

Worldwide Status of Hydrogen Fuel Cell Vehicle Technology and Prospects for Commercialization

David L. Greene

Oak Ridge National Laboratory

K. G. Duleep

HD Systems

May 14, 2013

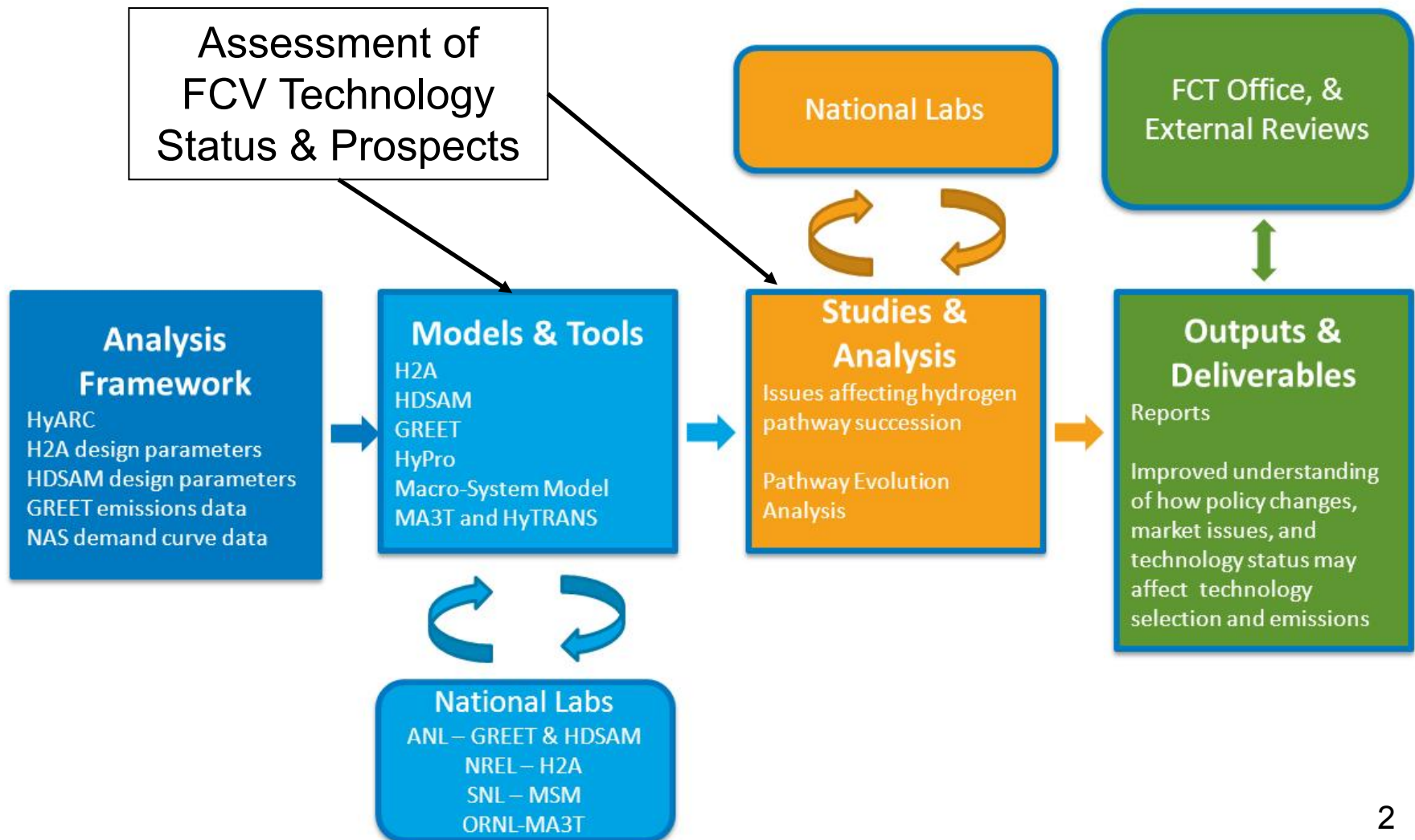
Project ID#
AN030

1

Project Overview

Approach

Effects of Technology Cost Parameters on Hydrogen Pathway Succession



Overview

Timeline

- Project start date: 5/1/2012
- Project end date: 10/2013*
- Percent complete: 100%

Budget

- Total project funding
 - DOE share: \$200,000
- Funding received in FY12: \$200,000
- Funding for FY13: \$300,000 is for new projects.

Barriers

- Future market behavior
 - Understanding the behavior and drivers of fuel cell, fuel and vehicle markets
- Inconsistent data
 - Establishing global technology, industry & deployment status
- Unplanned studies and analysis

Partners

- HD Systems
- Original Equipment Manufacturers (OEM) Developing Fuel Cell Vehicles (FCV)
- Ministry of Economy, Trade and Industry (METI), National Organisation Wasserstoff (NOW), Hydrogen Supply/Utilization Technology (HySUT), California Fuel Cell Partnership (CAFCP), International Council on Clean Transportation (ICCT)
- Project lead: ORNL

Relevance: Our goal was to establish the status of fuel cell vehicle technology and commercialization plans in Japan, Korea, EU and US.

