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Changing the World's Energy Future

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***Abstract*—Environmental and regulatory constraints are increasingly posing challenges to the optimal operation of hydroelectric facilities. Hydrogen energy storage (HES) is well-suited to address these challenges. Using excess or low-cost hydroelectric power during off-peak hours to produce hydrogen can help reduce water spills and unlock opportunities for energy arbitrage. Moreover, the oxygen byproduct of electrolysis can be used to improve the dissolved oxygen (DO) levels in tailrace water. This paper presents an innovative framework for modeling and assessing the integrated hydroelectric-hydrogen system, considering subsystem constraints and coupling, benefits in spill water reduction and DO mitigation, as well as diverse hydrogen utilization, including re-electrification, blending with natural gas, and direct sales. Comprehensive case studies were conducted to assess the techno-economic performance of the integrated system in different deployment scenarios.**

***Index Terms*—Energy storage, hydrogen, hydropower, optimization, water quality**

I. Introduction

Integrating renewable energy into power systems is essential to achieve the national goal of 100% carbon-free electricity by 2035 and reach net-zero economy-wide by 2050. The increasing penetration of wind and solar imposes challenges on power system operation due to their natural uncertainty and variability. Additional resources are required to ensure resource adequacy and system flexibility. In the Pacific Northwest, where hydro resource is abundant, hydroelectric power is highly valued for its reliability and flexibility to adapt to fluctuating demand, provide rapid ramping, and offer various ancillary services. However, environmental and regulatory constraints are increasingly posing challenges to the optimal operation of hydroelectric facilities. Various energy storage systems hold great potential for addressing these challenges, and their development has been gathering momentum over the past decade [1].

Hydrogen energy storage (HES) [2] is a promising long-duration energy storage technology that offers intra-day and seasonal energy shifting capability, complementing existing pumped storage hydropower [3]. In recent years, there has been a growing focus on the integration of HES into power systems. Just to name a few, a novel storage expansion planning tool is developed in [4] for a 100% renewable penetration, highlighting batteries as the primary source of short-term power reserves, supported by pumped-hydro, while hydrogen storage ensures long-term energy autonomy in a case study for Chile. In [5], the authors study energy storage planning to address high penetrations of renewable energy in Spain and show that HES is only economically attractive with 100% renewable penetration. The authors in [6] develop a novel power-to-hydrogen-heat-methane model with unit commitment, considering hydrogen impacts on both steady and dynamic gas flows. In [7], a comprehensive HES modeling and assessment framework is proposed toward three common energy delivery pathways and multiple grid and end-user services, considering physical capabilities and operational constraints associated with hydrogen production, compression, storage, and utilization.

Optimal operation of hydroelectric facilities is becoming increasingly challenging due to a rising set of environmental and regulatory limitations, including water use restrictions, fish migration accommodations, sediment management guidelines, dissolved oxygen (DO) level requirements, and flow management mandates. Pairing hydrogen with hydropower emerges as a promising solution to these operational challenges, simultaneously boosting energy efficiency, system resilience, and environmental sustainability. Building on this concept, the authors in [8] propose an off-grid water-hydrogen integrated energy system, where a two-layer method is used for optimal coordination and cost minimization of the integrated system. While this study provides valuable insights into an off-grid integrated system, it does not explore how such a system could tie into the power grid to provide essential services such as energy shifting, ramping, and ancillary services. In addition, other important energy flow pathways, such as blending hydrogen with natural gas and direct sales of hydrogen, are not considered. To bridge the gap, this paper develops an innovative framework for modeling and assessing the integrated hydroelectric-hydrogen system. Various interdependencies and interactions among subsystems are explicitly captured and advanced modeling methods are specifically developed to reduce spill water and improve DO levels. For the latter, the byproduct oxygen generated from the electrolysis process is innovatively utilized.

The remainder of this paper is organized as follows. The modeling methods and optimal dispatch problem formulation are presented in Section II. Section III presents comprehensive case studies to assess the integrated hydrogen and hydro in the Idaho Power system. Finally, Section IV offers concluding remarks.

