# Smart Ways for In-situ Totally Integrated and Continuous Multisource Generation of Hydrogen

## D2.: First level use case

***WP 2 , T 2.1***

***April, 2020 (M4)***

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## Technical References

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[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services).

RE = Restricted to a group specified by the consortium (including the Commission Services).

CO = Confidential, only for members of the consortium (including the Commission Services).

## Versions

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# Table of Content

# List of Figures

# List of Abbreviations

| | |
|---|---|
| BEV | Battery Electric Vehicle |
| CH2P | Combined Hydrogen and Power project |
| EV | Electric Vehicle |
| FCEV | Fuel Cell Electric Vehicles |
| FCHJU | Fuel Cells and Hydrogen Joint Undertaking |
| HRS | Hydrogen Refueling Station |
| OPEX | Operating Expense |
| PSA | Pressure Swing Adsorber |
| PV | Photovoltaic |
| SOE | Solid Oxide Electrolyzer / Solid Oxide Electrolysis |
| SOFC | Solid Oxide Fuel Cell |
| SWITCH | Smart Ways for In-situ Totally Integrated and Continuous Multisource Generation of Hydrogen project |

# 1 Abstract

The SWITCH project aims to develop an in-situ fully integrated and continuous multisource hydrogen production system, based on solid oxide cell technology. The system must be able to both efficiently generate hydrogen via water electrolysis (i.e. SOE), thus enabling green hydrogen production when renewable energy is available, as well as reversibly operating in fuel cell mode (i.e. SOFC). The latter allows for the use of other feedstock sources (e.g. methane, bio-methane) to produce hydrogen when renewable electricity is not economically viable or unavailable. This will allow a continuous and guaranteed production of hydrogen for contracted end users. Figure 1 shows both main operating modes with corresponding inputs and outputs.

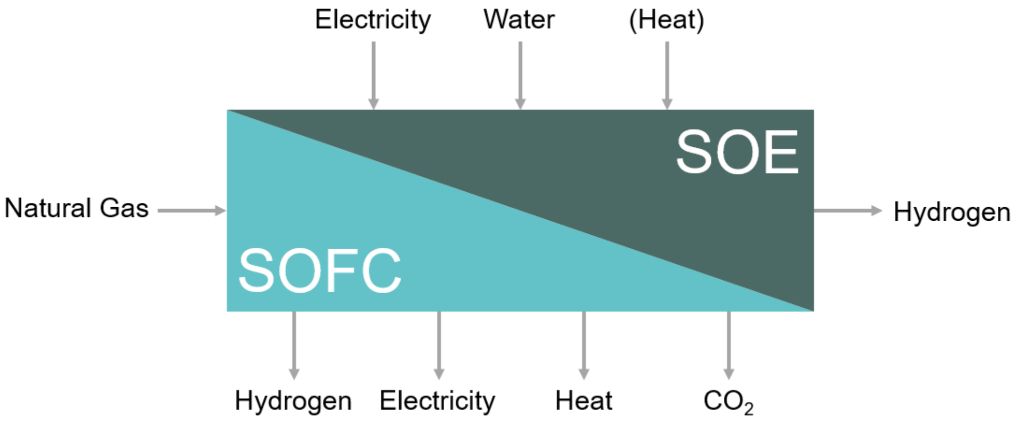

**Figure 1: Inputs and outputs for the SWITCH-system both in Fuel Cell mode (SOFC) and Electrolysis mode (SOE).**

This report defines the use cases for such a combined system by looking at the demand profiles for hydrogen and power. Demand profiles include hydrogen refuelling, as well as power consumption of the system itself and surrounding power consumers, charging of battery electric vehicles and power balancing. It also gives the implications of these demands in the form of an operating envelope with a set of operating points. These can be used for modelling and design of the SWITCH system.

It should be noted that the numbers and operating envelope provided in this document represent aspirational technical targets for the SWITCH system, based on a range of operating environments where the SWITCH system could be used, to be verified during this project.

It should also be noted that this document does <u>not</u> present a position on the feasibility to economically scale the SWITCH system to all the potential use cases described therein, nor did it consider possible footprint limitations when the SWITCH system is applied at large capacity.

