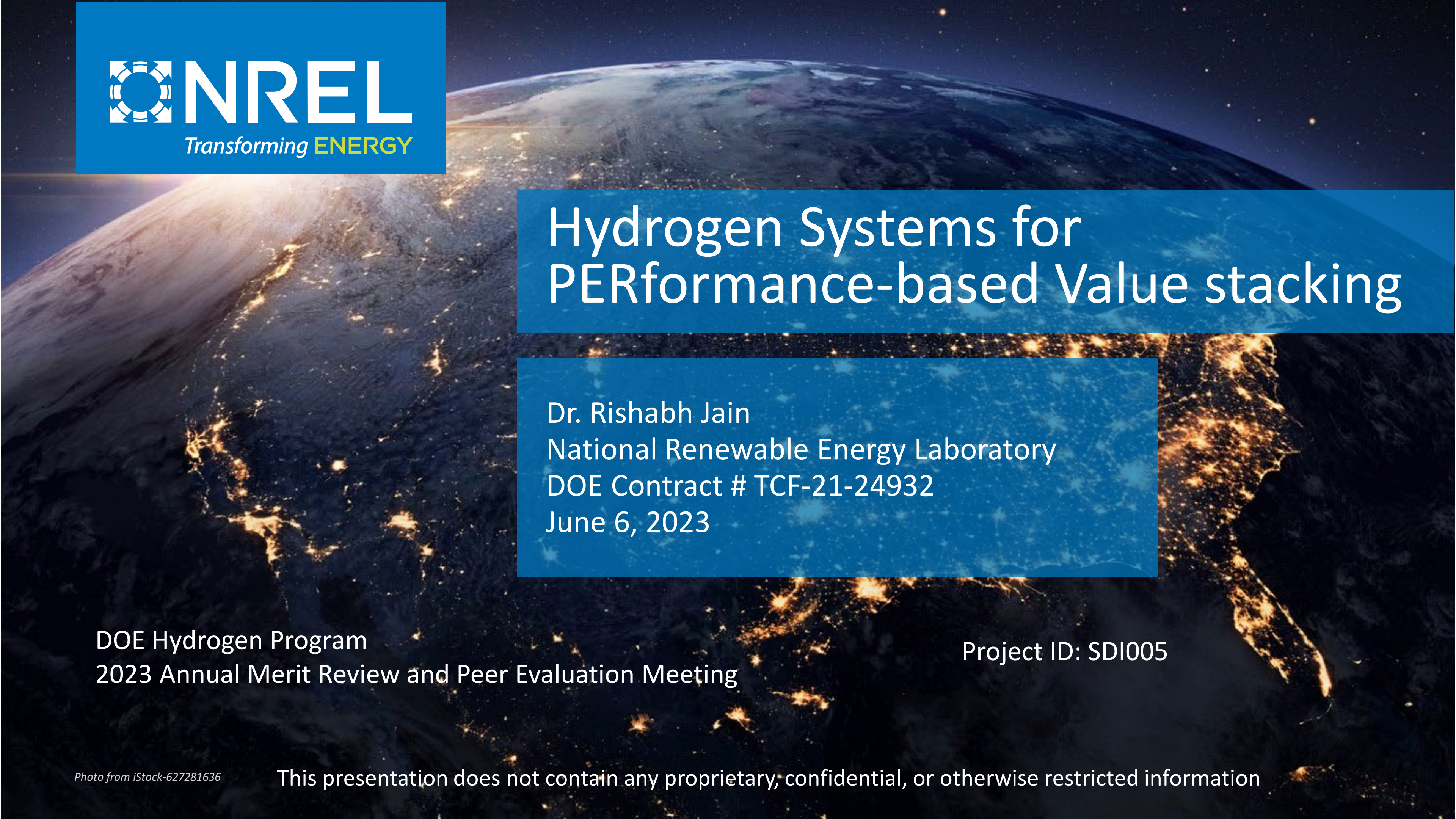


Hydrogen Systems for PERformance-based Value stacking

Dr. Rishabh Jain
National Renewable Energy Laboratory
DOE Contract # TCF-21-24932
June 6, 2023

DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

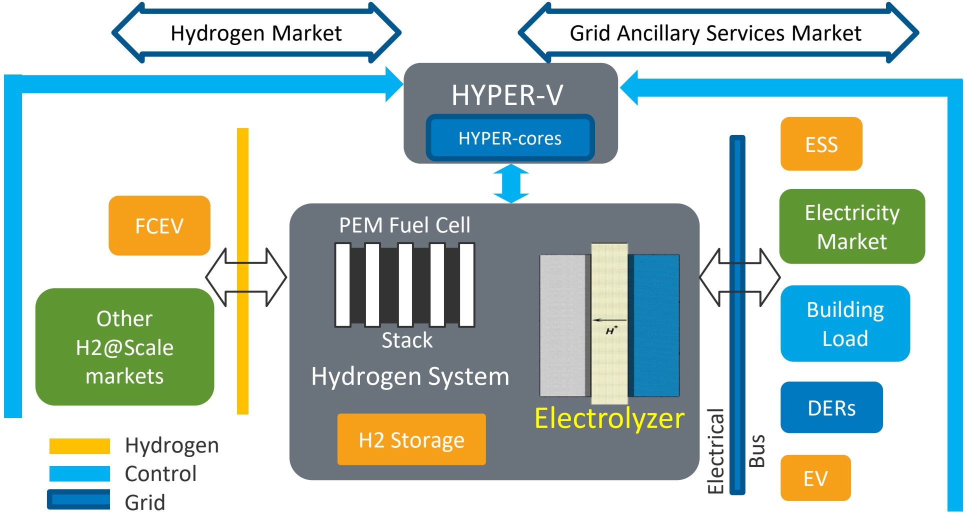
Project ID: SDI005

Photo from iStock-627281636

Project Goal and Impact

Developing a co-optimal design and control approach to allow hydrogen systems to reliably participate in electricity and hydrogen markets

- Develop control and planning modules for HYPER-V with uncertainty considerations for reliable operation
- Explore use-cases for electricity dependent, hydrogen-dependent business models
- Explore the techno-economic feasibility of the proposed design/planning using HYPER-V



Commercial site with electrical and hydrogen demands co-optimized using HYPER-V

Impact:

- One-of-its-kind platform that allows feasibility analysis of the business with considerations for value-stacked revenue streams
- Provide a sustainable path towards building clean energy infrastructure
- Provide pathways to private sector uptake.

Overview

Timeline and Budget

For Competitively Selected Projects awarded through FOAs and fully funded at project start:

- Project Start Date: 12/1/2021
- Project End Date: 6/15/2023
- Total Project Budget: $500,000
  - Total DOE Share: $250,000
  - Total Cost Share: $250,000
  - Total DOE Funds Spent*: $239,000
  - Total Cost Share Funds Spent*: $250,000

* As of 04/14/2023

This is the first AMR presentation for this project

Barriers

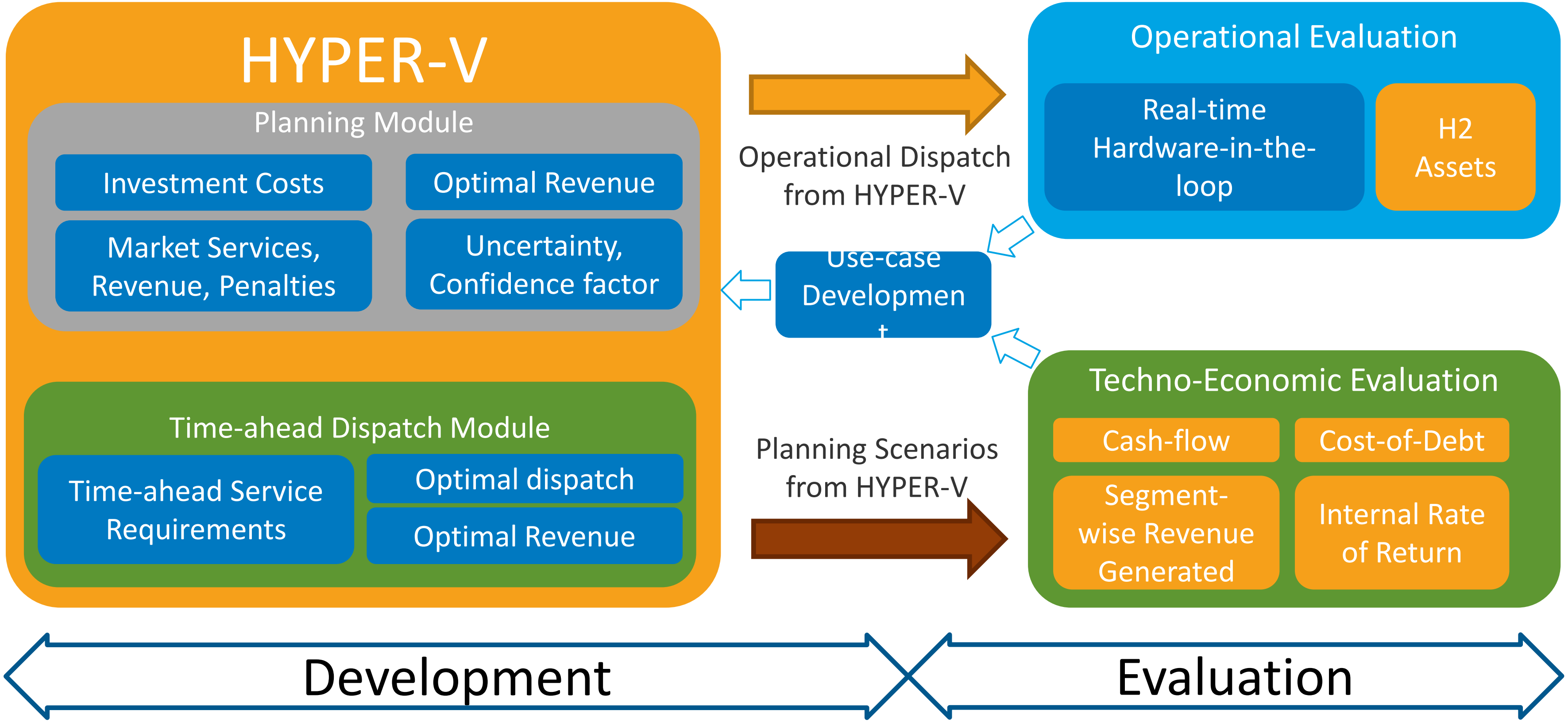
- Barriers and Targets
  - Lack of consideration for the unique electrical characteristics of the hydrogen system assets
  - Limited insight into developing turn-key solutions that allows revenue from multiple service streams
  - Bringing planning and operational design on a single platform that explores the mutual impact of decisions

Partners

- Rishabh Jain (PI), NREL
- Partner: Eaton

Tasks	Description	Q1	Q2	Q3	Q4	Q5
1	Hydrogen systems: Architecture and modeling					
1.1	Fuel cell model	x				
1.2	Compressed hydrogen storage model	x	x			
1.3	Architecture configuration strategies for integrated hydrogen systems	x	x	x		
M1.1	**Component models of hydrogen system assets for a single configuration**	x				
M1.2	**Component models of hydrogen system assets for multiple configurations**			x		
2	Market valuation of energy markets, Demand profiles					
2.1	H2@Scale: Grid services markets	x	x	x		
2.2	H2@Scale: Other markets		x	x		
M2.2	**Demand profiles based on 3 or more service market criteria**			x		
M2	**Techno-economic feasibility analysis for the different use-cases**					x
3	HYPER-V based Hydrogen Systems: Optimal configuration, control, and sizing.					
3.1	Application-specific configuration strategies		x	x		
3.2a	Optimal energy management and control – without Uncertainty considerations		x	x		
3.2b	Optimal energy management and control – with Uncertainty considerations				x	
3.3	Optimal sizing needs for hydrogen systems and energy storage			x	x	
M3.1	**HYPER-V formulation and operation planning for a test site**		x			
M3.2	**HYPER-V based control strategy, sizing approach for a test site**			x	x	
4	Lab Implementation: HYPER-V based hydrogen systems					
4.1	Real-time software-only simulation models of a customer site with integrated hydrogen systems	x	x			
4.2	Control development for Co-optimal service participation	x	x	x		
4.3	Use-cases and control-hardware-in-the-loop HYPER-V demonstration		x	x	x	
M4.1	**Software-only real-time demo: HYPER-V based on M3.1**		x			x
M4.2	**Control-hardware-in-the-loop demo: HYPER-V**					x

