

Secure • Sustainable • Together

IEA Hydrogen and Fuel Cells Technology Roadmap

This is not an ADB material. The views expressed in this document are the views of the author/s and/or their organizations and do not necessarily reflect the views or policies of the Asian Development Bank, or its Board of Governors, or the governments they represent. ADB does not guarantee the accuracy and/or completeness of the material's contents, and accepts no responsibility for any direct or indirect consequence of their use or reliance, whether wholly or partially. Please feel free to contact the authors directly should you have queries.

Paving Clean and Low Carbon Energy and Transport Systems using Hydrogen and Fuel Cells

ADB Transport Forum, September 16, 2016

jacob.teter@iea.org

www.iea.org

© OECD/IEA 2015





Introduction

- the Energy Technology Perspectives Roadmap Series
- the Hydrogen and Fuel Cells Technology Roadmap

Hydrogen

- In the transport sector
- In the buildings sector
- Key findings & actions
- Questions and discussion



Hydrogen and Transport



Regional development targets

Hydrogen stations for the 2DS high H₂ Scenario in the United States, EU 4 and Japan



Note: By the end of 2015 already 100 hydrogen stations are planned to be built in Japan.

Building out a fueling infrastructure network would require consistent dedicated funding

www.iea.org

1800 kg

500 kg



Hydrogen production costs without T&D for the 2DS high H₂ Scenario



- But excess grid power could potentially become an economically viable generation pathway
- carbon taxes can improve the economics

Benefits over battery electric and plug-in hybrid vehicles Well-to-wheel emissions vs. vehicle range

Secure • Sustainable • Together



 Fuel Cell Electric Vehicles (FCEVs) can achieve a mobility service compared to today's conventional cars at potentially very low well-to-wheel carbon emissions



But *low-carbon* hydrogen pathways must be prioritized

Specific PLDV stock on-road WTW emissions by technology for the United States, EU 4 and Japan in the 2DS high H₂ Scenario



 FCEVs offer comparable carbon benefits to Plug-in Hybrid EVs but with the potential for superior performance



International Energy Agency

Secure • Sustainable • Together

Hydrogen in Buildings



Japan case study: Ene-Farm

www.iea.org

Ene-Farm fuel cell micro co-generation cumulative sales, subsidies and estimated prices, 2009-14



The price of Ene-Farm fuel cell micro co-generation systems has fallen by more than 50% since 2009.



Key findings & key actions



Passenger car stock by technology in the 2DS high H₂ Scenario



- By 2050, the share of FCEVs on total PLDV stock is set to be 25%.
- Based on the assumed large-scale and rapid deployment of hydrogen technologies in transport, the economic barriers linked to the establishment of the hydrogen infrastructure are reduced.



Low-carbon H₂ generation requires a portfolio of technologies

Hydrogen generation by technology for the 2DS high H₂ Scenario in the US, EU 4 and Japan



- Steam methane reformation using NG and coal
- Biomass gasification
- Low cost renewable electricity



CO₂ mitigation potential of FCEVs in the 2DS high H₂ Scenario

United States EU 4 Japan 1 0 0 0 400 3 000 2 500 800 300 2 000 $Mt CO_2$ 600 1 500 200 400 1 0 0 0 100 200 500 0 2010 2020 2030 2040 2050 2030 2010 2020 2030 2040 2050 2010 2020 2040 2050 Other road avoid/shift/improve Other transport avoid/shift/improve FCEV

- The contribution of FCEVs to cumulative total transport CO₂ emission reductions between now and 2050 accounts for between 7% (United States) and 10% (Japan).
- Between now and 2050, almost 3 GtCO₂ are saved by FCEVs in these regions.



