Discussion - Hydrogen roadmap preliminary results
&
Milestones and key actions

Alex Körner
International Energy Agency
alexander.koerner@iea.org

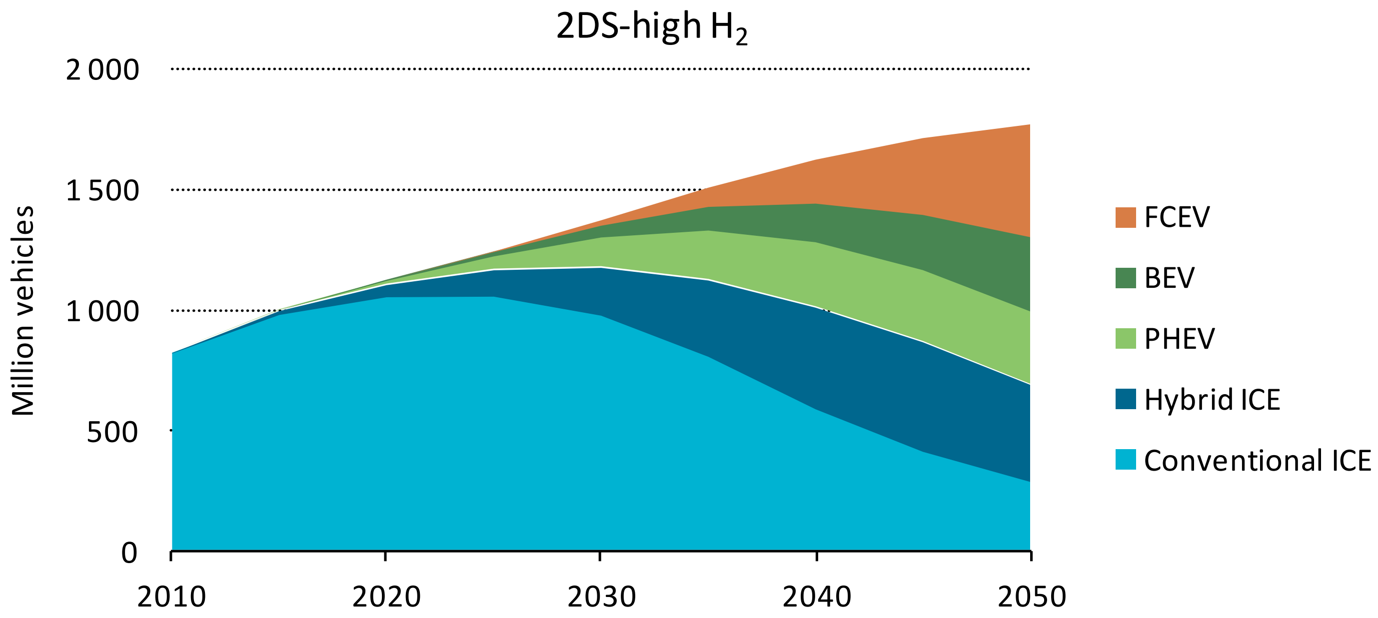
Aim of this session

- Explain and discuss preliminary roadmap results for
  - Transport
  - Energy storage and flexibility options
- Discuss proposed milestones and key actions
- Next steps

Transport – Preliminary results

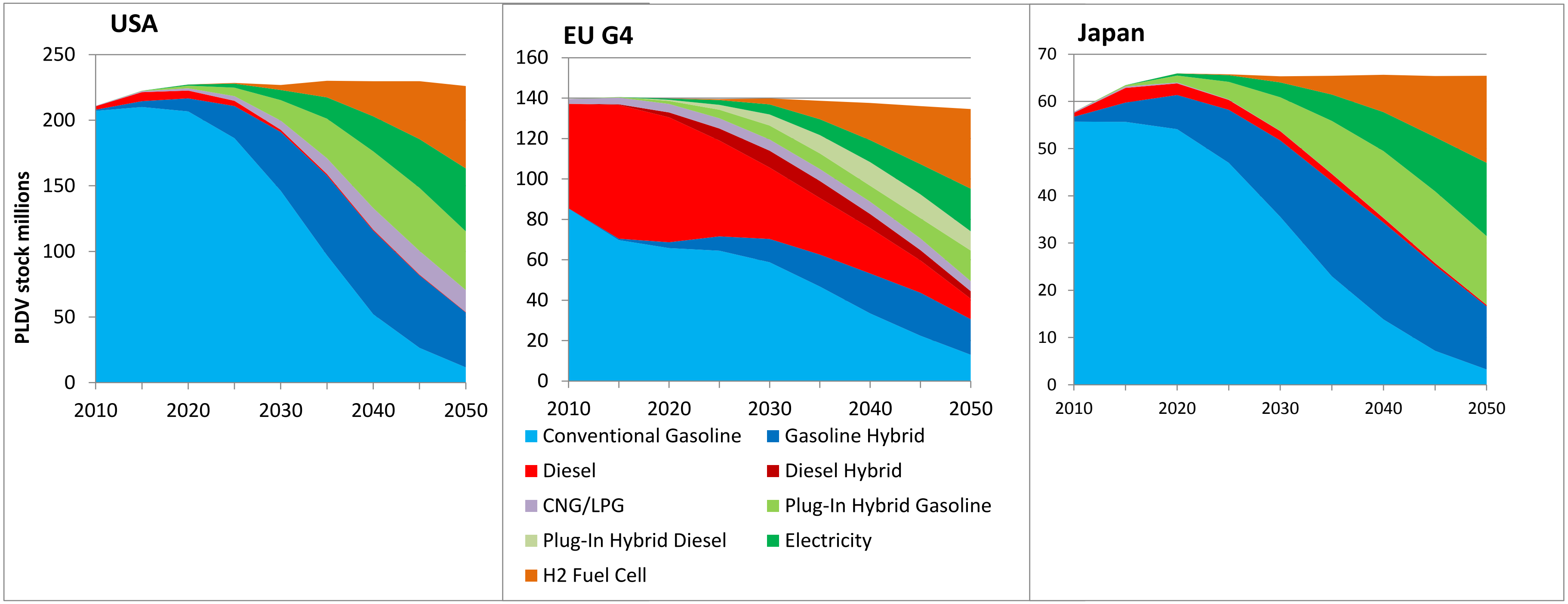
Vision – Transport

- **What if 25% of all PLDVs are FCEVs by 2050?**
  - **Discussion of vehicle sales**
  - **Discussion of fuel use and emission reduction potential**
  - **Examination of costs and benefits**
  - **Focus: Infrastructure requirements and costs**



