CONCEPTUAL ELECTRICAL DESIGNS & TOTAL CONTROL SYSTEM CONCEPT FOR GREEN HYDROGEN

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Abstract - Hydrogen is one of several options available to replace fossil fuels in order to meet climate goals. As project feasibility and cost of green hydrogen remains a key driver, it is necessary to optimize electrical design right from conceptual stage to realize high returns on a TCO basis.
Generally, process industries run on a continuous basis, with requirements of high availability of power at the receiving station. Similar attention is required in managing green hydrogen facility as there is a degree of uncertainty of available power through renewable energy sources.
In this paper, we introduce conceptual power system designs that could be adopted to achieve today's needs such as scalability and faster time to market. Detailed emphasis is provided on process and electrical digital twins at architectural level highlighting power and process system control concepts with special attention towards managing hybrid generation mix.

Index Terms — Hydrogen, Green hydrogen, Process electrification, Decarbonization, GHG emissions, Control system concept, Electrolyzer, Electrical design

I. INTRODUCTION

The decarbonization wave is on an accelerated path as end users have access to technologies which help them to track emissions and to formulate mitigation plans. A three-step approach [1] enables end users to address the situation systematically.

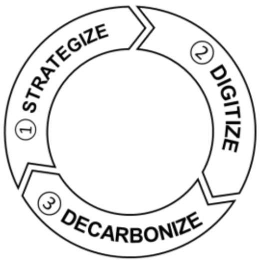

Fig. 1 Three-step approach to decarbonize an industrial facility [1]

Emissions are grouped by type or scope and must be addressed according to their classification [1]. Solutions can be applied in a systematic order to address decarbonization. Most of the major industries have pledged to significantly reduce their GHG emissions under scope 1+2 by 2030. Multi-faceted solutions are carefully devised; with the simplest solution being to directly avoid emissions or to reduce them by adopting best-in-class technologies.

A. Three pillars to address decarbonization stage for an industrial facility

Pillar-1: *Improve Energy Efficiency*
It begins with a holistic energy audit. Potential solutions are explored which can improve energy efficiency through reduction of energy needs in steam, electricity and heat. This is carefully exercised with reference to process needs and machinery requirements. (Direct reduction of GHG emissions)

Pillar-2: *Electrify industrial process*
Electrify industrial processes such as the application of high-power motor in place of existing GT or ST, and/or application of electrical heaters or boilers for heating needs. The key to this step is to have renewable energy substituting electrical energy needs, thereby reducing GHG emissions. (Direct reduction of GHG emissions)

Pillar-3: *Substitute energy needs*
This pillar is crucial especially in hard to abate sectors where it is difficult to electrify processes and thus energy needs are substituted with a clean fuel. This opens the door for current paper on green hydrogen. (Reduction of GHG emissions by adopting best-in-class available technologies)

B. Hydrogen

For many decades, hydrogen has been used in few industrial activities.

The direct and indirect emissions associated with any industrial manufacturing process are not much different in hydrogen production; with carbon intensity expressed in terms of kg CO_2e/ kg H_2. Based on the type of process and energy used for the production of hydrogen, we can classify hydrogen into several shades (colours); common shades are captured in Table I.

TABLE I
HYDROGEN NOMENCLATURE

Color of Hydrogen	Key Pointers	
	Production Technology	Estimated emissions from the production process (kg CO_2e/ kg H_2)
Brown/Black Hydrogen	Coal gasification	9 – 11
Grey Hydrogen	Steam methane reforming	9 – 11
Blue Hydrogen	Steam methane reforming with CCUS, Coal gasification with CCUS	0.4 – 4.5
Green Hydrogen	Water electrolysis with renewable electricity	~0

C. GH2 methodology for GHG emissions measurement

Emissions associated with renewable hydrogen are all indirect, arising from material flows and manufacturing associated with renewable energy. A simplified brick approach is presented in Fig. 2.

Reference [2] defines green hydrogen as hydrogen produced through the electrolysis of water with 100% or near 100% renewable energy resulting in close to zero greenhouse gas emissions (<=1 kg CO_2e per kg H_2 taken as an average over a 12-month period).

Energy mix can be one or several mix of: hydropower, wind, solar, geothermal, tidal, wave and other ocean energy sources. The GH2 Standard refers to “near 100% renewable energy” to provide some flexibility (e.g., for backup systems) so long as the maximum greenhouse gas emissions threshold is not exceeded.