Approach



HYPER-V

Planning Module

Investment Costs

Optimal Revenue

Market Services, Revenue, Penalties

Uncertainty, Confidence factor

Time-ahead Dispatch Module

Time-ahead Service Requirements

Optimal dispatch

Optimal Revenue

Operational Dispatch from HYPER-V

Use-case Developmen t

Planning Scenarios from HYPER-V

Operational Evaluation

Real-time Hardware-in-the-loop

H2 Assets

Techno-Economic Evaluation

Cash-flow

Cost-of-Debt

Segment-wise Revenue Generated

Internal Rate of Return

Development

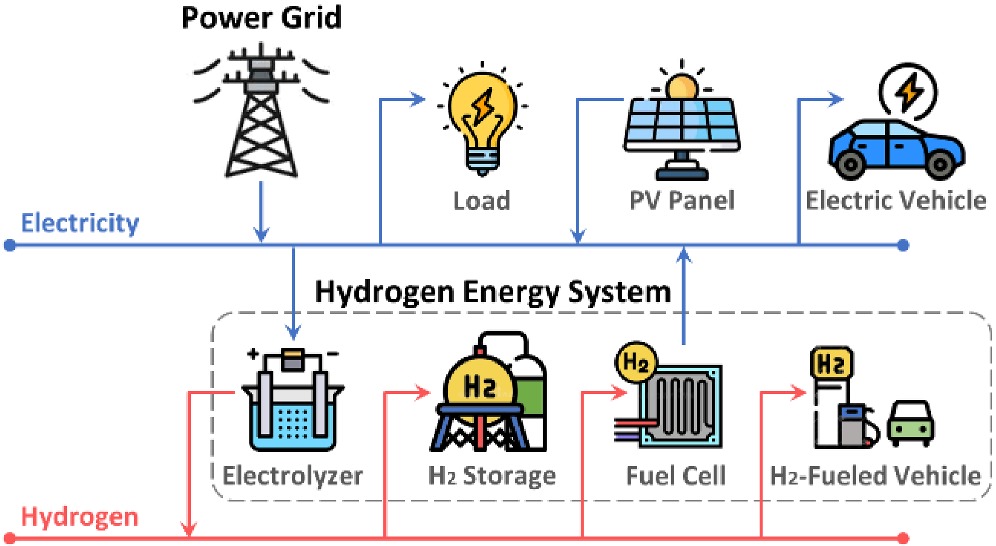
Evaluation

Accomplishments and Progress

HYPER-V Design, Use-case Outcomes

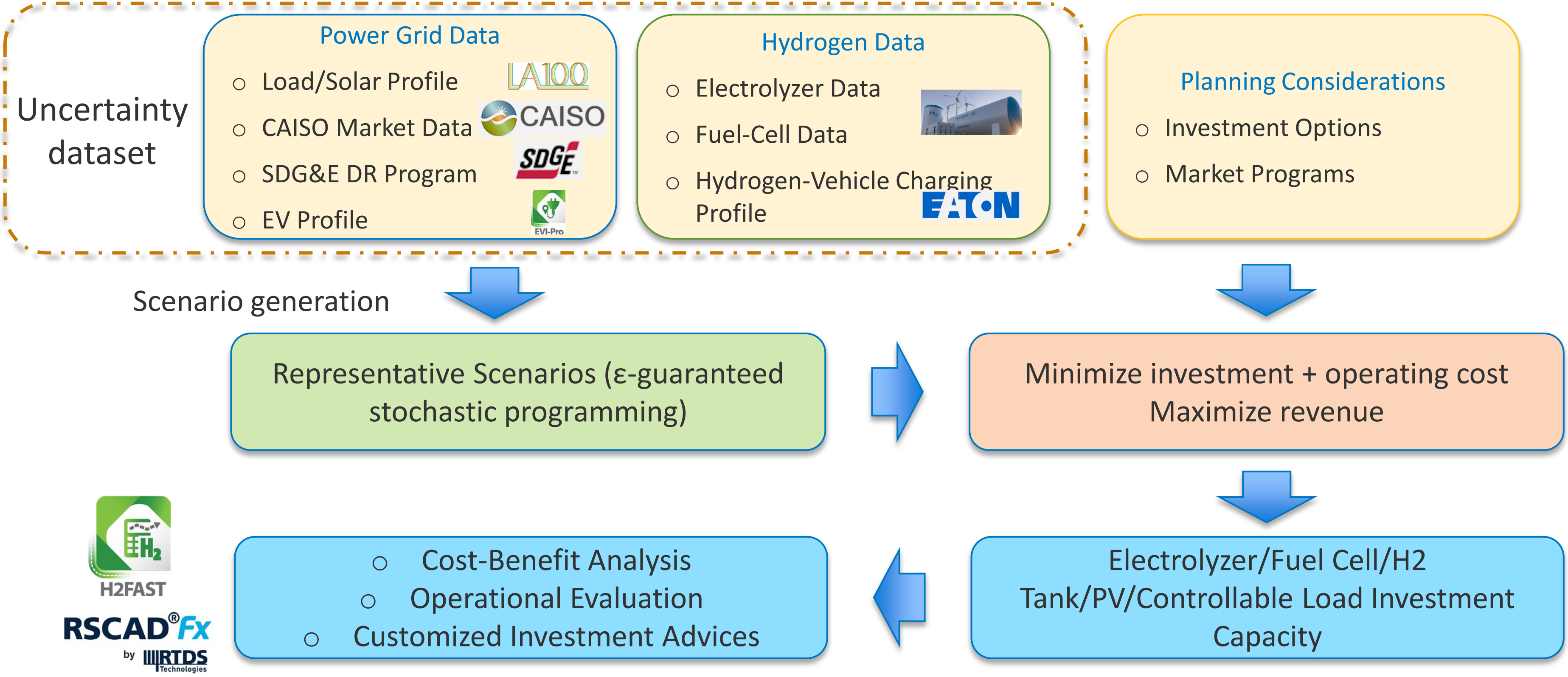
HYPER-V Integrated System Planning Model

- The planning model considers the different hydrogen systems and grid assets that are integrated to observe the impact on electricity and hydrogen[1] markets.



[1]. X. Zhao, Y. Yao, W. Liu , R. Jain, and C. Zhao, "A Hydrogen Load Modeling Method for Integrated Hydrogen Energy System Planning," *2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2023, pp. 1-5

Overview: HYPER-V Design



Uncertainty dataset

Power Grid Data

- ○ Load/Solar Profile
- ○ CAISO Market Data
- ○ SDG&E DR Program
- ○ EV Profile

Hydrogen Data

- ○ Electrolyzer Data
- ○ Fuel-Cell Data
- ○ Hydrogen-Vehicle Charging Profile

Planning Considerations

- ○ Investment Options
- ○ Market Programs

Scenario generation

Representative Scenarios (ε-guaranteed stochastic programming)

Minimize investment + operating cost
Maximize revenue

Electrolyzer/Fuel Cell/H2 Tank/PV/Controllable Load Investment Capacity

- ○ Cost-Benefit Analysis
- ○ Operational Evaluation
- ○ Customized Investment Advices

HyperV Optimal Planning Tool (Linear Programming + Open-source Google ORtools)

Decision Variables – Investment on:

- Hydrogen devices
- PV asset
- EV charging asses
- Controllable load asset

Objective Function – Minimize on:

Investment cost + Operating cost − Revenues from Electricity and Hydrogen markets + Penalty from electricity market

Subject to – Constraints on:

- Netload power balance constraints
- Hydrogen energy system operating constraints
- PV and Controllable oconstraints
- Electricity and Hydrogen vehicle service constraints

Numerical Tests: Cost Parameters

Key Parameters for Integrated System Planning

Parameter	Current Value	Future Value in 10 Years
$c_{\mathrm{PV,inv}}$	1,640 ($/kW) [9]	1,150 ($/kW)
c_{tank}	400 ($/kg) [10]	350 ($/kg) [10]
c_{EL}	107,800 ($/kg·h-1) [11]	55,000 ($/kg·h-1) [11]
c_{FC}	540 ($/kW) [12]	200 ($/kW) [12]
c_{fixed}	250,000 ($) [13]	200,000 ($)
λ_{H}	15 ($/kg)	8 ($/kg)
$\eta^{\mathrm{HS,EL}}$	70 (%)	80 (%)
$\eta^{\mathrm{HS,FC}}$	50 (%)	60 (%)

- Case 1: Current-value planning without considering any grid service
- Case 2: Current-value planning considering demand response and regulation services
- Case 3: Future-value planning considering demand response and regulation services.
- Case 4: Current-value planning considering more aggressive demand response and regulation services

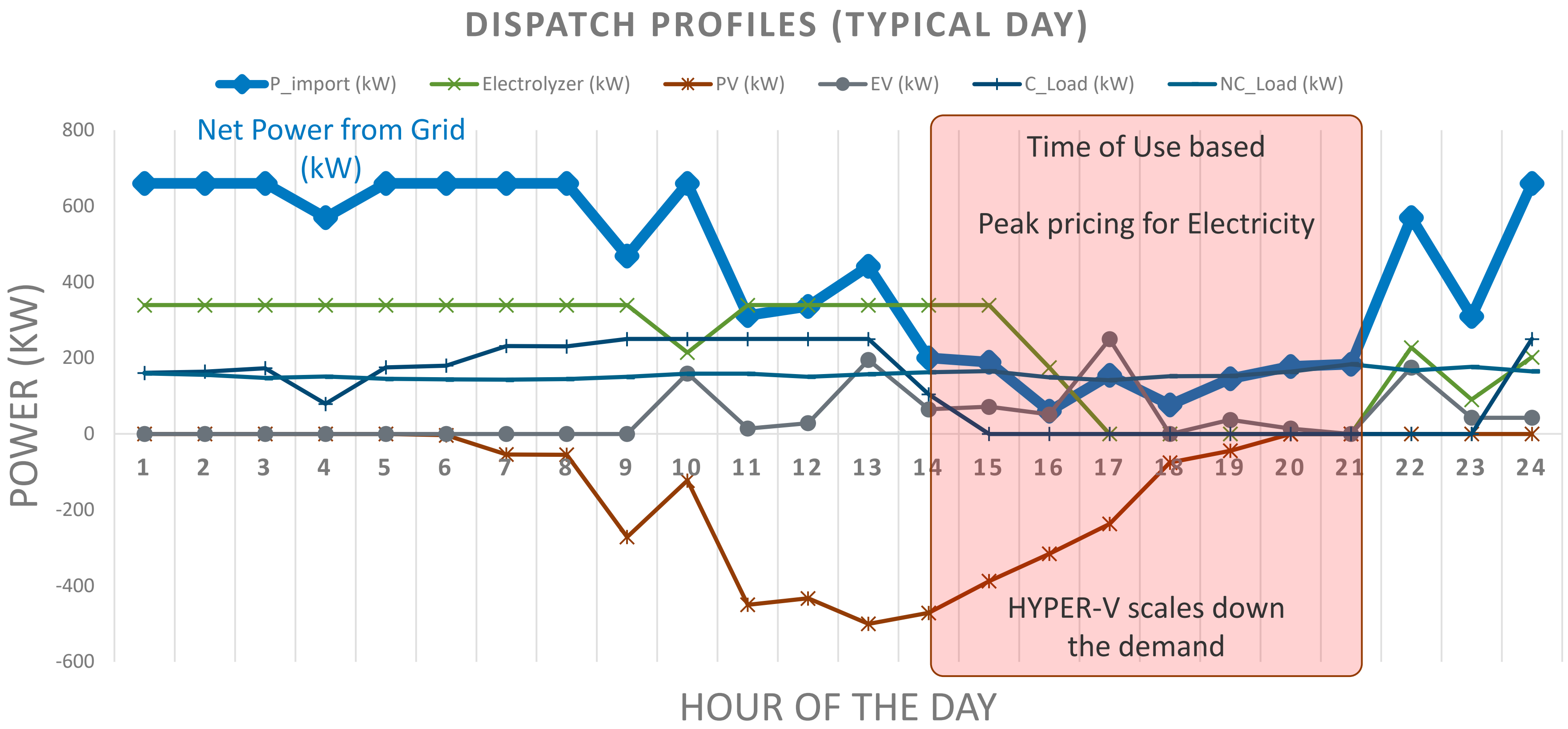
[10] . B. D. James, C. Houchins, J. M. Huya-Kouadio, *et al.*, “Hydrogen storage system cost analysis,” Strategic Analysis Inc., Arlington, VA, USA, *Tech. Rep. DOE-SA-0005253 7037787114*, 2016.

[11]. P. Graham, J. Hayward, J. Foster, *et al.*, “GenCost 2021-22: Final report,” CSIRO, Australia, Jul. 2022.

[12]. J. Hinkley, J. Hayward, R. McNaughton, *et al.*, “Cost assessment of hydrogen production from PV and electrolysis,” Report to ARENA as part of Solar Fuels Roadmap, Project A-3018, pp. 1–4, Mar. 2016.

[13]. K. Reddi, A. Elgowainy, N. Rustagi, et al., “Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen,” *International Journal of Hydrogen Energy*, vol. 42, no. 34, pp. 21855–21865, Aug. 2017.