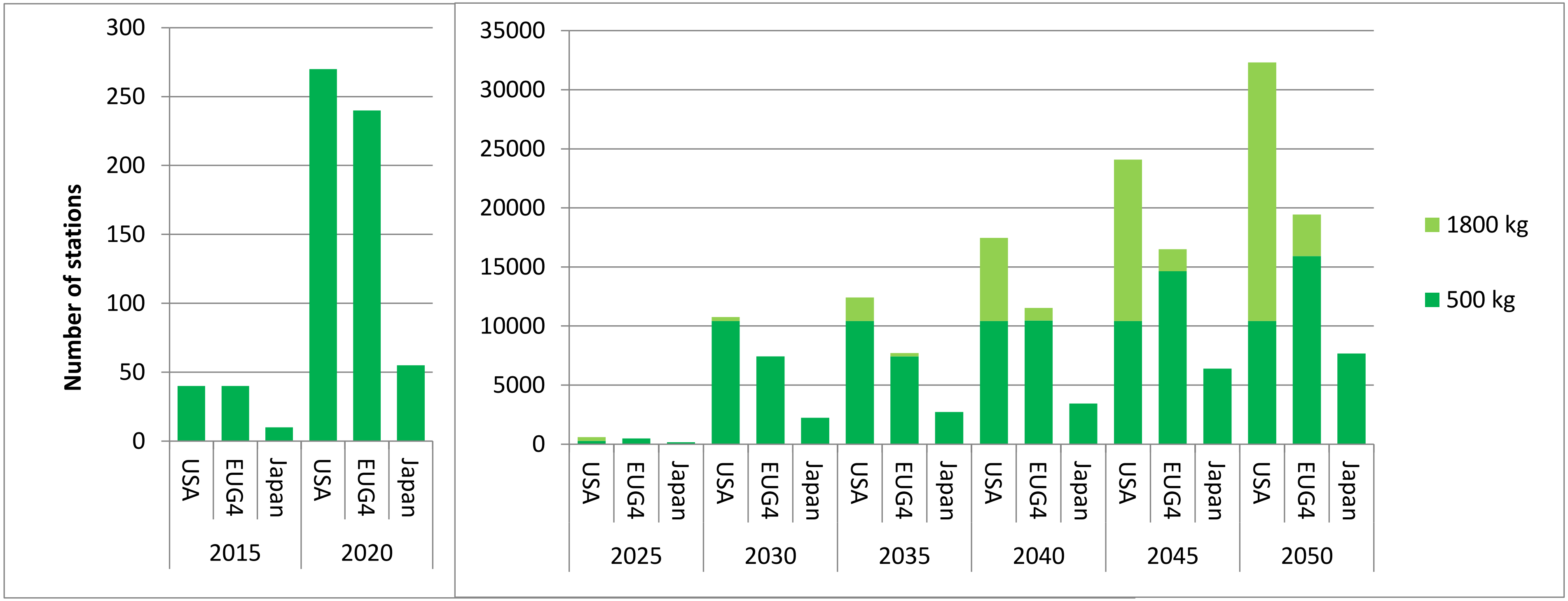
PLDV stock by region 2DS High H_2

International Energy Agency



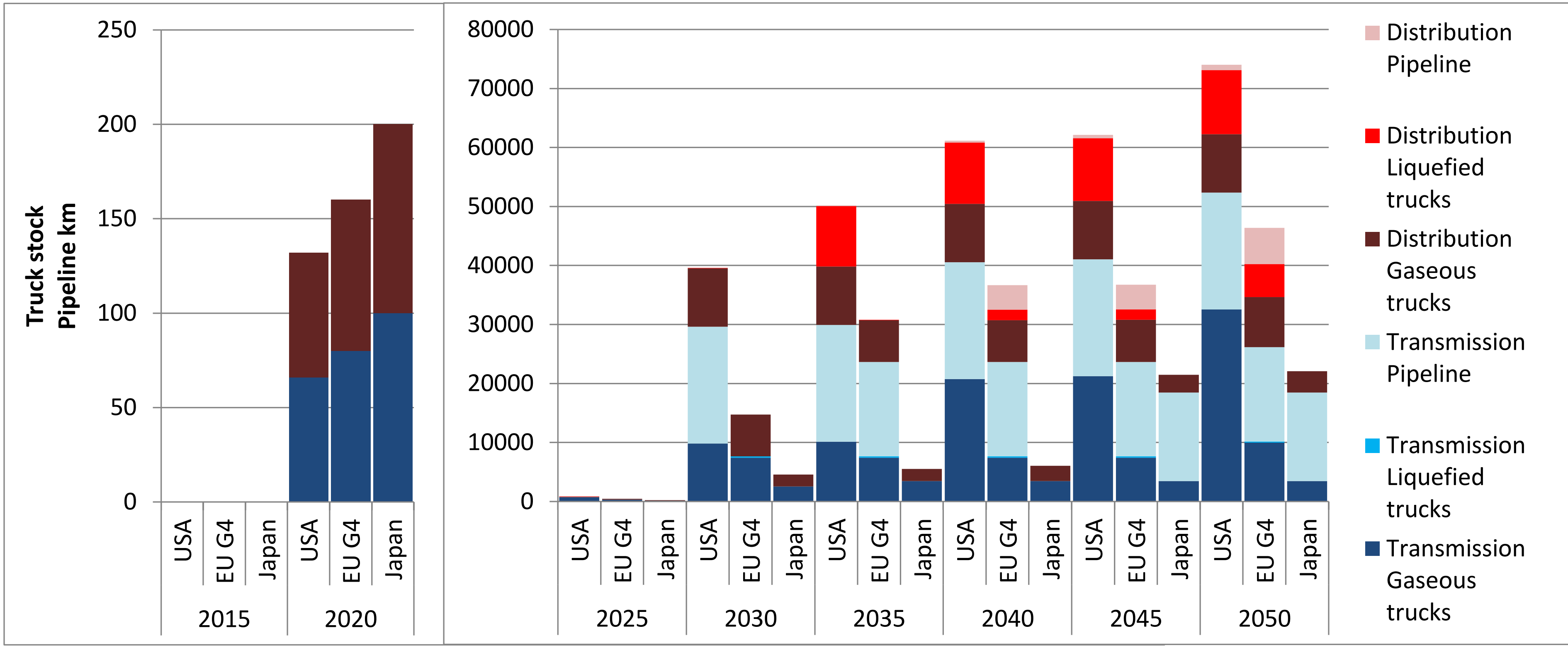
- **The PLDV stock over time shows significant regional differences**
- **EUG4 includes France, Germany, Italy and the United Kingdom**

Results – Hydrogen station infrastructure



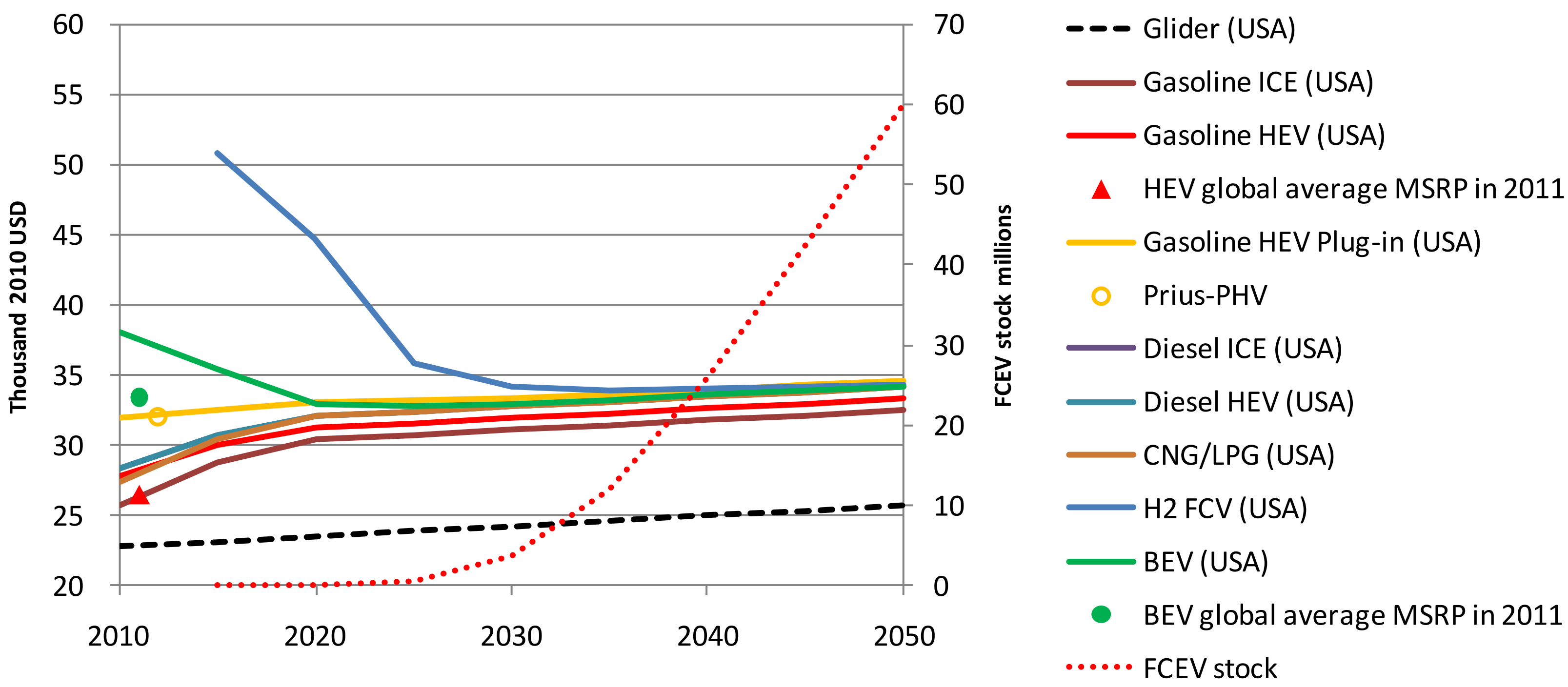
- **High spatial coverage creates demand for relatively small stations**
- **Smaller stations need to be built during FCEV roll-out**

Hydrogen T&D infrastructure



- **Transmission infrastructure requirements are very sensitive to assumptions on average transmission distance between point of H2 production and demand**