# 2 Introduction

## 2.1 Hydrogen as an energy carrier

Hydrogen is an energy carrier that has potential to help decarbonize worldwide energy systems. The Hydrogen Council recently issued a study into the cost competitiveness of hydrogen and considered 35 potential applications, ranging from transportation, heat and power for buildings, for industry and as an industry feedstock[1].

In the mobility sector hydrogen can be used in fuel cell electric vehicles (FCEVs), which qualify as zero-emission vehicles. Depending on the method of hydrogen generation and distribution, the well-to-wheel greenhouse gas emissions may approach zero also. Targets for FCEV deployment are becoming more ambitious. See, for example, the target set by the governments united in the Energy Ministerial to deploy 10 million FCEVs by 2030[1].

## 2.2 Power

In SOE mode the SWITCH system requires power to generate hydrogen via water electrolysis. By using 100% renewable electricity in this mode, the produced hydrogen will be green[2]. Availability and pricing of electricity (and specifically renewable electricity) is dependent on a range of factors. These include[2]:

- Variable or intermittent supply of renewable power (as the power yield is determined by weather and diurnal patterns for solar PV and wind energy);
- Total generation capacity, renewable generator penetration and the associated merit order for the location of interest (including both the dispatchable generators, like gas- and coal fire powerplants, nuclear and hydroelectric power generation, and non-dispatchable renewable sources like solar PV and wind);
- In some power markets: distance between the location of the generation and the load user;
- Differences between the predicted electricity demand versus the actual demand;
- Uncertainty in renewable energy production whereby forecasting errors may require balancing on short notice.

Differences between predicted power generation (or demand) versus actual power generation (or demand) require power balancing.

For example, in the Dutch power market electricity transmission system operator TenneT makes use of primary, secondary and tertiary reserve to balance the power grid and reimburses the suppliers of this power reserve. The minimal power capacity required to participate in this service is low MW-scale (i.e. min. 1 MW for primary reserve) and power

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[2] *Pending positive verification that the SWITCH system meets the applicable "green hydrogen" certification requirements for its target markets (like e.g. Certifhy's Guarantee of Origin scheme, www.certifhy.eu). Data generated during the SWITCH project will enable such verification.*

should be supplied within 30 seconds (for primary reserve) or within 15 minutes (for secondary reserve)[3].

These factors present an opportunity for the SWITCH system, as its ability to generate hydrogen both in SOE mode (using electricity) and SOFC mode (using a hydrocarbon source, whilst generating electricity) enables optimization of green hydrogen production capacity whilst minimizing OPEX (i.e. electricity costs) and/or $CO_2$ emissions and participate in smart load control of its local power grid. Further, the SOFC mode may open up the possibility of becoming a supplier of (secondary) power reserve and generate revenue for this service.

## 2.3 SWITCH project

The SWITCH project aims to develop an in-situ fully integrated and continuous multisource hydrogen production system, based on solid oxide cell technology. The system must be able to both efficiently generate hydrogen via water electrolysis (SOE mode), thus enabling green hydrogen production when renewable energy is available, as well as reversibly operating in fuel cell mode (i.e. SOFC). The latter allows for the use of hydrocarbon feed sources to produce hydrogen when renewable electricity is not economically viable or unavailable. This will allow a continuous and guaranteed production of hydrogen for contracted end users. In future, bio-methane and/or renewable hydrogen enriched natural gas is envisioned as feed when operated in fuel cell mode.

This project is supported by European funding provided by the Fuel Cells and Hydrogen Joint Undertaking (FCHJU, www.fch.europa.eu) and it is conducted in collaboration with other six industrial and academic partners (www.switch-fch.eu).

This work builds upon earlier work conducted with European funding together with several partners in the Combined Hydrogen and Power (CH2P) project (www.ch2p.eu).

This report specifies the use cases (possible operating environments) and associated operating points of the system developed in SWITCH.

# 3 Operating environment 1: Refuelling stations for light duty vehicles

The rollout of light-duty hydrogen retail stations has been ongoing in the past two decades, initially with focus on specific regions like Japan, California and Germany. Hydrogen refueling stations (HRS) are now operational in most European countries (see Figure 2). A typical refuelling station capacity of 100 to 200 kg/day hydrogen is assumed for this operating environment.