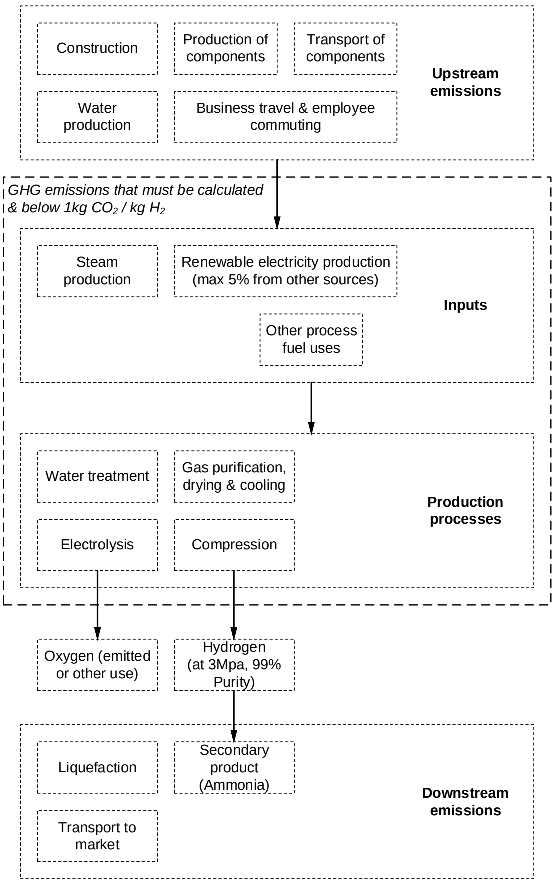

Fig. 2 Emissions breakup in green electrolysis process

GH2 Standard encourages end user to quantify upstream and downstream emissions, but they are not included in the 1kg CO_2e/ kg H_2 emission threshold. Emphasis is given towards GHG emissions that occur at inputs and production processes which needs to be below 1kg CO_2e/ kg H_2.

NOMENCLATURE

AEL Alkaline electrolyzer
AIS Air Insulated Switchgear
BOP Balance of Plant
CAPEX Capital expenditure
CCUS Carbon Capture Utilization and Storage
GH2 Green Hydrogen Standard Body
gH_2 Green hydrogen
GHG Greenhouse gases
GIS Gas Insulated Switchgear
GT Gas Turbine
GW Giga watt
HV High voltage
LCOE Levelized Cost of Electricity
LCOH Levelized Cost of Hydrogen
MV Medium voltage
MW Mega watt
OEM Original equipment manufacturer
OPEX Operational expenditure
PEMEL Polymer Electrolyte membrane electrolyzer
PF Power factor
PQ Power quality
RE Renewable Energy
RMU Ring main unit
SF_6 Sulfur hexafluoride
ST Steam Turbine
TCO Total Cost of Ownership
TSO Transmission System Operator

II. GREEN HYDROGEN

A. Green hydrogen

Green hydrogen (renewable hydrogen) is produced either by feeding renewables-based electricity into an electrolyser, the reforming of biogas or the biochemical conversion of biomass. In this paper, focus is given towards production of hydrogen by feeding renewables-based electricity

B. Building blocks to produce green hydrogen

The production process involves several aspects, right from the uncertainties in availability of renewable electricity sources to the management of net zero energy hub. A simplified approach is presented in Fig. 3.

Green Power (Renewable Energy)
- ✓ Sources: Wind & Solar, both offshore & onshore
- ✓ Ideal Source Ratio: electricity generated via wind-solar to feed electrolyzers in the ratio of 50:50
- ✓ High Wind Scenario: electricity generated via wind-solar to feed electrolyzers in the ratio of 75:25
- ✓ High Solar Scenario: electricity generated via wind-solar to feed electrolyzers in the ratio of 25:75
- ✓ Wind capacity factor: 50%