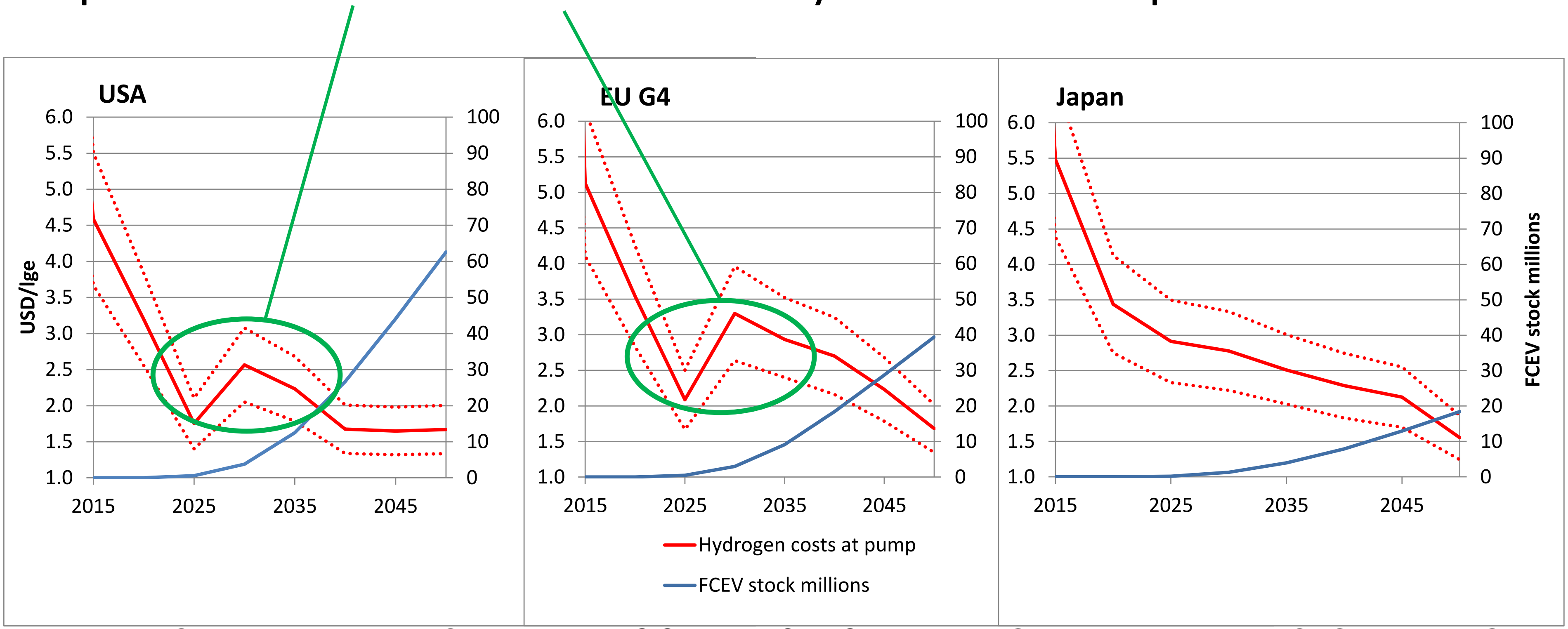
Fuel cell electric vehicle costs



- **FCEV costs drop quickly with sales if envisaged FC stack production costs can be achieved**

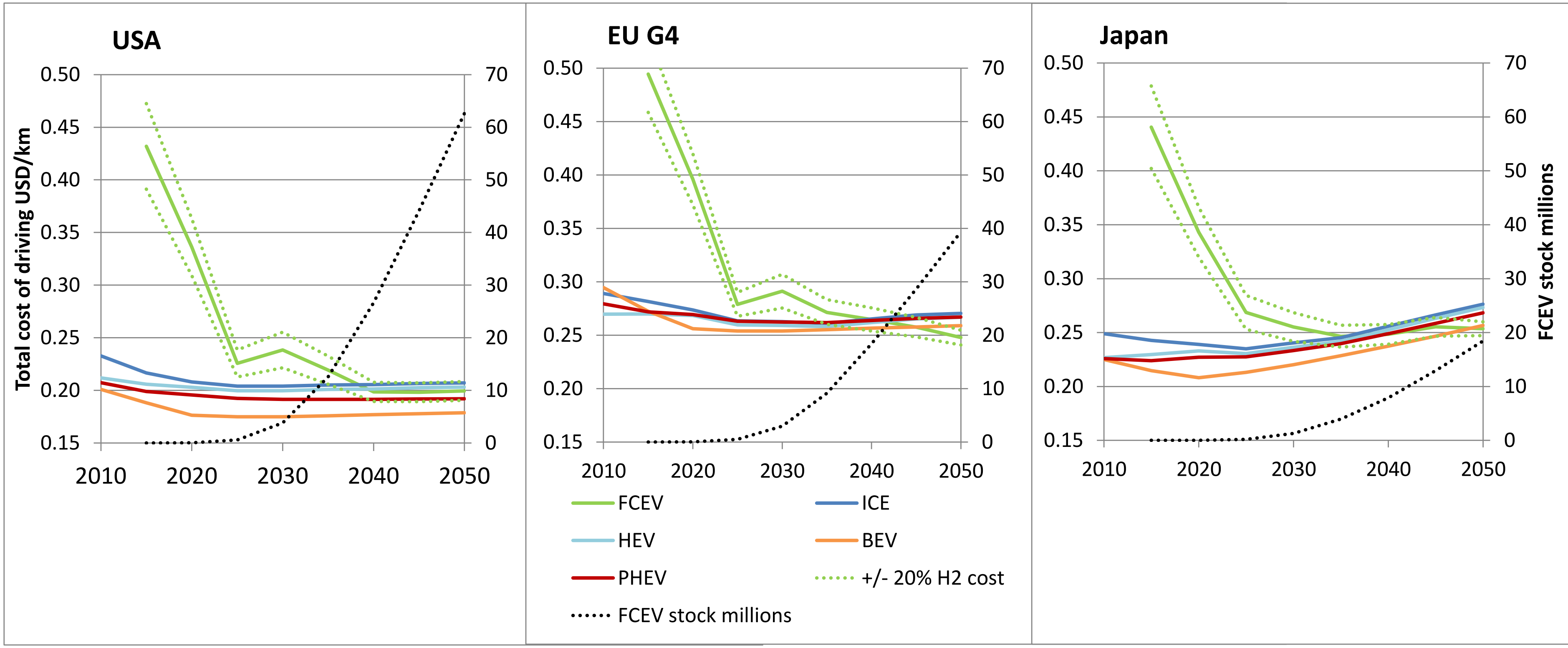
Hydrogen costs at the pump by region

Expansion of the H2 T&D and retail infrastructure beyond clusters induces uptake of H2 delivered costs



- **Hydrogen cost drop quickly with clustered stations and demand focused on big urban areas**
- **With higher spatial coverage and increasing size of the station, utilization rates might see another minimum in the medium term**
- **Japan offers unique opportunities due to high population density**