II. Modeling and Optimal Coordination Methods

A. Hydropower Flexibility

A primary advantage of integrating HES with a hydroelectric power plant is the enhanced operational flexibility it offers. While various comprehensive hydropower models exist in the literature, they often introduce unnecessary complexity for the purpose of evaluating HES for water spill reduction. This paper proposes a simple model to effectively capture how HES can be used to adjust hydropower generation, water outflow, spill water flow, and the water volume in the reservoir:

$$0 \leq p_k^{\mathrm{H}} + \Delta p_k^{\mathrm{H}} \leq \bar{p}_k^{\mathrm{H}}\,, \tag{1a}$$
$$\Delta p_k^{\mathrm{H}} = \alpha \Delta f_k\,, \tag{1b}$$
$$\Delta V_{k+1} = \Delta V_k - \Delta f_k - \Delta f_k^{\mathrm{S}}\,, \tag{1c}$$
$$0 \leq V_k + \Delta V_k \leq \bar{V}\,, \tag{1d}$$
$$f_k^{\mathrm{S}} + \Delta f_k^{\mathrm{S}} \geq 0\,. \tag{1e}$$

where p_k^{H} denotes the baseline hydropower generation at the corresponding reservoir location, $\bar{p}_k^{\mathrm{H}}$ is the rated power, and Δp_k^{H} is the hydropower generation deviation from the baseline. The coefficient α is introduced to characterize the linear correlation between the Δp_k^{H} and the water outflow rate deviation Δf_k. We use Δf^{S} to represent spill water flow deviation from the baseline f_k^{S}. The water volume deviation from the baseline V_k is denoted by ΔV_k and the maximum volume of the reservoir is $\bar{V}$.

B. Hydrogen Energy Storage

The modeling of HES system follows the framework in [7] with adaptations for the specific scenarios considered in the paper.

1) Electrolysis: An electrolysis system uses electrical energy to split water into hydrogen and oxygen:

$$h_k = \kappa_k^{\mathrm{E}} p_k^{\mathrm{E}} \Delta T\,, \tag{2a}$$
$$o_k = r^{\mathrm{oh}} h_k\,, \tag{2b}$$
$$\underline{p}^{\mathrm{E}} b_k^{\mathrm{E}} \leq p_k^{\mathrm{E}} \leq \overline{p}^{\mathrm{E}} b_k^{\mathrm{E}}\,, \tag{2c}$$

where h_k and o_k denote the hydrogen and oxygen produced in hour k, respectively, p_k^{E} is the operating power of the electrolyzer in hour k, κ_k^{E} is the ratio of hydrogen produced to electricity consumed by the electrolyzer, ΔT is one hour, and r^{oh} is the ratio between oxygen and hydrogen in mass. The electrolyzer's on/off status in hour k is indicated by a binary variable b_k^{E}. When the electrolyzer is on, the power consumption of the electrolyzer bounded between the minimum loading level $\underline{p}^{\mathrm{E}}$ and the rated power $\overline{p}^{\mathrm{E}}$.

2) Hydrogen flow: The produced hydrogen is either stored for later use or directly flows through different pathways.

- *Storage*:

$$h_k = h_k^{\mathrm{SC,in}} + h_k^{\mathrm{P,in}}\,, \tag{3}$$

  where $h_k^{\mathrm{SC,in}}$ is the amount of hydrogen intake by the storage compressor and $h_k^{\mathrm{P,in}}$ is the amount of hydrogen that is directly used along different pathways in hour k. The amount of hydrogen intake in hour k can be characterized as a function of power consumption by the storage compressor (p_k^{SC}), as expressed in (4), and its upper and lower bound in (4b):

$$h_k^{\mathrm{SC,in}} = \kappa_k^{\mathrm{SC}} p_k^{\mathrm{SC}} \Delta T\,, \tag{4a}$$
$$0 \leq h_k^{\mathrm{SC,in}} \leq \overline{H}^{\mathrm{SC,in}}\,, \tag{4b}$$
$$h_k^{\mathrm{SC,out}} = \left(1 - \sigma^{\mathrm{SC}}\right) h_k^{\mathrm{SC,in}}\,, \tag{4c}$$
$$H_{k+1}^{\mathrm{S}} = H_k^{\mathrm{S}} + h_k^{\mathrm{SC,out}} - h_k^{\mathrm{S,out}}\,, \tag{4d}$$
$$0 \leq H_k^{\mathrm{S}} \leq \overline{H}^{\mathrm{S}}\,. \tag{4e}$$