Typical Dispatch Day – Optimized by HYPER-V



Net Power from Grid (kW)

Time of Use based

Peak pricing for Electricity

HYPER-V scales down the demand

Numerical Tests: Planning Results

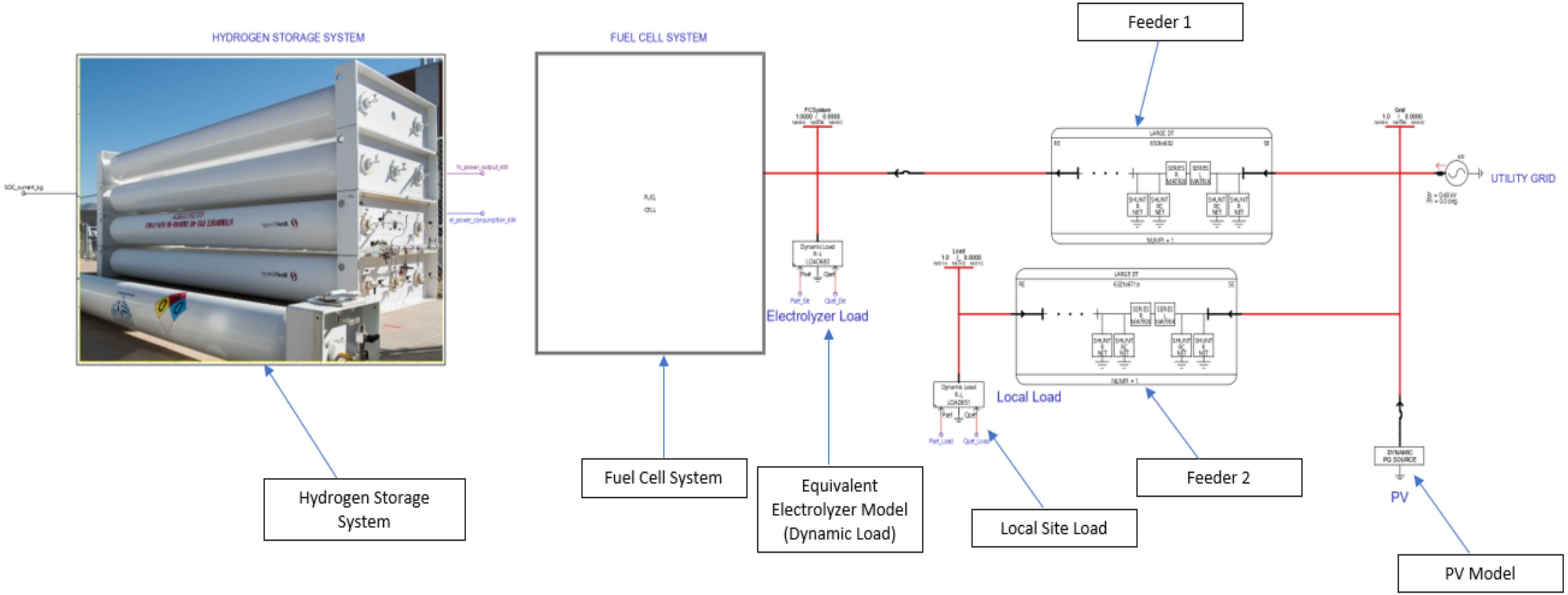
Case No.	1	2	3	4
Scenario	Revenue from selling H2 and EV charging	Case 1 + Grid-ancillary services included	Case 2: H2 sold @ $8/kg, Cheaper investment in H2 systems	Case 2: Double the Income Revenue from Grid Service
Tank capacity (kg)	3,620	3,620	5,431	3,620
Hydrogen production capacity (kg/h)	362	362	543	362
Fuel cell capacity (kW)	500	500	500	500
PV capacity (kW)	162	0	500	0
EV charger capacity (kW)	394	394	364	394
Demand response capacity (kW)	0	255	170	281.4
Controllable load (kW)	0	250	250	276.4

Accomplishments and Progress

Operation Feasibility Validation using
High-fidelity power system models

Evaluation Test Bed

Optimal Planning Tool → Setpoints → RSCAD® Fx by RTDS Technologies



Feeder 1

Hydrogen Storage System

Fuel Cell System

Equivalent Electrolyzer Model (Dynamic Load)

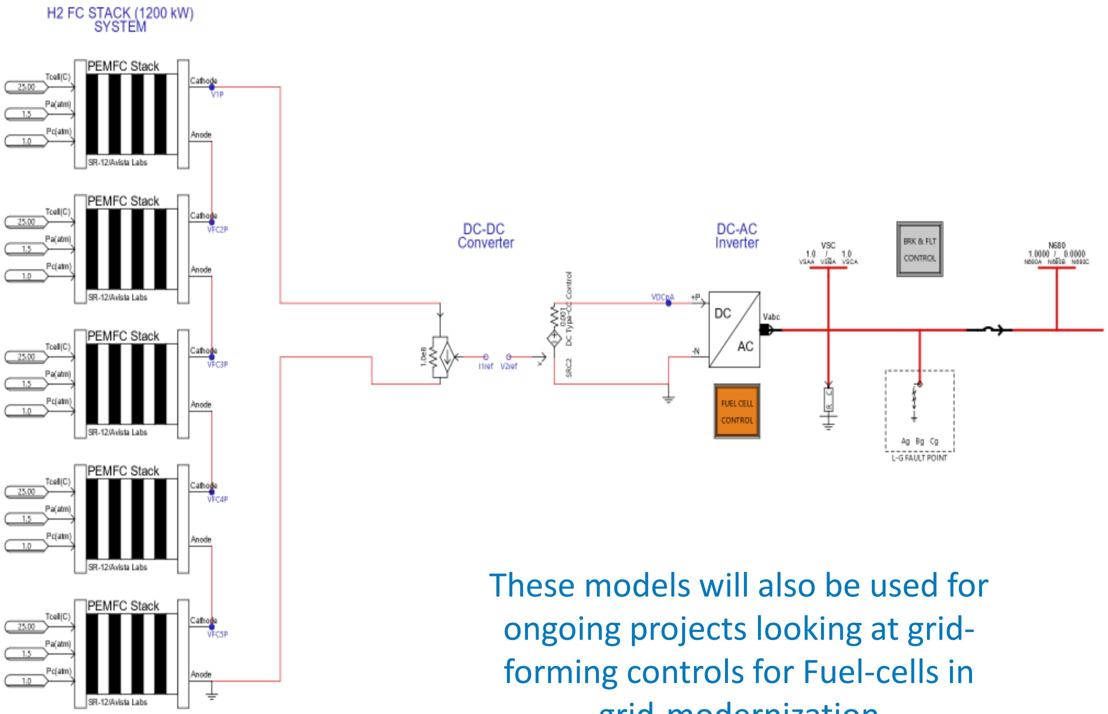
Local Site Load

Feeder 2

PV Model

Scalable Fuel-cell Module Design

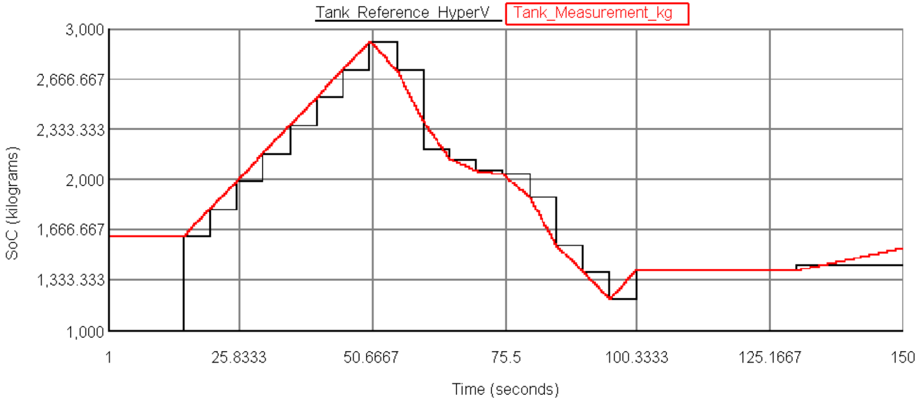
- Grid-connected MW-scale FC system modeled in a RTDS simulator to emulate interaction of inverter interfaced FC when connected to the utility grid
- PEMFC Stack, DC-DC converter and DC-AC inverter modeled in RSCAD
- PEMFC stack models electrochemical as well as terminal electrical response [1]
- For converters and inverters, average models are used given applications of interest span over several minutes/hours
- Fuel Cell model Validation performed using various steady-state and dynamic tests
- FC inverter controller set to operate in grid-following mode – tracking P and Q setpoints
- Optimal dispatch setpoints from the planning tool results are sent to FC inverter controller for emulating a 24-hours scenario



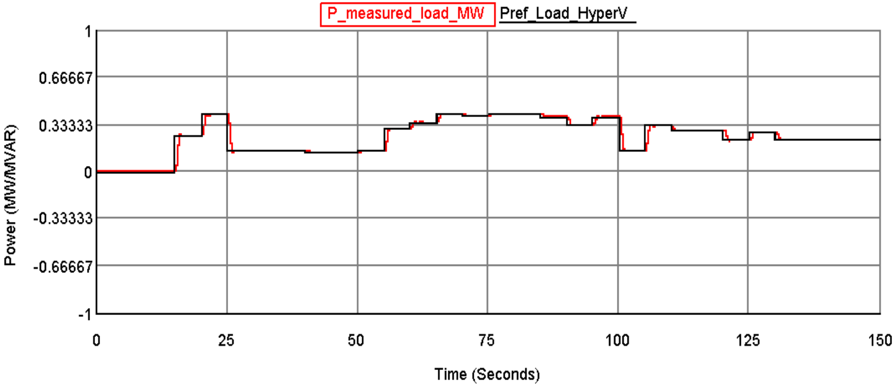
These models will also be used for ongoing projects looking at grid-forming controls for Fuel-cells in grid-modernization

[1] Modeling and Control of Fuel Cells: Distributed Generation Applications, M. Hashem Nehrir and Caisheng Wang

Results/Validation/Discussion – Case 1



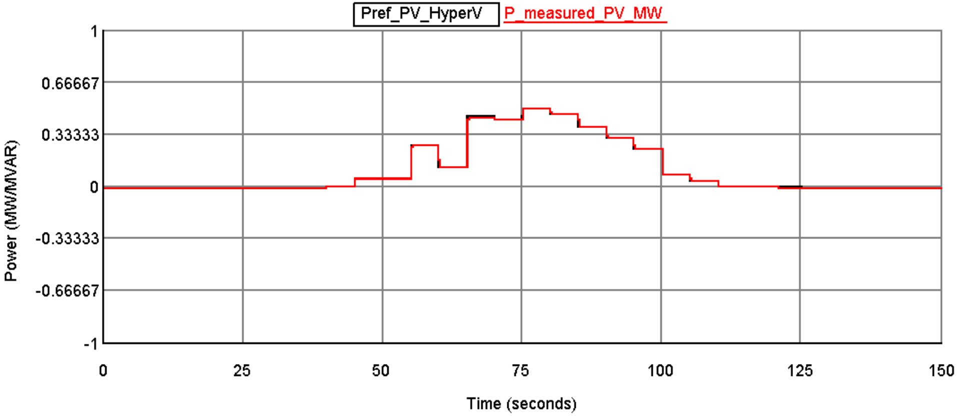
Comparison: Hydrogen in Tank (in kg) over 24 hour period - RSCAD Simulation Results



Comparison: Local Load Real Power Consumption (in MW) over 24 hour period – RSCAD Simulation Results

(Black) HYPER-V set points vs (RED) Actual Response

Results for other cases in backup slides

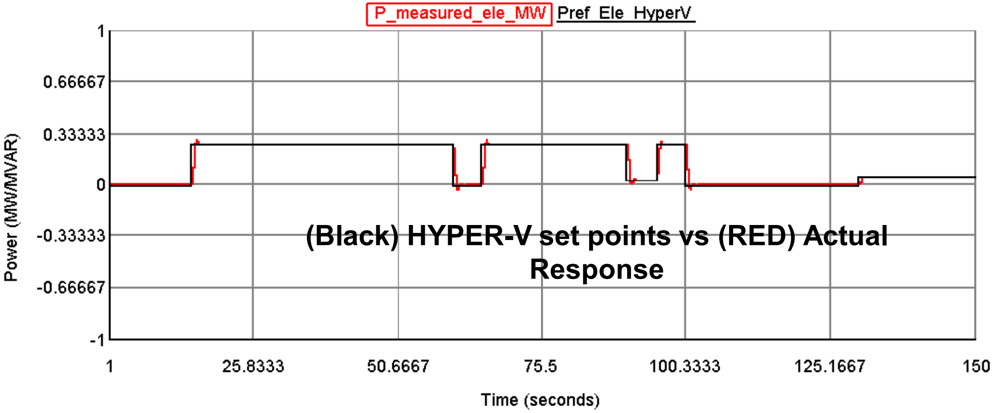


Comparison: PV Real Power Output (in MW) over 24 hour period - RSCAD Simulation Results