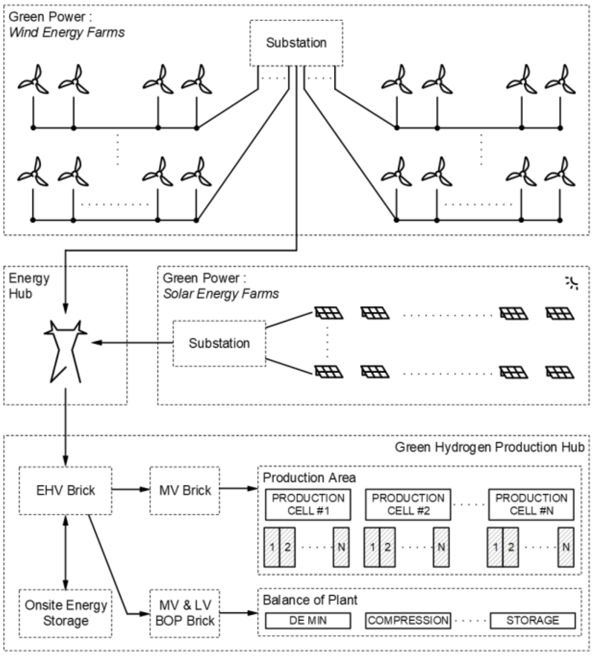

Fig. 3 Building blocks involved in the production of 'Green Hydrogen'

Energy Hub

- ✓ Collate energy via power producers
- ✓ Energy hubs can be either part of utility or gH_2 production hub
  - *When it's part of main utility grid, energy hubs are responsible for managing demand response and ensuring power system stability*
  - *When it's part of gH_2 production facility, energy hubs can aid the grid as well as be responsible for managing the production of green hydrogen*

Green Hydrogen Production Hub

- ✓ Operate and maintain production facility
- ✓ Comply with grid requirements

C. Set-ups for hydrogen production from electricity

Hydrogen can be produced through electrolysis using an off-grid or an on-grid setup [3] and are categorized into four (4) combinations.

1. Inflexible electrolyzer (grid to hydrogen)
2. Flexible electrolyzer (grid to hydrogen)
3. Co-located (island)
4. Co-located including grid connection (grid)

These scenarios make operational requirement very unique and control systems must be built to facilitate safe and reliable operation of green hydrogen production hub. Control aspects are further detailed in Section IV.

III. CONCEPTUAL ELECTRICAL DESIGNS

This section attempts to establish design approach on the electrical side of things for green hydrogen production hub.

It is recommended to split design into two parts: standard and non-standard design (Fig. 4).

Standard design includes a set of concepts (philosophies) which will establish ground rules in power system design, power system automation needs, process automation interface needs, and digital twin integration.

Non-standard design generally covers the part where country regulations come into picture. In order to capitalize efforts, a catalogue of non-standard architectures can be built which can be chosen as per project needs.

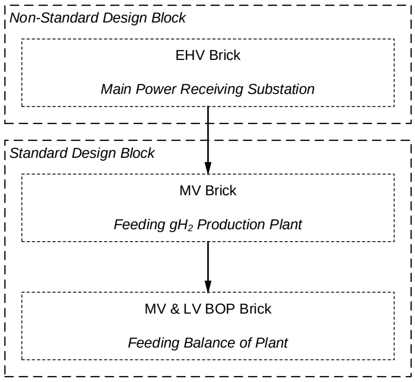

Fig. 4 Design standardization methodology

A. Establishing golden rules for electrical designs

Concept for electric power distribution undergoes series of studies with reference to project needs. Today, some of the biggest challenges are CAPEX and time to market.

As energy transition is not just limited to one geography, with most the major players owning operations globally. There is a strong need to standardize design as much as possible while keeping scalability in mind for both IEC and ANSI/NEMA/UL standards.

A simplified three (3) brick approach is presented in Fig. 5 where entire electrical system in a green hydrogen production hub is split into EHV, MV, MV & LV BOP bricks respectively.

Brick-1: *EHV Brick*
Currently, most of the large-scale projects in FEED stage are in the order of 500 MW to a few GW. Thereby pushing voltage levels at the receiving substation to EHV.

Brick-2: *MV Brick*
Generally, a 22 or 33 kV MV backbone is established, MV Brick further feeds electrical power to production (electrolyzer) area.

Brick-3: *MV & LV BOP Brick*
It is composed of 11 or 6.6 kV MV & LV distribution to feed balance of plant loads.

Optional Brick

Brick: *Onsite Energy Storage*
Facility can be equipped with an onsite energy storage for demand response management and power to feed critical auxiliary loads.