  where κ_k^{SC} is the ratio of hydrogen intake to electricity consumption by the compressor, $\overline{H}^{\mathrm{SC,in}}$ denotes the maximum intake rate of the storage compressor. The amount of hydrogen output of the compressor in hour k is $h_k^{\mathrm{SC,out}}$ is and σ^{SC} is the loss factor. H_k^S is the amount of hydrogen stored in the storage, which is limited by its capacity $\overline{H}^{\mathrm{S}}$, and $h_k^{\mathrm{S,out}}$ is the amount of hydrogen withdrawn from the storage. Both the hydrogen withdrawn from the storage $h_k^{\mathrm{S,out}}$ and produced hydrogen by the electrolyzer $h_k^{\mathrm{P,in}}$ are either directly sold to one of the destinations in $\mathcal{D}$ or consumed by a fuel cell:

$$h_k^{\mathrm{S,out}} + h_k^{\mathrm{P,in}} = \sum_{d \in \mathcal{D}} h_k^d + h_k^{\mathrm{FC}}\,, \tag{5}$$

  where h_k^d is the hydrogen sold to destination d and h_k^{FC} is the hydrogen consumed by the fuel cell.

- *Re-electrification*: The fuel cell power output in hour k (h_k) can be approximated as a linear function of the amount of hydrogen consumed:

$$p_k^{\mathrm{FC}} = \kappa^{\mathrm{FC}} h_k^{\mathrm{FC}} / \Delta T\,, \tag{6a}$$
$$\underline{p}^{\mathrm{FC}} b_k^{\mathrm{FC}} \leq p_k^{\mathrm{FC}} \leq b_k^{\mathrm{FC}} \overline{p}^{\mathrm{FC}}\,, \tag{6b}$$

  where κ^{FC} is the generated electrical energy (in kWh) per kg of hydrogen consumed and b_k^{FC} is a binary variable that indicates the on/off status of the fuel cell in hour k. When the fuel cell is on, its power output is bounded between the minimum generation $\underline{p}^{\mathrm{FC}}$ and the rated power $\overline{p}^{\mathrm{FC}}$.

- *Direct sale*: Hydrogen can be blended with nature gas for power generation and used as transportation fuel or industrial gas. The total revenue of hydrogen sales to all destinations is

$$\Pi^{\mathrm{Sale}} = \sum_k \sum_{d \in \mathcal{D}} \mu_k^d h_k^d\,, \tag{7}$$

  where μ_k^d is the equivalent price of hydrogen when sold to destination d in hour k and h_k^d is the corresponding amounts of hydrogen sold.

C. Interactions with The Grid

The difference in power output between the integrated system and standalone hydropower is:

$$p_k^{\mathrm{Grid}} = \Delta p_k^{\mathrm{H}} - p_k^{\mathrm{E}} - p_k^{\mathrm{SC}} + p_k^{\mathrm{FC}}\,. \tag{8}$$

In this paper, we consider only using the curtailed hydro generation to produce hydrogen. In addition, additional hydropower using the water that would be otherwise spilled can only be used to produce hydrogen and is not directed back into the grid. Therefore, p_k^{grid} should satisfy

$$0 \leq p_k^{\text{Grid}} \leq p_k^{\text{FC}} . \tag{9}$$

The electricity generation revenue of the integrated system is

$$\Pi^{\text{EE}} = \sum_k \mu_k^{\text{EE}} p_k^{\text{grid}} \Delta T , \tag{10}$$

where μ_k^{EE} represents the electric energy prices.

The regulation capacity is limited by the capability to deviate from the scheduled power, which depends on the on/off status, the scheduled power, and maximum and minimum power of the electrolyzer and fuel cell, as expressed in (11):

$$r_k \leq (p_k^{\text{E}} - \underline{p}_k^{\text{E}} b_k^{\text{E}}) + (\overline{p}^{\text{FC}} b_k^{\text{FC}} - p_k^{FC}) , \tag{11a}$$

$$r_k \leq \overline{p}_k^{\text{E}} b_k^{\text{E}} - p_k^{\text{E}} + (p_k^{\text{FC}} - \underline{p}_k^{\text{FC}} b_k^{\text{FC}}) . \tag{11b}$$

The regulation revenue is

$$\Pi^{\text{R}} = \sum_k \mu_k^{\text{R}} r_k , \tag{12}$$

where μ_k^{R} is the regulation price in hour k, r_k denotes regulation capacity in hour k in MW.

The capacity (resource adequacy) value is

$$\Pi^{\text{Cap}} = \mu^{\text{Cap}} \overline{p}^{\text{FC}} , \tag{13}$$

where μ^{Cap} is the annual capacity payment rate or its equivalent.