Total cost of driving



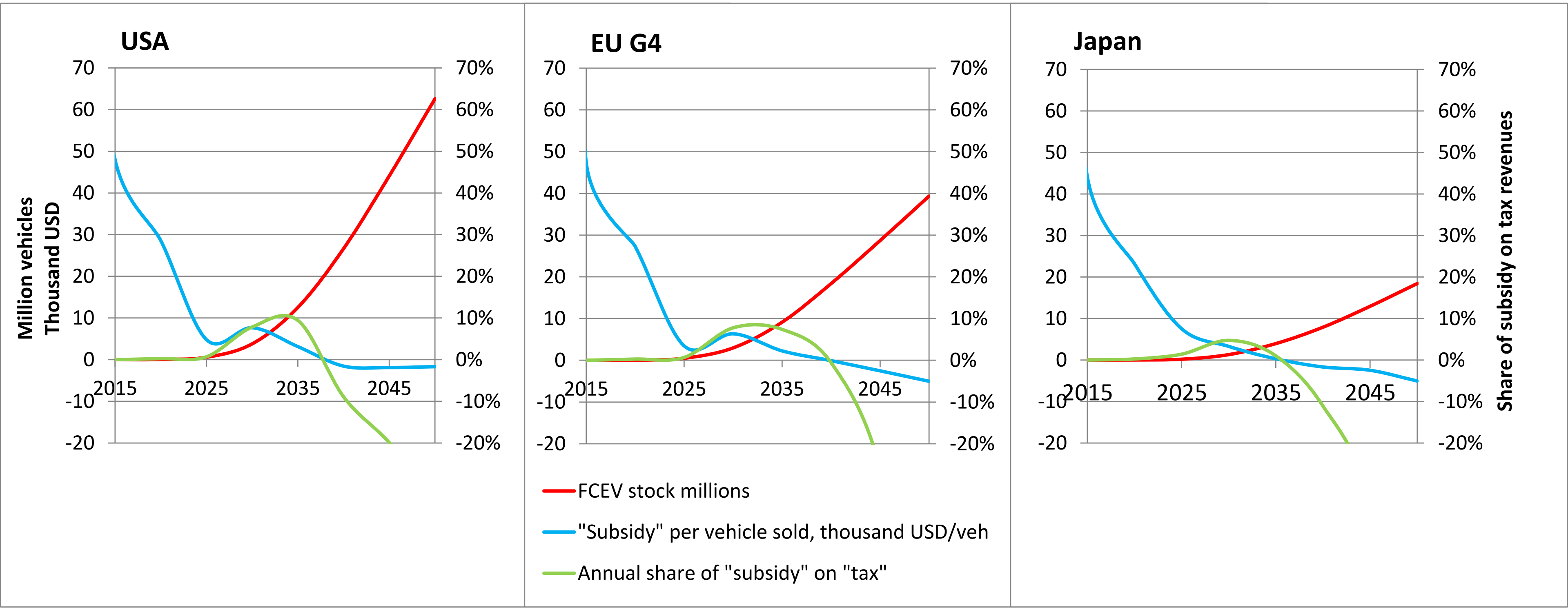
- **Total cost of driving (TCD) drop slower due to H2 generation and T&D cost, expanding the T&D and retail infrastructure beyond biggest urban areas to allow for significant FCEV market penetration provokes stagnation of total costs of driving in the medium term**
- **20% variation of hydrogen costs changes break even by +/- 5 years**
- **Based on TCD "economic gap" analysis can be conducted**

Subsidy as share of petroleum tax income

Assumptions ”petroleum fuel tax”:
US: 50%

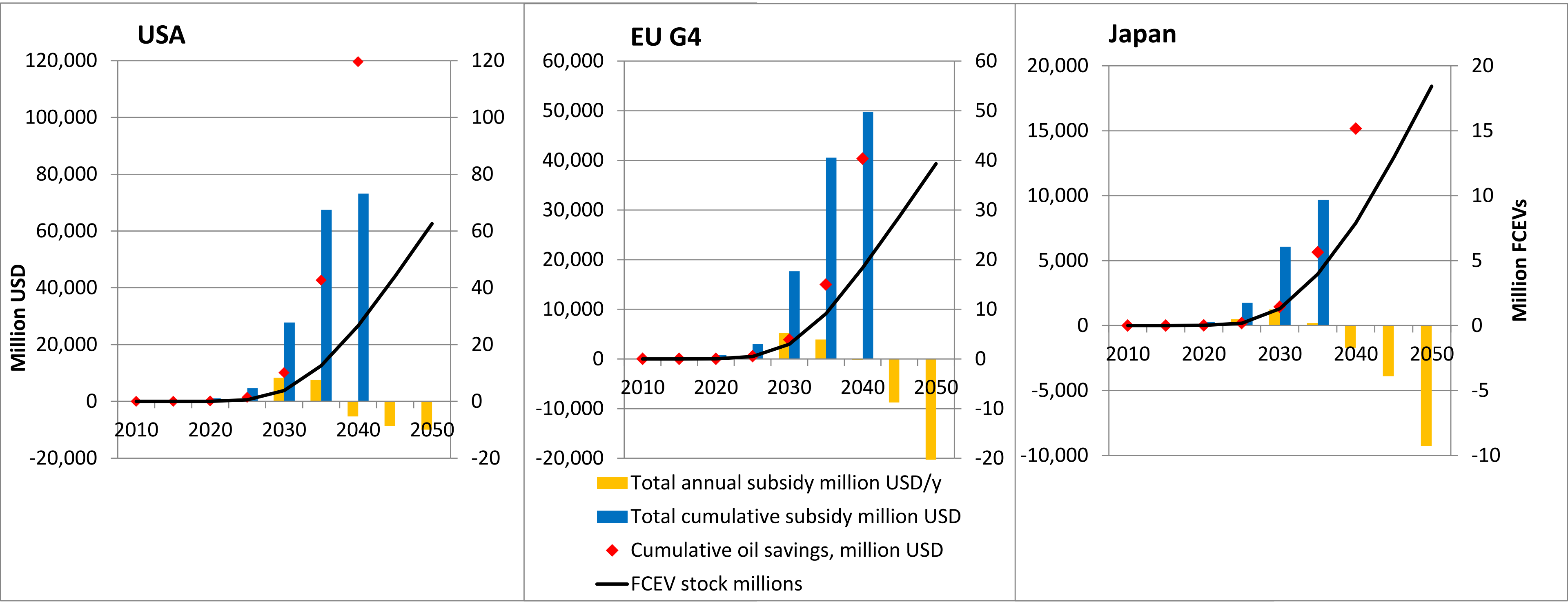
EU: 125%

Japan: 120%



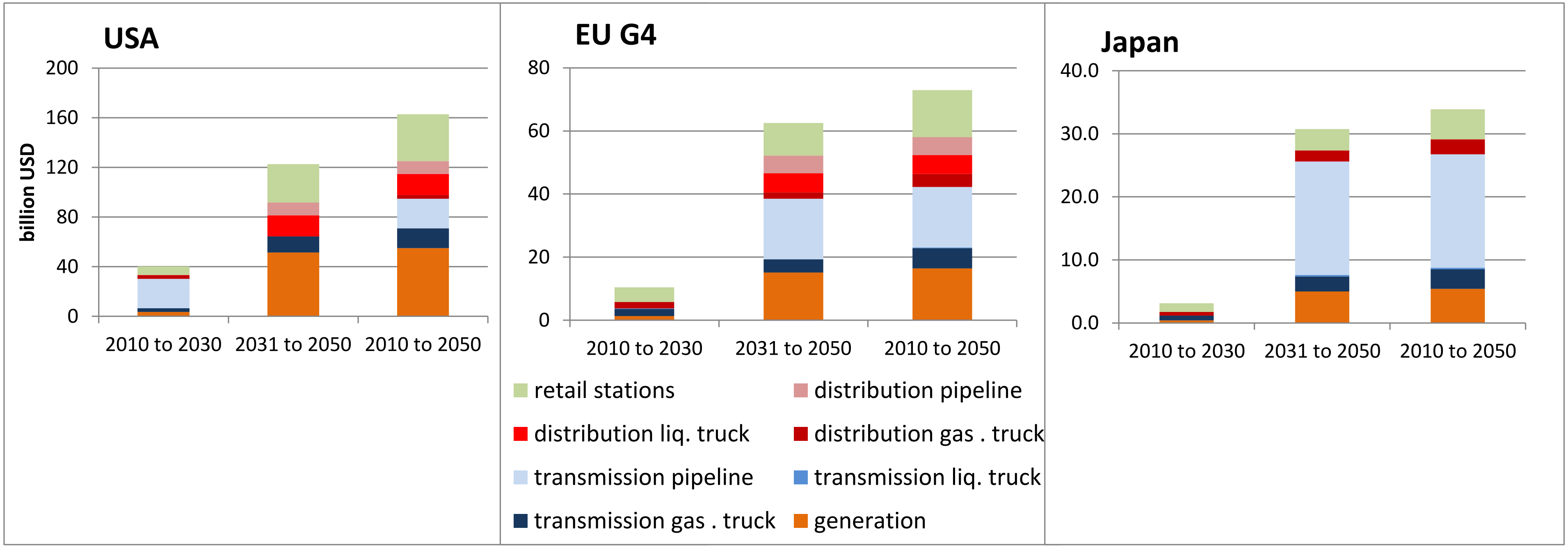
- Differences in regional taxation, vehicle size and fuel economy as well as annual mileage significantly affect total costs of driving and resulting subsidy needs to achieve breakeven with conventional ICE vehicles