Direct subsidies for FCEV roll-out in the 2DS high H₂ Scenario

United States EU 4 Japan Share of direct FCEV subsidy on 80% 80% 80% petroleum tax income 60% 60% 60 60 60% Million vehicles Thousand USD 40% 40 40% 40% 20% 20% 20 20 20% 20 0% 0% 0% 2040 2020 2030 2050 20102050 2010 2020 2030 2040 2010 2020 2030 2040 2050 -20% - 20 - 20 -20% - 20 -20% Subsidy per vehicle sold Annual share of subsidy on petroleum tax income FCEV stock

- With rapid market uptake and fuel tax exemption of hydrogen, FCEVs could be entirely cost competitive 15 to 20 years after market introduction
- Until 2035, around USD 90 billion would need to be spent to achieve parity of costs of FCEVs with high efficient gasoline PLDVs, and to bring on the road 30 million FCEVs in the United States, EU 4 and Japan.



Key near-term policy actions

Secure • Sustainable • Together

20	15 2020 Transport 2023	5
Fuel economy and low emission vehicle policies	Establish and strengthen fuel economy regulation and incentivise efficient vehicles through monetary measures like feebate schemes and CO ₂ based vehicle taxation. Support the uptake of FCEVs through zero-emission-vehicle policies	
Low carbon/ renewable fuel regulation	Incentivise the uptake of hydrogen as transport fuel through low carbon, sustainable fuel mandates	
Vehicle "perks" and consumer information	Introduce the free use of public parking, the use of high occupancy vehicle (HOV) lanes, the use of bus lanes and the exemption from road tolls. Establish labelling schemes	
Carbon pricing	Establish national, regional or international carbon pricing schemes.	
Grid integration measures and easy grid access	Incentivise VRE operators to adopt grid integration measures. Facilitate entry into energy markets for energy storage technologies including power-to-fuel, power-to-power and power-to-gas	
Benefits stacking	Enable benefit-stacking for energy storage systems	
Codes and standards: safety, metering, type approval	Strengthen and harmonise international codes and standards necessary for safe and reliable handling and metering of hydrogen in end-use applications and establish a performance-based global technical regulation for FCEV type approval	
Natural gas- hydrogen blend shares	Where necessary, establish natural gas-hydrogen blend quality and safety regulation	



International Energy Agency

Secure • Sustainable • Together

Thanks!



Technology development: longer-term target setting

20	15	2	020		2025		2030		2035
		1 1				1 1		1.1	
PEM electrolysers	Reduce cost to USD 800 per kM MW scale and achieve ramp-up	, increase efficiency to more rates to comply with the priv	than 80% (HHV), increa mary control power mar	se lifetime to at least 80 000 ket) hours, increase stack capacity to	multiple MW, increase total syste	m capacity to the 100		
Alkaline electrolyser	Reduce investment cost to beic increase operational flexibility	w USD 900 per kW, increase through reduction in minima	efficiency to more than 2 I load and increase oper	75% (HHV), increase current ating pressure	t density through higher operating) temperature and pressure, redu	uce O&M costs,		
SOEC	Prove commercial scale, increa	e lifetime to at least 20 000 i	hours at degradation rat	es below 8% per year and a	chieve a minimum operational flex	ibility to respond to future powe	er market requirements		
PEM FC mobile	Reduce real-world manufacturi least 5 000 hours. Reduce sens	ng costs to below USD 80 per tivity to hydrogen impurities	r kW through optimised i.	manufacturing and reduced	d need for precious metal, while ke	eping lifetime to at			
PEM FC stationary	Reduce investment cost to bein impurities and prove feasibility	w USD 800 per kW by reduci at large stack capacities. Ach	ng both the cost of the s nieve megawatt scale.	tack and the cost of balance	a of plant. Increase system efficient	ies to at least 50%. Increase lifet	lime to above 50 000 hours. Reduce s	ensitivity to hydrogen	
FCEVs	Achieve a price premium of 15 of the hydrogen tank and redu	% or less compared to hybrid ce specific costs to at least be	ised ICE vehicles at high low USD 15 per kWh. Ac	er volume annual productio hieve an on-road fuel efficie	n rates. Reduce the volume and th incy of 0.8 kg of hydrogen per 100	e weight km			
H ₂ stations	Define optimal hydrogen statio Design user-friendly and stand	n layout. Define standardised ardised dispensers. Reduce in	d refuelling pressures. Co westment costs to below	onsider proposals for modul USD-1 million for small stat	lar or mobile hydrogen stations. Re tions dispensing in the region of 2	educe station area footprint. 00 kg of hydrogen per day		Transp	ort
CCS	Raise the number of operating storage exploration and character	SMRs equipped with large-sc terisation, and development	ale CO, capture (e.g. 10 of CO, storage resources	0 000 tonnes of CO ₂ per yea in countries where hydrog	r [tCO ₃ /yr] and above) to five worl en production from fossil fuels wit	dwide. Implement policies that on https://www.commonscience.com/ h CCS is a cost-effective option	encourage	Station	ary
Data	Develop integrated modelling	tools to investigate the benef	its of hydrogen use and	energy system integration					