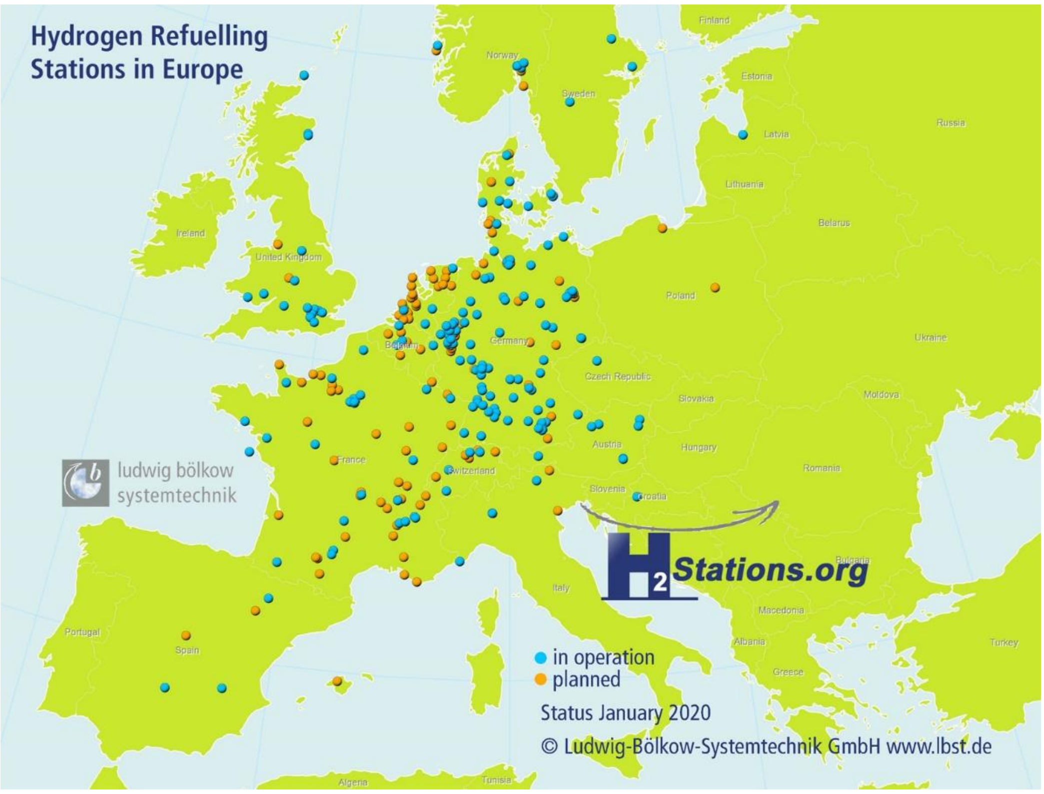

**Figure 2: Hydrogen refuelling stations in operation per January 2020 [4].**

An irregular customer refuelling pattern is assumed. Historic data from the Californian stations (over the period: Q3 2014 - Q4 2018)[5] indicates that most fills occur during the day time, much in line with a gasoline refuelling pattern (see Figure 3). An average of 3 kg hydrogen is dispensed under 4 minutes per fill, with a fill rate of just under 1 kg/min.

To satisfy customer needs, Shell decided to integrate most of its hydrogen filling stations for light-duty vehicles into existing fuel retail stations. This means that SWITCH systems may be installed at sites that have a convenience shop, a car wash and sell conventional fuels and potentially electricity for battery electric vehicle (BEV) charging, as well as hydrogen. The SWITCH system therefore needs to seamlessly integrate into such a station.