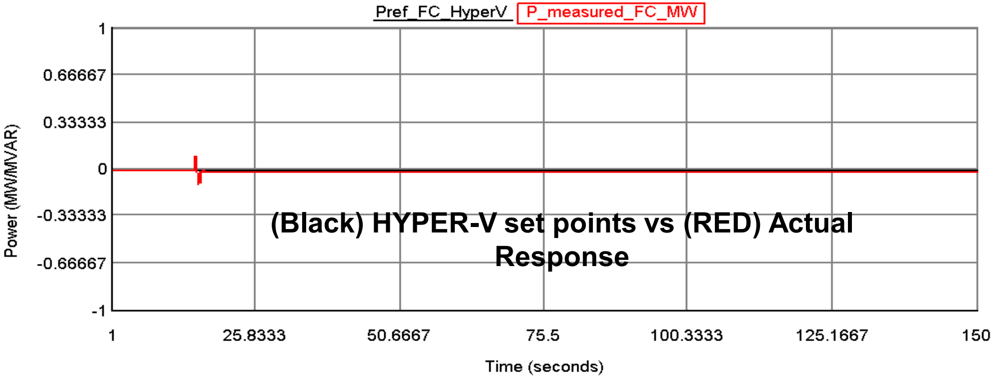
Results/Validation/Discussion – Case 1

- RTDS Validation plots are used to compare signals measured in the simulation vs setpoints dispatched by the planning tool (for 24 hours – 5 seconds in simulation = 15 minutes in the planning tool)
- For all dynamic components (PV, electrolyzer, local load and FC), the trend in measured signals show the dynamics associated with the EMT simulation
- The dynamics are governed by the underlying physical characteristics of the components, or the PI controllers used for reference tracking (Planning tool references)
- Simulation results for all 4 cases showed a stable response in the RTDS simulations

Results for other cases in backup slides



Comparison: Electrolyzer Power Consumption (in MW) over 24 hour period – RSCAD Simulation Results



Comparison: FC Power Injection (in MW) over 24 hour period – RSCAD Simulation Results

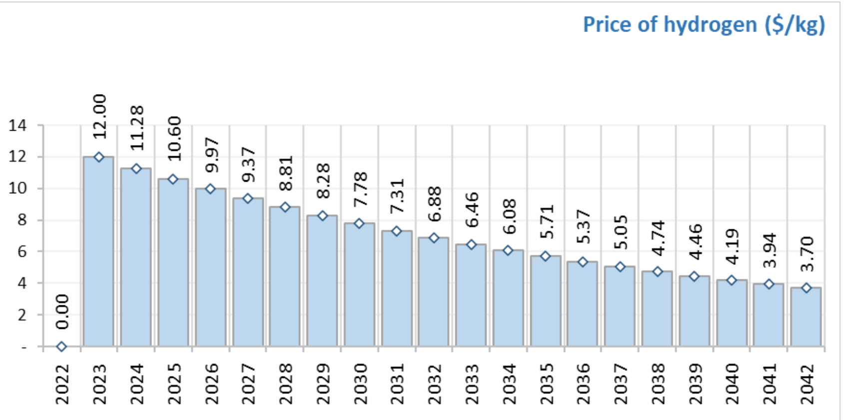
Accomplishments and Progress

Techno-economic Feasibility

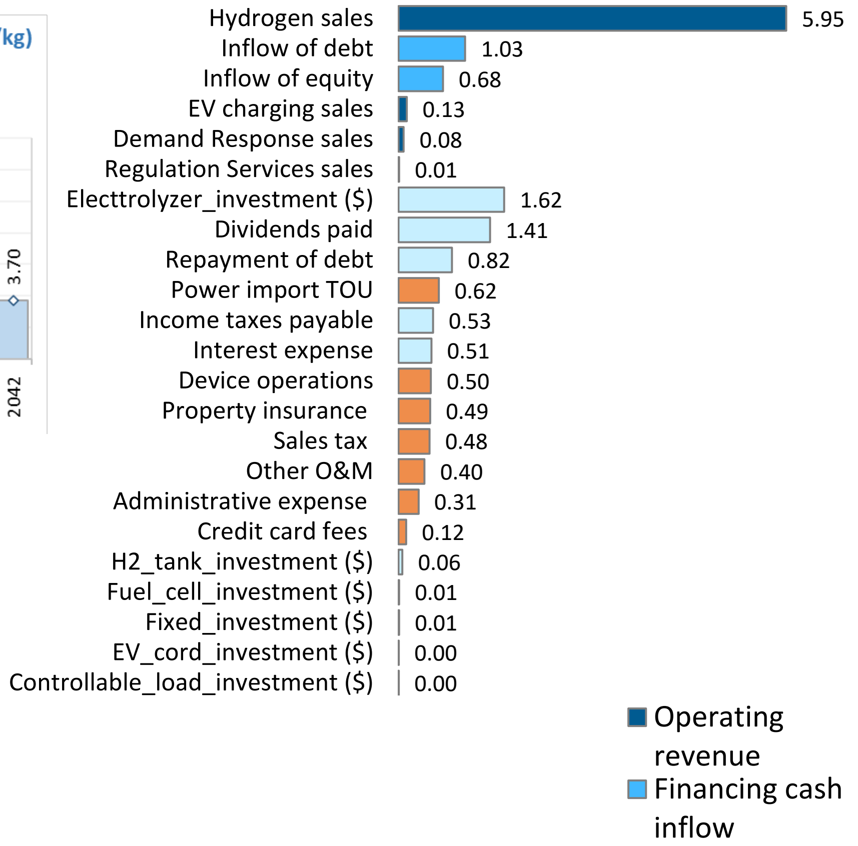
Cost-benefit Analysis – Considering a 60-40 split (60% loan, 40% capital)

Case No.	1	2	3	4
Scenario	Revenue from selling H2 and EV charging	Case 1 + Grid-ancillary services included	Case 2: H2 sold @ $8/kg, Cheaper investment in H2 systems	Case 2: Double the Income Revenue from Grid Service
Capital Cost ($)	$41.5M	$41.1M	$32.8M	$41.1M
Equity nominal IRR @8.34%	17.53%	18.79%	31.58%	21.87%
Profitability index	1.42	1.5	2.2	1.7
Investor payback period	4 years	4 years	3 years	4 years
After-tax, nominal NPV @ 8.34% discount	$7.1M	$8.1M	$15.7M	$11.6M

Investment Analysis: With less rewarding Grid service market



Real levelized cost breakdown of hydrogen (2023$/kg)



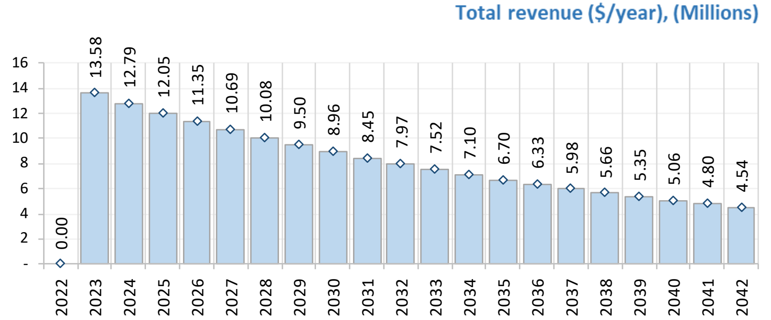
- We used H2FAST for the investment analysis
- Hydrogen is assumed to become more affordable (declining selling price) over the next 2 decades.
- Investment and Operating costs are considered to be same for baseline comparison
- Growth in demand is not modeled for this analysis
- Service

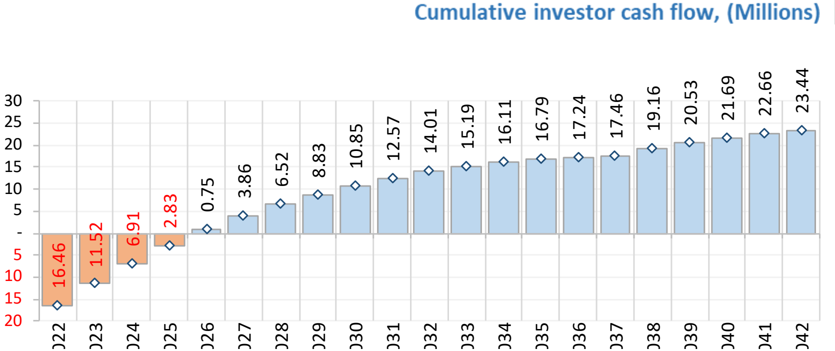
Investment Analysis: With less rewarding Grid service market

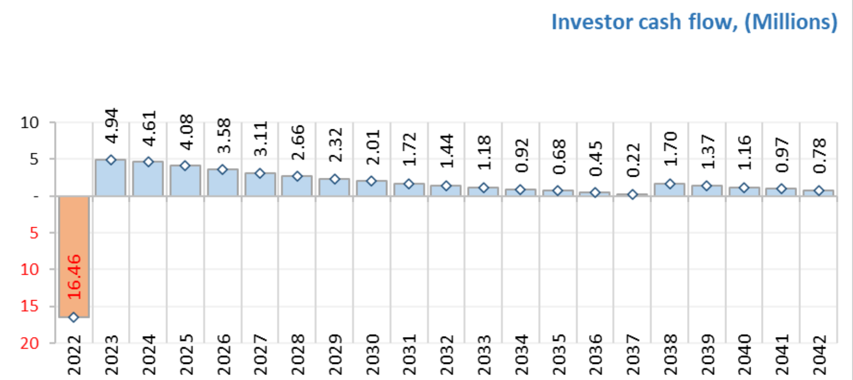
Equity nominal IRR	18.79%
Profitability index	1.50
Investor payback period	4 years
First year of positive EBITD	analysis year 1
After-tax, nominal NPV @ 8.34% discount	$8,187,054

Value stacking multiple services helps boost cash flow

HYPER-V is able to optimally size and provide operational estimates for investment analysis for potential investors


Total revenue ($/year), (Millions)

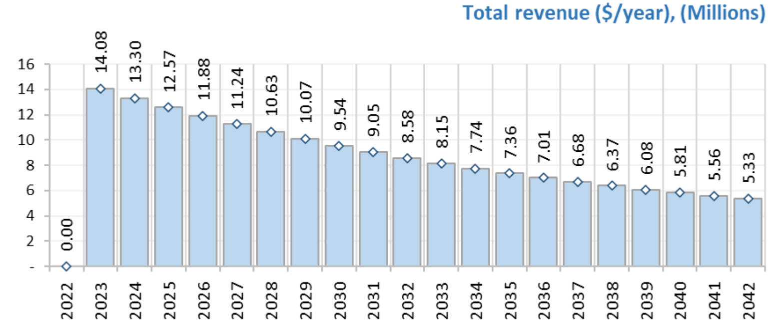

Cumulative investor cash flow, (Millions)

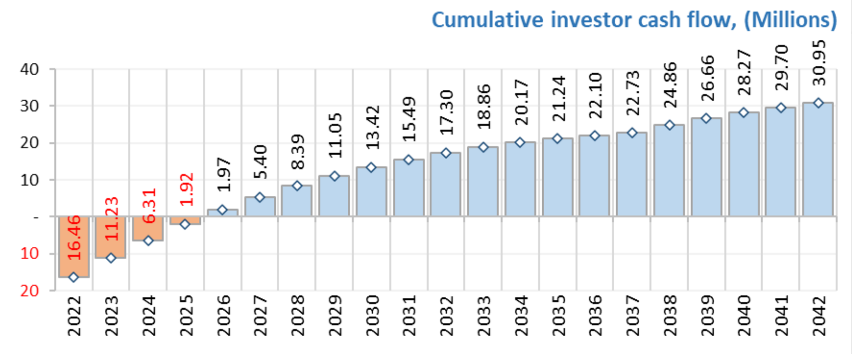

Investor cash flow, (Millions)