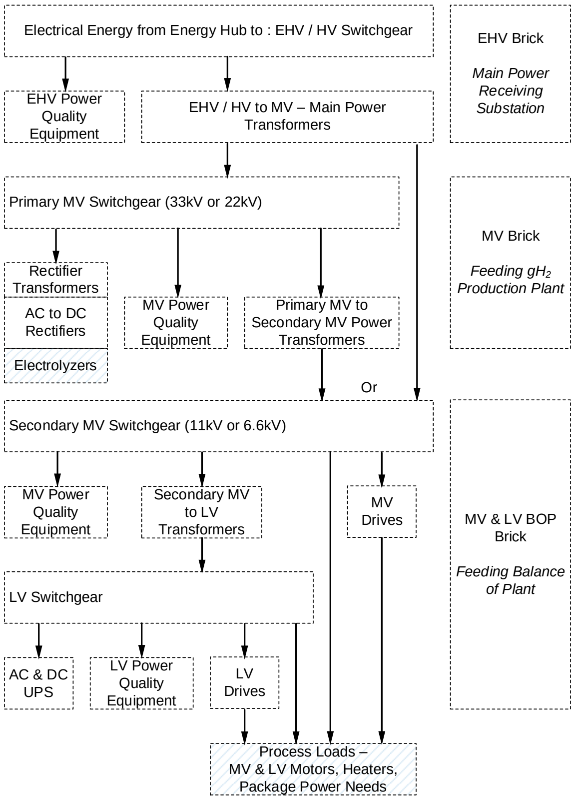

Fig. 5 Three brick approach to standardize electrical power system concept

B. Non-standard design – EHV Brick – Switchgear

Generally, EHV connection arrangement and Grid code compliance are key decision makers. Selection of voltage depends on project definition (in terms of MW's). Ideally a double circuit intake at 132 or 220kV is enough to design green hydrogen facilities up to 500MW; higher grid intake voltages such as 400kV or above when production capacity is expected to be in few GW's.

Due to SF_6 free solutions, EHV switchgear are more environment friendly than ever. Owing to their compactness, they can easily be integrated into a prefabricated substation, thereby improving lead time.

EHV architecture is driven by Reliability-Availability-Maintainability requirements of facility. Most commonly used architectures are listed below:

- ✓ Single busbar
- ✓ Double busbar – double CB
- ✓ Double busbar – single CB
- ✓ Double busbar – single CB with bypass
- ✓ Double busbar – single CB with transfer busbar
- ✓ One and a half circuit-breaker

A partitioned main busbar limits the impact of a major failure to a small compartment and subsequently decrease the repair time. Ideally, medium-class partitioning (up to three (3) bays shutdown during repair) to best partitioning (just single bay shutdown during repair).

Definition of UPS (regulated) DC & AC supplies are established, which feeds power supplies to different functions of control, supervision, signalling. Generally, power is distributed with a dedicated DC supply for each bay and one common DC supplies for the general section.

Degree of electrical protection at EHV are heavily influenced with local grid practices. Commonly practiced relay application principles are mentioned below:

- ✓ Main protection relay only (one relay)
- ✓ Main & back protection relay (one relay with main protection functions and other with back-up functions only)
- ✓ Two main protection relay (relay functions fully duplicated into two different relays and possibly with two different technology platforms or by different manufacturers)
- ✓ Two main & two back-up protection relay (where both main functions and back-up relay functions fully duplicated, totalling it into four different relays.

C. Non-standard design – EHV Brick – EHV or HV to MV Main Power Transformers

A clear planning criteria can further help when choosing optimum configuration for main power transformer architecture, and establishes requirements for MV Brick, hence care needs to be taken while design planning.

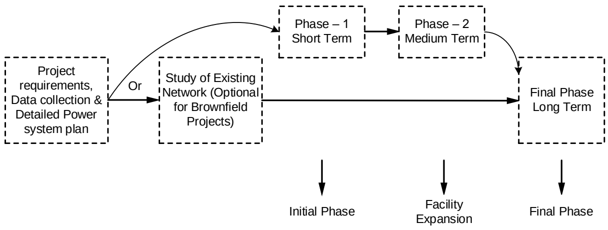

Fig. 6 Typical power system planning concept for execution of a large-scale green hydrogen production hub

Most commonly used transformer arrangements are:

- ✓ Single transformer feeding complete facility
- ✓ '2N' 2x100% transformer feeding dedicated plant (per phase wise) and systems expands as per network planning
- ✓ 'N+1' Block redundant transformer feeding dedicated plant (per phase wise) and systems expands as per network planning

While framing concepts for transformer arrangement, in order to optimize overall emissions within production process, it is necessary to choose transformer arrangement based on TCO and its lifecycle carbon emissions.