D. DO Mitigation Modeling

Hydropower facilities are required to maintain the DO level in the tailrace water above a certain threshold. When the DO level drops below the threshold, mitigation measures are necessary to keep the operation of the hydropower facility in compliance. Such mitigation measures include pumping air or oxygen into the water and spilling water from the reservoir to improve the DO with surface agitation. In the context of DO mitigation, the benefits brought by an HES system include reducing the amount of oxygen that needs to be purchased and reducing DO-triggered water spills.

The produced oxygen is either stored for later use or directly flowed through the blower for dissolved oxygen mitigation :

$$o_k = o_k^{\text{SC,in}} + o_k^{\text{D}} , \tag{14}$$

where $o_k^{\text{SC,in}}$ is the amount of oxygen intake by the compressor and o_k^{D} is the amount of oxygen that is directly used for DO mitigation in hour k.

Similar to hydrogen, the amount of oxygen generated in hour k can be characterized as a function of power consumption by the onsite oxygen storage compressor ($p_{o,k}^{\text{SC}}$), as expressed in (15), and it is bounded by (16):

$$o_k^{\text{SC,in}} = \kappa_k^{\text{SC}} p_{o,k}^{\text{SC}} \Delta T, \tag{15a}$$

$$0 \leq o_k^{\text{SC,in}} \leq \overline{O}^{\text{SC,in}}, \tag{15b}$$

$$o_k^{\text{SC,out}} = \left(1 - \sigma^{\text{SC}}\right) o_k^{\text{SC,in}} , \tag{15c}$$

where κ_k^{SC} is the ratio of oxygen intake to electricity consumption by the compressor, $\overline{O}^{\text{SC,in}}$ denotes the maximum oxygen intake rate of the storage compressor. The compressor oxygen loss is captured in (15c), where $o_k^{\text{SC,out}}$ is the amount of oxygen output of the compressor in hour k and σ^{SC} is the loss factor.

The dynamics of the onsite oxygen storage are captured by

$$O_{k+1}^{\text{S}} = O_k^{\text{S}} + o_k^{\text{SC,out}} - o_k^{\text{S,out}} , \tag{16a}$$

$$0 \leq O_k^{\text{S}} \leq \overline{O}^{\text{S}} , \tag{16b}$$

where O_k^S is the amount of oxygen stored in the storage and is limited by its capacity $\overline{O}^{\text{S}}$. The amount of oxygen withdrawn from the storage is denoted by $o_k^{\text{S,out}}$.

Both the oxygen withdrawn from the storage $o_k^{\text{S,out}}$ and byproduct oxygen from the electrolyzer o_k^{D} are delivered into the tailrace water to meet the oxygen demand for DO mitigation:

$$(o_k^{\text{S,out}} + o_k^{\text{P,in}} + o_k^{p})\eta \geq l_k^{\text{DO}} \tag{17}$$

where η denotes the uptake efficiency of oxygen in the water using the specified delivery method, and l_k^{DO} represents the DO demand in hour k. o_k^p denotes the purchased extra oxygen from the market.

The economic benefits in terms of DO mitigation is the cost saving on oxygen purchase:

$$\Pi^{\text{O}} = \mu^{\text{O}} \sum_k (o_k^{\text{base}} - o_k^{p}) \tag{18}$$

where μ^{O} is the oxygen price, o_k^{base} denotes the amount of oxygen purchased without HES system in hour k, which is not a decision variable but depends on the O_2 uptake efficiency.

E. Optimal Dispatch and Benefit Evaluation

The optimal dispatch of an HES system can be obtained by maximizing the economic benefits and minimizing the power consumption and loading level of different components, hence affecting hydrogen production, compression, and hydrogen usage in different pathways and the corresponding value streams.

Hence, the optimal dispatch problem formulation is written as below:

$$\underset{\boldsymbol{x}}{\text{maximize}} \quad \left(\Pi^{\text{EE}} + \Pi^{\text{Sale}} + \Pi^{\text{R}} + \Pi^{\text{Cap}} + \Pi^{\text{O}}\right) , \tag{19}$$

$$\text{subject to} \quad (2) - (18) \tag{20}$$

where $\boldsymbol{x}$ denotes the vector of decision variables.