Investment Analysis: With More rewarding Grid service market

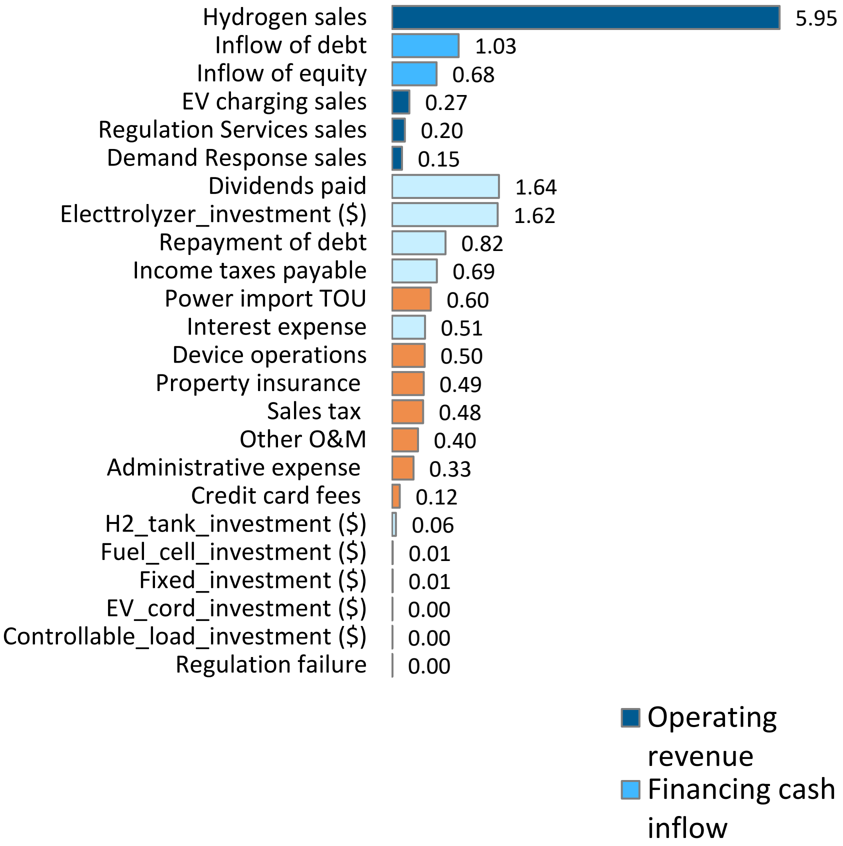
With a more rewarding participation in grid services, the $/kg can be improved significantly

Equity nominal IRR	21.87%
Profitability index	1.70
Investor payback period	4 years
First year of positive EBITD	analysis year 1
After-tax, nominal NPV @ 8.34% discount	$11,560,112





Real levelized cost breakdown of hydrogen (2023$/kg)



Opportunities offered by HYPER-V

- Cost reduction
  - Planning for better behind-the-meter load management
  - Investment in local generation
- Additional sources of revenue:
  - Optimize asset sizes for value stacked participation in multiple markets
- Optimal utilization
  - Time-ahead dispatch profiles to maximize the utilization factor
- Use-case development
  - Evaluate the impact of different drivers on investment/operational decisions

Key Conclusions

- Revenue is strongly co-related to the selling price of Hydrogen
- As H2 becomes more affordable, value stacking will help boost $/kg generated from the investments
- Investments offer a modest 17-20% IRR in most scenarios
- HYPER-V has developed into a versatile tool that can be used for planning and dispatch of hydrogen system assets

Technology Transfer Activities: Software Records, Publications

Software Records:

- SWR-22-71: EMT model of Fuel cell with Power converters
- SWR-23-45: Hydrogen Systems for Performance-based Value stacking – Planning (HYPER-VP)
- SWR-23-46: Hydrogen Systems for Performance-based Value stacking – Dispatch (HYPER-VD)

Publications:

[1]. X. Zhao, Y. Yao, W. Liu , R. Jain, and C. Zhao, "A Hydrogen Load Modeling Method for Integrated Hydrogen Energy System Planning," *2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2023, pp. 1-5

[2] J. R. Sawant, K. Nagasawa and R. Jain, "Fuel Cell Stack Model for Real-Time Simulation of Grid-Connected Applications," *2022 North American Power Symposium (NAPS), Salt Lake City, UT, USA*, 2022, pp. 1-6, doi: 10.1109/NAPS56150.2022.10012182.

[3] *Planned journal manuscript*: Opportunities with Value-stacked dispatch of Hydrogen systems for the evolving grid operations

Collaboration and Coordination

- Project Partner:
  - Eaton (Dr. Wenpeng Liu) - Industry
  - Role: Market Evaluation, Validation of the system models, Use-case development, Feedback and Data driving the project outcomes

- Collaboration with Eaton:
  - Market valuation of the different hydrogen-based revenue streams
  - Developing the use-cases for hydrogen fueling station
  - Validation of the operational and financial feasibility outcomes

Future Industry/Research Engagement

- Eaton: Utilizing the project outcomes to help determine opportunities for turn-key solutions
- Data-center owners/operators: Utilizing the fuel-cell based backup generation as a value-stacked service for robust power during outages and load management
- Supporting other DOE projects:
  - Ongoing CRADA project on Grid-forming inverter design using fuel-cells
- Using project outcomes to engage DoD through ESTCP opportunities
- Outreach through NREL Tech-transfer office:

Proposed Future Work

- Integration with **real-time controls**
- **Integrating cash flow and life cycle analysis** into the optimization:
  - Challenge: integrate millions/billions of scenario into the constraints
  - Get direct and global optimal cost-benefit and cash flow analysis results, it may be attractive and straight-forward to industrial customers from financial background
- **Consideration of soft-costs** for system integration
  - Hardware costs are part of the net production costs. HYPER-V should evolve to integrate with and support complimentary efforts to optimize system designs for soft costs

Thank You

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NREL

Transforming ENERGY

Technical Backup and Additional Information

(Include this "divider" slide before your technical backup slides [maximum 20]. These technical backup slides will be available for oral presenters to use for Q&A and will be included in the published web PDFs for oral and poster presentations.

Note there is ***one required slide*** *in this section and several suggested slides.)*

Planning as an Optimization: Variables and Objective

Variables:

- Decision: Invested Capacity of H2 Tank, Electrolyzer, Fuel Cell, PV, EV Charging, Controllable Load
- Ancillary: Dispatch of H2 Tank, Electrolyzer, Fuel Cell, PV, EV Charging, Controllable Load, Ramping, Demand Response

Objective:

- **Investment Costs**:
  - all investment decisions are made at the beginning of planning period;
  - the annuity of a one-time investment based on the planning year and the interest rate
- **Operating Costs:**
  - includes the net energy procurement cost and the maintenance costs of the hydrogen energy system, PV, and EVs;
- **Revenue from Electricity/Hydrogen Market:**
  - includes the revenue from electricity markets, and any compensation received to provide local services (i.e. EV and HV charging)
- **Penalty Costs:**
  - includes any penalties/loss of income incurred by failing to provide any requested grid services

Planning as an Optimization: Constraints

Power Balance:

- ensures that the net power imported is equal to the power consumed
- captures the ramp up, ramp down, and demand response products [2] [3]

Hydrogen Energy System:

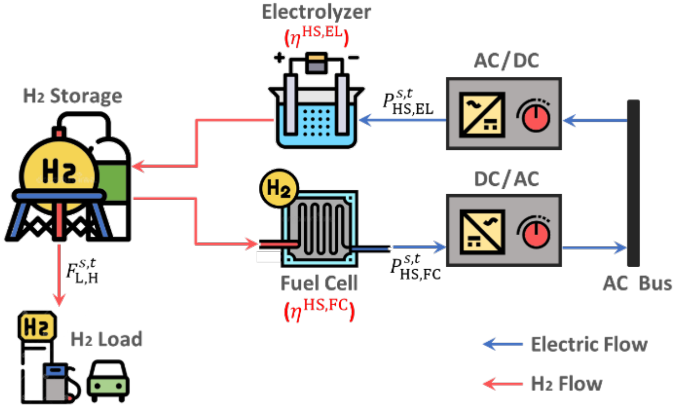
- the hydrogen generated by the electrolyzer can be stored in the tank for later use, such as meeting the vehicle fueling and generating power in fuel cells.
- determines the power and fuel (hydrogen) availability, efficiency, and capacity for the hydrogen systems.

PV Module:

- ensures that the PV investment and operation cost depend only on the invested capacity
- ensures that PV system can only generate power up to its rated capacity.

Electrical Vehicle:

- determines the EV investment and the operation costs based on its invested capacity.
- ensures EV load charging consumption w.r.t. rated capacity.



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[2]. https://www.caiso.com/informed/Pages/StakeholderProcesses/CompletedClosedStakeholderInitiatives/FlexibleRampingProduct.aspx

[3]. https://www.sdge.com/businesses/savings-center/energy-management-programs/demand-response/capacity-bidding-program

Planning as an Optimization: Scenarios

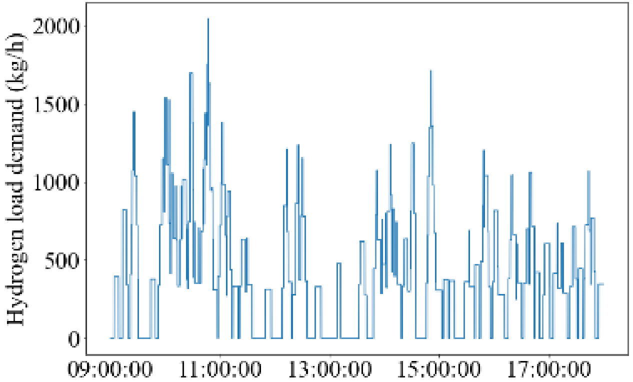
Hydrogen Load:

We propose the following assumptions to predict the daily hydrogen load profile:

- The fueling station works from 9 am to 6 pm daily
- The rate to refuel a hydrogen-fueled truck is constant
- The hydrogen fueling station can serve up to six trucks simultaneously
- Arriving trucks are served in a first-in, first-out order
- The interarrival times of trucks are independent and identically distributed (IID) random variables that are exponentially distributed with a mean of 5 min
- The fueling times of each truck are IID random variables that are normally distributed with a mean of 5.5 min and a standard deviation of 0.83 min

Basic Data of The Hydrogen Fueling Station

Asset	Parameter	Value
Hydrogen fueled truck	H2 tank capacity	33kg
	Fueling time	3–8 minutes
	Driving distance	<250 miles
Hydrogen fueling station	Number of trucks	80–130
	Electrolyzer efficiency	70%
	Fuel cell efficiency	50%
	Electrolyzer capacity	Varies
	Fuel cell capacity	Varies
	Hydrogen tank capacity	>3,000 kg

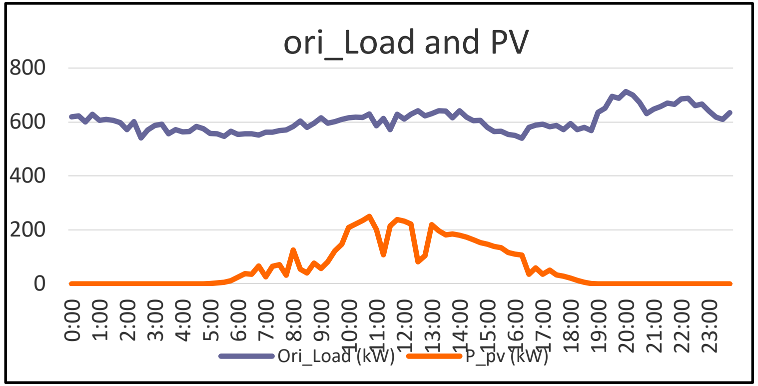


The hydrogen load profile on a typical day

Planning as an Optimization: Scenarios

Electricity load:

- Feeder Green (Long Beach, CA) [4], One year profile (2017), One-hour time resolution (8760 time steps)
- The largest three-phase commercial load from is picked: 1,366 kW (peak load),
- Installed PV capacity 250 kW, PV shape is also from gathered from field on feeder Green, Removed to let the Planning tool make decision
- CAISO MCP (SDG&E node) [5]; SDG&E TOU [6]; CAISO Flexible Ramping Product [2]; SDG&E DR-CBP [3]



Load/PV shape on May.21st, 2017 (spring peak)

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[4]. https://www.nrel.gov/analysis/los-angeles-100-percent-renewable-study.html

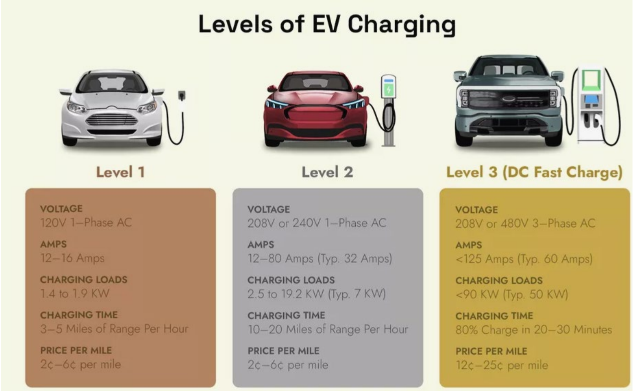
[5]. http://www.caiso.com/pricemap/Pages/default.aspx

[6]. https://www.sdge.com/regulatory-filing/2227/time-use-tou

Planning as an Optimization: Scenarios

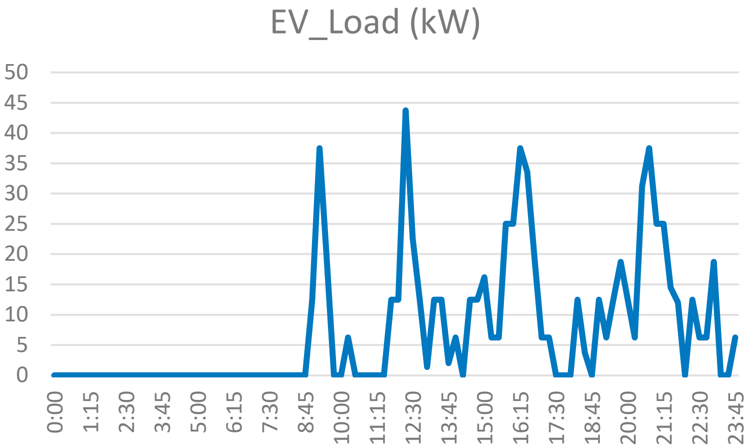
EV load and charging cords:

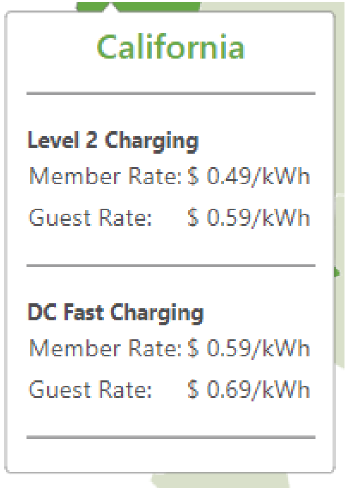
- 6 EBus (school buses/coaches) 14 EVs (sedans/SUVs), charging profile on May.21st, 2017 (12 kW ebus charging, 6.25 kW EV charging, 0.5 $/kWh) [7]



Levels of EV Charging

Level 1	Level 2	Level 3 (DC Fast Charge)
VOLTAGE 120V 1–Phase AC	VOLTAGE 208V or 240V 1–Phase AC	VOLTAGE 208V or 480V 3–Phase AC
AMPS 12–16 Amps	AMPS 12–80 Amps (Typ. 32 Amps)	AMPS <125 Amps (Typ. 60 Amps)
CHARGING LOADS 1.4 to 1.9 KW	CHARGING LOADS 2.5 to 19.2 KW (Typ. 7 KW)	CHARGING LOADS <90 KW (Typ. 50 KW)
CHARGING TIME 3–5 Miles of Range Per Hour	CHARGING TIME 10–20 Miles of Range Per Hour	CHARGING TIME 80% Charge in 20–30 Minutes
PRICE PER MILE 2¢–6¢ per mile	PRICE PER MILE 2¢–6¢ per mile	PRICE PER MILE 12¢–25¢ per mile





California

Level 2 Charging

Member Rate: $ 0.49/kWh

Guest Rate: $ 0.59/kWh

DC Fast Charging

Member Rate: $ 0.59/kWh

Guest Rate: $ 0.69/kWh

[7]. R. Jain et. al., *Application of Site Controllers for Electrification of Commercial Fleet Vehicles*, https://ieeexplore.ieee.org/abstract/document/9300038

Planning as an Optimization: Number of Scenarios to achieve the user-defined level of Confidence and Robustness

Stochastic Programming on Handling Uncertainties:

- represent the uncertainties by a number of representative scenarios (in this way, it is also known as “scenario approach”)
- ε-guaranteed corollary to determine the number of representative scenarios [8]. E.g., At least 90% of uncertainty realizations can be defiantly handled with at least 80% confidence.
- Utilize the K-means clustering method to select 50 representative scenarios from scenario pool [9].

$|s|\ (N_s)$ **under different robust and confidence level**

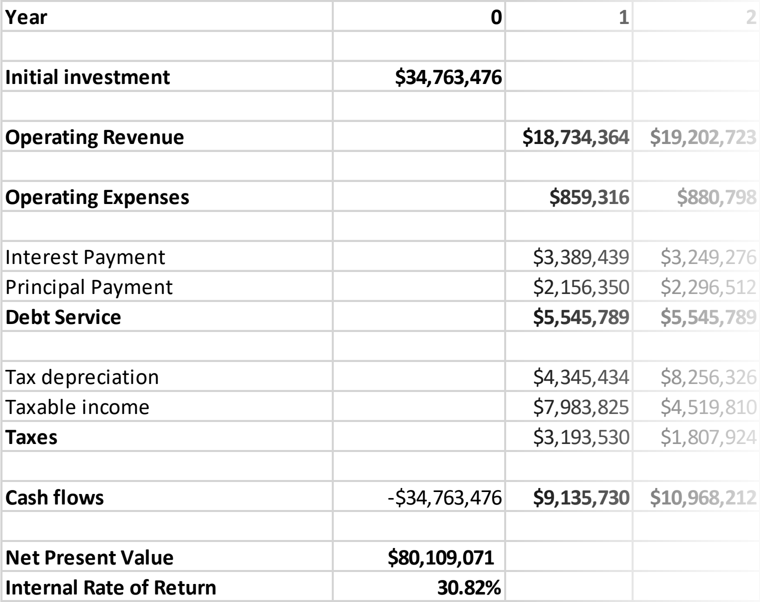
	70% Robustness	80% Robustness	90% Robustness
80% Confidence	399 (~17 days)	599 (~25 days)	1,199 (~50 days)
90% Confidence	799 (~33 days)	1,199 (~50 days)	2,399 (~100 days)
95% Confidence	1,599 (~67 days)	2,399 (~100 days)	4,799 (~200 days)

[8] . Yao, “Security-constrained unit commitment with uncertainties,” M.S. thesis, College of Electrical Engineering, Illinois Institute of Technology, Chicago, May 2015

[9]. W. Liu, Y. Yao, R. Jain, *et al.*, “Commercial building planning and retrofitting strategy for grid services,” *IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, pp. 1–5, April. 2022

Cost-Benefit Analysis

- Net Present Value (NPV)
  - Used to determine whether an investment or project will be profitable through the end of its economic lifecycle
  - Zero is good news
  - Depends on rate of return
- Internal Rate of Return (IRR)
  - Rate of return that brings NPV to zero



Year	**0**	**1**	**2**
Initial investment	**$34,763,476**		
Operating Revenue		**$18,734,364**	**$19,202,723**
Operating Expenses		**$859,316**	**$880,798**
Interest Payment		$3,389,439	$3,249,276
Principal Payment		$2,156,350	$2,296,512
Debt Service		**$5,545,789**	**$5,545,789**
Tax depreciation		$4,345,434	$8,256,326
Taxable income		$7,983,825	$4,519,810
Taxes		$3,193,530	$1,807,924
Cash flows	-$34,763,476	**$9,135,730**	**$10,968,212**
Net Present Value	**$80,109,071**		
Internal Rate of Return	**30.82%**		

NPV Calculation

- NPV of an investment is the sum of all future cash flows over the investment’s lifetime, discounted to the present value
- First year of operation from optimization

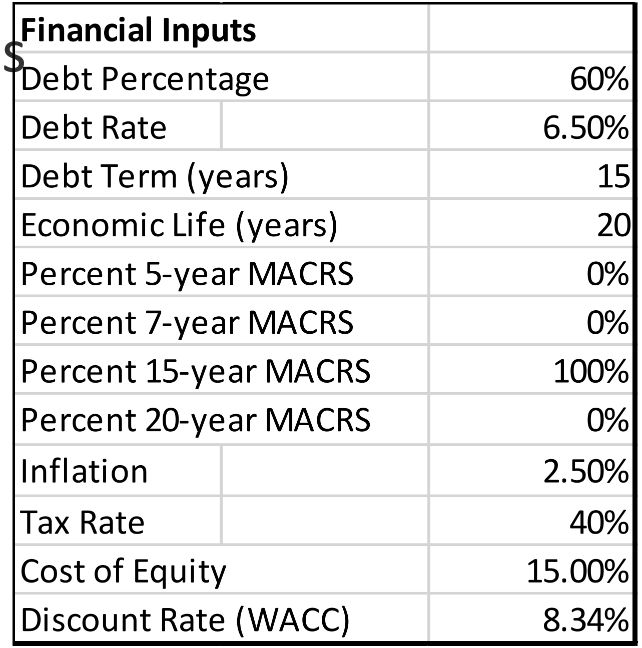
$$NPV = \frac{Cash\ Flow_1}{(1+r)^1} + \frac{Cash\ Flow_2}{(1+r)^2} + \frac{Cash\ Flow_n}{(1+r)^n} - Initial\ Investment$$

Operating revenue
-Operating expenses
-Debt service
-Taxes

Annual cash flow

Modeling

- Financial parameters using generic values
    - 15-year MACRS
- 20-year analysis period
    - Different equipment lifetimes



Financial Inputs	
Debt Percentage	60%
Debt Rate	6.50%
Debt Term (years)	15
Economic Life (years)	20
Percent 5-year MACRS	0%
Percent 7-year MACRS	0%
Percent 15-year MACRS	100%
Percent 20-year MACRS	0%
Inflation	2.50%
Tax Rate	40%
Cost of Equity	15.00%
Discount Rate (WACC)	8.34%

Numerical Tests: Results Validation

HyperV developed an optimization tool to plan hybrid hydrogen-electricity charging station with multiple solutions, i.e., :

Case 1

Case 2

Case 3

Case 4

For each Hyper-V planning solution,

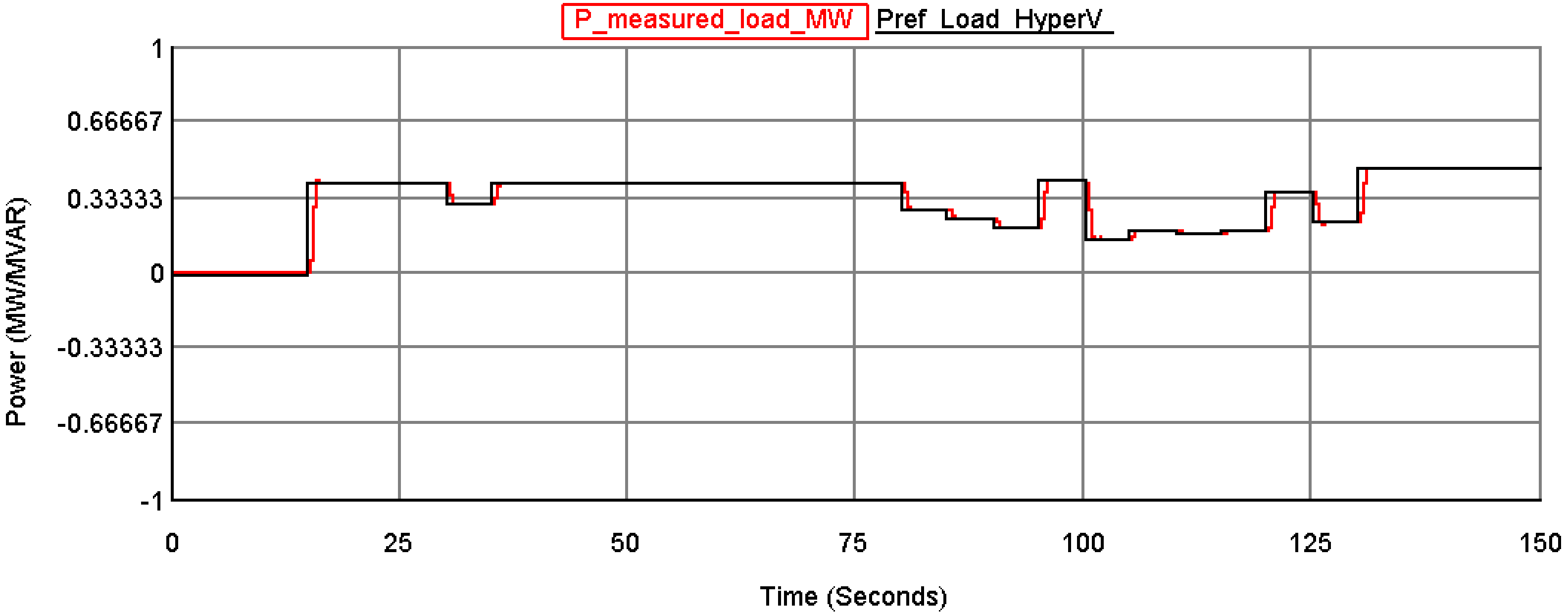
Hyper-V has an optimal scheduling tool to carry out time-series dispatch