Once transformer definition is established, manufacturer will be in a position to answer embodied and operational carbon,

Embodied Carbon:

- ✓ Emissions associated with materials – Steel, Copper, Oil
- ✓ Load loss – watts
- ✓ Emissions during transport

Operational Carbon:

- ✓ No Load Loss – watts
- ✓ Load loss – watts
- ✓ No load loss / year kWh
- ✓ Load loss /year kWh @40% load factor (for 2N system generally it is 40% and for N+1 architecture it is generally around 80%)
- ✓ Total loss / year kWh
- ✓ Total CO_2 Emission / year (Tons)

- ✓ Total CO_2 Emission for 25 years (Tons) (generally industrial plants are designed for 25years of operation)

Other Miscellaneous:

- ✓ Transformer impedance – reactive power needs

D. Non-standard design – EHV Brick – PQ Solutions

When green hydrogen production hubs are connected to local utilities (this generally happens when power is sourced through utility's infrastructure), design should allow compliances to utility grid code. In such situation, PQ solutions are required to ensure that system remains clean from harmonics.

E. Standard design – MV Brick

Transformer definition in EHV architecture has significant influence on MV Brick. MV brick is responsible for powering up the electroyzer, which is the heart of green hydrogen production hub. Compact substations are preferred and are generally located close to the process area; Gas Insulated Switchgear (GIS) is generally the preferred choice to distribute power to electrolyzer units either radially or in an open loop.

A typical power train, generally under the scope of supply of electrolyzer OEM, consists of rectifier transformer, rectifier and electrolyzer (option #1). There could be potential for optimization when designs are developed in cooperation with electrical equipment OEM's (option #2).

Let's examine design requirements in the following steps:

Step 1 Establish scope for gH_2 train

gH_2 train is composed of three (3) main elements, viz, rectifier, transformer, AC to DC rectification and mechanical equipment 'electrolyzer'.

Option#1	Electrolyzer OEM has complete scope (3 elements)
Option#2	Electrolyzer OEM supplies only electrolyzer and rest is under electrical equipment OEM scope

Step 2 Establish rectifier transformer concept feeding power train.

For an optimized approach, it is recommended to avoid 'one-size-fits-all'. For smaller installations (<30MW), it could be interesting to have several small units of electrolyzer with a standard transformer. With this approach, standard equipment can be applied.

The size and complexity will increase for medium to large size facilities; in these situations, care needs to be taken especially in managing overall power quality at the point of common coupling. It is suggested to explore possibilities of having special rectifier duty transformers rated either to 12Pulse or 24Pulse (Fig. 7); this approach helps to mitigate harmonics at MV bus.

Salient points for considering 6Pulse rectifier duty transformer:

- ✓ Construction of transformer is similar to a standard two winding transformer
- ✓ Transformers are de-rated to harmonic profile of AC/DC rectifiers
- ✓ Solutions are based on LV side currents; standard solutions are up to 6000A and higher current can be achieved with parallel disc busbar arrangement. This construction increases the cost of transformers very high
- ✓ In 6Pulse configuration, there could be higher resultant harmonic content, dedicated PQ solutions filter will be required in the MV system.

Salient points for considering 12Pulse rectifier duty Transformer (Fig. 7, right):

- ✓ A 12Pulse rectifier duty transformer can have one or two primary windings and two secondary windings with a 30^0phase shift between the secondary windings.
- ✓ One secondary winding is commonly star connected and the other is delta connected.
- ✓ Three types of rectifier transformers are preferably used for 12 -pulse rectification.
  - Three (3) windings with one (1) primary winding and two (2) closely coupled secondary windings. Coupling factor K > 0.9.
  - Three (3) windings with one (1) primary and two (2) loosely coupled secondary windings. Coupling factor 0.2 < k <0.9.
  - Four (4) windings with two (2) primary winding and two (2) uncoupled secondary windings. Coupling factor K < 0.2.

Salient points for considering 24 Pulses Rectifier Duty Transformer (Fig. 7, left):

- ✓ Special construction with odd phase shifts in transformer; four (4) secondaries with generally 15^0 phase shift. It is achieved with special configuration like extended star or extended delta.
- ✓ Phase shift can be achieved either from MV or LV windings.
- ✓ Older generation 24Pulse transformer's phase shifts were achieved with reference to LV, this approach is more complex from manufacturing point of view.
- ✓ Newer practices achieve phase shift in MV winding with extended delta configuration.
- ✓ Three (3) possible construction of 24Pulse transformer:
  - 2 nos 12Pulse active part within same (1) tank.
  - 2 nos 12Pulse active part in two (2) separate tanks.
  - 1 nos active part with 4 LV Phase shifted windings.