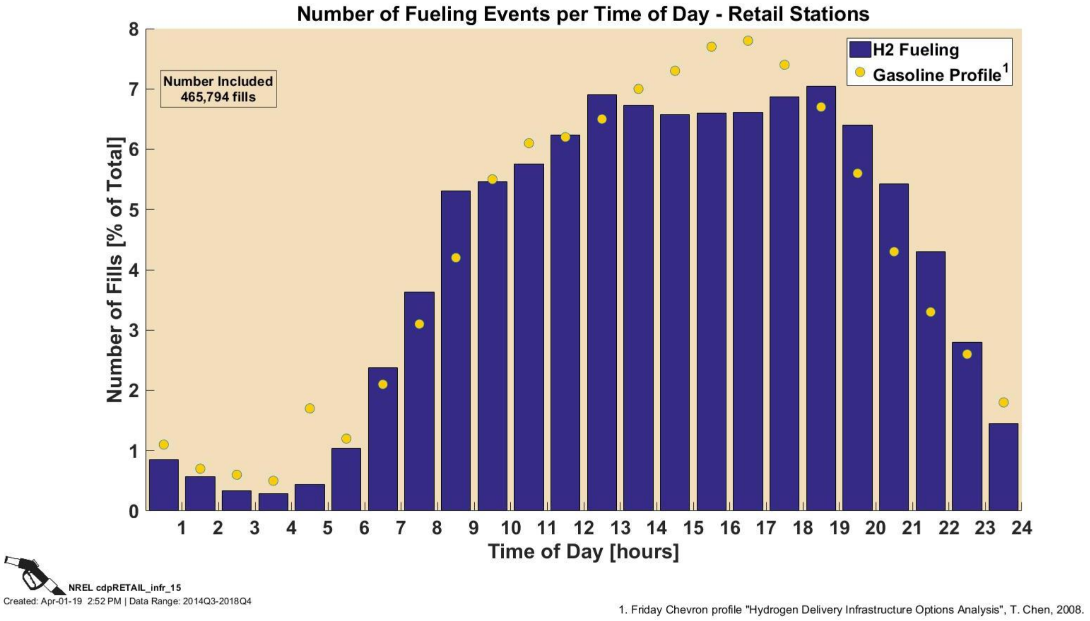

**Figure 3: Number of hydrogen fueling events per time of day. The data is based on 465794 fills in California in the period Q3 2014 to Q4 2018. Source: NREL/ U.S. Department of Energy (DOE) (2019)[6]**

## 3.1 Hydrogen station layout and electricity use

The boundary condition of the system in the SWITCH project is delivery of fuel cell quality hydrogen[3] at minimally 7 bar pressure[7]. This may require compression into the Low-Pressure Storage, which also acts as a buffer between the SWITCH system and the refuelling station to decouple hydrogen demand from hydrogen production (see Figure 4). The capacity of this storage is expected to be between 50% and 100% of the daily hydrogen station capacity. From this Low-Pressure Storage, the hydrogen is compressed further into the High-Pressure storage, before being cooled to -40°C and dispensed at 700 bar.

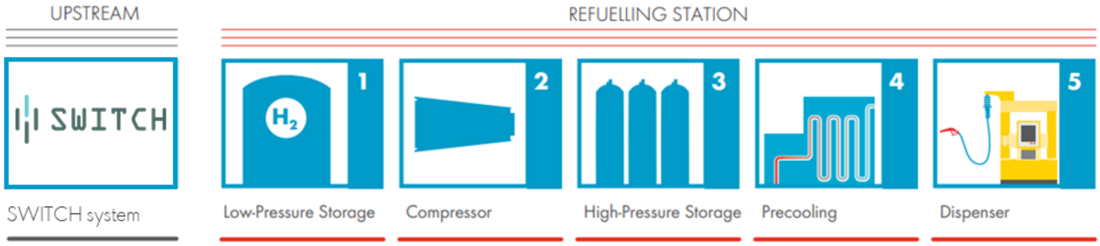

**Figure 4: Possible layout of a hydrogen refuelling station with a SWITCH system. Figure adapted from Shell (2017)[8].**

The power generated when the system is operating in SOFC mode can be used to fulfil the compressors, (inter)cooling and dispensing electricity needs. The efficiency of the

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[3] Fuel cell quality specified by ISO standard 14687: Hydrogen fuel quality – Product specification.

compressors depends on its throughput, inlet and outlet pressure and exact station configuration. For cooling, a power requirement of 0.2 kWh/kg is estimated. Compression data from actual refuelling stations indicate a power requirement varying from 2 – 6 kWh/kg hydrogen[9, 10, 11]. Part of this variation is explained by the impact of low utilization and variability of inlet and outlet pressures during operation.