Total subsidy need



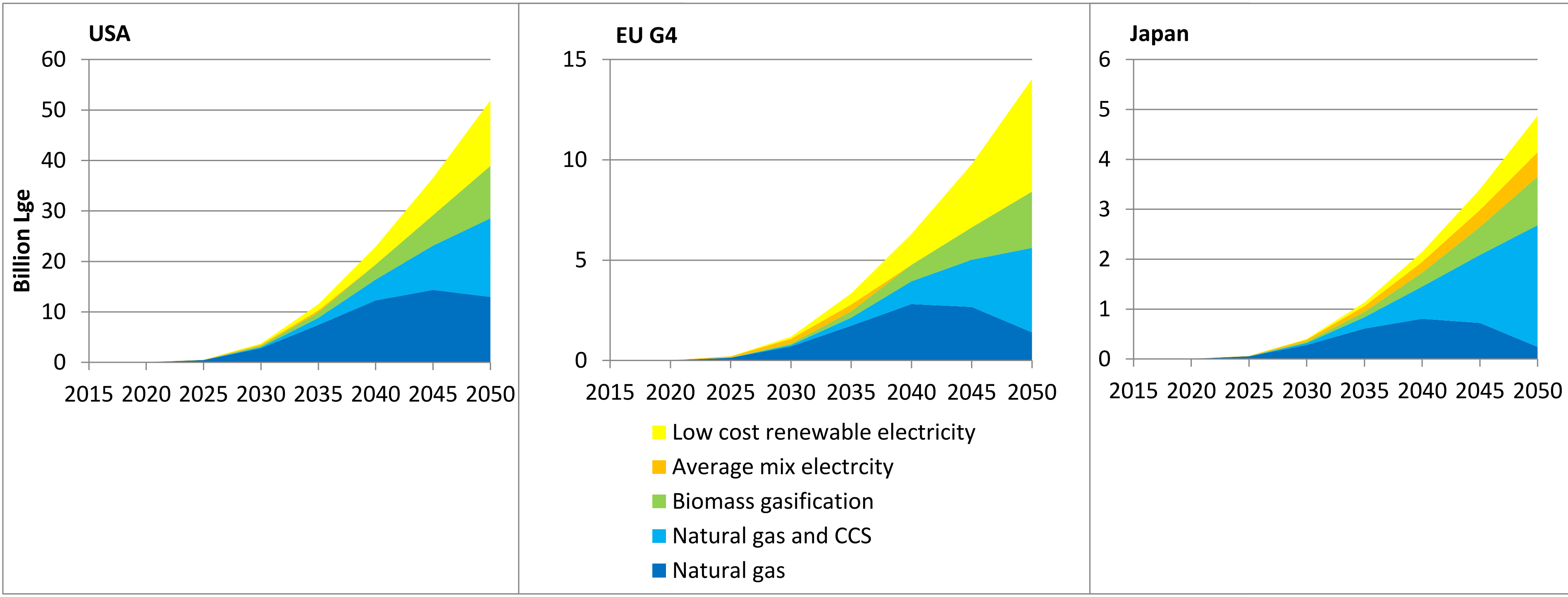
- Total subsidy needed is based on a breakeven of total cost of driving with conventional ICE vehicles
- When FCEVs reach breakeven with conventional ICEs, subsidies are completely or almost outweighed by saved oil expenditures
- When subsidies are phased out H2 needs to be taxed

Cumulative H_2 infrastructure costs



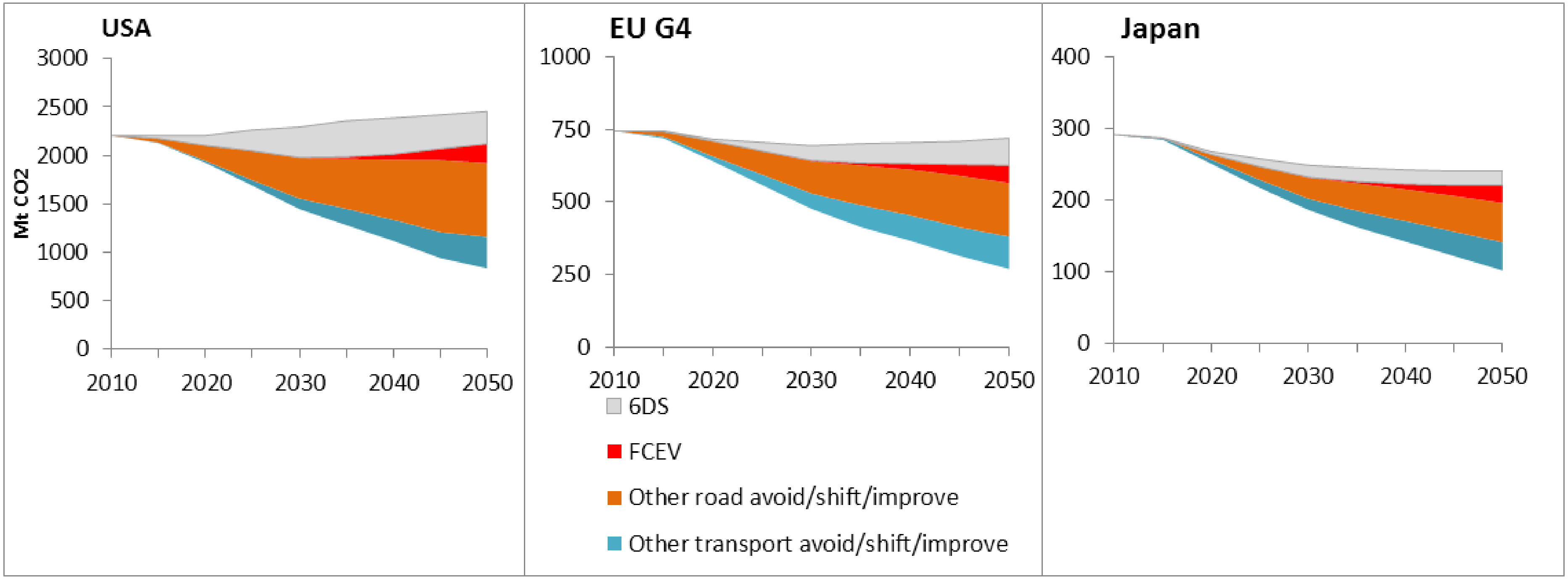
- **Long term infrastructure investment cost per vehicle are in the range of USD 1300 per vehicle in Europe and Japan and up to USD 2000 per vehicle in the US**
- **Differences in specific investment result from regionally different H2 demand per vehicle per year, due to different annual mileages and fuel economies**
- **Different population densities and transmission distances do also greatly impact specific infrastructure investment costs**

Hydrogen generation (not optimized)



- Imported H2 is not taken into account
- Estimate of H2 generation from low cost renewable electricity based on 2DS variable renewable generation and assumed curtailment rates calculated in external studies

FCEV emission savings



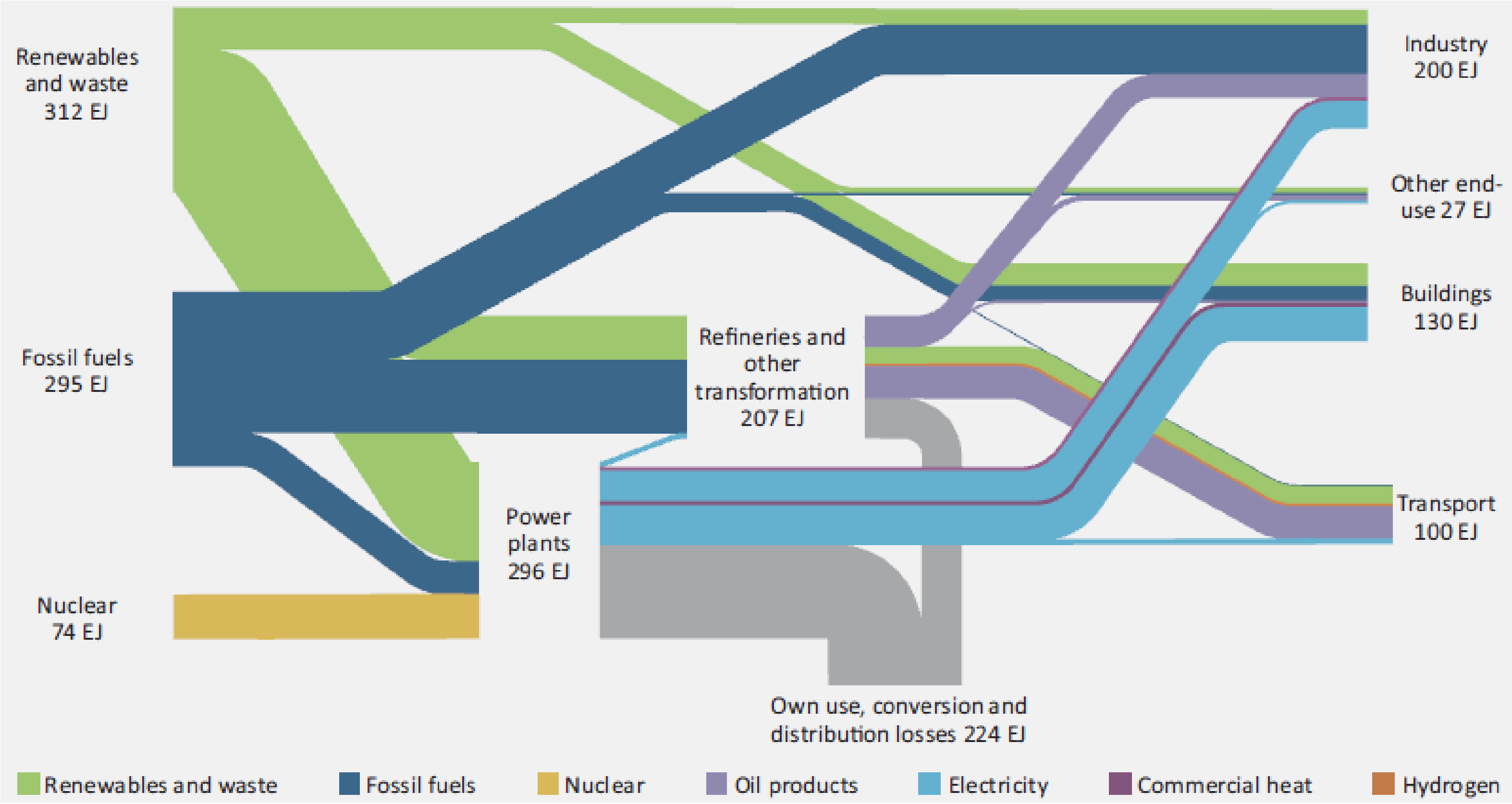
- **Within the underlying (preliminary) supply scenario hydrogen is decarbonized to match the 2DS transport sector emission results (from ETP 2014)**
- **In this scenario hydrogen is produced from natural gas with and without CCS, biomass gasification and low cost renewable electricity (incorporating curtailment levels shown in other studies)**