- Benchmark progress seen by OEMs
 - Performance of technology
 - Manufacturing cost
 - Timing of commercialization
- Document government and industry plans for deployment
- Recalibrate models of market transition

Approach

- Search and review literature
- Conduct briefings and confidential interviews with OEMs
- Conduct briefings and confidential interviews with governments and Non-governmental organizations (NGO).
- Analyze data obtained, remove identifying information, publish summary report.

Accomplishments and Progress

Stack performance is good enough for OEMs to begin commercialization in 2015.

- ▶ Today's stacks have 30% higher current density and output v. 2006 (1.9 kW/kg v. 1.5; 2.5 kW/L v. 1.9).
 - Boosted (1.8 to 2.2 bar) enabled by improved sealing.
 - Stamped metal bi-polar plates reduce size, weight and cost.
 - Thinner organic membranes → greater output/cell.
- ▶ Pt content for an 85 kW stack is down from 200g in 2000 to 100g in 2005 headed to 30g for manufacture in 2015.
 - 2016 target of 0.15g/kW causes loss of durability today.
- ▶ Cold start is no longer a problem (-20°C and below).
- ▶ Efficiency is 68-70% at light load, 54-55% at full load, with EU cycle efficiencies of 60-63%.
- ▶ Modes and mechanisms of fuel cell degradation now well understood.
 - Durability doubled from 2003-2009.
 - 12 to 15 years with a =<10% voltage drop (>=30g Pt).

Accomplishments and Progress

What will fuel cell vehicles cost in 2015?

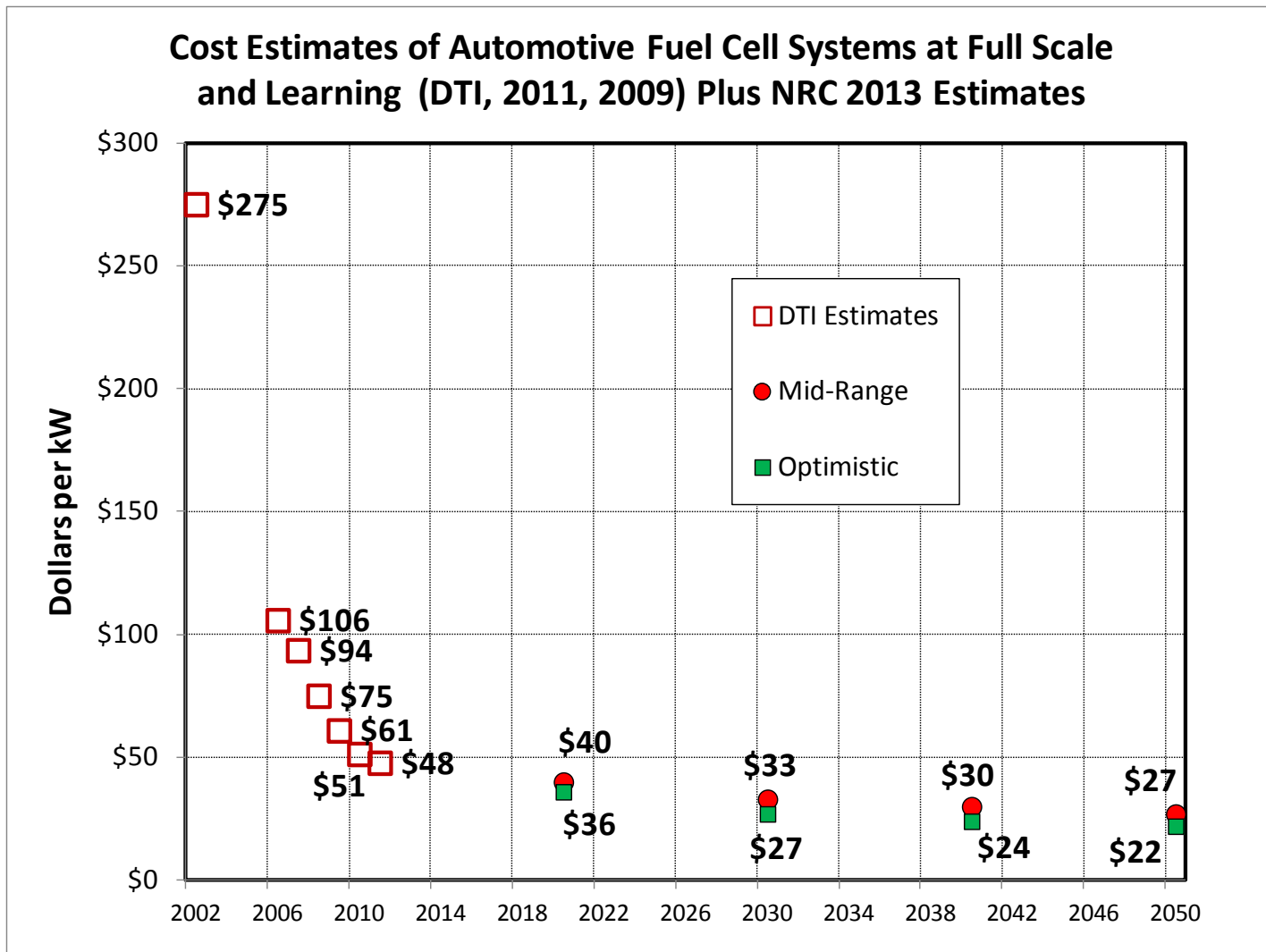
OEM's estimates range from \$50,000 to \$62,500.