III. Case Studies

Idaho Power Company (IPC), a regional utility serving southern Idaho and eastern Oregon, currently generates about 70% of its energy from non-carbon sources, setting a strong foundation for its ambitious goal of achieving 100% clean energy. Meeting this objective will necessitate the phasing out of existing carbon-based fuels and the integration of innovative technologies, including HES. Comprehensive assessments have been performed using the proposed framework to understand the techno-economic potential of HES for the

IPC system, considering different scenarios: HES located at a hydro facility, a gas plant, and an existing generation facility or off-site. Due to space limitation, this paper presents a subset of case studies assessing the integrated hydro and hydrogen at American Falls reservoir, Idaho to demonstrate the benefits of enhanced HES utilization, water spill reduction, and DO mitigation.

The system configuration, parameters, and key assumptions in the selected case studies are summarized as follows. In particular, Idaho Power's Integrated Resource Plan outputs together with historical prices were used to evaluate benefits of various grid services. The HES parameters, such as operation ranges, efficiencies, and auxiliary power consumption, were adopted from [7] and are not repeated here to save space.

- HES: a 10 MW electrolyzer, a hydrogen storage of 4 metric tons, and a 12 MW fuel cell.
- Hydrogen usage: electricity regeneration using the fuel cell and direct sale as clean transportation fuel ($10/kg) and industrial gas ($2/kg).
- Water spill: the annual spill water volume in 2017 is about 950 thousand acre-feet.
- DO mitigation: $1/kg as the oxygen procurement cost, a 50 metric tons onsite oxygen storage, and 20% oxygen uptake efficiency assuming an air blower is used to inject the oxygen.
- Grid services: energy shifting, frequency regulation, and capacity value.

Various case studies were designed to evaluate the potential benefits associated with different use cases and four of them were included in this paper, as outlined in Table I.

- In Case 1.0, a standalone HES system is studied, where the electricity from the grid is used to produce hydrogen through electrolysis. The produced hydrogen can be stored, converted back to electricity using fuel cell, and sold as transportation fuel and industrial gas. This case serves as a benchmark for evaluating the operation and economic viability of HES integrated into power systems. Comparing this case with Case 2.0, where the HES is coupled with the hydroelectric facility, enables us to quantify the benefits from such integration.
- In Case 2.0, the integrated system is studied. Instead of using the grid power to produce hydrogen as in Case 1.0, hydro power generated using the spilled water is used to produce hydrogen. Other settings and use cases remain the same.
- Case 2.1 is the same as Case 2.0 except DO mitigation use case is considered. The oxygen as a byproduct of electrolysis is used to improve DO levels and the associated benefits of cost saving in oxygen procurement is assessed.
- Case 2.2 is built upon Case 2.1 by including HES use cases for frequency regulation and resource adequacy.

A. Water Spill Reduction

To understand the potential benefits of an integrated hydro-hydrogen system, HES operation in Case 1.0 and Case 2.0 is

TABLE I
CASE STUDY SUMMARY

Case	Spill-water reduction	DO mitigation	Regulation	Capacity
1.0	-	-	-	-
2.0	✓	-	-	-
2.1	✓	✓	-	-
2.2	✓	✓	✓	✓

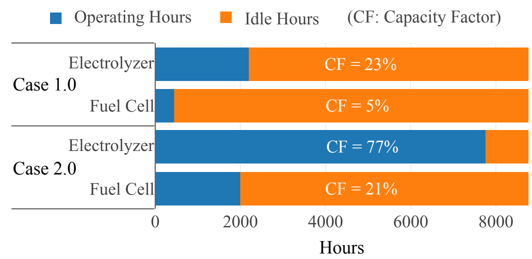

Fig. 1. Operating hours vs idle hours in Case 1.0 and Case 2.0

first compared. The HES operation hour statistics are provided in Fig. 1. Key observations and insights are offered as follows.

- In Case 1.0, the HES system is under utilized: the electrolyzer and fuel cell capacity factors are only 23% and 5%, respectively. This is mainly because of the low round-trip efficiency of HES system, which is 36% in this study. Given the efficiency, there are very limited opportunities for profitable energy shifting. In general, the price differences between off-peak and peak hours are not significant enough to compensate losses associated with energy shifting.
- When integrating HES with the hydropower facility in Case 2.0, hydrogen can be produced using free electricity generated using the spill water. As a result, electrolyzer and fuel cell capacity factors increase to 77% and 21%, respectively. Note that we applied a constraint limiting fuel cell operation to a maximum of 2,000 hours per year. This constraint was designed to ensure a 20-year operational lifespan, given the total lifetime of 40,000 operating hours. Consequently, this constraint also caps the fuel cell's capacity factor.