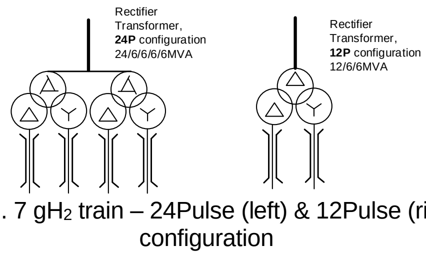

Fig. 7 gH_2 train – 24Pulse (left) & 12Pulse (right) configuration

Harmonics at MV bus can also be further optimized by combinations of PQ solution and rectifier technology.

Once gH_2 train definition is established, components can be assembled into a standard module for large scale deployment.

DC input voltage of electrolyzer varies over its life; wide variety of sizes are available from various electrolyzer OEM's. Generally, smaller size (<5MW) electrolyzer operates at DC input voltages around ~400V and medium to large size (≥5MW) electrolyzer operates either at ~650V or 900V.

24Pulse transformers are ideal to have for better harmonic profile at MV bus. However, construction becomes complicated due to high secondary currents which exponentially increases cost of the transformer. In such conditions, it is advantageous to have two numbers of 12Pulse transformers which can mimic 24Pulse configuration as indicated in Fig. 8.

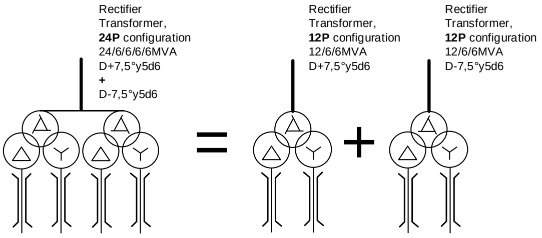

Fig. 8 gH_2 train – 24Pulse configuration with two (2) dedicated 12Pulse transformers

Fig. 9 indicates bus-duct interconnection from 12/6/6MVA, 33 kV / 655 V / 655 V Dry-type transformer to rectifier to 5MW + 5MW AC/DC rectifier.

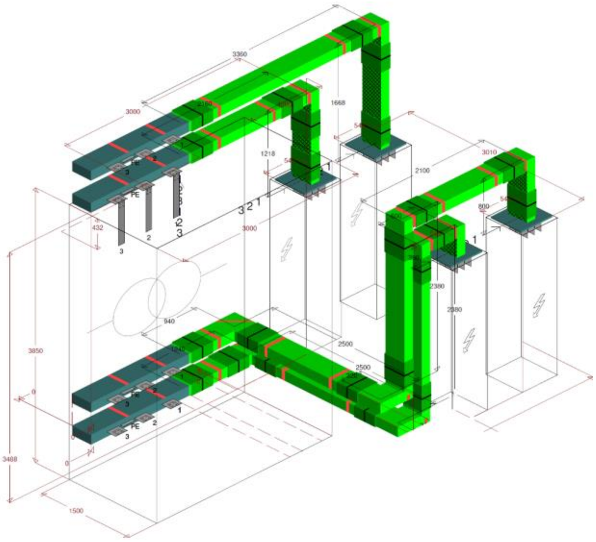

Fig. 9 Bus-duct interconnection from Dry-type transformer to rectifier

It can be noted from Fig. 9 that overall dimensions of transformer are ideal to fit within a standard container; thereby, making it an ideal size while choosing dry-type transformer. Fig. 10 indicates one such solution developed for a 10MW standard block which has a footprint of 8.3mtrx3.5mtr (2xRMU, 1x12/6/6MVA Dry-type transformer and 2x5MW AC/DC rectifier).

Step 3 Establish power distribution concept to feed power train

There are two possible options, radial and loop, to distribute power to various strings of gH_2 forming a sizeable power train. Radial design is generally chosen when sizes of electrolyzer are ≥ 5MW; for smaller sizes, loop design could result in significant cost savings.

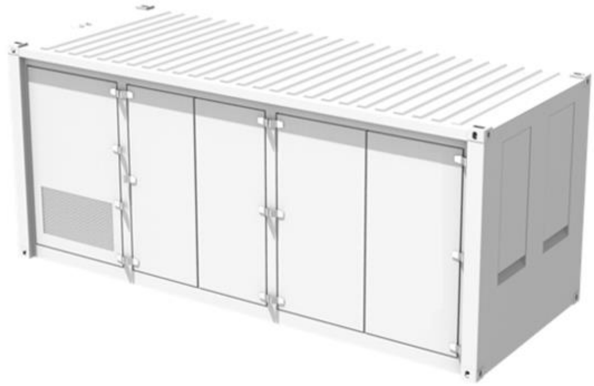

Fig. 10 Modular gH_2 train (excluding electrolyzer)

Detailed study was carried out to identify potential design optimization for an 150MW gH_2 facility.