- Electrolysers & Fuel cells
- T&D infrastructure (including H₂ stations)
- Carbon Capture and Sequestration



International Energy Agency

Secure • Sustainable • Together

Supplemental Slides



Secure • Sustainable • Together

Hydrogen and fuel cells in transport



Carbon Intensity – GHG emissions

Today's carbon footprint for various hydrogen pathways and for gasoline and compressed natural gas in the European Union



 Tradeoffs between production, distribution, and storage costs, production capacity, and emissions

International Energy Agency Hydrogen T&D technologies for hydrogen delivery in the transport sector Secure • Sustainable • Together www.iea.ora



iea



Scheme of hydrogen T&D and retail infrastructure as represented within the model



Distribution and storage technologies, current status

Current performance of hydrogen systems in the transport sector

Application	Power or energy capacity	Energy efficiency*	Investment cost**	Lifetime	Maturity
Fuel cell vehicles	80 - 120 kW	Tank-to-wheel efficiency 43-60% (HHV)	USD 60 000- 100 000	150 000 km	Early market introduction
Hydrogen retail stations	200 kg/day	~80%, incl. compression to 70 MPa	USD 1.5 million- 2.5 million	-	Early market introduction
Tube trailer (gaseous) for hydrogen delivery	Up to 1 000 kg	~100% (without compression)	USD 1 000 000 (USD 1 000 per kg payload)	-	Mature
Liquid tankers for hydrogen delivery	Up to 4 000 kg	Boil-off stream: 0.3% loss per day	USD 750 000	-	Mature

* Unless otherwise stated, efficiencies are based on lower heating values (LHV).

** All power-specific investment costs refer to the energy output.

Notes: HHV = higher heating value; kg = kilogram; kW = kilowatt.

Investments needed to reduce costs and improve performance



Infrastructure – current status

www.iea.org

Existing public hydrogen refuelling stations and targets announced by hydrogen initiatives

c		Planned	stations
Country or region	Existing hydrogen refuelling stations	2015	2020
Europe	36	~80	~430
Japan	21	100	>100
Korea	13	43	200
United States	9	>50	>100

Existing FCEV fleet and targets announced by hydrogen initiatives

	Dunning FCEV/c	Planned FCEV	/s on the road
Country or region	KUNNING FCEVS	2015	2020
Europe	192	5 000	~350 000
Japan	102	1 000	100 000
Korea	100	5 000	50 000
United States	146	~300	~20 000

Refueling and vehicle infrastructure are already emerging in key regions



How much will it cost? H₂ refueling station – cash flow curve



- Due to high costs and under-utilisation of the hydrogen refueling infrastructure, the "valley of death" can last for 10 to 15 years.
- Small and clustered stations are needed to minimize the time of negative cash flow.



www.iea.org

Supplemental Slides - Summary

- Techno-economic assumptions and parameters
- Hydrogen and fuel cells for variable renewable energy integration
- Hydrogen and fuel cells in industry and buildings



H₂ in industry and buildings



Current performance of fuel cell systems in the buildings sector

www.iea.org

Application	Power or energy capacity	Energy efficiency *	Investment cost**	Life time	Maturity
Fuel cell micro co-generation	0.3-25 kW	Electric: 35-50% (HHV)	<20 000 USD/kW (home system, 1 kW _e)	60 000- 90 000	Early market introduction
		Co-generation: up to 95%	<10 000 USD/kW (commercial system, 25 kW _e)	hours	

* = Unless otherwise stated efficiencies are based on LHV.