Energy integration and storage – Preliminary results

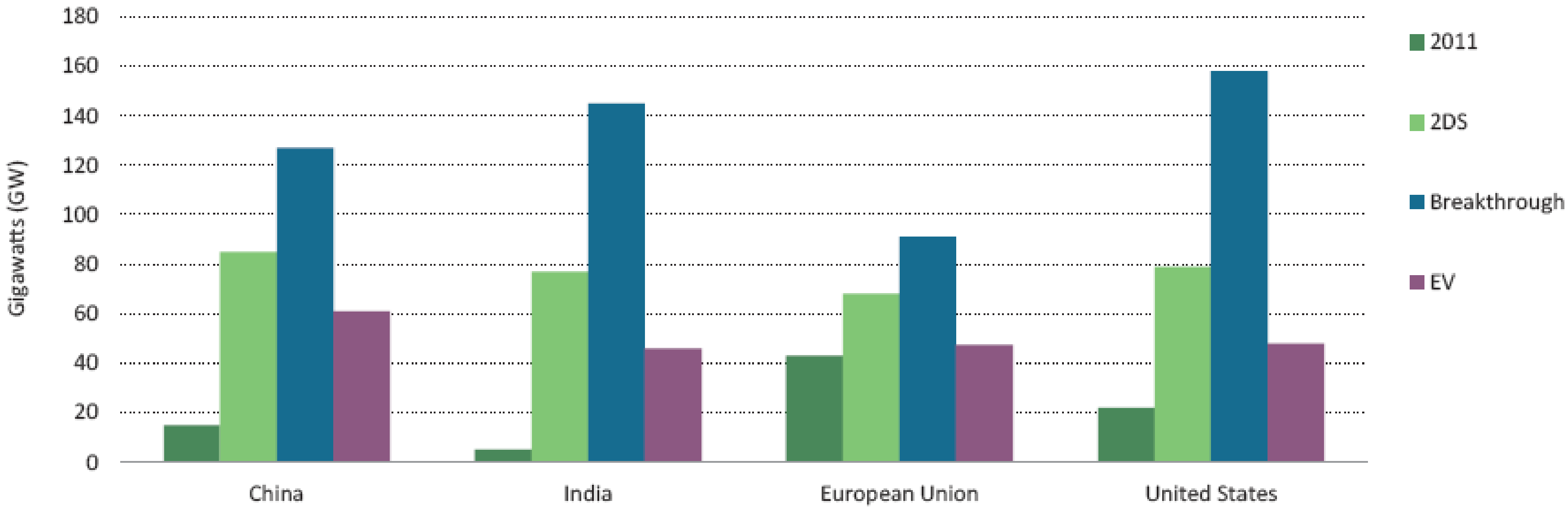
Vision – Hydrogen electricity storage

What if hydrogen electricity storage becomes competitive?

- Estimation of storage potentials in 2DS
- Costs/efficiencies of H_2 electricity storage technology to be competitive
- Are there synergies between energy storage/renewable energy integration and hydrogen T&D infrastructure for transport?



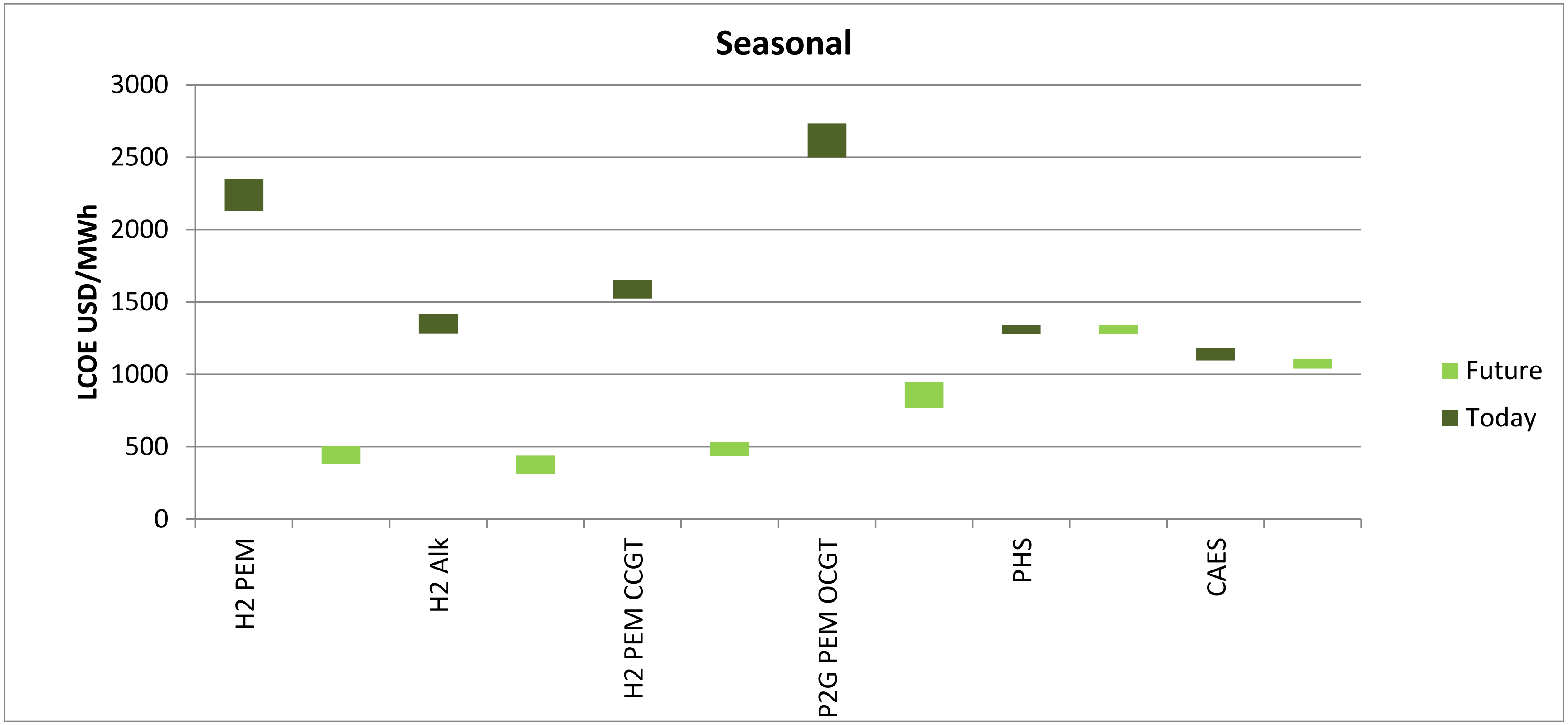
Electricity storage potential 2DS



- **Combination of long-term energy system optimization and dispatch model run with 2050 fixed power sector fleet**
- **Storage results captures only time-wise mismatch between supply and demand**
- **Breakthrough scenario assumes 50% reduction of investment cost of benchmarking technology**
- **Renewables penetration globally >70% by 2050 in the power sector**