Following are observations when design is changed from '2N' to 'N+1' redundancy at EHV transformer arrangement:

- ✓ Similar or better TCO and lifecycle emissions
- ✓ Cost reduction at MV brick by over 50%
- ✓ One additional EHV bay

TABLE II
MV BRICK ARCHITECTURE COMPARISION

Area of Comparison	150MW MV Brick		
	'2N'	'N+1'@ 33kV	'N+1'@ 22kV
Solution	GIS	GIS	AIS
BusBar Rated Current	4000A	2500A	3150A
Incomer & Bus Coupler	Special configuration, two (2) breakers in parallel	Standard Solution	Standard Solution
Short Circuit Current	31.5kA or 40kA	31.5kA or 25kA	31.5kA
Relative Cost (CAPEX)	100%	60%	40%

IV. TOTAL CONTROL SYSTEM CONCEPT

Hybrid Power Generation Management concepts were introduced in reference [1]; in current context, these digital layers allow industrial facility to manage energy mix (Fig. 11).

There could be several combinations of green hydrogen production hubs, such as pure production or production with utilization; this results in different operating scenarios. EU has defined rules for sourcing of renewable electricity [4] for the production of green hydrogen, and are summarized below:

Option #1	Direct connection
Option #2.a	Electricity grid with high share of renewable energy (at least by 90%)
Option #2.b	Electricity grid with low CO_2 emissions
Option #2.c	Using imbalance settlement periods
Option #2.d	All other grid situations

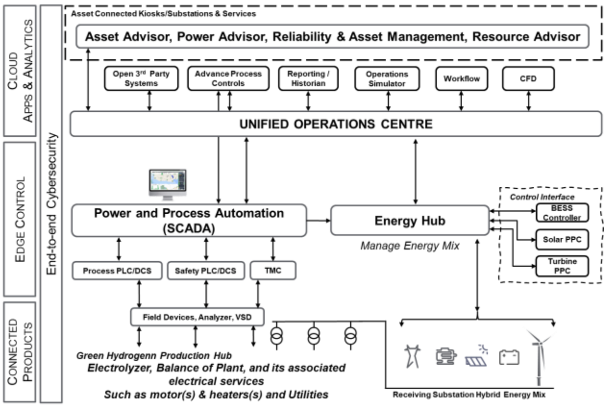

Fig. 11 Digital architecture for a full-scale green hydrogen production facility with hybrid energy management

Elements involved in the for the production of green hydrogen facility can be simplified (Fig. 3) into four blocks as represented below:

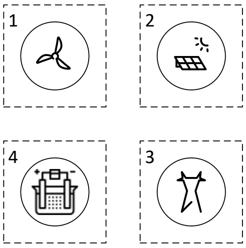

Fig. 12 Building blocks involved in the production of 'Green Hydrogen' – simplified version

Element #1	Green energy – Wind
Element #2	Green energy – Solar
Element #3	Energy Hub
Element #4	Green hydrogen production hub

Let us further explore electrolyzer operation modes (in continuation from Section II.C). When a gH_2 facility operates in flexible electrolyzer mode, they are expected to respond on shorter intervals. For example, based on RE prediction (hourly), flexible electrolyzers have to adapt their hydrogen output with fluctuations in RE supply that are available on the grid. Similar context can be extended to a facility where PPA's for RE are sourced through grid infrastructure.

Flexible electrolyzers are usually smaller in ratings over non-flexible ones and are more appropriate for use in systems with more penetration of RE. Thus, they contribute to grid stability and benefit from low electricity prices by using surplus RE when it is available for hydrogen production.

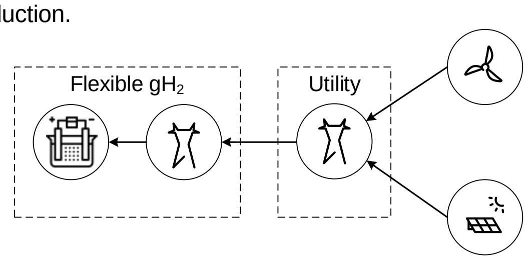

Fig. 13 Flexible electrolyzer with TSO features

Flexible electrolyzers are usually smaller than non-flexible ones and are more appropriate for use in distributed energy systems. In short, it solves the uncertainty of RE penetration to grid by regulating gH_2 production (by storing surplus power in the form of hydrogen), thus, helping power systems to be more resilient.