Cost in 2012 Euro	2020 (McKinsey)	Our 2015 (est.)
Fuel cell stack	€7,475	€18,890
Hydrogen storage	€2,550	€€5,100
Battery	€870	€1,000
Motor/Inverter/Drive	€3,630	€5,110
Subtotal Powertrain	€14,525	€30,100
Electric HVAC/pwr. acc.	€300	€675
Glider	€11,385	€11,385
Subtotal Manuf. Cost	€26,210	€42,160
Retail Price Equivalent	€30,900	€50,000

1 Euro = \$1.20 to \$1.40 over past 5 years. We use \$1.25.

Accomplishments and Progress

Most manufacturers are confident they know how to make stacks at \$40-\$50/kWh. But they do not know how another 50% reduction will be achieved.

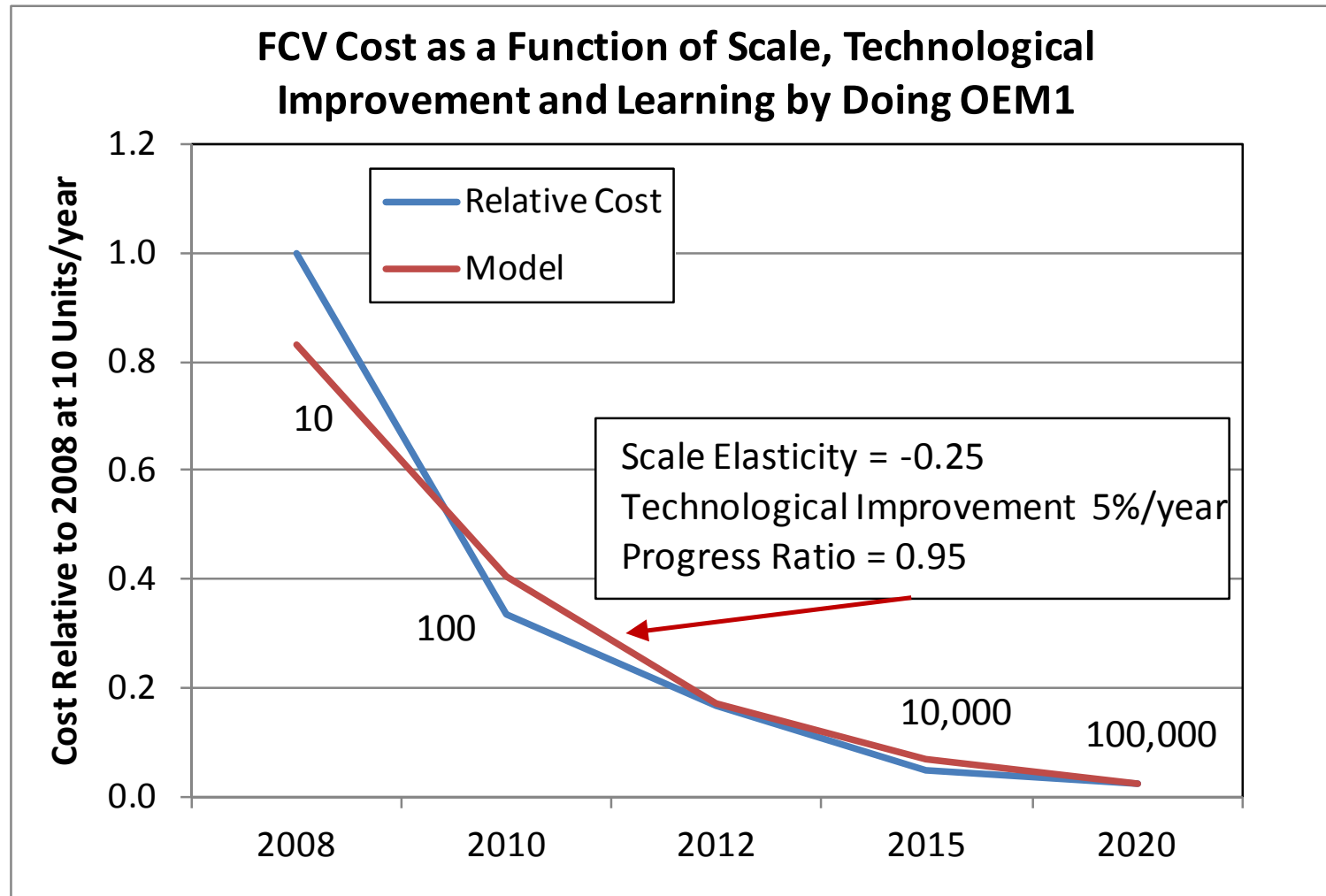


Accomplishments and Progress

All OEMs have agreed to on-board storage as compressed hydrogen at 700 bar.