RSCAD® Fx by RTDS Technologies

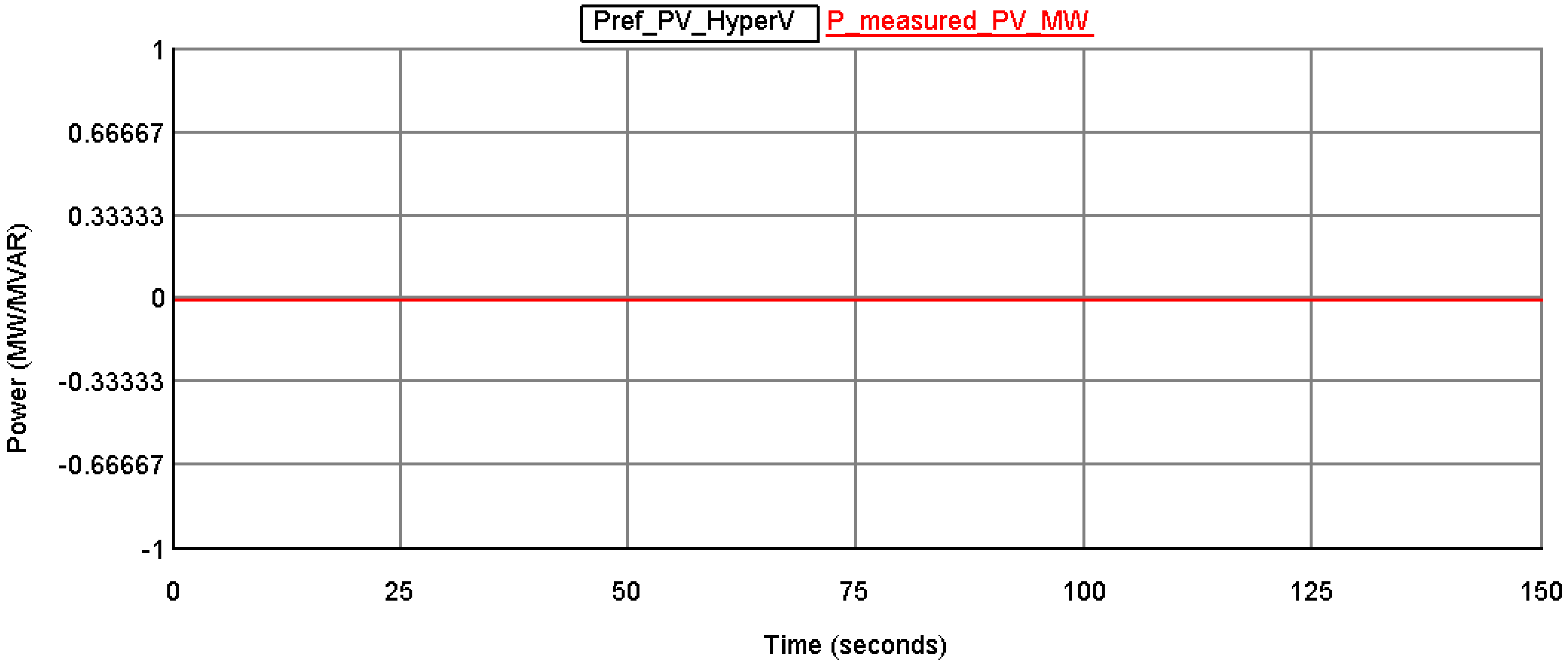
Simulate the dispatch of all devices (unit kw/kg) in RTDS to carry-out feasibility analysis:

Take the planning solutions and its corresponding times-series dispatch (unit $) to carry-out the cost-benefit analysis

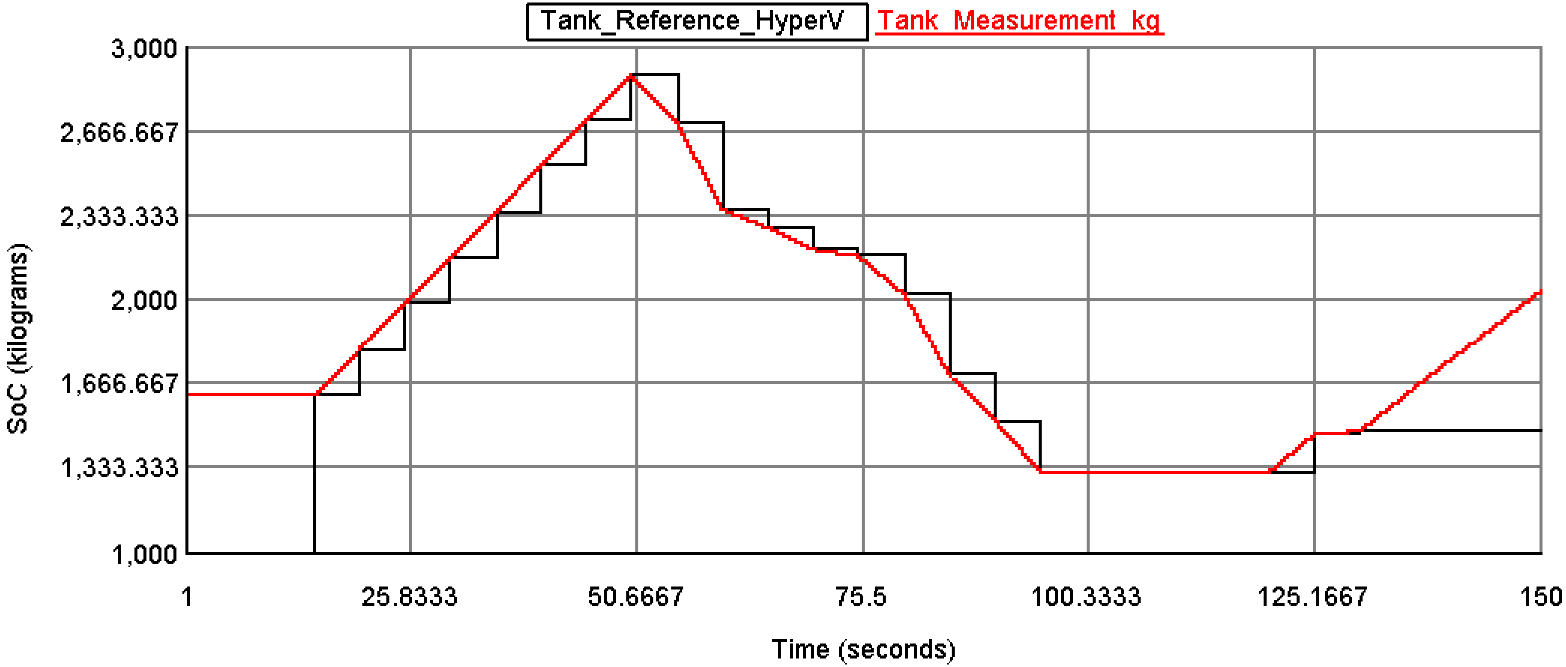
Case 2 – Old Cost – Grid Service - Load



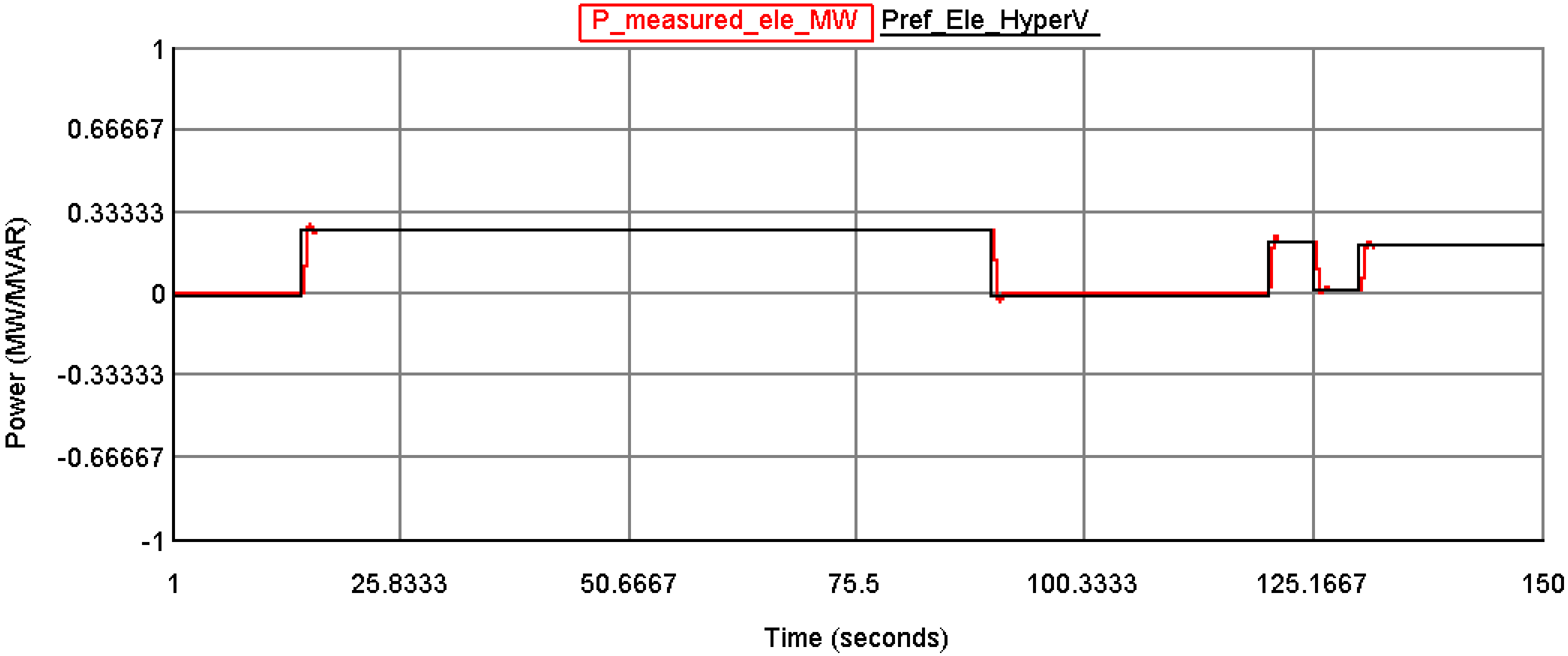
Case 2 – Old Cost – Grid Service – PV – No PV investment here



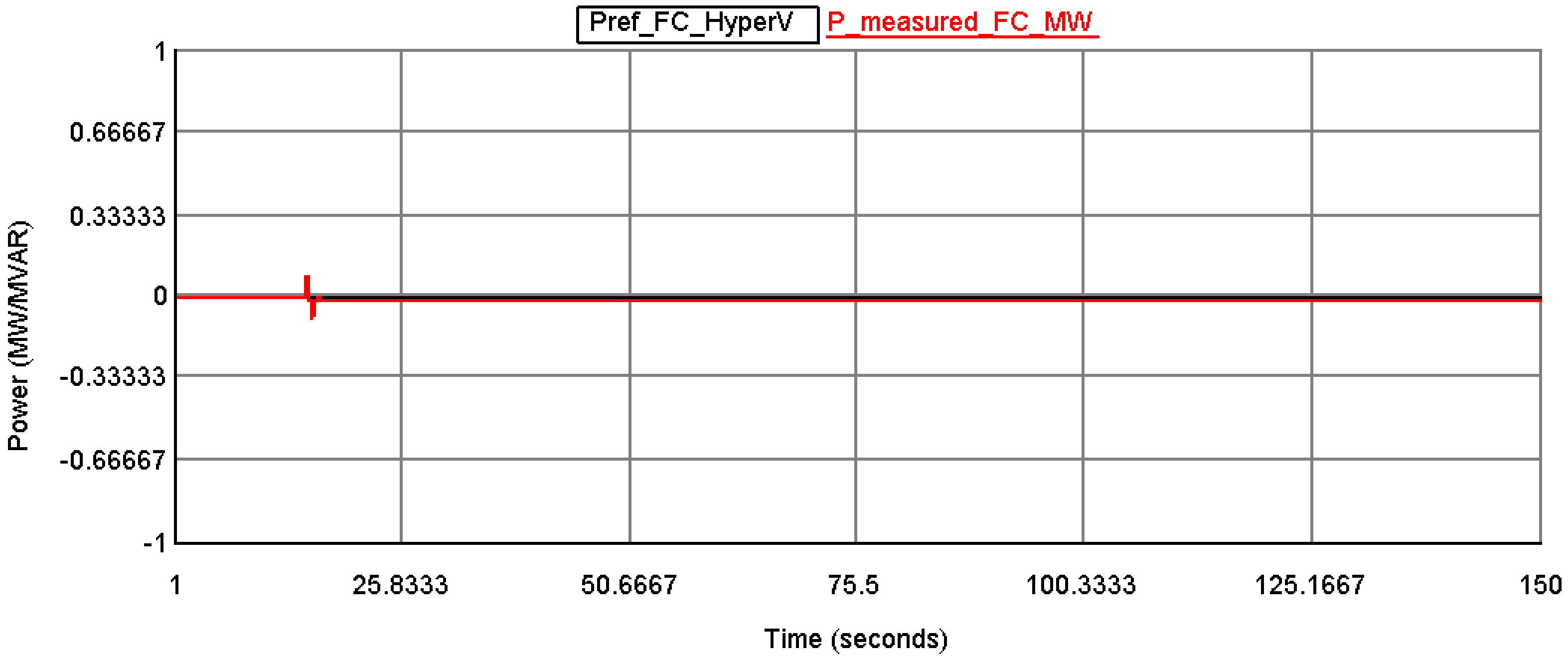
Case 2 – Old Cost – Grid Service – Tank Hydrogen