The design power production per kg hydrogen (at full SOFC power *and* hydrogen capacity) is ca. 30 kWh/kg hydrogen[9]; hence adequate to deliver the power demand for compressor, (inter)cooling and dispensing. The excess power (80-93% of max. power generated) may be used for:

- Powering the convenience shop, lighting and car wash
- Charging of (light-duty) BEVs (see Section 3.2)
- Return to the power grid, if local circumstances allow for this.

The electricity consumption of hydrogen- and conventional refuelling stations was measured and analyzed as part of the earlier CH2P project. Reference is made here to the CH2P usage scenario report [9]. Also see some of the resulting data from this report in Figure 5.

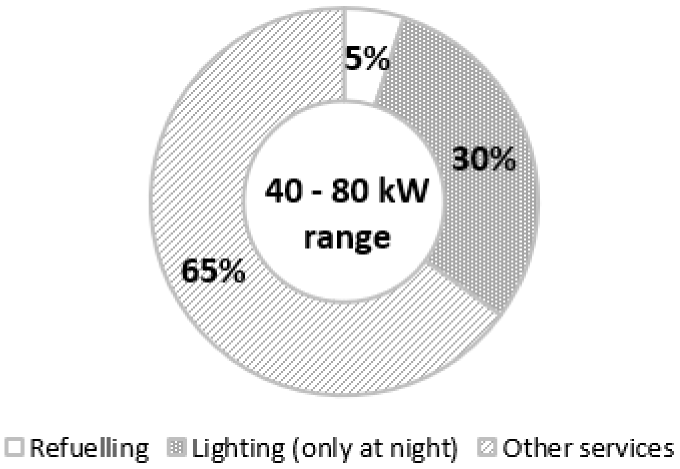

**Figure 5: Typical power consumption of a conventional retail station[9].**

## 3.2 Electricity use for charging battery electric vehicles

Infrastructure for charging BEVs is rolled out on a large scale. Simultaneously, power output per charger is increasing to enable faster fast-charging. Tesla requires 150 kW for its existing chargers and commenced roll out of its V3 Supercharger which will provide 250 kW peak rates[12]. Furthermore, Porsche/Volkswagen Group opened eighteen 350 kW DC fast-chargers in early 2020[13].

The SWITCH system in SOFC mode can be used to charge BEVs directly or via an intermediate storage battery located at the retail site. Onsite storage batteries will enable management of the fluctuating power utilization due to irregular refuelling patterns on the forecourt.

These power levels and fluctuations must be considered in the design of the SWITCH unit.

In addition to its use in light-duty FCEV vehicles, hydrogen is considered to have the potential to become a highly, or even most, competitive and low-carbon option by 2030 for other FCEV applications like: medium and heavy-duty trucking, long distance busses, taxi fleets and industrial vehicles like forklifts[1].

# 4 Operating environment 2: Refuelling stations for heavy-duty vehicles

Several studies indicate that hydrogen for heavy-duty transport is getting more traction[1,14]. Benefits of medium- and heavy-duty hydrogen fuel cell trucks include decarbonization of long-range transportation, avoidance of the size, weight and cost penalty for carrying the batteries required when opting for a BEV truck to decarbonize transport instead, and the potential for a shorter refuel duration vs charging (with a notional duration of two hours using a 500 kW fast charger[4] [1,15]).

Recent examples of this are:

- Toyota, Kenworth and Shell currently participate in a consortium on the Shore-to-Shore project in California, which includes developing three new heavy-duty refuelling stations with a capacity of 1 ton $H_2$/day, one of which will use hydrogen made from biogas; and the deployment of (initially) 10 heavy-duty hydrogen fuel cell trucks[16, 17]. The trucks will have a 300 mile (480 km) range and would require ca. 55 kg $H_2$ per refuelling at 700 bar pressure. Refuelling durations of 20 - 25 minutes are foreseen, with an ambition to lower this under 15 minutes[15];
- Similarly, Nikola and Nel announced plans in 2019 to develop heavy-duty vehicle refuelling stations with an initial capacity of 8 tons $H_2$/day (with potential to scale up to 24 tons $H_2$/day) and design capacity to serve ca. 150 trucks and 200 cars; based on on-site water electrolysis. Concept designs for such a station include a convenience shop and restaurant, similar to light-duty refuelling stations[18];
- The H2Haul project (Hydrogen fuel cell trucks for heavy-duty, zero emission logistics) is conducted with European subsidy under the FCHJU program and runs from 2019-2023. It will deploy 16 zero emission fuel cell trucks in four demonstration sites (https://www.h2haul.eu/).