With start up time less than 1 min, PEMEL is the most flexible type of electrolyzer for full scale facilities (onsite RE source). It also has quick response to production setpoints.

A gH_2 production facility can be within an industrial compound and is tasked to produce at a constant production rate is known as inflexible electrolyzer mode. AEL, even with its slower start up time of up to 10 mins, its higher efficiency makes it the best option. Thus, not suitable for use in systems with high RE penetration.

In flexible mode of operation, a sophisticated energy hub with TSO features will be required to maximize returns (better LCOH). In inflexible mode of operation, a basic energy hub would be sufficient. In both cases, process automation are expected to facilitate operations of gH_2 in a safe manner.

In some situations, it is possible to have RE generation and its management within gH_2 production facility; this is commonly referred to as co-located (island) mode of electrolyzer operation (Fig. 14). These are possible especially in sites containing large wind and/or solar farms. Such sites would also require emergency source (Element #5 Energy storage) to safeguard operation during RE disruptions.

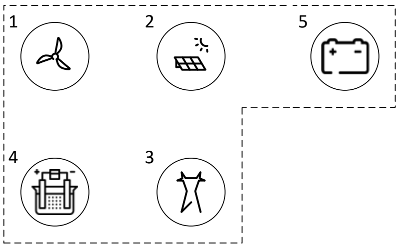

Fig. 14 Co-located (island) mode of electrolyzer operation

Energy hubs in co-located (island) case enable end user to manage RE, thus, empowering facility operations to be fed by decarbonized energy and at the same time manage traditional back-up generators (or energy storage).

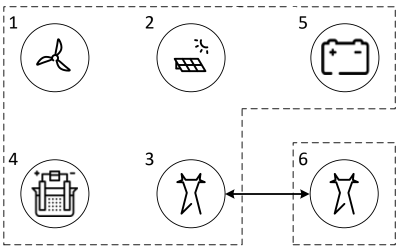

Fig. 15 Co-located including grid connection mode of electrolyzer operation

Lastly, we can have above case (Fig. 14) with grid tie-in (Fig. 15), termed as Co-located including grid connection (Element #6 Utility). Such systems require sophisticated digital layers to manage energy hubs and gH_2 production process.

V. KEY DRIVERS – UNCERTAINTIES – CHALLENGES

It is evident that gH_2 is one of our go-to-approach to substitute fossil source with carbon free energy, further research is still required in order to create demand and drive green hydrogen economy. Key drivers, uncertainties and challenges are summarized below:

Key Drivers

- ✓ Incentives to set up RE technology development and its application from local government(s)
- ✓ Incentives for end users to decarbonize their manufacturing processes using hydrogen
- ✓ Techno-economic analysis to support green hydrogen as a transition fuel for end user's manufacturing process

Uncertainties

- ✓ Availability of RE sources
- ✓ Striking balance between LCOE, LCOH and production demands
- ✓ Process OEM technology development to substitute energy with hydrogen fuel

Challenges

- ✓ End user perception to substitute their existing processes with hydrogen
- ✓ Limited electrolyzer life
- ✓ Efficiency of electrolyzer
- ✓ Technology for transportation of hydrogen in cryogenic state

VI. CONCLUSIONS

Once major processes are electrified and energy needs satisfied through renewable electricity, hydrogen will play a crucial role to substitute fossil energy in the decarbonization journey for achieving net zero.

Producers of gH_2 (under flexible electrolyzer) operate at a better LCOH, and at the same time, support utilities for grid stability (ancillary services) and can participate in spot market.

In order to boost hydrogen economy, large scale deployment would be required globally. This could be further aided by design standardization which reduces cost and improves time to market. With various control system concepts presented, attention is necessary to adopt best fit architecture.

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IX. APPENDIX

Appendix A shows a full-fledged, holistic, centralized, electrical and digital architecture with robust communication network infrastructure containing 3 layers of connected products, edge control and cloud analytics with full cybersecurity for asset and data protection and both design digital twin for simulation and operation digital twin for system management. Seamless integration of both electrical and process with the aid of digital helps to facilitate complete management of gH_2 production hub.

X. VITA

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Appendix A
Typical gH_2 electrical and digital architecture