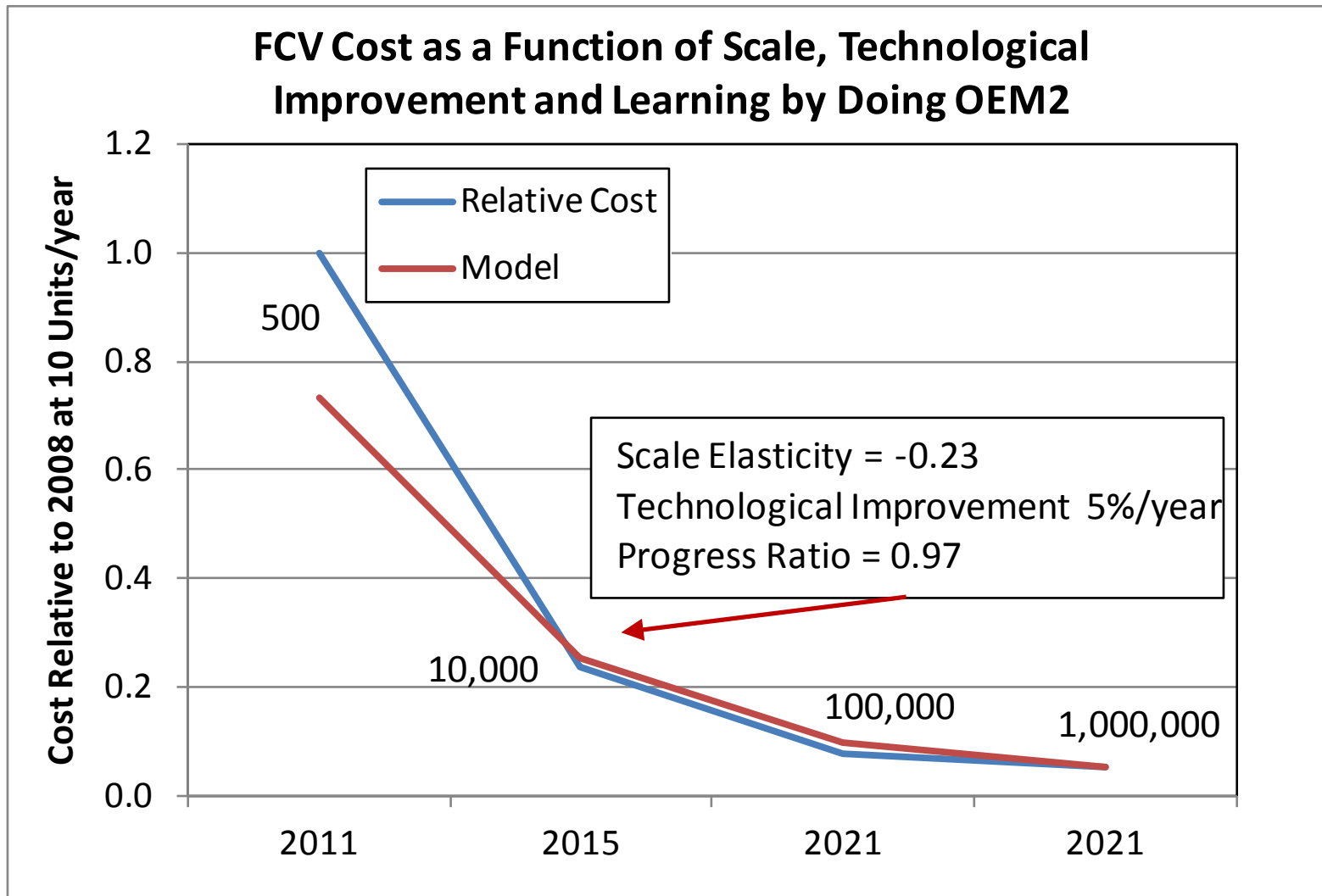
- Consensus that current tank costs are not a reliable indicator of future costs.
- Supplier base extremely limited, costs of regulators, etc. expected to decrease by factor of 10 with volume.
- High volume production cost of \$3,500 for 5.6kg tank optimistic to some, realistic to others.
- Potential for further 15% reduction using lower grade C-fiber.
- Consistent with Argonne National Laboratory estimate of \$3,334.
- This translates to high volume (20,000 to 200,000 units/yr.) storage costs of \$15.50 to \$18.50 per kWh.

OEMs' estimates of future cost reductions are consistent with conservative estimates of scale economies, technological progress and learning.