A typical refuelling station capacity of 1 to 6 tons/day hydrogen is assumed for this operating environment; whereby total electricity consumption in SOE mode, electricity production in SOFC mode and hydrogen production (in both modes) increase accordingly. This means the SWITCH systems requires a grid connection able to supply 2 to 11 MW, respectively. Vicinity to, or direct integration with, a renewable energy source may be advantageous.

Similar to a light-duty station, an irregular customer refuelling pattern is assumed. In principle a heavy-duty refuelling station will comprise the same system blocks as depicted in Figure 4, although the pressurized storage philosophy and hence required compression duties may be different.

The power generated when the SWITCH system is operating in SOFC mode can be used to fulfil the compressors, (inter)cooling and dispensing electricity needs. The efficiency of the compressors depends on its throughput, inlet and outlet pressure. For a 1 ton/day station, the compressor efficiency is expected to be ca. 52% (20 bar to 350 bar compression) to 49% (to 700 bar compression). Again, (inter)cooling and low station

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[4] In parallel, industrial activities are ongoing to develop heavy-duty vehicle fast charging > 1 MW, see for example the CharIN association[19].

utilization may increase this power requirement. This will correspond to a power usage of 2 – 4 kWh/kg hydrogen[20, 21].

Similar to a light-duty station, the SWITCH system in SOFC mode can be used to charge BEVs. This option will require an intermediate storage battery with a size matching the power generation capacity, to manage fluctuating power utilization due to forecourt recharging patterns.

The excess power may be used for:

- Powering the convenience shop, lighting, restaurant and car wash
- Charging of Battery Electric Vehicles (BEVs), either light-duty or heavy-duty vehicles depending on station power generation capacity and station location.
- Power grid balancing by becoming a supplier of power reserve.

# 5 Operating environment 3: Refuelling at a depot – busses, industrial vehicles

## 5.1 (Municipal/Urban) Bus fleet

Since the early 1990s, several hundred buses have been and are being operated with hydrogen worldwide. Fuel cell busses have reached a high level of technical maturity and (demonstration) projects deploying larger fleets have been announced in several geographies[8]. Benefits of a hydrogen fuel cell bus fleet include local emissions reduction and potential for a shorter refuel duration at the central depot vs. (overnight) charging of EV busses.

For example, the FCHJU NewBusFuel project (2015-2017)[22] showed that HRS capacities in the order of 1 to 6 ton $H_2$ per day will be required for a (mature) public bus fleet in the 50 to 250 vehicle size range; whereby a single bus would require 30 – 50 kg $H_2$ per refuelling at 350 bar pressure. A compression power usage similar to heavy-duty truck refueling is assumed[5].

Within the NewBusFuel project varying fleet refuelling patterns were found, but typically refuelling will occur in a 4 – 6 hour time window (for 10 to 40 busses), and during the evening and night when the fleet has returned to the depot. An example of a bus refuelling distribution from one of the NewBusFuel project case studies is provided in Figure 6.

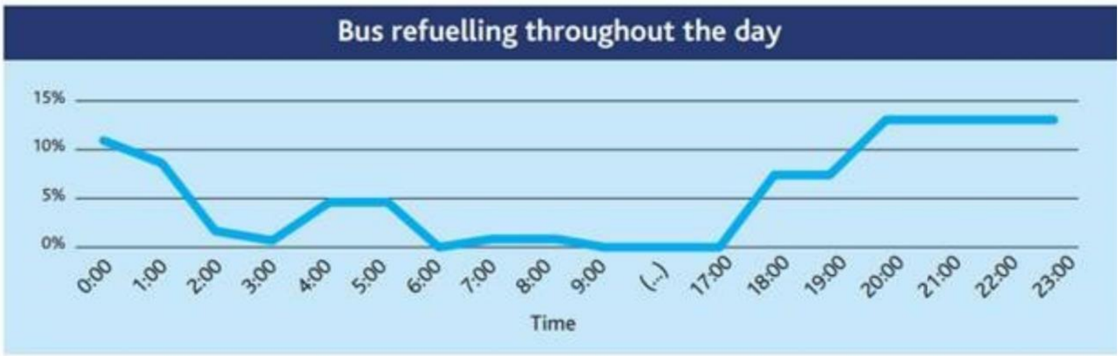

**Figure 6: Number of hydrogen fueling events per time of day. The data is based on the NewBusFuel project case studies. Source: NewBusFuel project[22]**