** = All investment costs refer to the energy output.

Notes: 1 kW_e = kilowatt electric output.

- Fuel cell micro co-generation systems are either based on a PEMFC or a solid oxide fuel cell (SOFC), the latter providing much higher temperature heat.
- Although systems with up to 50 kW electrical output exist, most commercially available systems have electrical power outputs of around 1 kW, therefore being insufficient to fully supply the average US or European dwelling.

Why Hydrogen?

Secure • Sustainable • Together

iea

International Energy Agency



- Hydrogen is a flexible energy carrier that can be produced from any regionally prevalent primary energy source
- Hydrogen can be effectively transformed into any form of energy for diverse end-use applications



split water into H2 and O2 with *electrolysers* Used as energy carrier, hydrogen can be efficiently transformed to electricity using *fuel cells*



H₂ based "power-to-x" trajectories

Power-to-power



- Hydrogen based electricity storage applications can include power-to-power, power-to-gas and power-to-fuel trajectories.
- Round trip efficiencies are low the availability of low value, surplus renewable electricity is a prerequisite for H₂ based electricity storage



Techno-economic assumptions & parameters



How much will it cost? Learning curves and cost targets

Production costs decline with annual production



 Although current PEMFC systems for FCEVs cost around USD 300 to USD 500 per kW, cost can be reduced dramatically with economies of scale.



Current and future costs based on learning curves

Cost of PLDVs by technology as computed in the model for the United States

	Today	2030	2050	Unit
Conventional ICE gasoline	28 600	30 900	32 300	USD
Conventional ICE diesel	29 300	31 700	33 100	USD
Hybrid gasoline	30 000	31 800	33 200	USD
Plug-in hybrid gasoline	32 400	33 200	34 400	USD
BEV (150 km)	35 400	32 800	34 000	USD
FCEV	60 000	33 600	33 400	USD

Techno-economic parameters of FCEVs as computed in the model for the United States

	Today	2030	2050	Unit
FCEV costs	60 000	33 600	33 400	USD
Thereof				
Glider*	23 100	24 100	25 600	USD
Fuel cell system**	30 200	4 300	3 200	USD
H ₂ tank**	4 300	3 100	2 800	USD
Battery**	600	460	260	USD
Electric motor and power control**	1 800	1 600	1 400	USD
Specific costs				
Fuel cell system (80 kW)	380	54	40	USD/kW
$H_2 \text{ tank } (6.5 \text{ kg } H_2)$	20	14	13	USD/kWh
Battery (1.3 kWh)	460	350	200	USD/kW
Other parameters				
Tested fuel economy	1.0	0.8	0.6	Kg H ₂ /100 km
Life time	12	12	12	Years

* future cost increase is due to light-weighting, improved aerodynamics, low resistance tyres and high efficient auxiliary devices.

** future costs are based on learning curves with learning rates of 10% (H₂ tank), 15% (electric motor, power control, battery) and 20% (fuel cell system) per doubling of cumulative deployment.



Secure • Sustainable • Together

Hydrogen and fuel cells for variable renewable energy integration



Current performance of H₂ generation technologies

www.iea.org

Application	Power or capacity	Ffficiency*	Initial investment cost	Life time	Maturity
Steam methane reformer, large scale	150-300 MW	70-85%	400-600 USD/kW	30 years	Mature
Steam methane reformer, small scale	0.15-15 MW	~51%	3 000-5 000 USD/kW	15 years	Demon- stration
Alkaline electrolyser	Up to 150 MW	65-82% (HHV)	850-1 500 USD/kW	60 000- 90 000 hours	Mature
PEM electrolyser	Up to 150 kW (stacks) Up to 1 MW (systems)	65-78% (HHV)	1 500-3 800 USD/kW	20 000- 60 000 hours	Early market
SO electrolyser	Lab scale	85-90% (HHV)	-	~1 000 h	R&D

* = Unless otherwise stated efficiencies are based on LHV.

** = All investment costs refer to the energy output.

Notes: PEM = proton exchange membrane; SO = solid oxide.