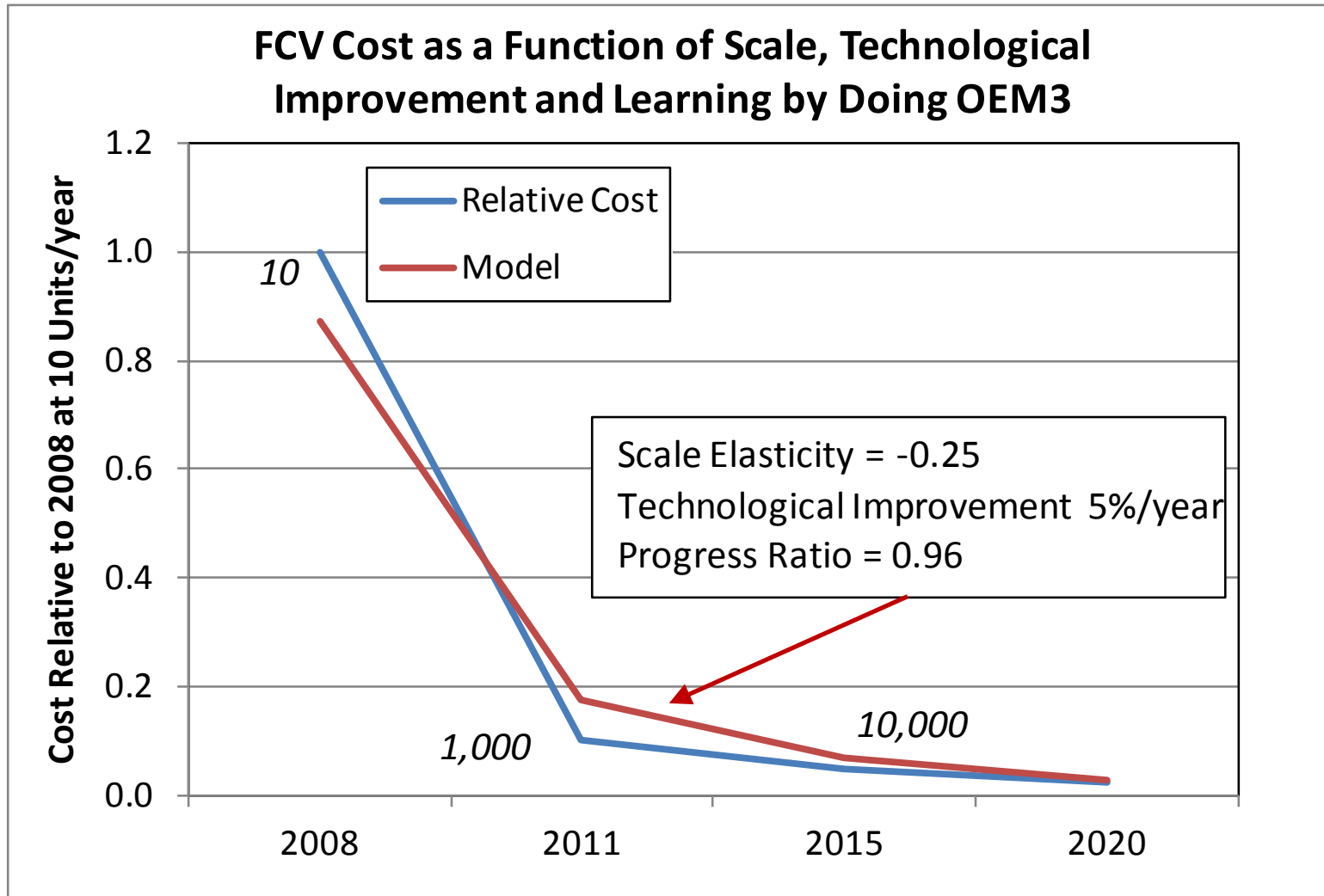
Accomplishments and Progress

Past progress exceeds the rates anticipated for the future. Of course, uncertainty remains.



Accomplishments and Progress

In this case volume was not provided by the OEM and so plausible values were guessed.



OEMs cost expectations appear to be based on conservative assumptions.

- Scale elasticities of -0.23 to -0.25.
 - 2% reduction in cost with 10% increase in volume
- Annual rate of technological progress of 5%.
- Progress ratios of 0.95 to 0.97.
 - 3% to 5% reduction in cost at for each doubling of cumulative production after first 1,000 to 10,000.

Accomplishments and Progress

“Consensus” cost estimates indicate that with continued progress FCVs at a volume of 200,000/yr would have a manufacturing cost of just over \$25,000, and Retail Price Equivalent (RPE) of just under \$37,000.

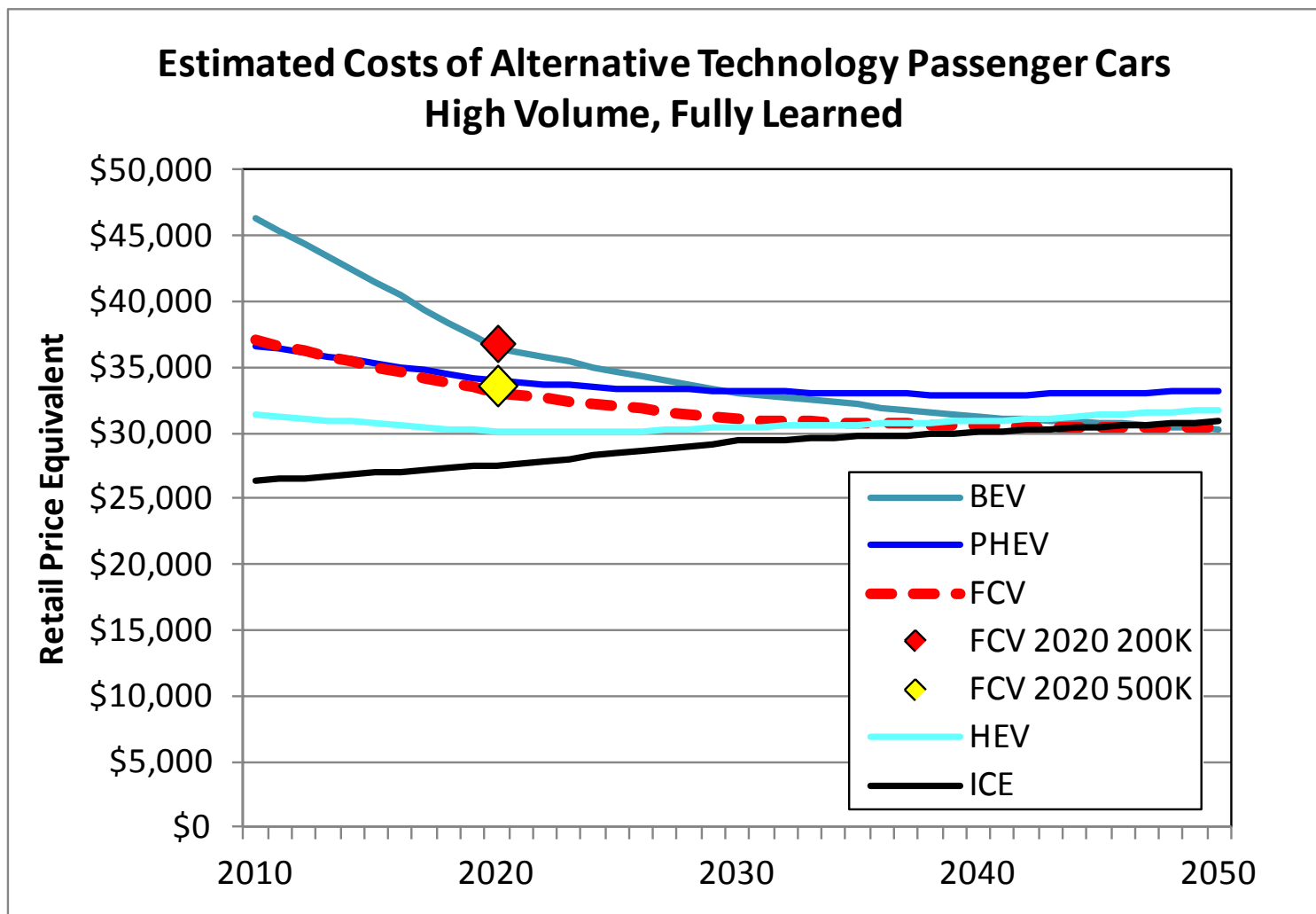
Substantial scale economies would still be achievable.

