76.8%
Capacity Factor	Gas Combustion Turbine		%	3.2%	3.2%	3.2%	4.4%
Capacity Factor	CCGT		%	38.0%	38.0%	39.8%	53.5%
Capacity Factor	Hydro NonPumped		%	9.8%	9.8%	9.9%	10.0%
Capacity Factor	Nuclear		%	98.6%	98.6%	98.4%	99.8%
Capacity Factor	Gas Steam Turbine		%	0.3%	0.3%	0.3%	0.3%
Capacity Factor	Geothermal		%	87.5%	87.5%	92.1%	93.7%
Capacity Factor	Solar		%	71.1%	71.1%	75.2%	81.5%
Capacity Factor	Wind		%	67.5%	67.5%	67.6%	70.7%
Carbon Intensity	Electricity	Attributional	$kgCO_2/MWh$	45	45	47	58
Carbon Intensity	Hydrogen	Attributional	$kgCO_2/kg\ H_2$	-	-	0.89	1.66
Carbon Intensity	Hydrogen	Consequential	$kgCO_2/kg\ H_2$	-	-	4.16	6.99
	Hydrogen fuel		GWh	-	0	24,250	133,732
HES Capacity	PEM Electrolyzer		MW	-	0	5,795	26,231
HES Capacity	Fuel Cell		MW	-	0	0	0
HES Capacity	H_2 Storage		GWh	-	0	38	304
Capacity Factor	PEM Electrolyzer		%	-	-	55.7%	67.9%
Capacity Factor	Fuel Cell		%	-	-	-	-
Capacity Factor	H_2 Storage		%	-	-	14.4%	17.4%
	Total Annual Emissions		Mtonne CO_2	70.1	70.1	73.2	98.2

Table 9. Summary statistics for comparison between scenarios

6. Conclusions

Hydrogen Energy Storage offers the potential to help mitigate a host of issues across the transportation and electricity sectors. This is accomplished by: (1) serving as a load-shaping tool, and (2) generating an energy storage medium that can serve multiple end uses. In conjunction, these two services help to: integrate intermittent generation, reduce fossil fuel consumption, lower the cost to operate the grid, reduce demand for peaker capacity, reduce demand for transmission capacity, and provide a source of potentially low carbon H_2 to be used as an alternative fuel. This study aimed to illuminate the optimal operation of an HES system in a highly renewable 2050 grid.

An economic dispatch model was created (ODESS) to simulate operation of the grid in question with minimal cost. Data was collected and compiled to generate a scenario of a highly renewable, 2050 WECC Base Case. This base case scenario was run with ODESS and then compared to further ODESS runs simulating various capacities of HES and post-generation hydrogen markets. The outcomes of these scenario runs can be seen in detail in Table 9. The model was able to capture differences in costs associated with various technologies, times, and locations and leverage them to achieve a greater penetration of renewable generation. Utilizing flexible hydrogen generation allowed the grid to reduce curtailment by up to 79 TWh while concurrently generating very low carbon fuel for millions of FCEVs.

Policy to support an economically successful HES system in the WECC should focus on three fundamentals:

1. Increasing the penetration of intermittent and zero-carbon generation sources
2. Increasing the stock of FCEVs – creating a reliable, long-term demand
3. Subsidizing capital investment in energy storage projects

Focusing on these three rudiments will help to establish an environment favorable for a more market-driven shift in energy management. A high penetration of intermittent renewables provides a surplus of zero-marginal cost generation that can be leveraged to generate H_2 at a competitive price to other fuels. An increasing penetration of FCEVs would provide security and reliability for investors who would otherwise be hesitant to enter the market. Finally, subsidies for energy storage projects could help to bring HES systems online, increasing hydrogen supply and advancing the learning curve.

Future work on this topic could be meaningful in further illuminating the benefits of HES in grid stabilization and alternative fuel production. Conversion of ODESS to a non-linear model would enable greater detail in operational constraints such as ramp-rates, mandatory operational times, and frequency regulation. Additionally, a comparison of various storage technologies, both separate from and in conjunction with HES could be of interest. Finally, modeling a more complex ancillary market could provide great insights into the value of various H2 pathways. Such pathways could include: additional transportation markets, industrial refining, mixture into the natural gas pipeline, NH3 production, and synthetic fuel generation.

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