Around 48% of hydrogen is currently produced from natural gas using the SMR process

Deployment potential of different International **Energy Agency** electrolyser technologies Secure • Sustainable • Together www.iea.ora



Note: A/cm^2 = ampere per square centimetre.

162

Although alkaline electrolysers are a mature and affordable technology, PEM and SO electrolysers show a greater potential to reduce capital costs and to increase efficiency.



H₂ conversion – fuel cells

www.iea.org

Production volumes of fuel cells according to application



 Currently, more than 80% of all fuel cells sold are used in stationary applications.

The economics of renewable hydrogen

Secure • Sustainable • Together

International

www.iea.org



 Low-carbon electrolytic hydrogen requires low-cost renewable electricity and a combination of higher natural gas and carbon prices to be cost competitive.



Variable renewable power in the 2DS



Electricity storage potential in the 2DS

Secure • Sustainable • Together

162

International Energy Agency



- Under the 2DS, electricity storage accounts for up to 8% of total installed power capacity.
- Annual electricity output from energy storage reaches shares of between 3% and 9% of total VRE power generation.

Hydrogen-based electricity storage

Secure • Sustainable • Together

iea

International Energy Agency

www.iea.org



Note: CAES = compressed air energy storage; PHS = pumped hydro energy storage.

Hydrogen-based electricity storage covers large-scale and long-term storage applications.

Energy Agency Hydrogen-based large-scale energy storage

Secure • Sustainable • Together

lea

www.iea.org

Application	Power or energy capacity	Energy efficiency*	Lifetime	Maturity	
Power-to-power (including underground storage)	GWh to TWh	29% (HHV, with alkaline EL) - 33% (HHV, with PEM EL)	1 900 (with alkaline EL) - 6 300 USD/kW (with PEM EL) plus ~8 USD/kWh for storage	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration
Underground storage	GWh to TWh	90-95%, incl. com-pression	~8 USD/kWh	30 years	Demonstration
Power-to-gas (hydrogen- enriched natural gas, HENG)	GWh to TWh	~73% excl. gas turbine (HHV) ~26% incl. gas turbine (PtP)	 1 500 (with alkaline EL) - 3 000 USD/kW (with PEM EL), excl. gas turbine 2 400 (with alkaline EL) - 4 000 USD/kW (with PEM EL), incl. gas turbine (PtP) 	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration
Power-to-gas (methanation)	GWh to TWh	~58% excl. gas turbine (HHV) ~21% incl. gas turbine (PtP)	 2 600 (with alkaline EL) - 4 100 USD/kW (with PEM EL), excl. gas turbine 3 500 (with alkaline EL) - 5 000 USD/kW (with PEM EL), incl. gas turbine (PtP) 	20 000 to 60 000 hours (stack lifetime electrolyser)	Demonstration

* = Unless otherwise stated, efficiencies are based on LHV.

** = All investment costs refer to the energy output.

Notes: excl. = excluding; incl. = including; PtP = power-to-power; GWh = gigawatt hour; TWh = terawatt hour.

Abatement costs of hydrogen based variable renewable energy integration



In the long term, power-to-fuel applications offer the lowest marginal abatement costs to integrate otherwise curtailed renewable power in the energy system.



Characteristics of geological formations suitable for hydrogen storage

www.iea.org

	Salt caverns	Depleted oil fields	Depleted gas fields	Aquifers	Lined rock caverns	Unlined rock caverns
Safety	++	+	-	-	-	-
Technical feasibility	+	++	++	++	о	-
Investment costs	++	О	О	О	+	+
Operation costs	++	-	0	+	++	+

Source: adapted from HyUnder (2013), Assessment of the Potential, the Actors and Relevant Business Cases for Large Scale and Seasonal Storage of Renewable Electricity by Hydrogen Underground Storage in Europe - Benchmarking of Selected Storage Options.

A geological formation can be suitable for hydrogen storage if:

- tightness is assured,
- the pollution of the hydrogen gas through bacteria or organic and nonorganic compounds is minimal, and
- the development of storage and the borehole is possible at acceptable costs.
- Actual availability of suitable geological formations is another limiting factor.