Cost in \$	2016 (200K/yr)	2020+ (200K/ yr) “Low Tech”	2020+ (200K/yr) “High Tech”
Fuel cell stack (85 kW)	15,150	13,650	7575
Hydrogen storage (5 kg)	5,300	4,750	3,500
Battery (35 kW,2 kWh)	1,300	975	975
Electric Motor/Inverter/ Drive (110 kW peak, 60kW continuous)	3,150	2825	2400
Gearbox	350	350	350
Total Power-train	25,250	22,550	14,800
Electric HVAC/ Regen. Brakes (incremental)	750	650	650
Glider (constant weight)	11,000	11,000	11,000
Total FCV cost	37,000	33,200	26,300

Almost twice
DTI 2012
high volume
estimate.

Accomplishments and Progress

Our estimates of FCV retail price equivalent (incl. overheads and profit) in 2020, scaled to a production volume of 500,000 units/year, are consistent with those of National Research Council (NRC, 2013) and ICCT (2013) studies.



Accomplishments and Progress

Cost reductions in dispensing hydrogen are also needed for competitive hydrogen costs.

- Germany:
 - Cost today is € 0.8 million
 - € 600,000 by 2020
 - Long-run target is € 250,000
- Japan:
 - METI 2013 budget ¥5 B for 50% of 20-25 stations.
 - Cost: ¥1 B/SMR, ¥0.8 B for stations where H₂ is trucked in.
 - Stations costs very high (US\$10M) in Japan due to very strict regulations on hydrogen storage and production. Expect 15% cost reduction per year.

Accomplishments and Progress

A critical concern for all OEMs is uncertainty about future infrastructure availability.

- The egg (infrastructure) must come first.
- There are very few hydrogen stations in operation in any country.
 - Japan: 12 in 2012, 100 by 2015, 1,000 by 2025 (2% vs. 47,000 petrol stations).
 - Germany: 15 in 2012, 50 by 2015 (Daimler & Linde, Air Liquide, Total), 1,000 by 2030
 - Korea: 18 in 2013, 43 in 2015, 168 in 2020, 500 by 2030.
- All the governments and NGOs had plans but none had actually funding in hand at the time.
- It is also not clear that current plans are adequate or coordinated with credible estimates of FCV sales in country.
 - OEMs express confidence in early station numbers but when pressed are unsure.
 - Japanese and German OEMs are concerned that US does not plan to control the price of hydrogen during the early transition.
 - The German plan is to concentrate losses at the retail outlet and subsidize there to insure that hydrogen costs 25% less than gasoline or diesel for 10-15 years.
 - The Japanese plan is to subsidize station capital costs and rely on agreement with station operators (oil, gas and utility companies) to price in accordance with policy.