Long term electricity storage

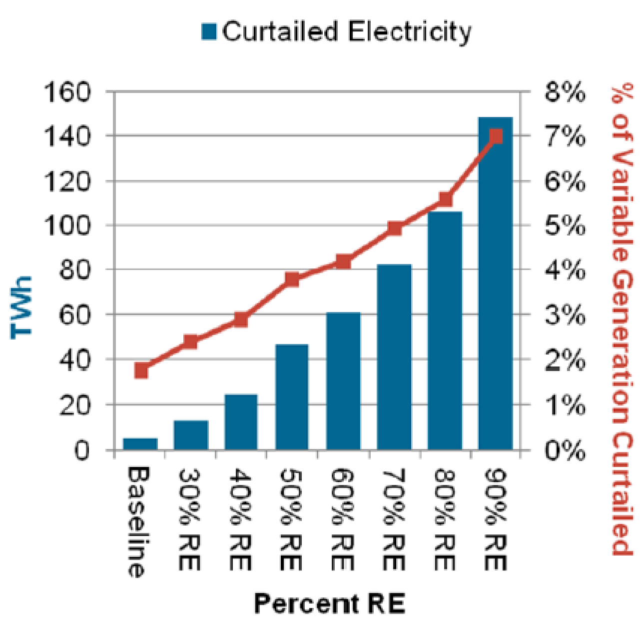
Assumptions: 500MW output, 120h discharge at nameplate power, 5 cycles a year, ranges show difference between free electricity and electricity at 50 USD/MWh



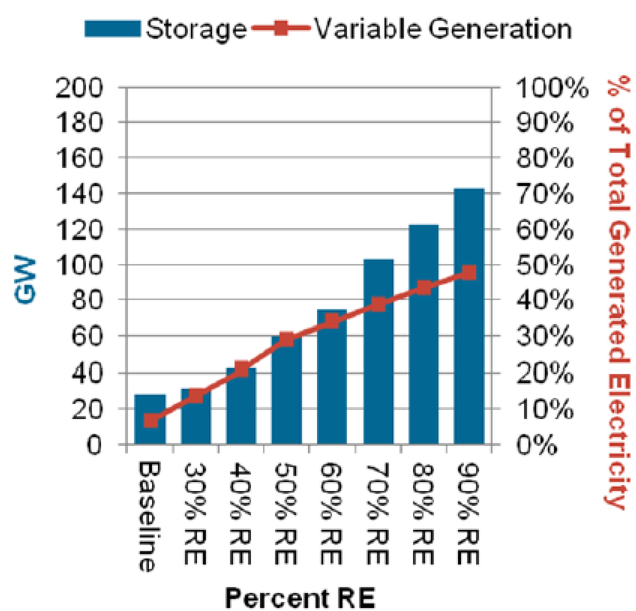
- **Hydrogen offers the only option to get anywhere close to acceptable LCOE for large scale, long-term electricity storage**
- **Large scale, long-term electricity storage always suffers from low load factors if no other services are provided**

Vision – Power-to-fuel

- **What if otherwise curtailed electricity could be used to produce H_2 for transport?**
  - **Even under optimistic cost/efficiency assumptions of electrolyzers, low value electricity needs to be used to make renewable H2 competitive with NG steam reforming**
  - **Can the inherent storage need for transport refueling infrastructure serve as a storage for VARres integration?**



(a) Curtailed electricity in 2050



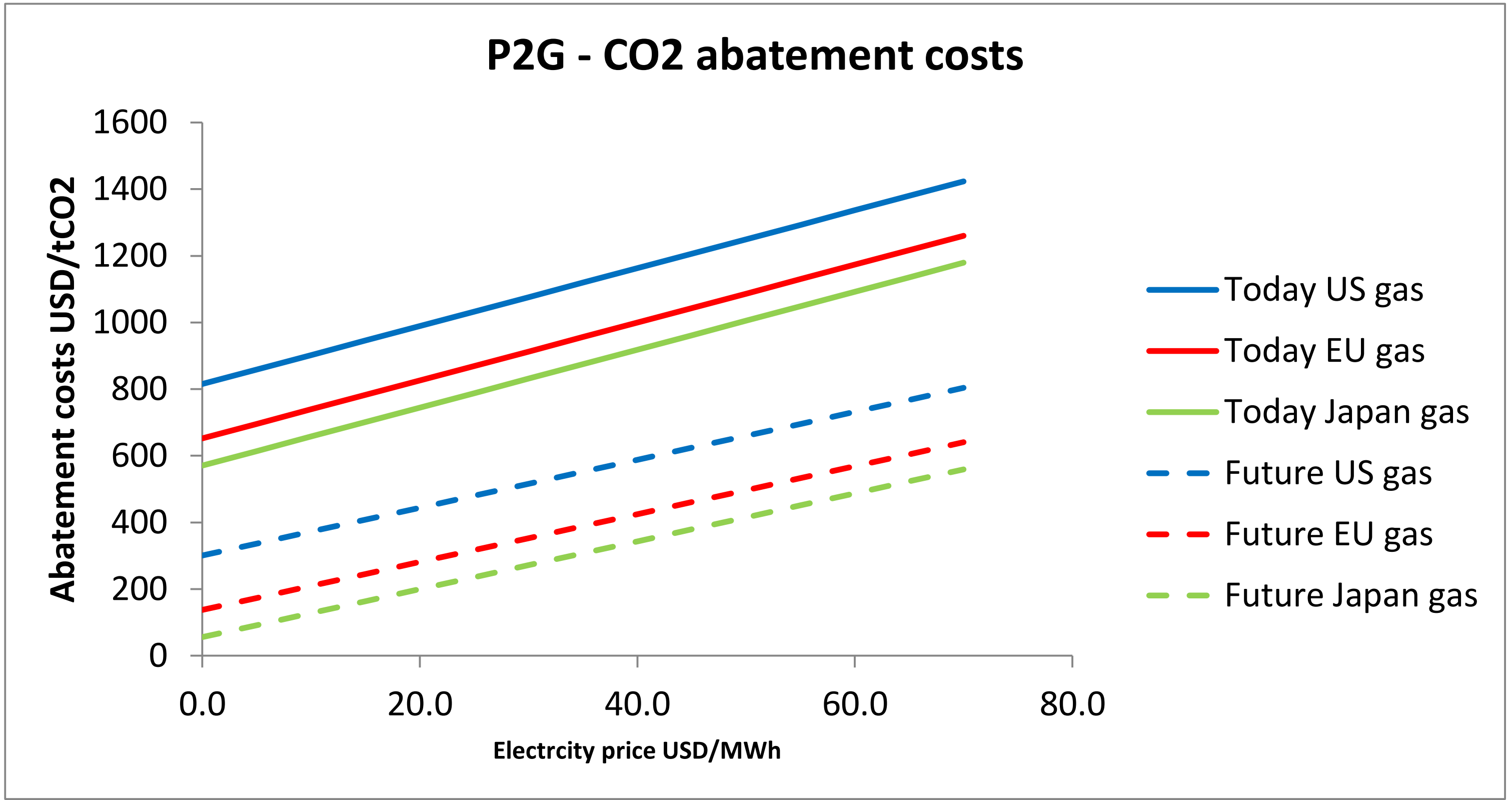
(b) Storage capacity in 2050

Source: Renewable Electricity Futures Study, Volume 1, NREL 2013

Vision – Power-to-gas (HENG)

Can power-to-gas be a competitive flexibility option?

- At which carbon price power-to-gas can get competitive?
- Estimates of regional storage potential within existing NG infrastructure under certain blend shares based on existing studies
- What techno-economic parameters of electrolyzers needs to be achieved?



Proposed milestones and key actions for discussion

Milestones – Key hydrogen conversion technologies

Metric	Possible milestones and targets	Proposed time frame
Electrolyzer in general	Optimize both capital costs and efficiency. Optimize current density, operating pressure and temperature with respect to capital costs, efficiency and lifetime. Focus on increasing operational flexibility and such characteristics as ramp-up rates, start times and stand-by energy use. Draw upon the modularity of electrolyzers and the respective flexibility of power capacity.	
PEM electrolyzer	Reduce in vestment cost to USD 600 per kW. Investigate impact of economies of scale on investment costs and examine possible spill-over effects from large scale fuel cell production processes in the transport sector. Reduce or avoid the use of precious metals and increase stack capacity as well as maximum stack size. Increase efficiency to more than 80%.	
Alkaline electrolyzer	Reduce investment cost to below USD 600 per kW. Increase operational flexibility and reduce maintenance costs. Increase technical lifetime and optimize power density. Increase efficiency to more than 80%.	
Solid oxide electrolyzer	Increase cell lifetimes to at least 20,000h at acceptable degradation. Improve operational flexibility.	
Operational aspects	Monetize all byproduct streams. Optimize operation and maximize benefits of all energy services such as hydrogen production, provision of negative control power, provision of heat and oxygen.	