Limitations on the blend share of hydrogen by application

70% 60% 50%																			··· ·						,		••••			<i></i>				Further research needed
40% 30% 20% 10%			···· ···· ····	••••••••••••••••••••••••••••••••••••••	· · · · · · · · · · · · · · · · · · ·		•••• • • • • • • • • • • • • • • • • •			•••••	 					13		••• ••• ••• ••• •••							·		· · · · · · · · · · · · · · · · · · ·			111 <i>11</i> 11111 11111		• • • • • • •		Adjustment & modification needed
0%	Transmission pipelines	Gas turbines	Compression stations	Cavern storages	Pore storages	Tanks	Storage installations	Steel pipelines	Plastic pipelines		Seals	Connections	Las riow detectors	Valves	House installation	Ultrasonic meters	Turbine meters	Diaphragm meters	Quantity transformers	Gas chromatographs	Pressure regulation		Odorisation	Engines	CNG tanks	Gas burners	Fan burners	Condensing boilers	Fuel cells		Stirling motor	Gas stoves	Co-generation plants	H2 blending uncritical
	Tra	nsp	ort		Stor	age				D	istri	buti	on			N	/leas	urin	g ar	nd c	onti	rol					Ap	plia	nce	s				

Blending hydrogen into the natural gas grid faces several limitations:

- H₂ can embrittle steel materials (pipelines & pipeline armatures), which necessitates upper blending limits of around 20% to 30%, depending on the pipeline pressure and regional specification of steel quality.
- The much lower volumetric energy density of hydrogen compared to natural gas significantly reduces both the energy capacity and efficiency of the natural gas T&D system at higher blend shares.



Secure • Sustainable • Together

Hydrogen and fuel cells in industry and buildings



Techno-economic parameters

www.iea.org

The Roadmap is a rich source of technoaround the worl from leading parameters hydrogen researchers economic

Application	Power or capacity	Efficiency *	Initial investment cost	Life time	Maturity
Alkaline FC	Up to 250 kW	~50% (HHV)	USD 200-700/kW	5 000-8 000 hours	Early market
PEMFC stationary	0.5-400 kW	32%-49% (HHV)	USD 3 000-4 000/kW	~60 000 hours	Early market
PEMFC mobile	80-100 kW	Up to 60% (HHV)	USD ~500/kW	<5 000 hours	Early market
SOFC	Up to 200 kW	50%-70% (HHV)	USD 3 000-4 000/kW	Up to 90 000 hours	Demon- stration
PAFC	Up to 11 MW	30%-40% (HHV)	USD 4 000-5 000/kW	30 000- 60 000 hours	Mature
MCFC	KW to several MW	More than 60% (HHV)	USD 4 000-6 000/kW	20 000- 30 000 hours	Early market
Compressor, 18 MPa		88%-95%	USD ~70 /kWH ₂	20 years	Mature
Compressor, 70 MPa	-	80%-91%	USD 200-400/kWH ₂	20 years	Early market
Liquefier	15-80 MW	~70%	USD 900-2 000/kW	30 years	Mature
FCEV on-board storage tank, 70 MPa	5 to 6 kg H_2	Almost 100% (without compression)	USD 33-17/kWh (10 000 and 500 000 units produced per year)	15 years	Early market
Pressurised tank	0.1-10 MWh	Almost 100% (without compression)	USD 6 000-10 000/MWh	20 years	Mature
Liquid storage	0.1-100 GWh	Boil-off stream: 0.3% loss per day	USD 800-10 000/MWh	20 years	Mature
Pipeline	-	95%, incl. compression	Rural: USD 300 000- 1.2 million/km Urban: USD 700 000-1.5 million /km (dependent on diameter)	40 years	Mature

* = Unless otherwise stated efficiencies are based on LHV.

** = All investment costs refer to the energy output.



IEA Technology Roadmap Series https://www.iea.org/roadmaps/





Con martin

Technology Roadman

Technology Roadmap

(JNEA





Technology Roadmap

Technology Roadmag

Technology Roadmap



Technology Roadmap

Technology Roadmap

Technology Roadmap























Technology Roadn Nuclear Energy





Technology Roadmap

Hydrogen and Fuel Cells

















Technology Roadma