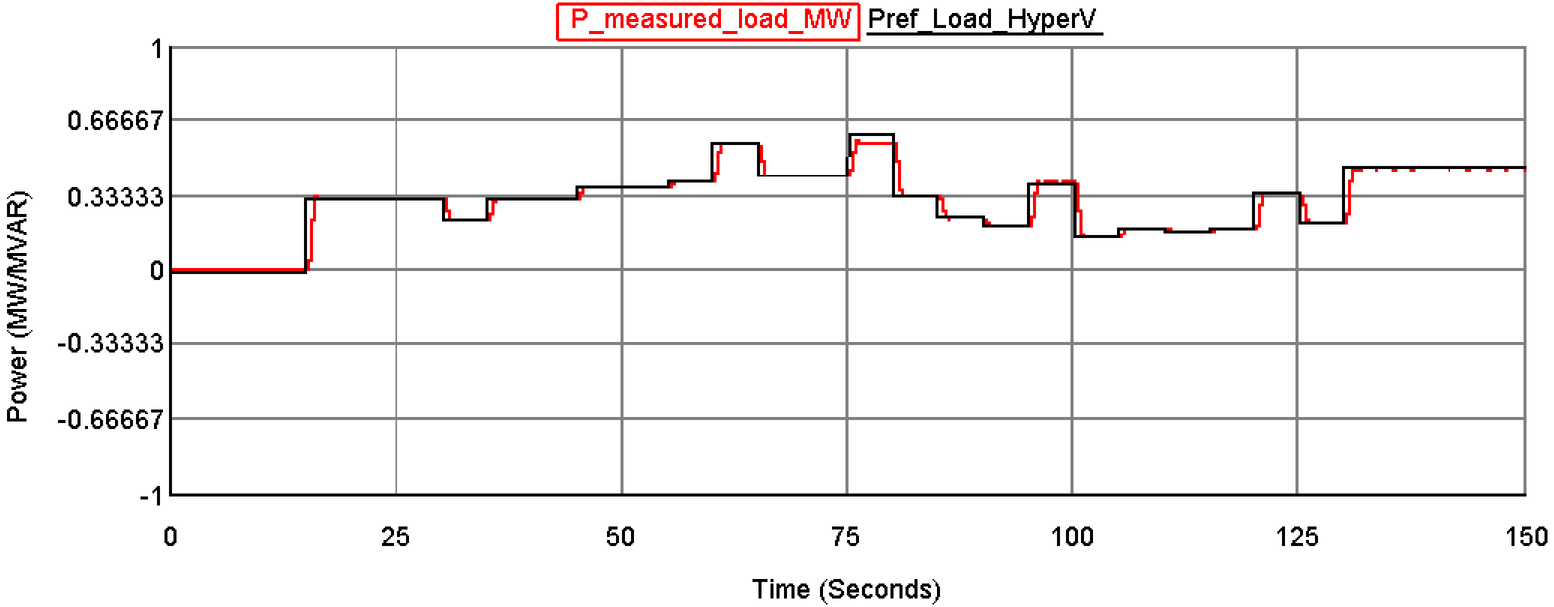
Case 2 – Old Cost – Grid Service - Electrolyzer



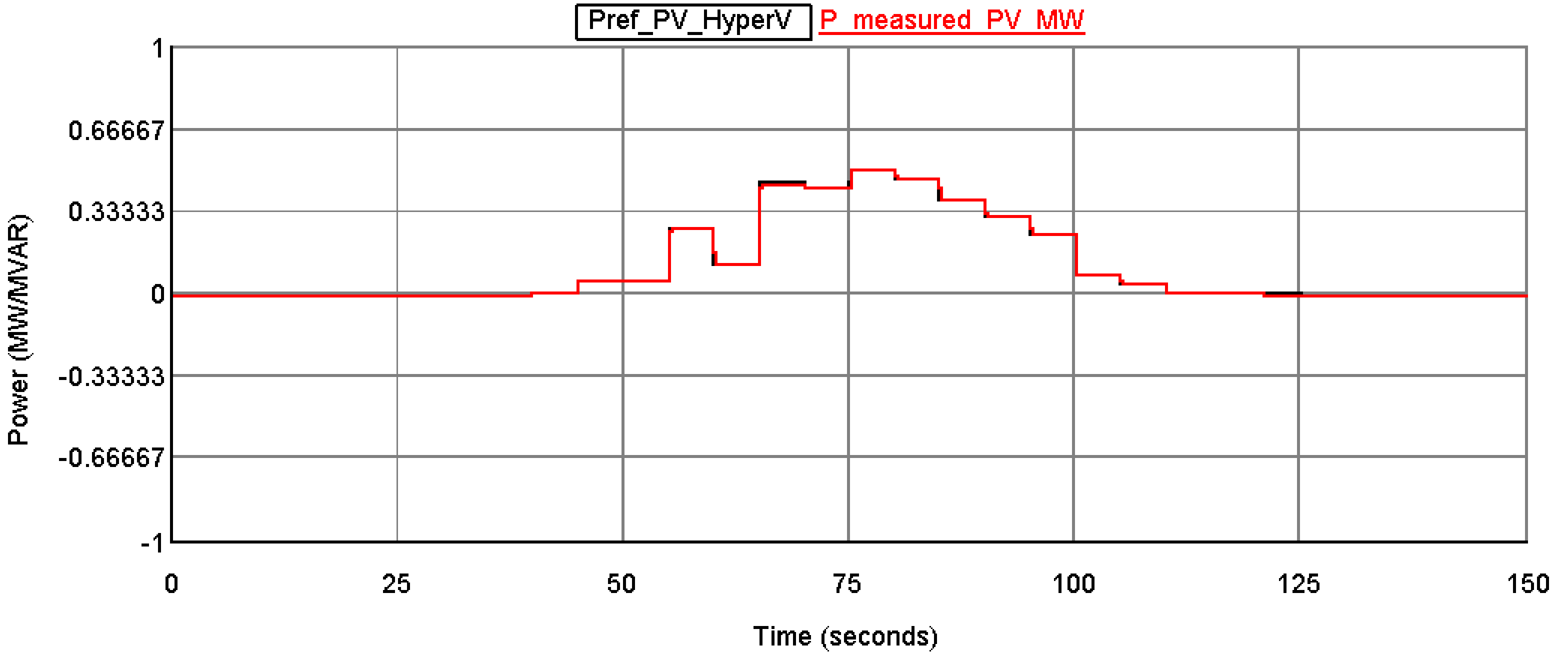
Case 2 – Old Cost – Grid Service - FC



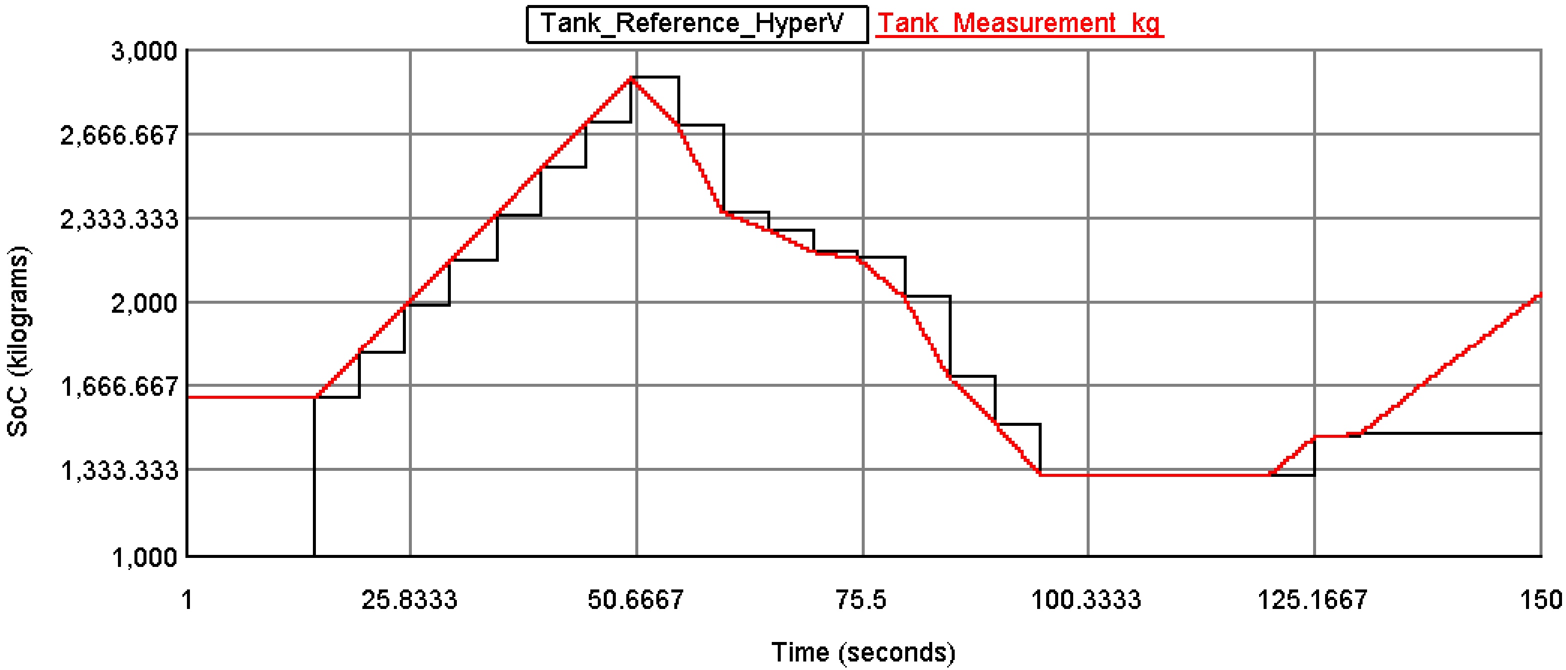
Case 3 – New Cost – Grid Service - Load



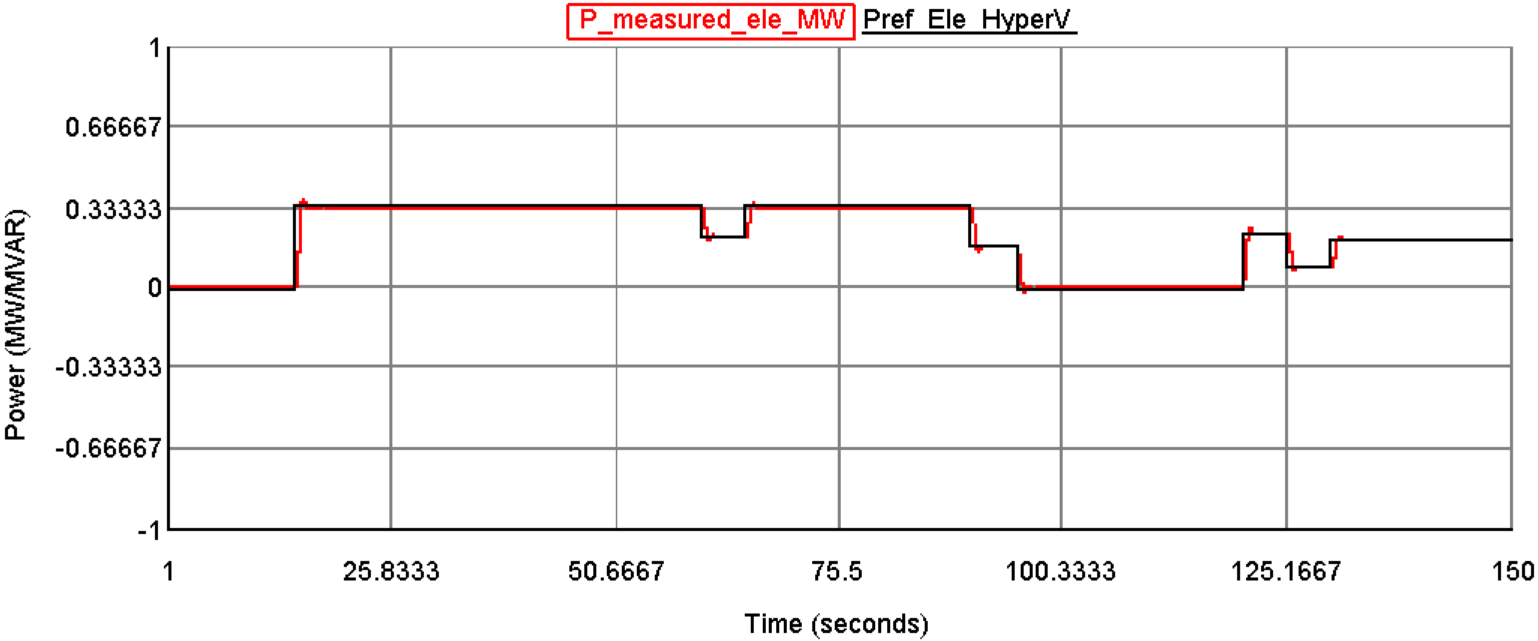
Case 3 – New Cost– Grid Service – PV – No PV investment here



Case 3 – New Cost– Grid Service – Tank Hydrogen



Case 3 – New Cost– Grid Service - Electrolyzer



Case 3 – New Cost– Grid Service - FC