The hydrogen production and usage in Cases 1.0 and 2.0 are summarized in Fig. 2. As can be seen, the hydrogen produced in Case 2.0 is about 4 times of the hydrogen produced in Case 1.0. While the hydrogen sales as transportation fuel and industrial gas are capped at the maximum demand of 52 tons, the additional hydrogen produced is re-electrified and fed back to the grid. In this case, the low round-trip efficiency is not a limiting factor of energy shifting as the electricity used to produce hydrogen is at zero cost using the spilled water. In addition, it was found that 99.8% of the water spill was eliminated in this case, showing the effectiveness of pairing HES with hydroelectric facility to improve system operating efficiency.

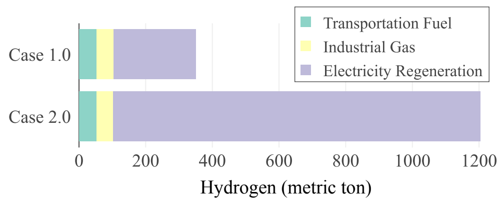

Fig. 2. H_2 allocation

TABLE II
DO Mitigation Results Summary

Case	DO↑ (mg/L)	Purchased O_2 (t)	DO-triggered spill hours ↓
2.1	0.25	1007	29
2.2	0.2	1007	28

B. DO Mitigation

Adequate DO level is essential and critical to the resilience of the aquatic environment and respiration for aquatic life. The oxygen as a byproduct of the HES system can be used to improve DO levels. A summary of DO mitigation results in Cases 2.1-2.2 are provided in Table II, including DO level increase, oxygen purchased, and DO-triggered spill hours reduction. While both cases satisfy the requirement of DO levels, adding use cases of frequency regulation and resource adequacy in Case 2.2 decreases oxygen produced by the HES system and thereby the contribution of HES in increasing DO levels. The oxygen demand would be 1,577 tons with the HES system and utilizing the oxygen produced through the electrolysis can save about $570 thousand in oxygen procurement.

C. Value Stacking

Value stacking is crucial for energy storage projects as it maximizes the utilization and economic viability of the system by enabling multiple revenue streams and grid benefits. The proposal framework is capable of maximizing the total benefits from the stacked value streams, accounting for various couplings and trade-offs. Annual benefits from different value streams in Cases 2.0-2.2 are summarized in Fig. 3. As can be seen, O_2 purchase saving accounts for about 30% of the overall benefits in Case 2.1 and about 11% of the overall benefits in Case 2.2. Using the flexible electrolyzer and fuel cell for ancillary services and resource adequacy can further increase the total benefits. Although the electricity generation revenue and oxygen purchase savings decrease slightly, the total benefit still increases significantly by 68%. The hydrogen sales benefits are almost the same for Cases 2.0-2.2, where sales as transportation fuel and industrial gas are both capped at the maximum demand. In particular, Case 2.2 emerges as the most economically attractive, yielding annual benefits exceeding $5 million, while Case 2.0 yields the lowest benefit of approximately $1.5 million.

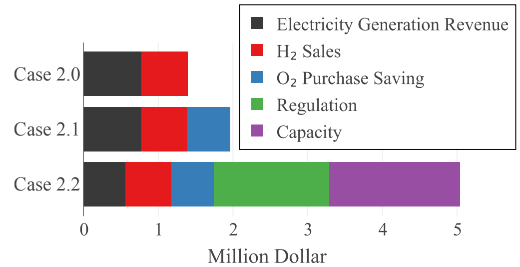

Fig. 3. Annual benefits from different value streams

IV. Conclusions

This paper presented a modeling and assessment framework for the integrated hydroelectric-hydrogen system, considering both operational and environmental benefits. Innovative models were developed to capture the interaction between the two subsystems and to represent how the integration can help enhance HES utilization, reduce water spills, and improve DO levels. Comprehensive case studies were carried out to understand the techno-economic potential of the integrated system for IPC. The results show that, when appropriately sized, integrating HES with hydropower plants can nearly eliminate water spills while optimizing HES operation, thereby improving energy efficiency and cost-effectiveness.

Moreover, the oxygen produced by electrolyzers can be used to increase the DO level, thereby reducing the need for external oxygen procurement. The corresponding cost-saving accounts for about 11% of the overall benefits of the integrated system. Using the flexible electrolyzer and fuel cell for ancillary services and resource adequacy can further increase the total benefits by 68%.

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