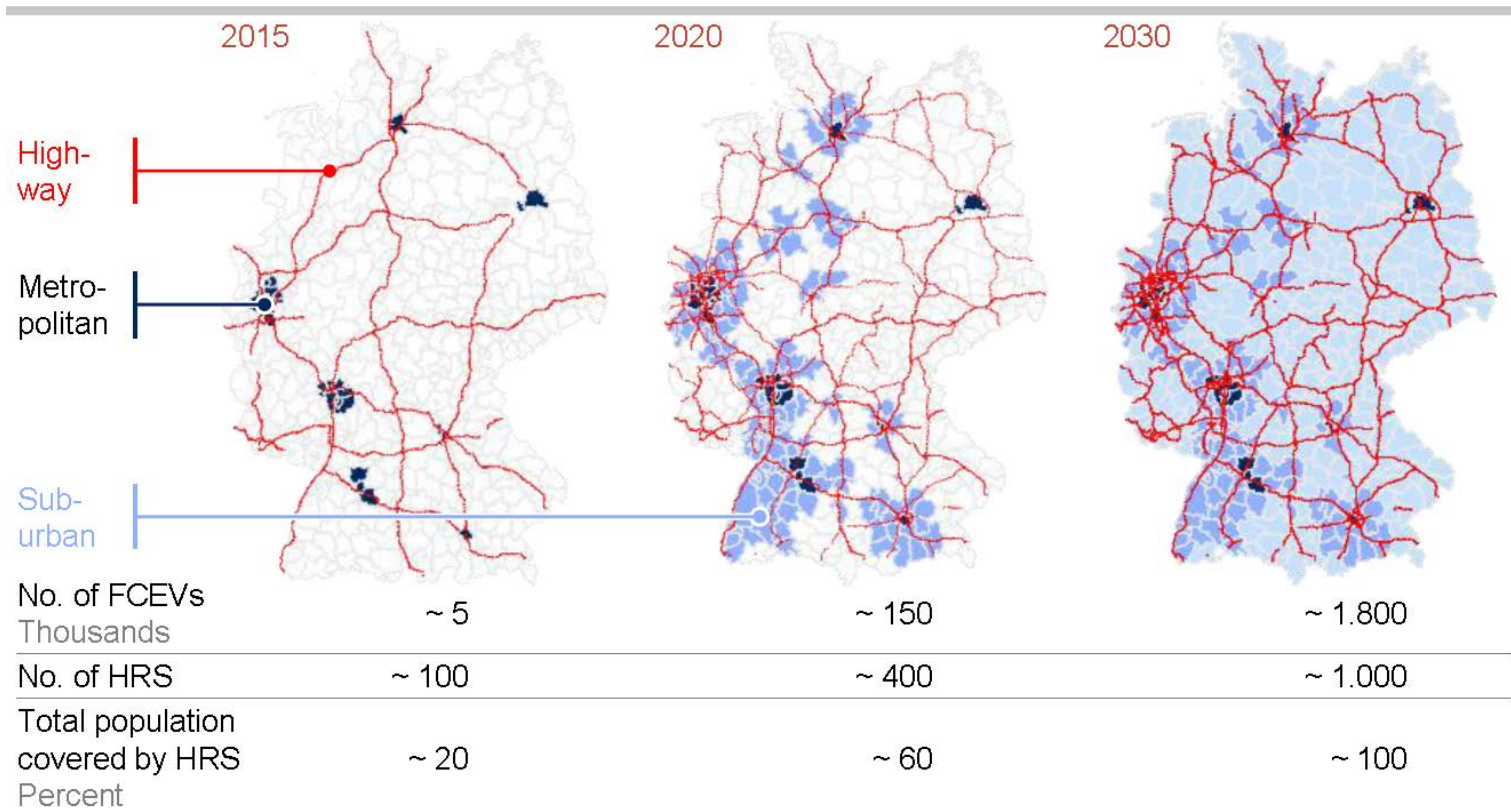
Accomplishments and Progress

NOW's deployment plan, like others, is too optimistic given some OEM's decisions to delay commercial production.

H₂ Mobility

Potential HRS rollout in Germany

- Tier-1 regions
- Tier-2 regions
- Tier-3 regions



Plans for Remainder of FY 13

Future analyses should quantify the implications of coordinated international market development for the U.S. transition to hydrogen vehicles.

- ICCT study demonstrated interdependencies due to scale economies and learning-by-doing.
- Enhance and update LAVE-Trans used in NRC 2013
 - Consistent technology costs, performance and production
 - Recalibrated scale economies, learning rates
- Expand model to include interdependencies of electric drive production within and outside of the U.S. (FY13)
 - Analyze and quantify interdependencies among regions and benefits of coordinated market development.
- Publish ORNL report on technology status: May 2013
- Publish ORNL report documenting costs and benefits of global market development: June 2014
- Contribute to development of hydrogen infrastructure planning.

Collaborations

We are grateful to those who shared essential information.

- OEMs and Industrial Gas Producers in the U.S., Germany, Japan and Korea.
 - Confidential meetings with key technical staff
 - Study not possible without their cooperation
- Government agencies and NGOs
 - METI
 - German Ministry of Environment
 - California Air Resources Board
 - National Organisation Wasserstoff
 - HySUT
- Especially principle subcontractor, Mr. Gopal Duleep, HD Systems, Inc.