Mixed fleet bus depots (both FCEVs and BEVs) could be an interesting use case benefitting from the generated electricity in SOFC mode. Bus depots at the edge of a city would fuel (mid to long distance) intercity busses with hydrogen as well as charge (short distance) intra-city BEV-busses, since electric busses have a favorable total cost of operation for short distance routes.

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[5] The NewBusFuel project assumed 4 kWh/kg hydrogen to compression to 350 bar[22].

## 5.2 Industrial vehicles

Similar to fuel cell busses, industrial trucks (like forklifts and tow trucks) used in intralogistics have reached a high level of technical maturity and sizable commercial deployment. Benefits of a hydrogen fuel cell industrial trucks include low noise levels and no local emissions, which are clear benefits for indoor operation, and short refuelling durations (e.g. ca. 2 – 3 minutes)[8].

The utilization of a refuelling facility dedicated to a depot or logistical environment should be high as the fleets that are being serviced, operate within a controlled environment (versus a publicly used light- or heavy-duty refuelling station), and hydrogen demand will be predictable and managed.

Bus fleet operators, logistics providers and retailers may invest in generating their own renewable power[6]. This electricity could be used to operate a SWITCH system in SOE mode.

Reversely, bus depots and logistical environments operating such fleets are likely able to use any excess power generated (in SOFC mode), as they will have a sizable on-site electric load. Similar to above, any excess power may be used for:

- Charging of Battery Electric Vehicles (BEVs), either light-duty or heavy-duty vehicles depending on power generation capacity and existence of an in-house BEV fleet.
- Power grid balancing by becoming a supplier of power reserve.

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[6] Many examples are available for this: e.g. Amazon’s solar rooftop systems on its warehouses[24].

# 6 Operating environment 4: Hydrogen terminal

Currently most of the hydrogen refuelling stations rely on centrally produced (or imported) hydrogen, which is then transported to the various refuelling stations. Onsite hydrogen generation at a hydrogen terminal using a SWITCH system, combined with hydrogen supply routes to several nearby refuelling stations, combines the benefits of minimizing hydrogen distribution efforts (akin operating environments 1 and 2) with high utilization of the terminal, as in this supply chain the hydrogen demand profile will be more predictable (akin operating environment 3)[24].

Local distribution would typically occur using compressed hydrogen tube trailers that have capacities in the order of 500 – 1000 kg hydrogen[25, 26]. Similar to operating environment 2 and 3, any excess power generated in SOFC mode can be used to fulfil on-site electric load, BEV charging, or power grid balancing.

# 7 Usage scenarios

The objective of the SWITCH project is to realize and test an in-situ fully integrated and continuous multisource hydrogen production system, based on solid oxide cell technology. The project will explore the different operating modes required for potential use cases (cf. above) and see if the heat management and system dynamics observed, will be an attractive value proposition for future hydrogen refueling activities in different market segments. The system must be able to both efficiently generate hydrogen via water electrolysis (SOE mode), thus enabling green hydrogen production when renewable energy is available, as well as reversibly operating in fuel cell mode (i.e. SOFC). The latter allows for the use of other feedstock sources (e.g. methane, bio-methane) to produce hydrogen when renewable electricity is not economically viable or unavailable. This will allow a continuous and guaranteed production of hydrogen for contracted end users.

The SWITCH operating envelope required to meet all considered use cases is given in Figure 8 for a 1 ton/day unit, which is 10 times larger than the demo unit that will be built for the SWITCH project. The Pressure Swing Adsorber (PSA) of the SWITCH demo unit, which will purify the hydrogen to fuel cell quality, has a minimum throughput equal to 15% of its design capacity. Therefore, the demo unit operating envelope has a minimum hydrogen production capacity equal to 15% of its hydrogen production design capacity in SOE mode. This corresponds to 37.5% of its hydrogen production design capacity in SOFC mode. The commercial SWITCH system will either have more than one PSA, resulting in a lower minimum throughput limitation, or be designed with an option to bypass the PSA altogether, thus enabling a “power production only” operational mode.