Milestones – Key hydrogen conversion technologies

Metric	Possible milestones and targets	Proposed time frame
Fuel cells in general	Optimize both capital costs and efficiency. Increase lifetime.	
PEM fuel cells	Reduce investment cost to below USD 800 per kW for stationary applications by reducing both the cost of the stack and the cost of balance of plant . Reduce costs for mobile applications to below USD 100 per kW. Reduce precious metal requirements and increase lifetime at the same time. Reduce sensitivity to impurities of hydrogen and prove feasibility at large stack capacities.	
Alkaline fuel cells	Increase operational flexibility and reduce maintenance costs. Increase technical lifetime to more than 10,000h and optimize power density.	
Solid oxide fuel cells	Reduce investment costs to below USD 200 per kW. Increase cell lifetimes at acceptable degradation to more than 10,000h. Improve operational flexibility.	
Operational aspects	Recover and monetize process heat generated in fuel cells when used in stationary applications to improve overall efficiency.	

Milestones – Energy storage

Metric	Possible milestones and targets	Proposed time frame
Underground storage potential	Evaluate and establish inventories of the potential of underground caverns for hydrogen storage on a national basis. Prove the feasibility of hydrogen storage in salt caverns, depleted oil and gas fields as well as aquifers with respect to different parameters such as undesired reactions, capacity, development costs, location & existing infrastructure	
Metal hydrides	Reduce costs, increase weight specific storage capacity and reduce charging times.	
Gaseous storage cylinders	Reduce material costs for on-board storage in fuel cell electric vehicles.	
Liquid hydrogen storage	Improve thermodynamic parameters of liquid storage tanks to reduce boil-off rates. Improve efficiency of the liquefaction process through heat recovery and improved compressors.	

Milestones – Fuel cell electric vehicles

Metric	Possible milestones and targets	Proposed time frame
Vehicle costs	Achieve a price premium of 20% or less compared to conventional ICE vehicles at production rates compared to today's hybrid vehicles production (1 to 1.5 million s per year)	
FC stack durability	Achieve a lifetime of 5000 hours with a stack voltage degradation of less than 10%	
Fuel efficiency	Achieve fuel efficiencies of 1 to 0.8 kg of hydrogen per 100 km to allow a range of at least 500km	
Technology packaging	Achieve technology packaging to make FCEVs models compatible with conventional vehicle chassis – therefore increase power density and specific power of the fuel cell system	
On-board hydrogen storage	Reduce the volume and the weight of the hydrogen tank. Reduce specific costs to at least below USD 12 per kWh. Therefore reduce manufacturing costs of the carbon fiber layer	
International refueling standard	Establish an international standard for refueling pressure and shape of the nozzle	

Milestones – T&D and refueling infrastructure

Metric	Possible milestones and targets	Proposed time frame
Refueling station coverage	Achieve coverage with hydrogen stations of all cities >200,000 to 250,000 inhabitants as well as interconnecting highways	
On-board pressure and nozzle standards	Agree on international standard for on-board hydrogen storage pressure and nozzle shape. Therefore find optimal storage pressure to balance vehicle storage requirements and investment at the station for compression	
H2 measuring and billing standard	Agree on international standard to measure and bill hydrogen flow at the station	
H2 safety codes and standards	Introduce reasonable safety codes and standards for hydrogen handling and storage at refueling stations	
Investment risk	Reduce investment risk. Agree on strategies between vehicle OEMs and infrastructure owners for technology roll-out. Fast ramp-up rates for vehicle stock and intelligent clustering of infrastructure around early demand centers avoid long times of asset underutilization and increase expectations on return of investment	
Station footprint	Evaluate impact of station footprint on costs. Include results when setting up safety codes and standards for hydrogen handling and storage on hydrogen stations	

Milestones – Hydrogen generation

Metric	Possible milestones and targets	Proposed time frame
Carbon footprint of hydrogen generation	Agree on long-term hydrogen decarbonization strategies with an eye towards near term implications of renewable hydrogen requirements on hydrogen costs and infrastructure pay-back times	
Generation of hydrogen for energy use in the near term	Evaluate cautiously the real level of "excess" hydrogen generation capacity at today's existing generation sites in the refining and chemical industry, taking into account already very high levels of utilization of hydrogen generation assets Evaluate synergies between increasing demand of hydrogen with decreasing crude oil quality in the refining industry and additional hydrogen demand e.g. from the transport sector	
Hydrogen quality requirements	Agree on standards for hydrogen purity for use in fuel cell electric vehicles and re-evaluate the economic potential of using waste hydrogen flows in the chemical industry against these quality requirements	
Quantify curtailment levels with increasing variable renewable share in the power sector	Quantify possible levels of curtailment of renewable electricity in the power sector taking into account high shares of variable renewable energy. Use tools which allow to take into account high timely resolution of variable renewable supply and electricity demand **and** high spatial resolution of sources and sinks to realistically balance expansion of alternative energy use, storage and transmission infrastructure	
Quantify optimal pathways for use of biomass	Evaluate optimal pathways for the use of biomass taking into account different energy vectors in the power and heat generation, transport and residential sector	

Milestones – Power sector flexibility

Metric	Possible milestones and targets	Proposed time frame
Power-to-gas (HENG)	Establish agreed maximum blend shares for different natural gas based end use applications, both with respect to absolute limits but also with respect to rates of changes in quality. Investigate the storage potential of the existing natural gas grid taking into account different points of injection of hydrogen and downstream compatibility with end-users as well as seasonal changes in pipeline dynamics Expand legislation to fully take into account the benefits of lower-carbon natural gas blends	
Power-to-fuel	Prove the technological and economical viability of multiple input multiple output demonstration plants which aim at providing energy services such as negative control power and peak-shaving to the power grid and hydrogen from electricity, natural gas and/or biomass to the transport sector.	
Hydrogen based electricity storage	Adapt power market regulation to enable benefits stacking and remuneration of all services provided by energy storage applications to the power system such as provision of negative and positive control power, infrastructure investment deferral or variable renewable integration.	

Near term actions – Governments

Metric	Possible milestones and targets	Proposed time frame
Government	Push forward long term climate targets. Strengthen fuel economy regulation, greenhouse gas emission standards and pollutant emission regulation beyond the time frames already covered by today's approaches. Evaluate alternative fiscal measures to incentivize alternative fuel vehicles, e.g. feebate systems. Improve methods to quantify directly and indirectly occurring upstream greenhouse gas emissions during transport fuel generation, transmission, distribution and retail beyond the focus on carbon dioxide emissions Plan for compensation of lower fuel tax income due to switch to alternative fuels, which needs to exempted from taxes to incentivize technology uptake during the first decade(s) Establish programs for consumer information campaigns. Establish a power market framework which allows for the adequate remuneration of all power system services provide by energy storage technologies	

Near term actions – Governments

Metric	Possible milestones and targets	Proposed time frame
Academia	Provide the tools necessary to analyze the entire energy system including all energy demand and energy supply sectors with the time-wise and spatial resolution necessary to adequately examine synergies between hydrogen demand, variable renewable integration and energy storage. Improve the data on resource availability and costs necessary to adequately examine optimal pathways of energy transformation from primary energy to final energy in an integrated assessment modeling environment. Improve the tools to better represent the set-up and expansion of hydrogen transformation, distribution and retail infrastructure based on real GIS data and detailed localization of hydrogen sources and sinks. Include and improve linkages between different energy infrastructure systems (e.g. the power grid and the natural gas grids) in national energy system modeling efforts.	

Next steps

- Finalizing analysis for energy storage and energy integration
- Collection of case studies for several H2 projects
  - Integrated energy storage and transportation project
  - Case study power-to-gas
  - Case study electrolyser and control power market
  - Case study fuel cell micro CHP (Japan)
- Further developing analysis for industry
- Drafting of milestones and key actions (additional WS?)
- Drafting of the document
- Circulation of the document for review Q4 2014
- Publishing the roadmap Q1 2015

International Energy Agency

Thank you!