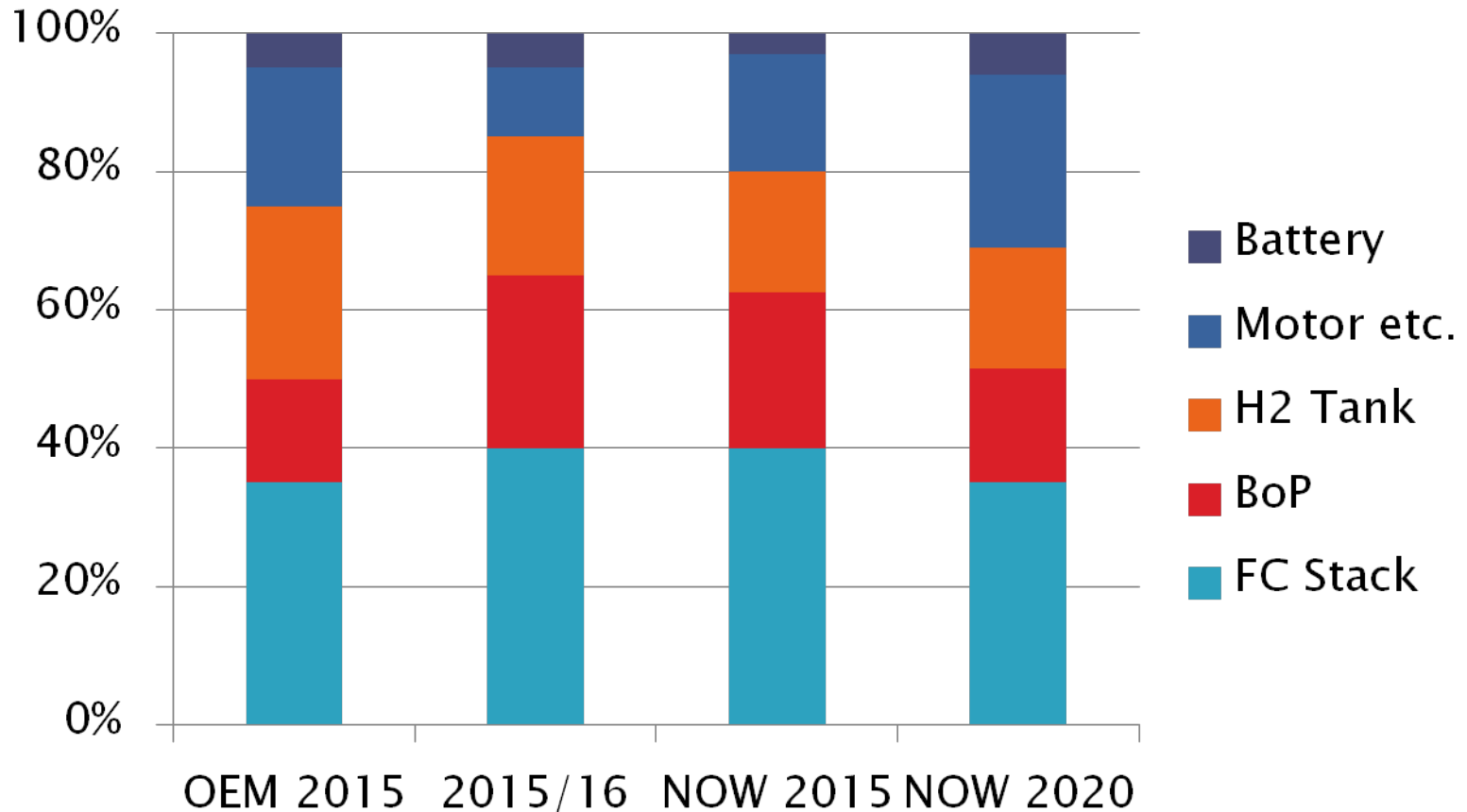
Summary

Technological development is on track, OEM production plans are lagging chiefly due to uncertainty about infrastructure.

- ▶ FCV performance is ready for introduction in 2015.
 - OEM expected to begin limited commercial sales in 2013, 2015, 2017 and 2020.
 - Conditional on availability of hydrogen refueling infrastructure.
- ▶ FCV drive train costs 2X too high (at scale).
 - Key technological barrier: Pt vs. durability trade-off
 - Meeting cost targets consistent with conservative assumptions about scale economies, LBD and technological progress.
- ▶ Availability of infrastructure is the key concern affecting the timing of commercialization.

Technical Back-Up Slides

For the near future the fuel cell stack and balance of plant (BoP) are likely to comprise at least half of the cost of the drive train. One OEM expects very low electric motor costs, another low H₂ storage tank costs.



Next generation stacks appearing in 2015-16 will be substantially improved over today.

- ▶ Specific power of 2.2 kW/kg and 2.9 kW/L at 2 to 2.5 bar.
- ▶ Pt loading of 0.3 to 0.35 g/kW (25-30g for 85 kW).
- ▶ Stack life of 12 to 15 years with <10% voltage loss.
- ▶ Overall cycle efficiency of 60% to 65%.
- ▶ On-board storage at 700 bar for a 400 mile range.
- ▶ Manufacturers are therefore confident that fuel cell vehicles will meet all technical requirements for market introduction.
- ▶ Cost reduction and refueling infrastructure are now the greatest concerns.

In particular, the CAFCP's FCV sales estimates are highly optimistic relative to our information.

Station Deployment and Expected Vehicles Sales in California					
Year	Start of Year Station Total	Added Stations	CAFCP Number of Vehicles on the Road	CAFC Sales	Estimated Minimum ZEV Sales Requirement
2012	4	4	312	100	0
2013	8	9	430	118	0
2014	17	20	1389	959	0
2015	37	31	10000	8611	2134
2016	68	Market needs	20000	10000	2269
2017	84	Market needs	53000	33000	2297
2018	<i>100</i>	Market needs	<i>95000</i>	<i>42000</i>	2943
Sources: CAFCP, 2012, table 5; ICCT estimates.					
Numbers in italics have been approximated based on lower bounds given in CAFCP table 5.					