The following operating points have been notionally developed (see Figure 7):

1. SOFC mode: Minimum hydrogen production and supply to the Hydrogen station; power production to provide base load electricity for the retail station.
2. SOFC mode: Partial utilization by the Hydrogen station at maximum hydrogen production capacity in SOFC mode (e.g. hydrogen storage is sufficiently filled to meet near-term expected hydrogen demand); power production to provide (base load and peak load) electricity consumption of the retail station + compression, cooling, dispenser.
3. SOFC mode: Partial utilization of the Hydrogen station at maximum SOFC capacity (e.g. hydrogen storage is sufficiently filled to meet near-term expected hydrogen demand); maximum power production.
4. SOFC mode: 50% of maximum SOFC capacity, both in hydrogen and power production.
5. SOFC mode: Minimum utilization of the Hydrogen station and full power production.
6. SOE mode: Turndown mode (assumed turndown ratio = 15%)
7. SOE mode: Full utilization of the Hydrogen station at maximum SOE capacity. Requires that sufficient (renewable) power is available and affordable.

When scaling a SWITCH system to a capacity well above 1 ton/day, operating modes 1. and 2. will not scale up in the same ratio as the hydrogen design capacity, as the power consumption of the associated retail station will remain approximately the same.

In order to enable the SWITCH system to participate in smart load control or even supply power reserve, the system must be able to switch between power consumption and power production within a relevant time scale. Renewable power intermittency due to the diurnal-cycle requires such a switch within an hour, whereas (secondary) power reserve typically needs to be available within a shorter time period, e.g. ca. 15 minutes[3].

Therefore a maximum duration of 15 minutes for the power production to power consumption switch (i.e. SOFC mode to SOE mode) will be designed for. Further, a maximum duration under 30 minutes for the power consumption to power production switch (i.e. SOE mode to SOFC mode) will be designed for.

Key technical performance aspects of the SWITCH-system enabling this operational envelope are system heat management and its transients in terms of time intervals between the different operational modes. In some cases, additional cooling of the system is required (high current density in SOFC mode), whereas additional heating may be required in high $H_2$ production mode in SOE mode.

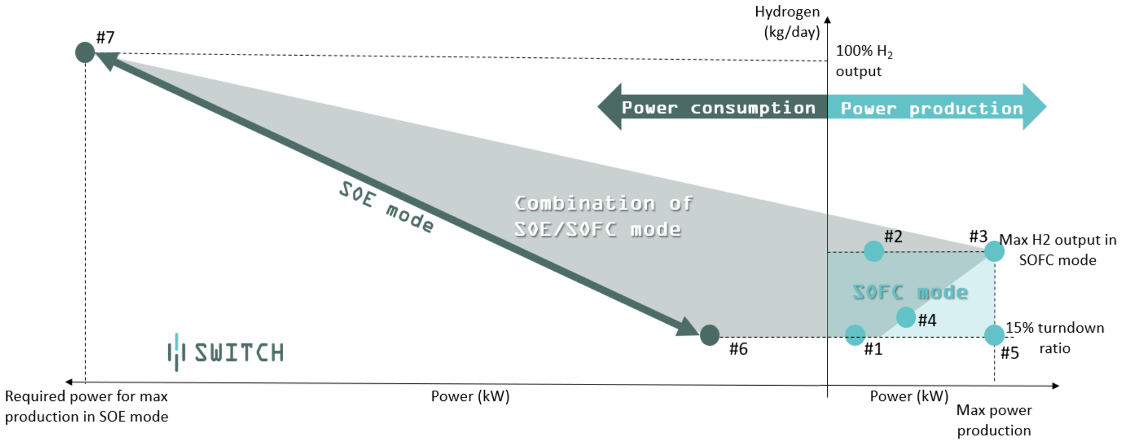

**Figure 7: Operating envelope of the (1 ton/day) SWITCH system; 7 operating modes are indicated. Note that these numbers are aspirational targets for the SWITCH-system, to be verified during this project.**

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